Simulation Modelling Practice and Theory 118 (2022) 102529

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

High level architecture-based framework for modeling interdependent critical infrastructure systems

Joseph Jonathan Magoua [a], Fei Wang [a], Nan Li [a,b,*]

[a] *Department of Construction Management, Tsinghua University, China*
[b] *Hang Lung Center for Real Estate, Tsinghua University, China*

ARTICLE INFO

Keywords:
Critical infrastructure system
High level architecture
Co-simulation
Interoperability
Interdependency
Domain knowledge
Systemic heterogeneity

ABSTRACT

Interdependencies among urban critical infrastructure systems (CISs) significantly impact the reliability and performance of CISs and the resilience of modern societies. Although several approaches exist for modeling interdependent CISs and studying their behavior, models developed in previous studies often fail to incorporate CIS domain knowledge, capture systemic heterogeneities among the CISs, and accurately model CISs interdependencies. Consequently, existing models have a limited ability to simulate interdependent CISs with sufficient detail and accuracy. To address these limitations, this study proposes a high-level architecture (HLA)-based framework for modeling interdependent CISs that can leverage and integrate well-tested practices, knowledge, data and simulation tools accumulated over years of wide usage in various CIS domains. The framework provides a methodology for co-simulating heterogeneous fine-grained CIS domain-specific models and modeling complex interactions between them and with their external environments, hence reproducing with high fidelity the complex coupled systems. A case study of two interdependent power and water systems was conducted, which demonstrated the efficacy of the proposed framework. Simulation results revealed that the HLA-based CISs model could capture the heterogeneous behaviors of the CISs and reveal a variety of failure-induced system vulnerabilities and feedback loops which may not be observable when using other existing modeling approaches.

1. Introduction

Critical infrastructure systems (CISs) such as water supply system, power supply system, transportation system, banking and finance system, telecommunication system, and so on, play a major role in the sustainable development of modern societies. If disrupted, CISs would have a debilitating impact on the resilience, defense and economic security of cities [1], thus the reliability and performance of CISs should be constantly monitored and improved. With the growth in scale and complexity of modern cities, CISs increasingly rely on each other for proper operation. The interdependencies among CISs may have both positive and negative effects on system behavior. Leveraging the advantages of interdependencies can contribute to improving the efficiency of CISs [2]. For example, the transportation system plays a significant role in the distribution of resources and goods required or produced by other systems, and thus a slight improvement of the transportation system may significantly improve the efficiency of the dependent systems. On the other hand, the undesirable effect of interdependencies among CISs is the increase in system vulnerabilities [3], as various events in recent

* Corresponding author
E-mail address: nanli@tsinghua.edu.cn (N. Li).

https://doi.org/10.1016/j.simpat.2022.102529
Received 21 November 2021; Received in revised form 11 March 2022; Accepted 14 March 2022
Available online 16 March 2022
1569-190X/

history have repeatedly demonstrated that failure of a CIS can lead to a catastrophic succession of adverse events in other CISs [4]. It is therefore crucial to identify system vulnerabilities under normal operational conditions, and to assess and predict the reliability and performance of interdependent CISs under unfavorable conditions such as hazards or system malfunctions. To study how the presence of interdependencies affects CISs, it is necessary to design interdependent CISs models that can accurately represent (1) the topological, functional and operational heterogeneities among CISs; (2) the complex interdependencies among the CISs, and with their respective external environments; and (3) the complex simulation scenarios to which the CISs are subjected.

According to prior research [2], a comprehensive interdependent CIS model must: (1) leverage new or legacy software applications for accurately modeling systems and agents; (2) integrate a wide variety of domain knowledge; (3) capture, with high fidelity, the dynamic interplay and interdependencies among models; and (4) accommodate a broad range of analysis contexts and simulation scenarios. Over the years, several models were proposed for analyzing interdependencies and systems behavior. The earlier models relied mainly on mathematical formalisms such as Markov chains [5], petri nets [6], hierarchical holographic modeling (HHM) [7], and so on. The complexities in model representation, nature of CIS interdependencies, and study scenarios have led researchers to turn to more sophisticated computational approaches such as agent-based modeling (ABM) and network-based (NB) modeling. ABM and NB are the most commonly adopted approaches in prior studies for modeling interdependent CISs models as monolithic models [8–11]. A significant challenge when adopting monolithic models is to reasonably model, within a single conceptual framework, the heterogeneous nature and behavior of multiple systems, interdependencies among them, and their interactions with the external environment [2,12]. For example, in real life, CISs are very different in terms of their physical network features, transported material properties, operational mechanisms, and disaster response patterns, but when modeled under a monolithic framework, it is challenging to capture all these heterogeneous dimensions. The primary reason being that most monolithic models adopt a top-down design strategy for modeling systems, capturing only the top-level features of the CISs and missing the low-level features that embody most of the systems' domain knowledge and heterogeneities [12]. Another reason is that the commonly used models might not support some of the mathematical and logical formalisms needed to reproduce, with high fidelity, the component functionalities specific to certain CIS domains. To address the above limitations of monolithic models, a few studies have attempted to co-simulate multiple CIS models [13–15]. However, these studies face the challenge of ensuring the interoperability of heterogeneous models. Hence, prior studies that adopted this approach either used highly abstracted CIS models to facilitate model interoperability, simulating only basic system interactions between the models, or relied on homogeneous CIS models. In sum, the existing approaches for modeling interdependent CISs suffer the challenge of modeling interdependent CISs with sufficient details and accuracy, resulting in their limited ability to provide new insights about the heterogeneous behavior of increasingly complex interdependent CISs. Therefore, there is a need for more advanced modeling approaches that can leverage, integrate and coordinate well-tested practices, data, and simulation tools accumulated over years of wide usage in the various CIS domains.

In light of this knowledge gap, this study proposes a framework for modeling interdependent CISs, one that allows for the integration of multiple fine-grained CIS domain-specific models, implemented by custom or off-the-shelf simulation tools, in a shared simulation environment. The study provides a novel solution for developing interdependent CIS models that can (1) extensively utilize domain-specific knowledge to simulate CISs functions; (2) capture various systemic heterogeneity dimensions among the CISs; and (3) simulate complex dynamic interactions and interdependencies between the CISs, and with their external environments. The proposed framework adopts the high level architecture (HLA) standards for distributed simulation (federations) [16] to manage data exchange and synchronization of heterogeneous models and simulation tools. The proposed framework was tested in a case study to model two interdependent power and water systems. The case study helped to demonstrate the efficacy of the framework. Moreover, the case study results revealed the importance of incorporating domain knowledge and accounting for systemic heterogeneity when simulating interdependent CISs behavior.

The contribution of this study is that it pushes the boundaries of interdependent CISs studies by providing a methodology for developing more detailed and granular models of interdependent heterogeneous CISs. The proposed framework will facilitate the use of fine-grained domain specific CIS models, with complex non-linear mechanisms specific to each CIS domain, to simulate with more detail and accuracy the heterogeneous behavior of CISs. Thus, models developed using the proposed framework have the potential to provide more accurate assessment and prediction of CISs reliability and performance while unveiling system vulnerabilities, failure propagation mechanisms, feedback loops, and so on, that otherwise would be difficult to discover.

The remainder of this paper proceeds as follows: Section 2 presents a background summary on HLA and federation development. The proposed framework is introduced in Section 3, followed by Section 4 that describes a case study of two interdependent power supply and water supply systems. The results from the case study are presented in Section 5 and discussed in Section 6. Section 7 concludes the paper.

2. Related work

2.1. State of the art on modeling interdependent CISs

A large volume of literature has been published on the modeling of interdependent CISs, either proposing and optimizing models or applying existing models in various study contexts. According to [2,8], in recent years, the most commonly adopted interdependent CISs modeling approaches include the system dynamics (SD) modeling, NB modeling, and ABM approaches.

SD modeling is an approach for modeling and understanding the nonlinear behavior of complex CISs over time using stocks, flows, internal feedback loops, table functions and time delays. SD models provide a highly abstract representation of CISs and have been adopted in several studies to investigate nonphysical cause and effect relationships between CISs [17–19]. The primary weakness of the

SD approach is that it cannot model the physical and operational attributes of interdependent CISs at a component-level. The levels of granularity and detail of the models are low, and hence, the heterogeneous behaviors and systemic heterogeneities of the CISs cannot be captured. This weakness limits the applicability of the SD approach in modeling large-scale complex interdependent CISs.

ABM and NB modeling are the most commonly adopted approaches in prior studies for studying interdependent CISs. The ABM being a bottom-up modeling approach allows for the development of relatively detailed models that are able to model and simulate various physical and operational attributes of interdependent CISs in the form of autonomous interacting agents. The ABM approach has been adopted in various interdependent CISs related studies to model and assess system interdependencies, vulnerabilities, resilience, and so on [20–22]. The NB approach on the other hand is a top-down modeling approach that models interdependent CISs as interconnected networks of nodes and links, without attempting to replicate the exact functionalities of each system component. The NB approach is mostly used to model the topological characteristics and physical interdependencies between CISs [23,24], though a number of improved NB models have also been proposed to model material and information flow between interconnected nodes [25–28]. ABM and NB models of interdependent CISs display some significant weaknesses when implemented as monolithic models or using a single integrated simulation engine. Firstly, it is challenging to reasonably model multiple complex heterogeneous systems using a single conceptual framework. This is because the features and functionalities of CISs components, agents and subsystems differ from one domain to another. The modeling principles and equations of one approach may not be applicable to all the CISs under consideration. By using a single framework, the differences in network features, material and information flows, system operations, and disaster response patterns of the CISs are not properly accounted for, which may significantly affect the accuracy of the simulation results. Secondly, the scale, granularity and level of details achievable by a monolithic model is limited by the computational power of a single simulation engine. This weakness limits the re-usability, adaptability and expandability of monolithic models, thus affecting their applicability for more complex interdependent CISs studies.

Other modeling approaches include physics-based modeling [29] and some hybrid approaches based on open hybrid automata [30], co-simulation using an integrated simulation engine [31,32], integrated formalisms for modeling functionally interdependent CISs [33,34], and so on. Majority of these approaches rely primarily on mathematical formalisms to model the dependencies and communication between system components. A main challenge faced by such approaches is to achieve the interoperability of heterogeneous models. Moreover, some of the approaches are tailored for specific types of CISs, and thus not applicable for a wider range of CIS domains. The above challenges, coupled to requirements for high computational efficiency and restrictions on computational time, are the main reasons why CIS domain-specific models in which the flow of commodities are governed by complex non-linear equations specific to each CIS are seldom used to develop interdependent CISs models [35].

In summary, the existing approaches for modeling interdependent CISs suffer the challenge of modeling CISs and their interdependencies with insufficient detail and accuracy due to the intrinsic limitations of the approaches or because of computational limitations. With the rapid growth in scale and complexity of modern CISs, these existing modeling approaches may not be able to accurately depict CISs, provide new useful insights about the heterogeneous behavior of interdependent CISs, and accurately assess the vulnerability and resilience of the systems. The limitations described above highlight the need for an improved modeling approach that can integrate multiple heterogeneous, fine-grained CISs models while ensuring the interoperability of the models and the proper consideration of system interdependencies. Such a modeling approach can be made possible by leveraging the data exchange, management, and time synchronization abilities of co-simulation techniques such as HLA-based modeling.

2.2. HLA-based modeling of interdependent CISs

HLA is a family of IEEE co-simulation standards that describes the architecture, modeling rules or guidelines, and communication protocols of federated models [16,36]. An HLA federation consists of models/simulators known as federates that communicate via a middleware known as the run-time infrastructure (RTI). The RTI provides services such as data distribution management, time management, and synchronization, to the federation, the details of which are specified within the federation object model (FOM) [16]. HLA has been adopted in several areas such as cyber-physical system modeling [37], large-scale computer networking [38], military simulations [39], and so on, using a variety of different simulation techniques and tools, and under very diverse simulation scenarios.

HLA-based co-simulation was initially adopted to model single domain CISs involving multiple complex agents and cyber-physical systems. For instance, Jain [40] tested the feasibility of adopting HLA standards for simulating complex transport systems by developing a transport system model that simulated road network, traffic, cars and commuters. Wei and Wang [41] developed a federated power distribution system model to assess the vulnerability of infrastructure system components under various threats. HLA standards were also adopted to develop a co-simulation framework for smart grids monitoring networks [42].

HLA is slowly paving its way into interdependent CISs studies as an approach to address simulation interoperability for interdependent CISs. Nonetheless, prior to the emergence of HLA in this field, a few other approaches for co-simulation or federated modeling of CISs had been tested in literature [43]. One category of studies relied on special purpose systems with dedicated middleware for synchronization and data exchange. Projects such as the Electric Power and Communication Synchronizing Simulator (EPOCHS) [44], and the Integrated Risk Reduction of Information-based Infrastructure Systems (IRRIIS) [45] fall under this category. Another category of studies developed customized frameworks for integrating dedicated simulations. This category includes projects such as the Agent-based Interdependency Modeling and Simulation (AIMS) [46], and Infrastructures Interdependencies Simulation (I2Sim) [47]. Communication protocols such as Distributed Interactive Simulation (DIS) [48] and Interoperable Distributed Simulation (IDSim) [49] have also been occasionally used. HLA on the other hand is a more advanced general framework of distributed federations with standard middleware. A few studies have adopted HLA to model interdependent CISs focusing on either interoperability problems [50–53] or system-specific problems [54–56]. Two approaches have commonly been adopted in such prior studies to model interdependencies among CISs. The first approach involves the direct exchange of input-output data amongst the CIS models through the RTI middleware [50,52,54]. The limitation of this approach 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. Hence prior studies either adopted homogeneous models to represent their CISs or relied on general-purpose simulators, which can provide better interoperability but lack simulation functions specific to the modeled CIS domain. Consequently, the developed models could neither account for systemic heterogeneity nor leverage the domain knowledge offered by specialized domain-specific simulation tools. The second approach involves merging the output produced by domain models in an abstract model to reproduce the inter-system interactions [51,53,56]. The abstract model describes the operational level or quality of service of the interdependent components. The limitation of this approach is that by abstracting the functionalities of the system components, the developed compound model may significantly lose its ability to accurately simulate systems behavior. The reason being that portions of the data representative of component states, functions and operations are lost, resulting in significant limitations in the type and complexity of interactions and interdependencies that can be captured and simulated.

Depending on the scale and complexity of a simulation project, the development of an HLA federation may sometimes be a time-consuming process that requires a considerable amount of knowledge and mastery of the models, tools, and other resources that constitute the federation [57]. However, HLA-based modeling of interdependent CISs presents several advantages over commonly adopted modeling approaches. The HLA-based approach allows for the development of larger-scale interdependent CISs models since the design and computational load can be distributed over multiple engines and geographical locations, thus increasing the computational power, resource availability and fault tolerance [58]. Security is also improved when adopting HLA federations since federation participants need to abide by certain federation agreements or protocols, and participants can publish only the data they are willing to share and not have to submit their models and data to a centralized server [59–62]. Moreover, HLA-based modeling provides a useful solution for re-using existing models with minimal modifications to the original codes, thus reducing the cost to develop a complex system model and facilitating cooperative simulation projects in which advanced models developed separately need to be co-simulated [39].

3. Methodology

This study proposes an HLA-based framework for co-simulating existing CIS domain-specific models. The study also describes a novel approach for modeling cross-domain interdependencies and ensuring the interoperability of heterogeneous models. The proposed framework comprises a federation architecture and a federation development process.

3.1. Interdependent CISs federation architecture

The proposed interdependent CISs federation architecture consists of several functionally distinct modules that communicate via a central RTI, as illustrated in Fig. 1. 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. Each module in the federation architecture is explained in detail below.

A *CIS module* consists of all the models and simulation tools responsible for simulating a particular CIS. 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 CIS behavior as well as management and control functionalities such as SCADA (supervisory control and data acquisition), backup systems, decision-making, and resource allocation. The organizational layer consists of the mathematical formalisms defining the relationship between the subscribed data and simulator input. 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. The *External Environment module* consists of models that simulate the various external factors that interact with the interdependent CISs, such as natural disasters, human systems, supply chains, and so on. The *User module* consists of

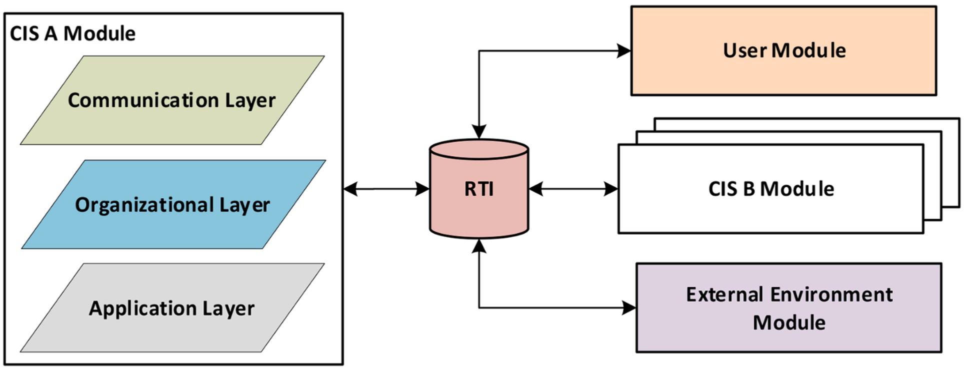


Fig. 1. The proposed interdependent CISs federation.

the user interfaces, visualization tools, data monitors, and so on, that facilitate the interactions between the federation and the modelers.

3.1.1. The application layer

This layer consists of the CIS model (federate) that simulates a particular CIS. The CIS model is represented as a collection of *model entities* $E = \{e_i\}_{i=1}^{n}$, where e_i represents the ith entity of the model. A model entity refers to any interacting component of the CIS model, for example, a pump station of a water supply system model. Each entity has a set of *attributes* $A_i(t) = \{a_{j,t}^{i}\}_{j=1}^{m_i}$ at time t, with $m_i \geq 1$. An attribute is a parameter that describes the status of an entity, for example, the efficiency of a pump. The state of a model, $\mathscr{I} = \{E, A\}$ is the collection of all the model entities and attributes at a particular time, with $A = \cup_{i=1}^{n} A_i(t)$

The interaction between interdependent entities (input-output) is in the form of services exchange. That is, each entity has a *service demand*, $d_j^i(t)$, and a *service supply*, $s_j^i(t)$, that describes the amount of service required from an interdependent entity to sustain the entity's functionalities, and the amount of service that the entity can make available to other entities, respectively. It should be noted that since the proposed framework is concerned with integrating existing models, only the demand-supply mechanism between interdependent entities from different CISs is described in the following section. The internal demand-supply mechanism of each individual CIS is specific to the domain-specific CIS model selected for the study.

3.1.2. The organizational layer

Unlike existing federated CIS models, in which the CIS simulators exchange data directly with the RTI, the proposed framework introduces an improved data exchange and management mechanism for modeling CISs interdependencies and ensuring the interoperability of heterogeneous models without altering the CIS simulator codes. The improved data exchange and management mechanism, depicted in Fig. 2, involves the use of data processing units (DPUs) between a federate and the RTI, making up the organizational layer.

The DPUs serve the primary purpose of modeling cross-domain dependencies (external dependencies) and the effect of external constraints such as disaster impact, management and control operations, and so on, on the CISs. The proposed framework mainly considers functional dependences as defined under Zimmerman's classification of CISs dependencies [63]. Functional dependences exist due to the exchange of services (resources or information) between the components of interdependent systems. Considering two interdependent model entities *a1* and *b1* belonging to two interdependent CISs A and B, respectively, the functional dependence between the model entities is modeled as an exchange of information about the services requested by the entities (d_j^{a1}, d_j^{b1}), the services supplied by the entities (s_j^{a1}, s_j^{b1}), and the services supplied to the entities by other interdependent entities ($\hat{s}_j^{a1}$, $\hat{s}_j^{b1}$), as depicted in Fig. 3. Each entity can publish or subscribe to multiple services indicated by the subscript j.

I_{b1} denotes the input variables of entity $b1$, which includes all the services that the entity receives, $\hat{s}_j^{b}$, the services demand of the interdependent entity, d_j^a, and other variables related to external constraints, V_j^b. On the other hand, O_{b1} denotes the output of entity $b1$, which includes the services requested by the entity, d_j^b, and the services supplied by the entity, s_j^b. Similarly, I_{a1} and O_{a1} denote the input and output variables of entity $a1$, respectively.

An entity may lose its ability to function properly and deliver its required services when the entity's own demand is not met or when affected by external constraints. The framework allows for two methods to model the loss in functionality of an entity. In method one, the DPU automatically updates the parameters of the entity at each simulation time step based on the input variables and then allows the CIS domain-specific model to simulate the CIS's behavior based on the updated model parameters. This method, as illustrated with

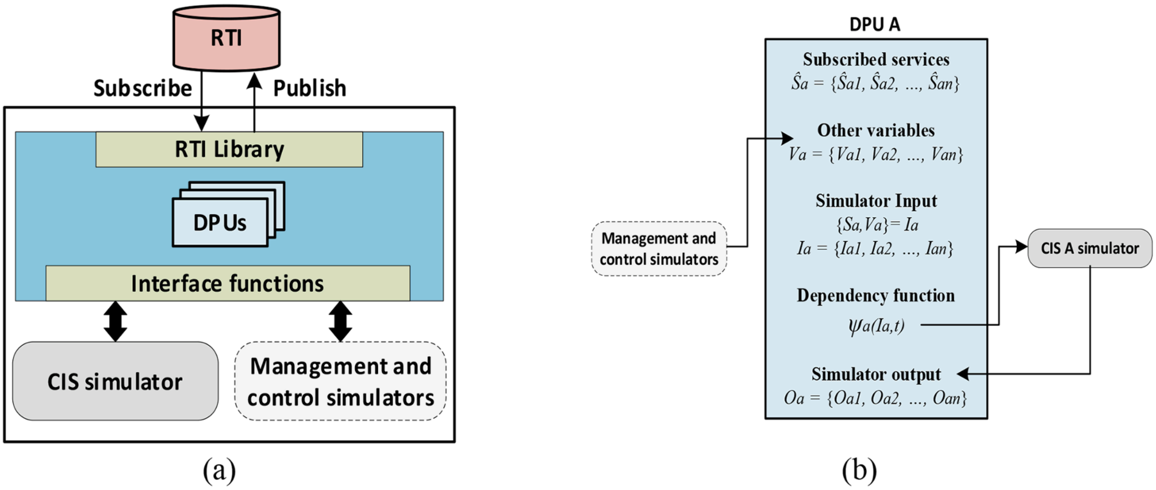


Fig. 2. Data exchange and management mechanism of the proposed federation.

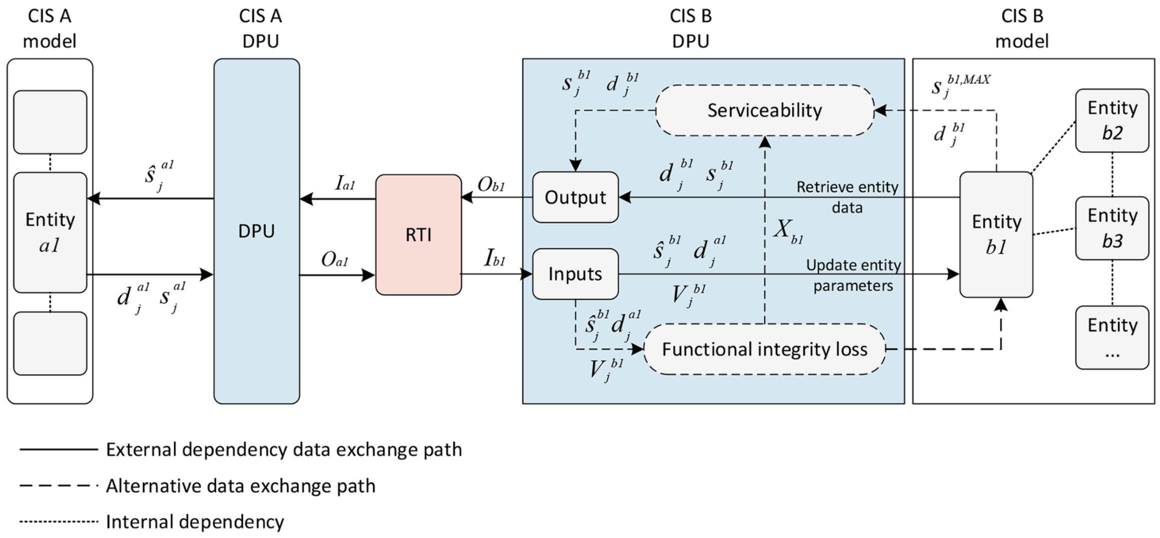


Fig. 3. Modeling the functional dependency between interdependent entities.

the external dependency data exchange path in Fig. 3, applies when all the input variables to be processed by the DPU are supported by the selected CIS simulation domain-specific model. In method two, the DPU first computes the functional integrity loss and serviceability of the entity based on the input variables, and then adjusts the service output of the entity accordingly, as illustrated with the alternative data exchange path in Fig. 3. In this method, the CIS domain-specific model simply reports the maximum amount of services the entity can supply at each simulation time step based on the model state. The DPU updates the domain-specific model, adjusts the service output values, and publishes the data to the rest of the federation through RTI.

The functional integrity loss of an entity i at time t, $X_i(t) \in [0,1]$, comprises the functionality losses due to insufficient services supplied to the entity and functionality losses due to the impact of external constraints. That is, the functionality of an entity would decrease when the services it receives are lower than the entity's demand, and would be zero if no service is delivered. At the same time, the constraints imposed on the entity may cause a decrease in the functionality or even complete failure of the entity. Functionality losses due to insufficient services supplied to the entity and functionality losses due to the impact of external constraints may occur simultaneously, which would cause a higher loss in functional integrity of the entity. Functional integrity loss can be calculated as follows:

$$X_i(t) = 1 - \left(\prod_{j=1}^{n} \left(\frac{\widehat{s}_j^i(t)}{d_j^i(t)} \right) \times \prod_{k=1}^{m} \left(1 - x_k^i(t)\right) \right) \tag{1}$$

where $d_j^i(t)$ denotes the demand of service j at time t, $\widehat{s}_j^i$ denotes the supply of service j to the entity by an interdependent entity from another CIS, and $\widehat{s}_j^i < d_j^i$. The variable $x_k^i(t) \in [0,1]$ denotes the loss in functionality due to external constraints k, on the entity and can be calculated as follows:

$$x_k^i(t) = x_k^i(t-1) + f_k\left(v_k^i,\ \Delta t\ \right) \tag{2}$$

$$\Delta t = t - t' \tag{3}$$

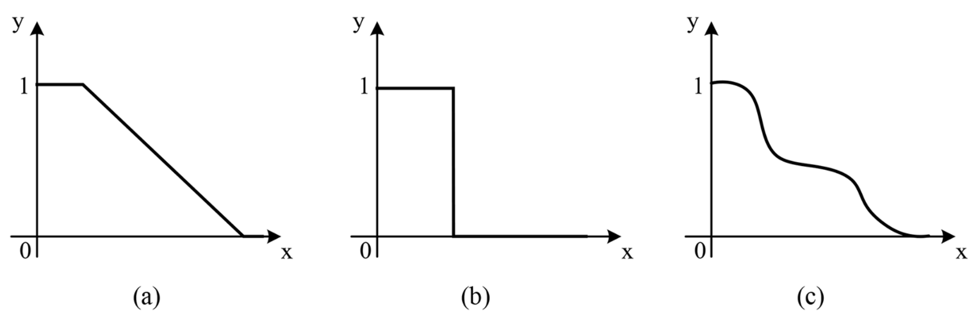


Fig. 4. Examples of monotone decreasing functions: (a) linear function; (b) threshold function, (c) logistic function.

where v_k^i is the intensity of the constraint k on entity i, and t' is the time at which the constraint is imposed on the entity. The function $f_k(v_k^i, \Delta t) \in [0,1]$ is a monotone decreasing function which defines the dynamic through which the functional integrity reaches its new steady value. The function $f_k(v_k^i, \Delta t)$ is determined based on the nature of the constraint being modeled and can take the form of a linear function, threshold function, logistic function, and so on, as depicted in Fig. 4 below [64,65]. Then the functional integrity loss is used to determine the serviceability of the entity, ω_i(t), as follows:

$$\omega_i(t) = \omega_i^{MAX} \times (1 - X_i(t)) \tag{4}$$

where ω_i^{MAX} denotes the maximum serviceability of the entity.

One assumption of Eq. (1) is that an entity's functionality loss due to insufficient supply depends entirely on the services received from another entity in an interdependent system. This may not always be the case, for example, a system may have an internal backup mechanism to temporarily meet the demand of certain components when services from an external source is unavailable or does not meet the entity's demand. To consider this complexity, a buffered switching mechanism can be introduced in Eq. (1), to alternate between external service supply and backup supply when the external supply is detected to be insufficient or unavailable, as shown in Eq. (5):

$$X_i(t) = 1 - \left(\prod_{j=1}^{n} \left(\frac{\widehat{s}_j^i(t) + \vartheta(t) \ \times s_j^{'i}(t)}{d_j^i(t)} \right) \times \prod_{k=1}^{m} \left(1 - x_k^i(t)\right) \right) \tag{5}$$

where, $\vartheta(t)$ is a buffer switching signal and $s_j^{'i}(t)$ is backup supply. The switching signal $\vartheta(t) = 1$ if a backup mechanism is available and operational, otherwise $\vartheta(t) = 0$. The above equation only serves as an example for simple adaptations that could be made to the framework to support more complex implementations.

In addition to managing subscribed data, the DPUs are also used to retrieve simulator output to be published to the rest of the federation, and generate logfiles for model users.

3.1.3. The communication layer

This layer consists of the API functions, HLA functions and other case-specific codes that are used to establish communication between federates following the federation agreement. The federation agreement defines the operational procedures of federates and the HLA services used throughout the life-cycle of the federation, as summarized in Fig. 5. The specific HLA functions used in each

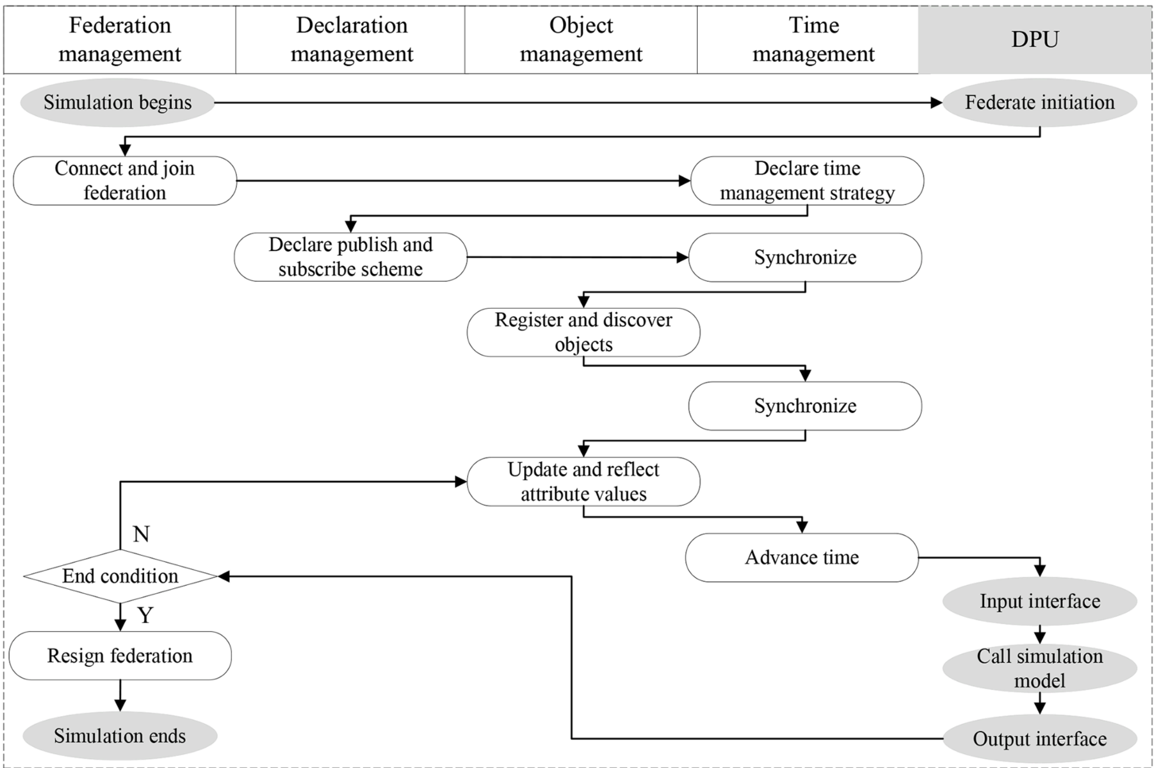


Fig. 5. Federation life-cycle.

activity under federation management, declaration management, object management, and time management should be agreed upon by the member federates prior to federation execution Table 1. lists the HLA functions for a typical federation implementation, which can be adjusted to suit any particular case. The simulation begins with the DPUs initializing the CIS models by means of API functions and case-specific codes. Then, one federate, known as the Master federate, connects to the RTI and creates a federation execution which is joined by all member federates. After all the federates have joined the federation, the remaining activities in the federation life-cycle are executed following the sequence presented in Fig. 5 and the time advance mechanism described in the following paragraph. Once the "end condition" of the simulation is met, such as reaching a specific timestamp or completing a specific simulation event, the member federates resign from the federation and the Master federate destroys the federation.

Time management is one of the most critical and challenging aspect of the communication layer concerned with the mechanisms for synchronizing and controlling the advancement of time during federation execution. Time management is faced with interoperability issues due to the heterogeneous nature of CIS domain-specific models. For example, simulation models may have different internal time flow mechanisms (timestepped or event driven simulation) and operate following different logical time scales (milliseconds, seconds, minutes, and so on). The models may also use different message ordering mechanisms that could degrade the causality between simulation events or system behaviors. The above heterogeneities, if not properly accounted for, may result in delays, data losses or numerical errors that could defeat the purpose of co-simulating interdependent CISs [66]. To minimize delays and numerical errors, and ensure that causality is maintained between the interdependent CISs models, the federates need to synchronously advance in time (preferably at the speed of the slowest federate), and no data with timestamp "in the past" (that is, with timestamp smaller than a federate's current time) should be generated.

To achieve this, either conservative or optimistic time management protocols could be used [66]. Conservative protocols prevent any simulation entity from ever processing events out of timestamp order, while optimistic protocols use a rollback mechanism to detect and recover out-of-order executions. In this study, the HLA implementation of conservative protocols using time constraint and time regulation services is adopted, and time is advanced following a time advance request/grant and lookahead mechanism [67]. To ensure that the information delays imposed by the discrete time steps do not degrade the true interdependency between two CISs (where the behavior of one system affects the behavior of another system, and vice-versa) and lead to numerical errors, relatively small time steps should be used depending on the timescale of the selected models/simulators, and the logical time step of the RTI is set to equal the smallest time step among the CIS models. When applicable, computational costs can be reduced by updating attribute values only for interactive activities and not local activities [68]. Fig. 6 illustrates the time management mechanism for an example scenario.

3.2. CISs federation development process

In this section, a federation development process is proposed that aims at providing a methodology for the design and implementation of the federation architecture described in Section 3.1. The proposed development process builds upon the development steps of the FEDEP (Federation Development and Execution Process) developed by the IEEE [69], but addresses its abstractness by introducing development activities that capture or provide key information, decisions, and other items necessary to develop the interdependent CISs federation. The proposed federation development process maintains the first three development steps of the FEDEP (objective development, conceptual design, and federation design), which include most of the activities specific to CISs modeling. In contrast, the last four development steps (federation development, integration & testing, federation execution, and data analysis & evaluation of simulation results), which include more generic HLA development activities, are synthesized into a single development step named federation implementation, as illustrated in Fig. 7.

Table 1
List of HLA functions invoked during federation execution.

Activity	Federate initiated function	RTI initiated function
Connect and join federation	Connect Create federation execution Join federation execution	
Declare time management strategy	Enable asynchronized delivery Enable time constraint Enable time regulation	Time constraint enabled Time regulation enabled
Declare publish and subscription scheme	Subscribe object class attribute Publish object class	
Synchronize	Register synchronization point Synchronization point achieved	Confirm synchronization point Announce synchronization point Federation synchronized
Register and discover objects	Register object instance	Discover object instance
Update and reflect attribute values	Update attribute values	Reflect attribute values
Advance time	Time advancement request	Time advancement grant
Resign federation	Resign federation Destroy federation Disconnect	

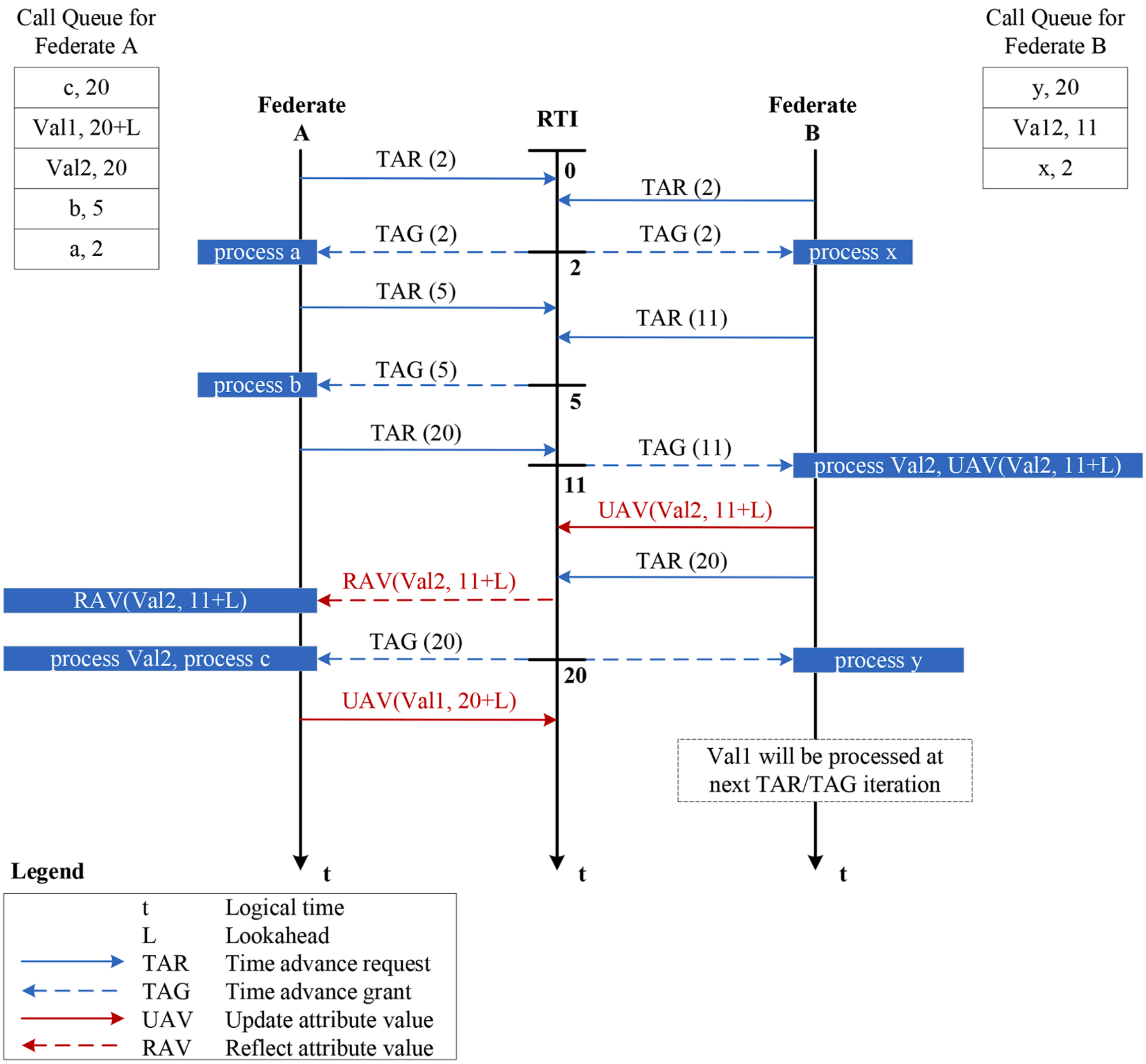


Fig. 6. Time management mechanism, adapted from [67]. Example scenario: Two CIS federates, Federate A and Federate B, have to process local activities a, b, c, x, y at logical timestamp 2, 5, 20, 2, 20, respectively. Federate B publishes an updated value of interactive activity Val2 (at timestamp 11) and subscribes to Val1. Federate A subscribes to Val2 and at the reception of the value of activity Val2 publishes an updated value of activity Val1.

3.2.1. *Objectives development*

The primary purpose of this step is to develop a list of the problems to be addressed by simulating the interdependent CISs model. Objectives development involves the identification of the *research focus* and *study purpose*. Research focus refers to the main object(s) under study, which can be a specific CIS, group of CISs, or even external models interacting with the interdependent CISs. The study purpose may include information generation, vulnerability assessment, system optimization, resource management, and so on. The simulation objectives serve as an input to the conceptual design of the federation.

3.2.2. *Conceptual design*

This step aims to design a conceptual model of the interdependent CISs that can meet the simulation objectives identified in the previous step. This design involves the following activities:

a) Design the simulation scenario. Simulation scenario refers to the simulation environment (e.g., regular operation or disaster event) and the course of triggered events (e.g., cascading failure), to which the interdependent systems are subjected;
b) Based on the designed simulation scenario, identify all the components that make up the interdependent CIS model (including the CISs, management and control components, databases, and the external agents that interact with the interdependent systems);
c) For each component identified in b), identify the entities and attributes involved in the data exchange process during simulation;

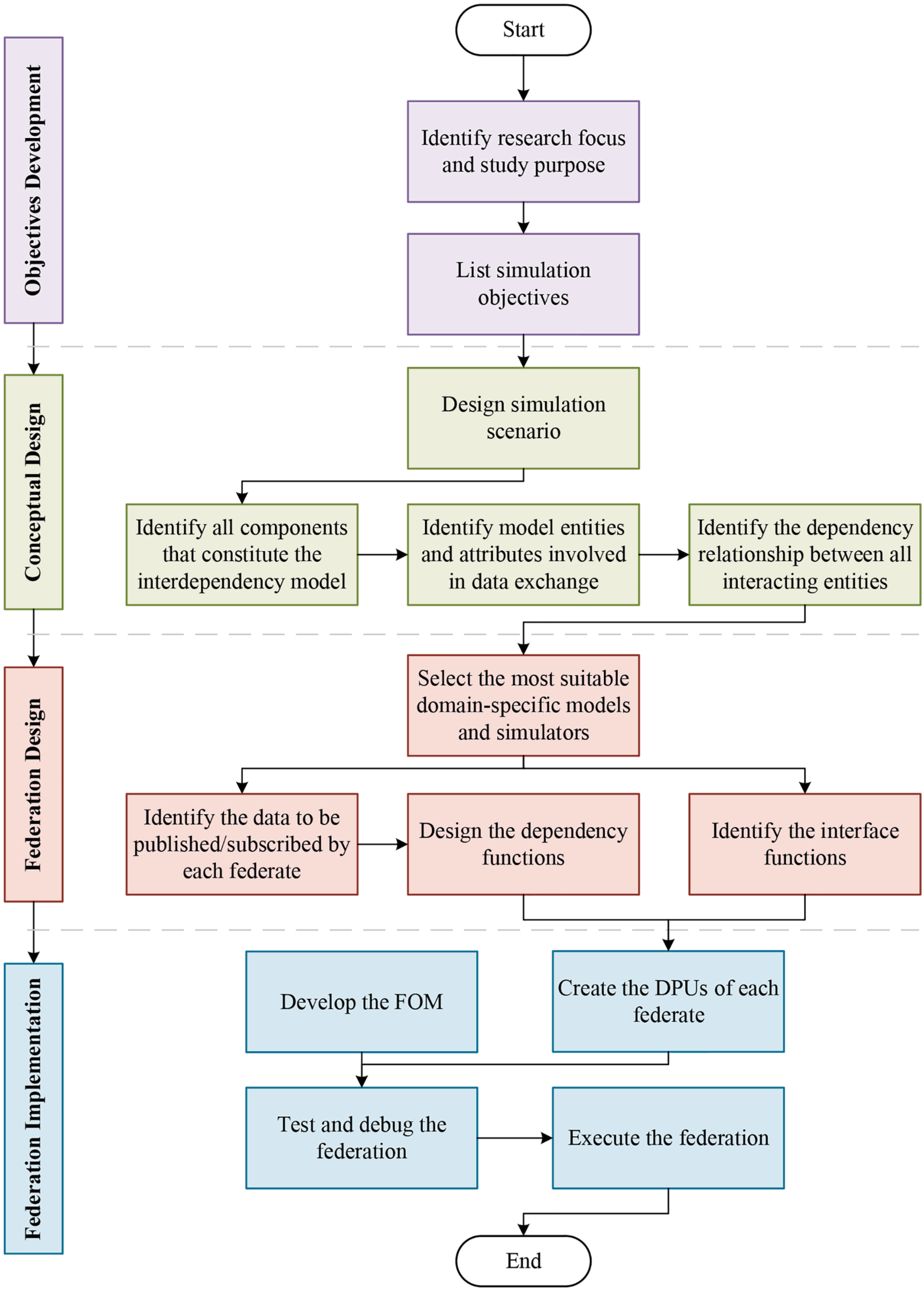


Fig. 7. Proposed federation development process.

d) Identify the dependency relationships among all the entities identified in c), including a description of how they interact, the type of data exchanged between them, and the external factors or variables affecting their interactions. The dependency relationships can be identified through a review of relevant literature or interview with industry professionals.

3.2.3. Federation design

In this step, the federate interactions are designed, including the following activities:

a) Select the most suitable domain-specific models and simulators for implementing the conceptual model;
b) Identify the data to be published and subscribed by each federate;
c) Design the dependency functions that relate subscribed data to simulator input;
d) Identify the interface functions necessary to interact with the application layer simulators.

3.2.4. Federation implementation

In this step, the organizational layer of each CIS module is formalized as a set of DPUs, interface functions and RTI library functions, using the application programming interfaces (API) supported by the selected simulators and RTI. Federation implementation also involves generic HLA modeling activities such as FOM development, federation testing, debugging, and federation execution, which are not specific to modeling CISs, and thus are not detailly covered in this section. These activities are completed following the technical guidelines of the HLA standards that can be found in [16].

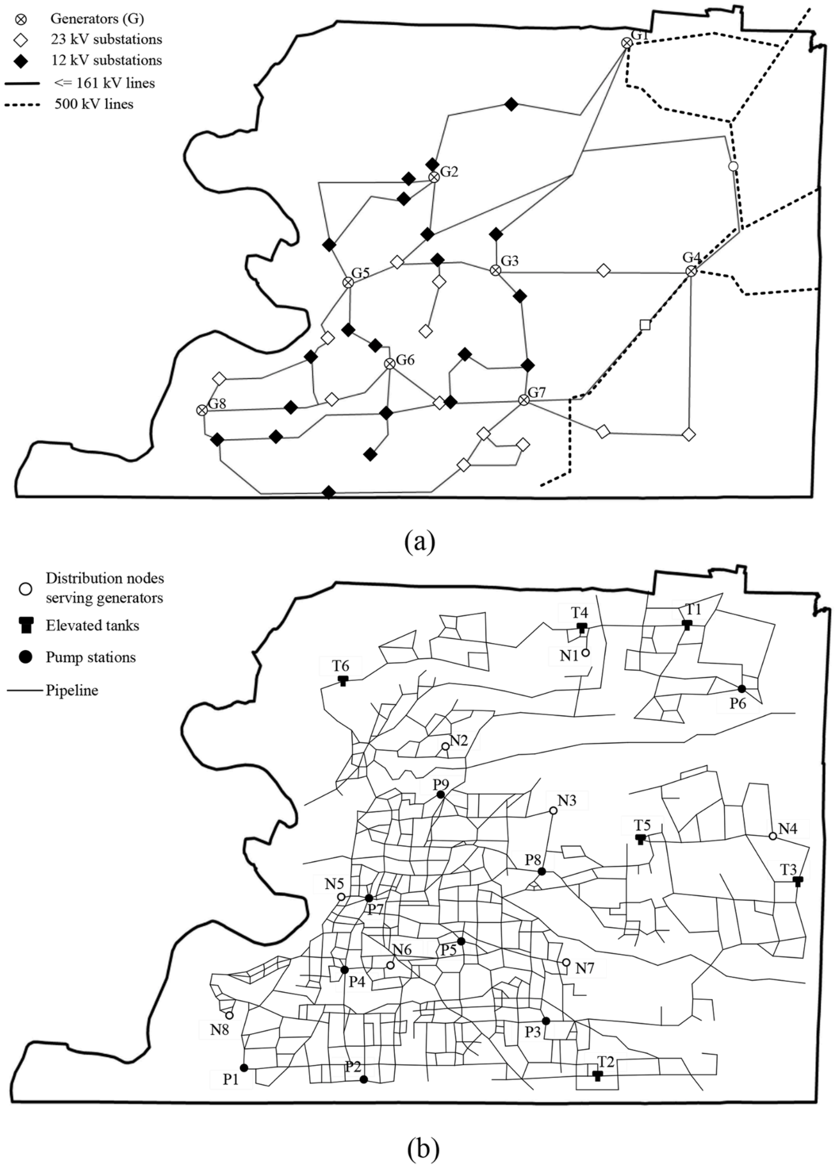


Fig. 8. (a) Topology of the power system (not to scale); (b) Topology of the water system (not to scale).

4. Case study

4.1. Case descriptions

The proposed framework was adopted in a case study to model the interdependent water and power supply systems of Shelby County, Tennessee (TN), United States. Shelby County is the state's largest county, both in terms of population and geographic area. The water and power supply systems in Shelby County are managed by the Memphis Light, Gas and Water (MLGW) division and Tennessee Valley Authority (TVA) and consist of numerous facilities and widespread distribution networks. This case is selected for the following reasons: Firstly, the Shelby County case has been extensively studied in the existing literature on interdependent CISs, with several articles providing details about the systems and the topography of the area. Therefore, the systems can be reproduced with high fidelity, which is rare for other real-world cases of similar scale and complexity. Secondly, the power-water-interplay presents strong bi-directional functional dependencies that are ideal to showcase the capabilities of the proposed framework in modeling complex influence mechanisms such as feedback loops. Thirdly, these two systems and their interplays have been examined extensively in prior research, therefore, documented scenarios and data exist that can be used to compare and verify the findings of the present study and compensate for the lack of the ground truth.

4.1.1. Power supply system

According to the descriptions provided in [70–72], the Shelby County power network consists of eight gate stations that act as the system's supply facilities. The gate stations provide the electric power generated by plants outside of the Shelby County. The electric power is then transmitted to a total of thirty-six 23 kV and 12 kV substations. The substations are considered the demand facilities, which relay the electric power to end-users in a specific electric power service area. Power is transmitted through 500 kV, 161 kV, 115 kV and 23 kV transmission lines. Fig. 8(a) depicts the simplified power supply network. The gate stations in the network were modeled as power generators independent of plants outside of the county. This was done so that the dependency of power generators to the water network could be represented in the interdependent CISs model.

4.1.2. Water supply system

According to the descriptions provided in [70,72], the Shelby County water supply system consists of nine pumping stations and nine booster pumps. Water is drawn from an artesian aquifer through deep wells and delivered to six elevated storage tanks that supply the distribution nodes via buried pipes. The pipe diameters range from 16 cm to 122 cm. The network, depicted in Fig. 8(b), consists of approximately 1150 links and 730 distribution nodes with elevations ranging between 63.6 m to 126.6 m.

4.1.3. System interdependencies

The power and water supply systems depend on each other to perform their intended functions. The pumping stations of the water supply system depend on the electric power provided by the power networks substations, while the generators of the power supply system depend on water supplied at the distribution nodes of the water network. When modeling the interdependent systems, the power consumption of the pumps were modeled as loads on the power substations. In contrast, the power generators were modeled as demand nodes on the water network.

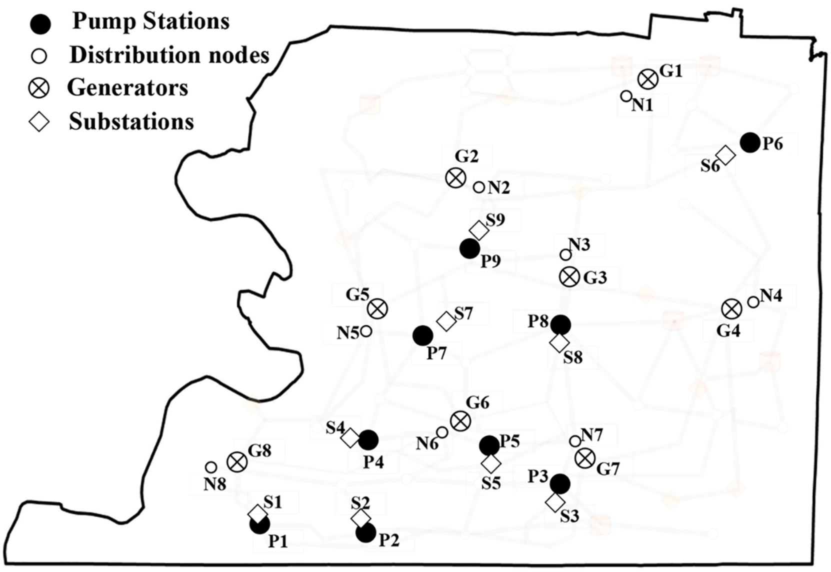


Fig. 9. Dependent component pairs of the case systems.

The power consumption of a pump can be modeled either as a constant horsepower or as a variable determined by the pump's performance curve. When considering a pump's performance curve, the load on the corresponding substation varies over time following the pump's activity. In case a pump station is closed, the load on the substation is minimal.

The power generators depend on the water supplied at the distribution nodes for functions such as the cooling of engine parts. Hence, the water flow, temperature and pressure at the distribution nodes supplying water to the generators may affect the serviceability or operational level (OL) of the generators ($0 \leq OL \leq 1$). To demonstrate the applicability of the proposed framework in modeling such complex, non-linear relationship, in this case study, an adaptation of the relationship described in [9] is adopted. A threshold pressure level is introduced, above which the OL of the generators is 100%, and below which the OL of the generators decreases following the eqs. (1) and (4) above.

The approach for establishing network coupling was based on the geographic proximity of the network facilities, as depicted in Fig. 9. Each pump station and power generator were linked to the closest power substation and water node, respectively. The components were coupled as G-N (generator - distribution node) or S-P (substation - pump station), with each pair sharing the same ID number as suffix (e.g., G1 – N1; S7 – P7).

4.2. Model development

This section presents step-by-step descriptions on how the proposed federation development process was implemented to develop the interdependent CISs model in the case study.

4.2.1. Objectives development

The purpose of the case study was to develop a federation of interdependent CIS domain-specific physics-driven models and demonstrate the efficacy of the proposed approach in addressing the limitations of monolithic models. The simulation objectives included: model system functions and simulate systems behavior with high granularity and details, capture a variety of systemic heterogeneity dimensions among the CISs, and simulate complex interactions between the CISs.

4.2.2. Conceptual design

To achieve the simulation objectives mentioned above, two simulation scenarios are designed that can: (1) showcase various system functionalities that are unique to each CIS domain, (2) reveal a variety of systemic heterogeneities among the simulated systems and how they affected system behavior, and (3) require the modeling of dependency functions, and reveal the impact of the interdependencies on system behavior.

Scenario one. In this scenario, the interdependent systems are simulated under normal operating conditions for 48 hours. The water demand, in terms of flow, at each water distribution node is the product of a base demand and a multiplier that follows a typical urban daily water consumption pattern with the least demand between 12 am to 6 am, and peak demand around 8 am and 7 pm [73], as depicted in Fig. 10. This demand is met by the coupled action of the pump stations and elevated water tanks. The pump stations pump water from water wells into the water network to fill the tanks and maintain reasonable pressure levels. 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. The energy consumption of each pump is determined by its performance curve, and this energy consumption is translated as a load on 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. The OL of each of the generators varies depending on the water pressure at the corresponding water distribution nodes. To choose a reasonable threshold value of water pressure for the case study, the water system model was first independently simulated to estimate the fluctuation limits of water pressure at the distribution nodes. A pressure height was then selected to ensure observable fluctuations in the OL of the generators without considerably impairing their functionality.

Scenario two. The simulation settings of this scenario are similar to those of scenario one above. However, a localized component malfunction is triggered in the power network 12 hours into the simulation, to cause the failure of substations S4 and S8, and the loss of

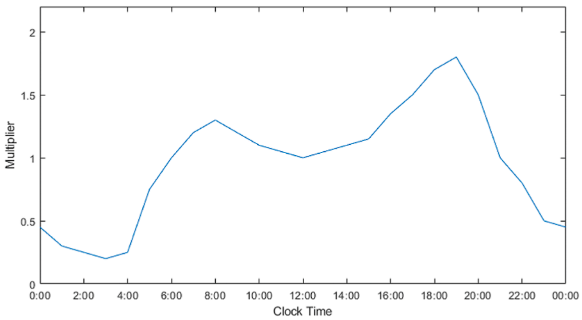


Fig. 10. Daily demand pattern at the water distribution nodes.

functionality of the dependent pump stations. The failed components are repaired and restored to their fully-functional state after 24 hours following their failure. This scenario aims to reveal the dependency of the water system on the power system more clearly, which may not be evident under scenario one.

Table 2 presents the list of model entities and attributes necessary to simulate the behavior of the two systems under the simulation scenarios.

4.2.3. Federation design

To meet the requirements regarding the accurate modeling of systems topology and functionalities, and to leverage the domain knowledge of each CIS, highly specialized tools were selected to model the CISs. The water supply system was modeled using the EPANET v2.2 software. EPANET is a widely used open-source software application for modeling and simulating water distribution systems [74]. It is a standalone software that can execute a comprehensive set of hydraulic analyses. The electric power supply system was modeled using the OpenDSS v9.0 software. OpenDSS is a comprehensive simulation tool for electric utility power distribution systems [75]. It has been used since 1997 in support of various research and consulting projects requiring distribution system analysis. In addition, EPANET and OpenDSS could model both the physical network and supervisory control system of the infrastructure systems. Therefore, no additional system control and management simulators were required for this case study. Fig. 11 illustrates the publish-subscribe scheme of the federates.

The interface functions of both simulators were provided as part of their software packages. Based on the simulation scenario and the publish-subscribe scheme of the models, the DPUs of the organizational layer were designed, which consisted of RTI library functions, dependency functions, and interface functions. The CERTI software application was used as the middleware to establish communication between the federates. CERTI 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 [76]. In this case study, all user-model interactions were completed within the user interfaces of the federates selected above; thus, no additional tools belonging to the User module were required.

4.2.4. Federation implementation

The organizational layer of both CIS modules were developed using MATLAB wrappers. The RTI library functions were implemented using the MatlabHLA toolbox that is part of the CERTI package, while the interface functions invoked the DLL of the selected CIS simulation tools.

The FOM was developed as an XML file using a free FOM editor tool developed by MAK Technologies. The FOM contained two main groups of items, including (1) entity types (also known as the object classes) and their attributes, and (2) interaction classes and the parameters they control. The former describes the data types exchanged between the federates, while the latter describes the event types that affect both systems Table 3. summarizes the main content of the FOM.

After developing the DPUs and FOM, the federates were connected to the RTI to create, test and debug the federation execution following the federation lifecycle and time management mechanism described in section 3.1.3. The selected power simulator operated on a second timescale, while the default hydraulic time step of the selected water simulator was one minute. Time was constrained and regulated using HLA services and fixed lookaheads were set for each federate. The final simulation output of each federate was

Table 2
List of model entities and attributes (* data exchanged between models).

System	Entity type	Attributes
Water system	Pump	Status*
		Performance curve
		Power consumption*
		Flow
	Junction (distribution node)	Elevation
		Water demand
		Water pressure*
	Tank	Elevation
		Volume
		Water levels
	Pipe	Roughness
		Dimensions
		Status
		Flow
Power system	Generator	Maximum power output (OL)
		Power output
		Status
	Substation Load	Power supply*
		Status
	Transmission line	Geometry
		Length
		Resistance
	Transformer (substation)	Hours to repair
		Voltages
		Status

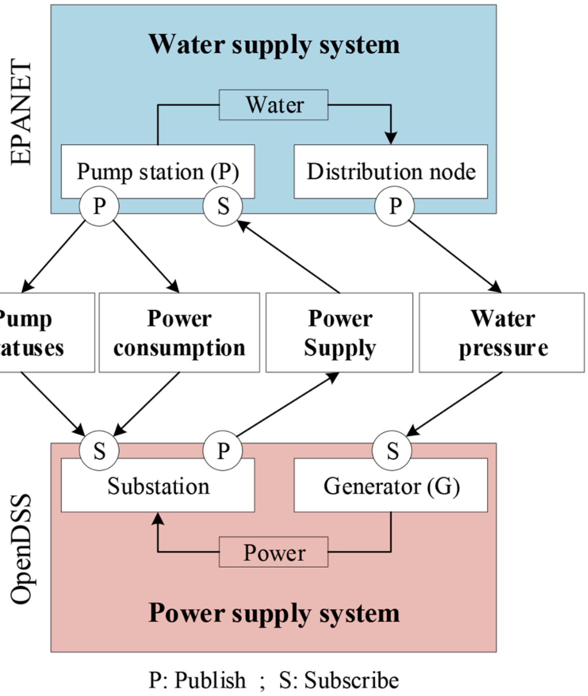


Fig. 11. Publish-subscribe scheme of the models.

Table 3
Main content of the FOM.

	Class	Attribute/Parameter	Data type
Objects	Pump	ID	HLAinteger32BE
		PowerConsumption	HLAfloat32BE
		Status	HLAboolean
	DistributionNode	ID	HLAinteger32BE
		Pressure	HLAfloat32BE
	SubstationLoad	ID	HLAinteger32BE
		PowerSupply	HLAfloat32BE
Interactions	LoadScenario	ScenarioName	HLAunicodeString
		SimulationTime	HLAinteger32BE
	Start		
	PauseResume		

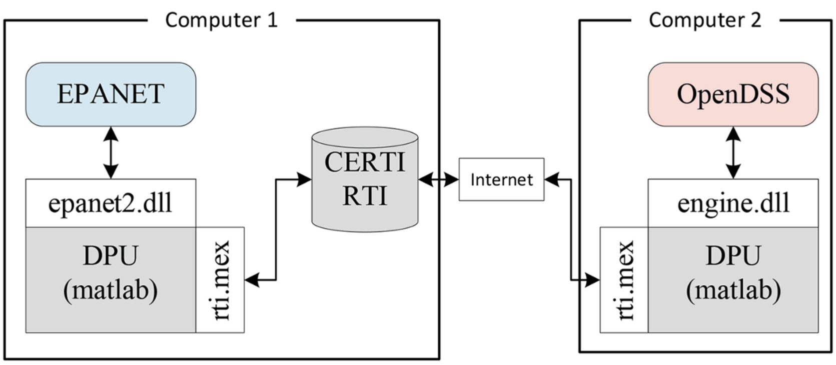


Fig. 12. Federation implementation.

generated by its DPU as spreadsheets, enumerating all entity attributes of the federate at each simulation time step, for follow-up analysis.

To test how the performance of the developed interdependent CISs federation would be affected by the hardware configuration, the federation was simulated using three different hardware configurations and the computational time of all the configurations were recorded and compared. In configurations 1 and 2, the federation was implemented on a single computer with hardware specifications E5-2640 v3 CPU @ 2.60GHz 32GB RAM (computer 1) and i7-4710 CPU @ 2.50GHz 16GB RAM (computer 2), respectively. In configuration 3, the federation was implemented on two separate computer hardware (computers 1 and 2) connected over the internet. Computer 1 housed the water system federate and the RTI, while computer 2 housed the power system federate, as depicted in Fig. 12. The three configurations were tested for scenario 2 of the case study. Each configuration conducted 20 replications for a total of 60 executions.

A fourth configuration using a single more powerful computer with hardware specification i7-10700 CPU @ 2.90GHz 64GB RAM (computer 3) was later introduced to investigate the computational cost of reducing the hydraulic time step / lookahead of the water model to its smallest possible value of 1 second, matching that of the power model. This configuration also aimed to investigate if any changes would be observed in the simulation results when the synchronization of the models are improved. Two settings were run using this configuration namely Setting 1 (power model lookahead = 1 second & water model lookahead = 1 minute) and Setting 2 (power model lookahead = water model lookahead = 1 second).

4.3. Model verification and validation

The verification and validation (V&V) of the developed federation was conducted following the IEEE recommended practice for the V&V of HLA federations [16] and consisted of four main steps designed in parallel with the federation development process proposed in this study (Fig. 13). The four V&V steps included: verify simulation objectives, verify and validate the conceptual model, verify the federation design, and validate and accept the federation.

In step 1, a V&V team consisting of two federation developers and four subject matter experts (SME) verified the consistency, completeness and correctness of the simulation objectives defined in section 4.2.1. Based on the simulation objectives, three federation acceptability criteria were defined namely, (1) the federation execution is able to showcase various system functionalities that are unique to each CIS domain, (2) the federation execution is able to reveal a variety of systemic heterogeneities among the simulated systems and how they affected system behavior, and (3) the federation execution is able to reveal the impact of the interdependencies on system behavior.

In step 2, the V&V team validated the conceptual model of the interdependent systems by (1) verifying the composition of each CIS model, including model entities, attributes, entity interactions and so on, and (2) verifying the interdependencies between the two CISs.

Step 3 involved assisting the selection of appropriate CIS domain-specific models and API packages by the V&V team, verifying the case systems data and their sources, and verifying the design of the FOM and DPU codes.

In the final step of the V&V process, the V&V team supervised the federation implementation process and provided support for federation testing, debugging and execution. Finally, the simulation results were used to assess whether the federation acceptability criteria were satisfied.

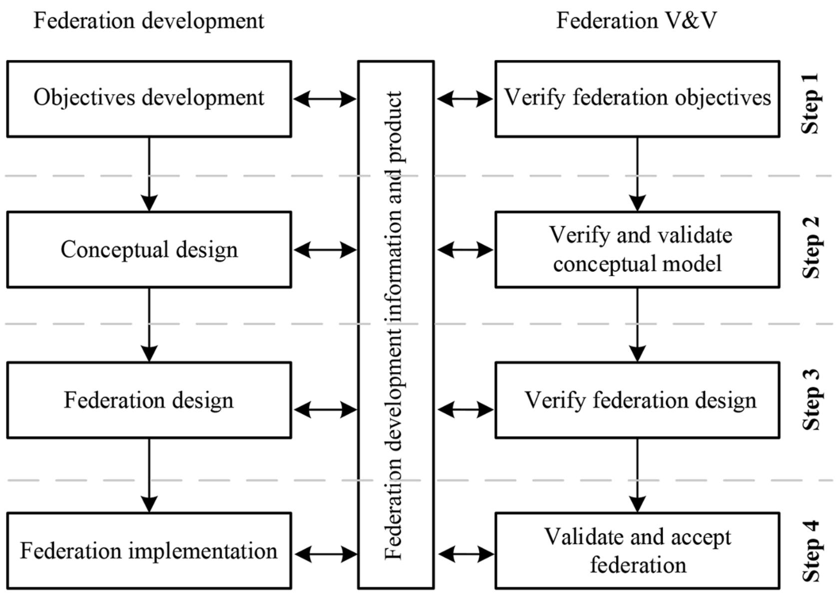


Fig. 13. V&V process of the developed federation.

5. Simulation results

5.1. Scenario one

The developed interdependent CISs model was simulated for 48 hours under scenario one, starting at midnight of day one. Fig. 14 (a) shows the statuses of the pump stations, Fig. 14(b) shows the water levels of the six elevated tanks, and Fig. 14(c) shows the pressures at the distribution nodes over the simulation period. Fig. 14(d) shows the loads on substations supplying power to the pump stations. It is observed that at timestamp 0:00, eight of the nine pumps were open and pumped water into the water network. The water demand between timestamps 0:00 and 6:00 was relatively low, as depicted in Fig. 10, and thus the tanks rapidly filled up. Consequently, the control system of the water network closed pumps P1, P3 and P7 at timestamps 1:00, 0:18, and 2:59, respectively, to prevent the tanks from overflowing. The closure of these pumps, coupled to the rise in water demand at the distribution nodes between timestamps 6:00 and 19:00, caused a gradual drop in the water pressure throughout the network. As a result, the tanks gradually emptied to meet the water demand and maintain a stable pressure within the network. As the water levels in the tanks dropped, the control system reopened P1, P6 and P7 at timestamps 16:30, 8:06 and 7:53, respectively, to refill the tanks. After timestamp 19:00, when the water demand dropped substantially, the water levels at the tanks and the pressure at distribution nodes increased rapidly. This cycle of events was repeated in the rest of the simulation. From Fig. 14(c) it can be observed that distribution nodes N1 and N4 demonstrated a slightly smoother pressure pattern compared to the other nodes. The difference in the patterns was due to the positions of N1 and N4 within the networks. These two nodes were isolated from the action of the pump stations and were supplied primarily by the tanks, providing a steadier flow. The above results demonstrate the level of granularity and details in the modeling of system functions and behavior that can be achieved using the proposed framework. The high granularity and details are useful to capture systemic heterogeneities when studying the behavior of CISs at a components level rather than a system level.

It can be observed from Fig. 14(c) that the pressure levels at nodes N1 to N8 were all above the threshold level of 20 m selected in this study. Hence, all eight generators operated at 100% OL throughout the simulation of this scenario. It can be observed from Fig. 14

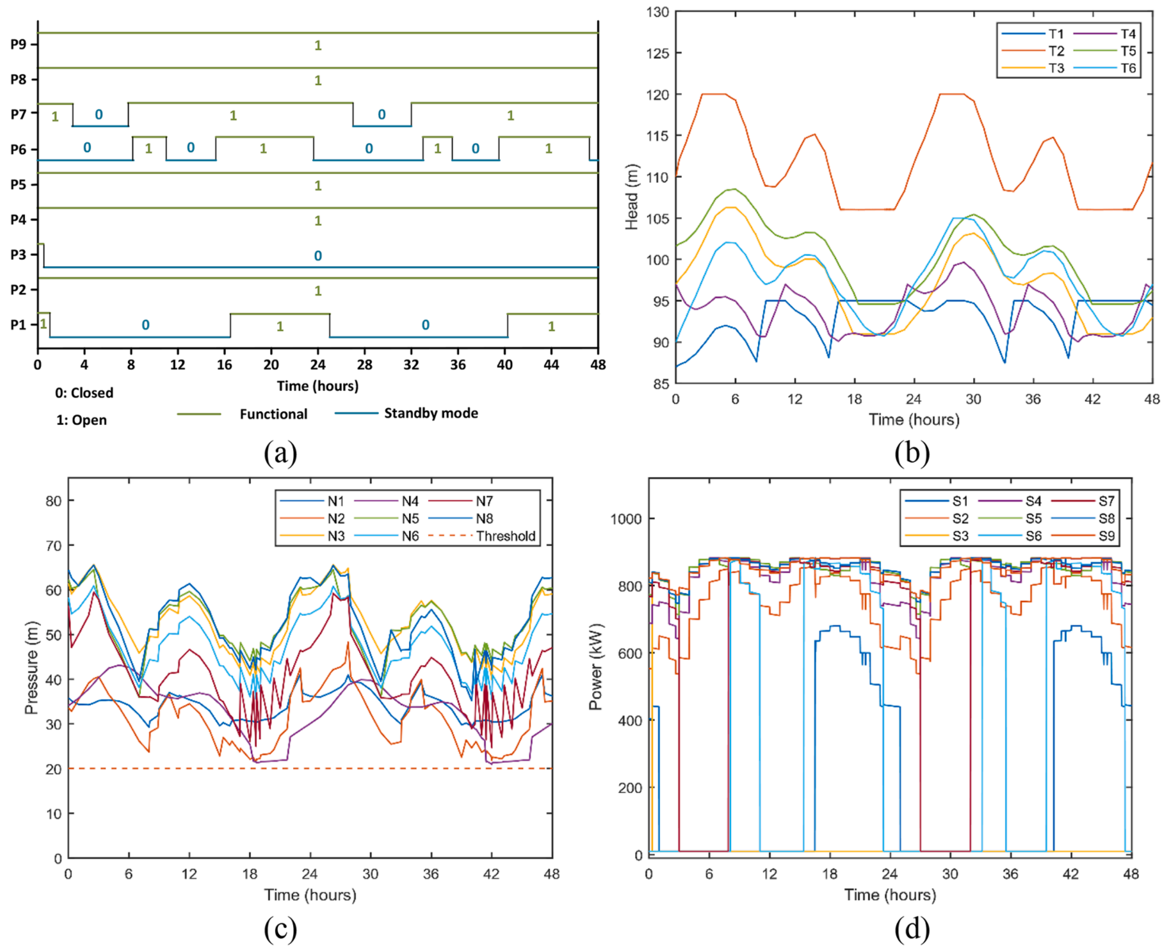
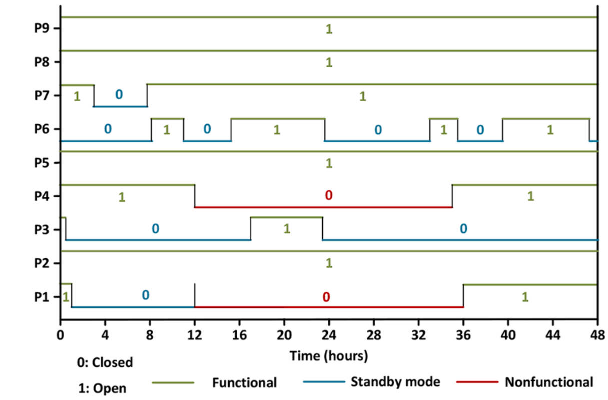
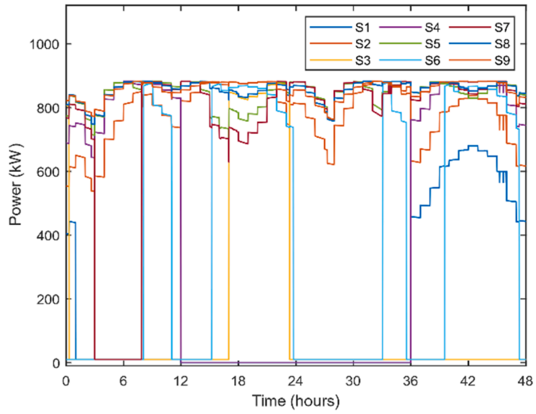


Fig. 14. (a) Pump statuses in scenario one; (b) Water levels at the elevated water tanks in scenario one; (c) Water pressures at the distribution nodes in scenario one; (d) Loads on substations in scenario one.

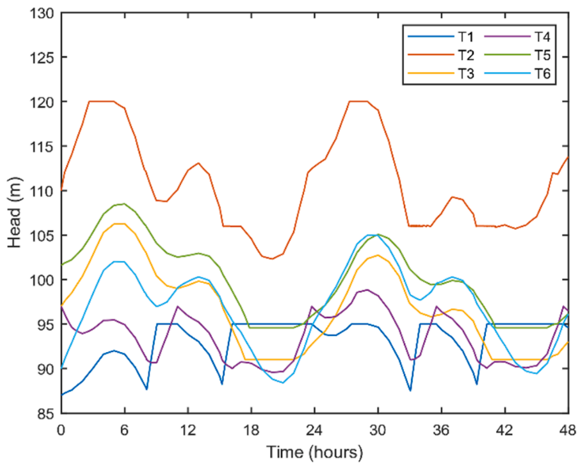
(d) that as the statuses of the pump stations changed from open to closed, the corresponding loads on the substations of the power network suddenly dropped to a minimal power value close to zero. On the other hand, when the statuses of the pump stations changed from closed to open, the loads on the substations would suddenly bounce back up. In addition, when the status of a pump was open, the load on the corresponding substation would vary according to the power consumption of the pump. It can be observed that between



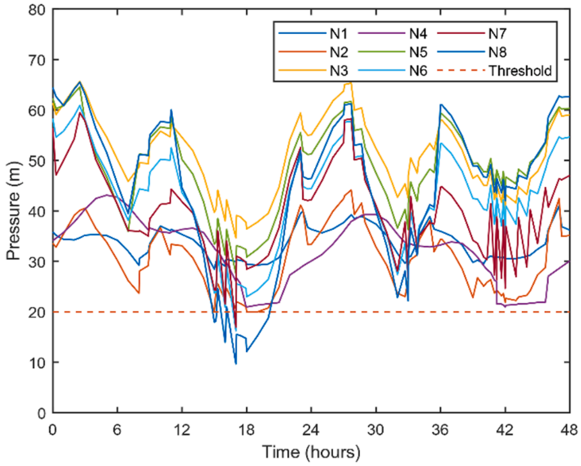
(a)



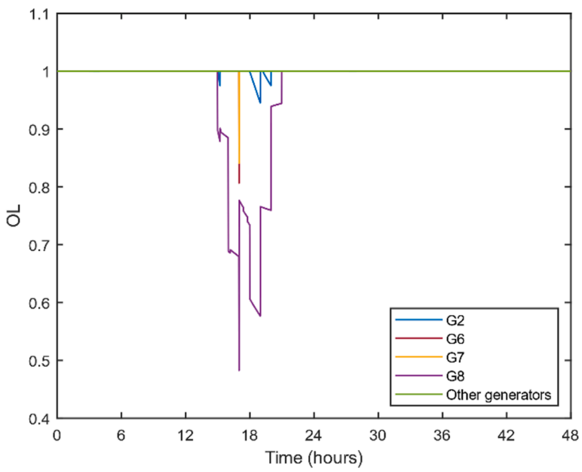
(b)



(c)



(d)



(e)

Fig. 15. (a) Pump statuses in scenario two; (b) Loads on substations in scenario two; (c) Water levels at the elevated water tanks in scenario two; (d) Water pressures at the distribution nodes in scenario two; (e) OL of power generators in scenario two.

timestamps 19:00 and 27:00 when the pumps were less solicited, the loads reasonably dropped as it would be expected in reality. The results demonstrate the effectiveness of the proposed framework in modeling the functional interdependencies between the CIS.

5.2. Scenario two

This scenario involved a failure event that originated from the power system from timestamps 12:00 to 36:00. Fig. 15(a) shows the statuses of the pump stations, Fig. 15(b) shows the loads on substations supplying power to the pump stations, Fig. 15(c) shows the water levels of the six elevated tanks, Fig. 15(d) shows the pressures at the distribution nodes, and Fig. 15(e) shows the OL of the power generators over the simulation period. Between timestamps 0:00 and 12:00, the simulation results in this scenario were identical to those in Scenario 1. However, at timestamp 12:00, the substations S1 and S4 failed, and no power was supplied to pumps P1 and P4. Consequently, P1 and P4 immediately became nonfunctional causing the corresponding loads to drop to zero, as depicted in Fig. 15(b).

It can be observed in Fig. 15(d) that this sudden loss in functionality of P1 and P4, in a period of relatively high-water demand on the water network, resulted in a general down spike in the pressure levels at water nodes. Specifically, N6 and N8, the closest nodes to the nonfunctional pumps, suffered the most adverse effect. The control system of the water network responded by opening pumps P3 and P6 at timestamps 16:01 and 15:14, respectively. Also, the operational pumps were operating at relatively higher efficiency compared to scenario 1 to stabilize the pressure levels of the system. However, it can be observed from Fig. 15(d) that between timestamps 15:00 to 19:00, when the water demand was at its highest, the pressure levels in the network were largely unstable due to the system malfunction. Fig. 15(c) shows that during the malfunction period, the water head of the tanks was much lower compared to scenario one. The reason being that water tanks acted as backup components that helped stabilize the water system under the unfavorable conditions. As the inflow of water in the network decreased due to the failure of pumps P1 and P4, the water pressure in the network became unstable and rapidly decreased. The tanks were then observed to deliver more water into the network to compensate for the drop in water supply and stabilize the pressure levels. Such a non-linear mechanism is of high value when assessing the reliability and resilience of a system, and can only be captured when the systems are modeled with sufficient granularity and details. These results demonstrate how the ripple effect of the malfunction within a system was captured by the proposed modeling framework, further highlighting the advantage of the proposed framework.

At timestamp 36:00, S1 and S4 were repaired and, consequently, P1 and P4 were restored to their functional state reflected by a rapid surge in water pressure throughout the water network.

Between timestamps 15:00 and 21:00, it can be observed that the water pressure at distribution nodes N2, N6, N7 and N8 dropped below the threshold level. The water pressures at N6 and N8 were the most severely affected by the failure event due to their proximity to the nonfunctional pumps. Consequently, the OL of generators G2, G6, G7 and G8 temporarily decreased below the maximum OL, as depicted in Fig. 15(e). As a result, the flow was immediately redistributed within the power network, with the unaffected generators compensating for the deficiency in power supply of G2, G6, G7 and G8. The fact that a failure event that originated in the power system was able to cascade to the interdependent water system and then back to the power system demonstrates the effectiveness of the proposed framework in modeling cross-domain dependencies and revealing feedback loops between the interdependent CISs.

Table 4 summarizes the simulation performance of the federation for the three different hardware configurations. The computational time of configurations 1 to 3 are averaged over 20 replications. It can be observed from Table 4 that configuration 1 had a shorter average computational time (1892 s) compared to configuration 2 (1959 s). This can be explained by the fact that the CPU and RAM of computer 1 were slightly more advanced compared to computer 2. Configuration 3 on the other hand outperformed both configurations 1 and 2 with a computational time of 1604 s. The computational load was distributed over two separate hardware resulting in faster simulation speeds. Therefore, it can be inferred that by distributing interdependent CIS models over multiple hardware and simulation engines, the simulation performances of the federation can be significantly improved. Minor variations in computational time were observed between the replications of each configuration, generally of just a few seconds (with maximum variations not more than 30 s observed in configuration 3). Since the simulation results were identical for all replications of each configuration, the differences in computational time could be attributed to the varying quality of the internet connection during message transfers and the dynamic loads on the CPU.

Table 4 also reports the results for hardware configuration 4. It can be seen that under Setting 1, the computational time was 723 s, compared to 42232 s under Setting 2, which is roughly 58 times increase in computational cost for 60 times increase in temporal granularity of a single federate. This result shows an almost linear relationship between the computational time and temporal granularity of the simulation when all other parameters are left unchanged. The result also demonstrates that addressing interoperability issues and improving the modeling of CIS interdependencies using HLA co-simulation may come at a considerable

Table 4
Summary of the simulation performance under different hardware configurations.

Configuration #	Hardware specification	Computational time (s)	
1	E5-2640 v3 CPU @ 2.60GHz 32GB RAM (computer 1)	1892	
2	i7-4710 CPU @ 2.50GHz 16GB RAM (computer 2)	1959	
3	Computers 1 and 2	1604	
4	i7-10700 CPU @ 2.90GHz 64GB RAM (computer 3)	723 (Setting 1)	42232 (Setting 2)

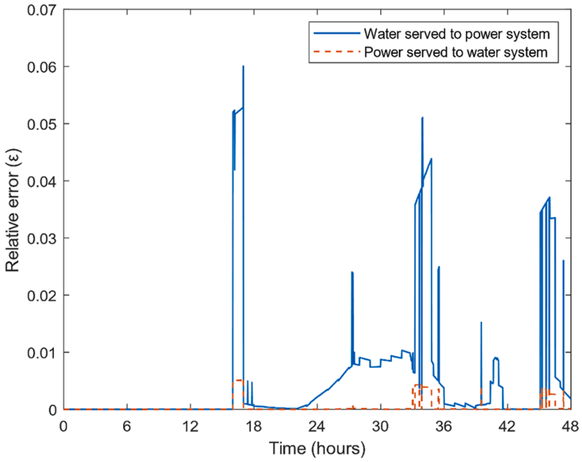


Fig. 16. Relative numerical error of Setting 1 compared to Setting 2.

computational cost.

Regarding data distribution delays, since the federated model adopted fixed lookahead values for both systems in Settings 1 and 2, the data distribution rate was constant. For example, in Setting 1, it would take a consistent 1-minute logical time for the water supply system to update new pump statuses, power demand, and water pressure levels after substations failed in the power system. During this time, the power model would have run a number of iterations of power redistribution based on “outdated” data from the water system, degrading the real interdependency between the systems. Under Setting 2, there was a consistent 1-second delay in the feedback loop between the models, which meant a higher data distribution rate and faster update of model parameters, compared to Setting 1.

When comparing the simulation results from Settings 1 and 2, it was observed that the difference in lookahead time between the two settings resulted in differences in numerical output under each setting. Considering Setting 2 as a baseline setting (since the lookahead of the CIS models was set to the lowest value supported by the selected simulators), the numerical errors observed in Setting 1 were quantified by comparing the results of Setting 1 to those of Setting 2 using a relative error metric $\boldsymbol{\varepsilon}^{\boldsymbol{\tau}}$ as follows:

$$\varepsilon^{\tau}(t) = \left| \frac{q_2^{\tau} - q_1^{\tau}}{q_2^{\tau}} \right| \tag{6}$$

where q_1^{τ} and q_2^{τ} denote the quantity of services that system τ delivered to the other system over a time step t under Setting 1 and Setting 2, respectively. Fig. 16 shows the relative error for power served to the water system and water served to the power system. It can be observed that between timestamps 15:48 and 48:00 the relative error fluctuated notably for both systems, maxing out at about 6% for the water served to the power system and about 0.51% for the power served to the water system. Before timestamp 15:48 the relative error is close to zero but not zero. The above observations can be explained by the fact that as the systems became destabilized by the simulated malfunction scenario, their performance fluctuated more rapidly, which could not be accurately captured by Setting 1 that had a larger lookahead. The spikes in the relative error, as observed in Fig. 16, correspond to the timestamps at which both systems experienced the most rapid and severe changes in performance (see Figs. 15(d) and 15(e)).

In summary, Setting 2 considerably improved the synchronization and simulation of interdependencies but resulted in significantly longer computational time, as shown in Table 4 above. It is worth mentioning that because the water supply system is relatively slow (that is, changes in flow, pump efficiency, pressure and so on happen gradually over an extended period of time), data distribution delays have a relatively low impact on the overall simulation. However, when coupling faster systems like power and communication systems, a 1-second delay may cause some switching commands to be missed, which may significantly affect the simulation. Therefore, it is important to consider the nature of the coupled systems when setting the time granularity of the simulation.

6. Discussions

The primary reason for using CIS domain-specific models was to incorporate the domain knowledge of each of the modeled CISs in the interdependent CISs model. The simulation results revealed that the system components were very different in their functionalities, the data they provided, and how they interacted with each other. This is because different CIS components followed very distinct mathematical and logical laws specific to their domain. For example, the formalisms for calculating the energy consumption of the pumps, flow rates and pressure at nodes, and so on, were based on data and practices accumulated over years of usage in the water system domain. Similarly, the formalisms for calculating flow redistribution, power losses, and so on, were specific to the power system domain. The domain knowledge from each CIS was incorporated in the developed interdependent CISs model, and the impact on system behavior was revealed. For example, Figs. 14(d) and 15(b) show that the model could provide specific values of pump power consumption at each time step based on the actual state of the water system, continually affecting the behavior of the power system. Also, Figs. 14(c) and 15(d) show 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, resulting in N4 and N8 exhibiting a completely different pressure pattern from other distribution nodes. These observations demonstrate a significant improvement in the level of details of the simulated systems behavior compared to existing interdependent CISs models. By considering only the operational state of system components or adopting harmonized flow indices, models proposed in previous studies can provide only limited information on how CISs affect each other during the simulation. It can therefore be inferred that incorporating a wide range of domain knowledge in the interdependent CISs models can help unveil more knowledge on the behavior of interdependent CISs and their interdependencies. This conclusion is supported by the results from [31] in which the water-energy nexus was studied using domain-specific models, revealing high levels of details and granularity in the systems behavior, similar to the results obtained in the present study.

The water supply system and power supply system are two heterogeneous systems that show significant differences in their physical, functional and operational characteristics. Capturing systemic heterogeneities when modeling interdependent CISs is crucial to ensure the accuracy of the simulated systems behavior. For example, if systemic heterogeneity is overlooked, the predicted disaster impact on interdependent CIS might be overestimated [77]. The simulation results of the case study revealed a few systemic heterogeneities captured by the interdependent CISs model and their impacts on the behavior of CISs. These systemic heterogeneities include heterogeneities in operational mechanism and material flow properties of these two systems. With regard to the heterogeneity in operational mechanism, it is observed from the simulation results that the tanks of the water system acted as both storage and natural backup components, adding to the robustness of the system. On the other hand, in the power system, the power generated was equal to the sum of all loads connected to the network, and was consumed as soon as it was generated. From Figs. 14(b) and 15(c), it can be observed that when the pumps were closed or nonfunctional, the tanks would empty up to stabilize the pressure throughout the system and meet flow requirements at the nodes, a feature not observed in the power network. With regard to material flow properties, it can be observed in Figs. 14(b), 14(c), 15(c) and 15(d) that changes in the water levels within the water network were relatively slow and gradual. A significant amount of time was necessary to alter the system's stability or bring it to a new stable state when changes occurred in the system components. In contrast, changes in flow across the power network were abrupt. Any slight variation in the component attributes resulted in an almost instantaneous redistribution of flow across the network. This heterogeneity in material flow property can significantly affect the behavior of the interdependent CISs, since it affects 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. The described heterogeneity factors cannot be captured using existing interdependent CISs modeling approaches because these approaches either model the CISs using homogeneous frameworks or tend to oversimplify the CIS models by abstracting out most of their operational and functional characteristics. Therefore, existing interdependent CISs models have a limited ability to accurately simulate system behavior, justifying the need for the proposed framework.

Moreover, the simulation results show that the behavior of one system was reasonably affected by changes in the other system due to their interdependencies. For example, when comparing Figs. 14(c) and 15(d), it is observed that the power shortage at S1 and S4 between timestamps 12:00 and 36:00 in scenario 2 caused a general drop in the pressure levels throughout the water network due to the failure of the dependent pump stations. Moreover, the loss in water pressure at the distribution nodes supplying water to the power generators caused the OL of the dependent generators to drop. After S1 and S4 were repaired and the functionality of P1 and P4 was restored, the pressure levels in the water system rose back to a new stable state, bringing both systems back to their normal operating state. This chain of events demonstrated that the data exchange, management and synchronization capabilities of the developed interdependent CISs model ensured the interoperability of the heterogeneous models and helped capture the dependencies between the CISs. Moreover, the failure scenario revealed a feedback loop between the CISs, which demonstrated the applicability of the proposed framework in simulating possible cascading failures across interdependent CISs. The observed influence mechanisms, and feedback loops are consistent with simulation results from prior studies that modeled and simulated Shelby County's interdependent CISs under different disruption scenarios [78–80]. The advantage of the present study however is that thanks to the high level of detail and granularity of the simulation results, causality can be analyzed more detailly, which could help increase the confidence of decision-makers in real-life management application.

Finally, the results of the simulation performance analysis demonstrated how hardware capabilities and configurations played a significant role in the overall performance of the developed federation. The increase in complexity of CISs has driven the need for more advanced and complex CIS models that come at high computational costs. Restrictions on the computational time required for an analysis has been a major challenge dissuading the use of advanced domain-specific CIS models where the flow of commodities involve complex non-linear equations [35]. The results from this study showed that distributing the computational load of large-scale interdependent CIS models can significantly reduce the computational time of the models and hence increase computational efficiency. Therefore, the proposed framework can facilitate the adoption of advanced domain-specific CIS models when modeling interdependent CISs while maintaining a reasonable level of computational efficiency.

In summary, the developed model was able to leverage the domain knowledge of both CISs, capture various heterogeneity factors among the CISs, and simulate various types of dependencies between the systems, thus meeting the objectives of this case study. The case study results indicate that the proposed framework has the potential to push the boundaries of research on interdependent CISs by addressing most of the limitations and challenges identified in related literature. Moreover, the proposed framework can also provide researchers and industry professionals with a useful methodology for testing and analyzing CIS designs, and predicting complex system behaviors such as cascading failures in different simulation environments or scenarios, so as to provide safer and more resilient infrastructure systems [81,82].

7. Conclusions

As modern CISs are becoming increasingly complex, so are the interdependencies existing among them. An event that may have been considered irrelevant to a particular CIS can still potentially affect it because of its strong dependence on other CISs. This study explored the feasibility of adopting an HLA-based framework to model and simulate the behavior of interdependent CISs. The framework addressed the limitations of existing simulation approaches by proposing a methodology to leverage, integrate and coordinate well-tested practices, knowledge, data and simulation tools from various CIS domains. The conducted case study showed that the interdependent CISs model developed based on the proposed framework could incorporate the domain knowledge specific to each CIS and capture various systemic heterogeneities among the CISs, resulting in a more detailed and accurate simulation of CISs behavior.

One limitation of the proposed framework is that it heavily relies on the capabilities of the selected API tools to control and update the domain-specific models during simulation. Some simulation tools provide only partial control of model parameters or functions, which may limit the amount of control the organizational layer of the CIS module has on a domain-specific model. Another limitation is that compared to other modeling approaches, the proposed approach may result in relatively longer computational time. This is due to the conservative time management mechanism adopted by the framework. As the number of federates and complexity of the federation increases, the difference in computational time may become more significant. Lastly, developing or expanding an interdependent CISs federation may require some significant development effort (dependent on the complexity of the model, the distributed simulation architecture, and complexity of the interplay between the systems), and various consistency checking (syntactic, semantic, and pragmatic analyses) are needed to ensure interoperability among the models. Moreover, federation developers have to address important but challenging topics, such as fault-tolerance for federation robustness and load balancing across hosts, to improve the performance of their federations. Nevertheless, a growing amount of resources, such as open-source software, add-ons, toolboxes, and so on, has been made available to facilitate the design and implementation of HLA federations.

In future works, the framework will be further improved by testing other approaches for implementing the organizational and communication layers of the CIS modules that can address the above limitations. Moreover, the framework will be adopted in more complex simulation scenarios in which the model developed in the case study will be re-used and expanded by adding extra modules and federates for studies on the cascading failure and restoration of interdependent CISs, and the incorporation of human factor in the modeling of interdependent CISs.

Acknowledgments

This material is based on work supported by the Beijing Natural Science Foundation (BJNSF) under Grant No. 8202027, and the National Natural Science Foundation of China (NSFC) under Grant No. U1709212. The authors are grateful for the support of BJNSF and NSFC. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies.

References

[1] Department of Commerce, “Critical foundations: protecting America's infrastructures,” 1997.
[2] S.M. Rinaldi, J.P. Peerenboom, T.K. Kelly, Identifying, understanding, and analyzing critical infrastructure interdependencies, IEEE Control Syst. Mag. 21 (6) (2001) 11–25, https://doi.org/10.1109/37.969131.
[3] Q. Mao, N. Li, Assessment of the impact of interdependencies on the resilience of networked critical infrastructure systems, Nat Hazards 93 (2018) 315–337, https://doi.org/10.1007/s11069-018-3302-3.
[4] S. Abraham, "Us-canada power system outage task force," *Final report on the August 14, 2003 Blackout in the United States and Canada: Causes and recommendations,*2004.
[5] C. Asavathiratham, S. Roy, B. Lesieutre, G. Verghese, The influence model, IEEE Control Syst. Mag. 21 (6) (2001) 52–64, https://doi.org/10.1109/37.969135.
[6] O. Gursesli, A.A. Desrochers, Modeling infrastructure interdependencies using Petri nets, in: *Proceedings of the SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme - System Security and Assurance (Cat. No.03CH37483)* 2, 2003, pp. 1506–1512, https://doi.org/10.1109/ICSMC.2003.1244625.
[7] B.C. Ezell, J.V. Farr, I. Wiese, Infrastructure risk analysis model, J. Infrastruct. Syst. 6 (3) (2000) 114–117, https://doi.org/10.1061/(ASCE)1076-0342(2000)6:3(114).
[8] M. Ouyang, Review on modeling and simulation of interdependent critical infrastructure systems, Reliab. Eng. Syst. Saf. 121 (2014) 43–60, https://doi.org/10.1016/j.ress.2013.06.040.
[9] J.R. Thompson, D. Frezza, B. Necioglu, M.L. Cohen, K. Hoffman, K. Rosfjord, Interdependent critical infrastructure model (ICIM): an agent-based model of power and water infrastructure, Int. J. Crit. Infrastruct. Prot. 24 (2019) 144–165, https://doi.org/10.1016/j.ijcip.2018.12.002.
[10] L. Duenas-Osorio, J.I. Craig, B.J. Goodno, A. Bostrom, Interdependent response of networked systems, J. Infrastruct. Syst. 13 (3) (2007) 185–194, https://doi.org/10.1061/(asce)1076-0342(2007)13:3(185).
[11] C. Nan, G. Sansavini, A quantitative method for assessing resilience of interdependent infrastructures, Reliab. Eng. Syst. Saf. 157 (2017) 35–53, https://doi.org/10.1016/j.ress.2016.08.013.
[12] I. Eusgeld, D. Henzi, W. Kröger, Comparative evaluation of modeling and simulation techniques for interdependent critical infrastructures, in: *Proceedings of the presented at the 9th International Probabilistic Safety Assessment Conference (PSAM 9)*, 2008, p. 2008 [Online]. Available:http://hdl.handle.net/20.500.11850/82316.
[13] S.Y. Lin, et al., Framework for modeling interdependent effects in natural disasters: application to wind engineering, J. Struct. Eng. 145 (5) (2019), 04019025, https://doi.org/10.1061/(asce)st.1943-541x.0002310.
[14] S.C. Muller, et al., Interfacing power system and ICT simulators: challenges, state-of-the-art, and case studies, IEEE Trans. Smart Grid 9 (1) (2018) 14–24, https://doi.org/10.1109/tsg.2016.2542824.
[15] C. Nan, I. Eusgeld, W. Kroger, Analyzing vulnerabilities between SCADA system and SUC due to interdependencies, Reliab. Eng. Syst. Saf. 113 (2013) 76–93, https://doi.org/10.1016/j.ress.2012.12.014.

[16] IEEE, IEEE standard for modeling and simulation: high level architecture (HLA)– framework and rules, IEEE Std 1516-2010 (Revision of IEEE Std 1516-2000) (2010) 1–38, https://doi.org/10.1109/IEEESTD.2010.5553440.
[17] N. Kollikkathara, H. Feng, D. Yu, A system dynamic modeling approach for evaluating municipal solid waste generation, landfill capacity and related cost management issues, Waste Manage. 30 (11) (2010) 2194–2203, https://doi.org/10.1016/j.wasman.2010.05.012.
[18] W. Mo, Z. Lu, B. Dilkina, K. Gardner, J.-C. Huang, M. Foreman, Sustainable and resilient design of interdependent water and energy systems: a conceptual modeling framework for tackling complexities at the infrastructure-human-resource nexus, Sustainability 10 (2018), 1845, https://doi.org/10.3390/su10061845.
[19] K.M. Faust, D.M. Abraham, D. DeLaurentis, Coupled human and water infrastructure systems sector interdependencies: framework evaluating the impact of cities experiencing urban decline, J. Water Resour. Plann. Manage. 143 (8) (2017), 04017043, https://doi.org/10.1061/(ASCE)WR.1943-5452.0000794.
[20] V.K. Mishra, V.R. Palleti, A. Mathur, A modeling framework for critical infrastructure and its application in detecting cyber-attacks on a water distribution system, Int. J. Crit. Infrastruct. Prot. 26 (2019), 100298, https://doi.org/10.1016/j.ijcip.2019.05.001.
[21] M.I. Dubaniowski, H.R. Heinimann, A framework for modeling interdependencies among households, businesses, and infrastructure systems; and their response to disruptions, Reliab. Eng. Syst. Saf. 203 (2020), 107063, https://doi.org/10.1016/j.ress.2020.107063.
[22] V.K. Kandiah, E.Z. Berglund, A.R. Binder, An agent-based modeling approach to project adoption of water reuse and evaluate expansion plans within a sociotechnical water infrastructure system, Sustain. Cities Soc. 46 (2019), 101412, https://doi.org/10.1016/j.scs.2018.12.040.
[23] X. He, E.J. Cha, Modeling the damage and recovery of interdependent critical infrastructure systems from natural hazards, Reliab. Eng. Syst. Saf. 177 (2018) 162–175, https://doi.org/10.1016/j.ress.2018.04.029.
[24] J.-Z. Yu, H. Baroud, Modeling uncertain and dynamic interdependencies of infrastructure systems using stochastic block models, ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg 6 (2) (2020), 020906, https://doi.org/10.1115/1.4046472.
[25] N. Goldbeck, P. Angeloudis, W.Y. Ochieng, Resilience assessment for interdependent urban infrastructure systems using dynamic network flow models, Reliab. Eng. Syst. Saf. 188 (2019) 62–79, https://doi.org/10.1016/j.ress.2019.03.007.
[26] S. Dunn, M. Holmes, Development of a hierarchical approach to analyse interdependent infrastructure system failures, Reliab. Eng. Syst. Saf. 191 (2019), 106530, https://doi.org/10.1016/j.ress.2019.106530.
[27] S. Lee, M. Choi, H.-S. Lee, M. Park, Bayesian network-based seismic damage estimation for power and potable water supply systems, Reliab. Eng. Syst. Saf. 197 (2020), 106796, https://doi.org/10.1016/j.ress.2020.106796.
[28] M.R. Najafi, Y. Zhang, N. Martyn, A flood risk assessment framework for interdependent infrastructure systems in coastal environments, Sustain Cities Soc. 64 (2021), 102516, https://doi.org/10.1016/j.scs.2020.102516.
[29] Y. Yang, S.T. Ng, S. Zhou, F.J. Xu, H. Li, A physics-based framework for analyzing the resilience of interdependent civil infrastructure systems: a climatic extreme event case in Hong Kong, Sustain. Cities Soc. 47 (2019), 101485, https://doi.org/10.1016/j.scs.2019.101485.
[30] C. Heracleous, P. Kolios, C.G. Panayiotou, G. Ellinas, M.M. Polycarpou, Hybrid systems modeling for critical infrastructures interdependency analysis, Reliab. Eng. Syst. Saf. 165 (2017) 89–101, https://doi.org/10.1016/j.ress.2017.03.028.
[31] S. Zuloaga, P. Khatavkar, V. Vittal, L.W. Mays, Interdependent electric and water infrastructure modelling, optimisation and control, IET Energy Systems Integration 2 (1) (2020) 9–21, https://doi.org/10.1049/iet-esi.2019.0039.
[32] T. Grafenauer, S. König, S. Rass, S. Schauer, A simulation tool for cascading effects in interdependent critical infrastructures, in: *Proceedings of the 13th International Conference on Availability, Reliability and Security, Hamburg, Germany*, 2018, https://doi.org/10.1145/3230833.3240507.
[33] L. Galbusera, P. Trucco, G. Giannopoulos, Modeling interdependencies in multi-sectoral critical infrastructure systems: evolving the DMCI approach, Reliab. Eng. Syst. Saf. 203 (2020), 107072, https://doi.org/10.1016/j.ress.2020.107072.
[34] E.M. Hassan, H. Mahmoud, An integrated socio-technical approach for post-earthquake recovery of interdependent healthcare system, Reliab. Eng. Syst. Saf. 201 (2020), 106953, https://doi.org/10.1016/j.ress.2020.106953.
[35] R. Holden, D.V. Val, R. Burkhard, S. Nodwell, A network flow model for interdependent infrastructures at the local scale, Saf. Sci. 53 (2013) 51–60, https://doi.org/10.1016/j.ssci.2012.08.013.
[36] J. Dahmann, R. Fujimoto, R. Weatherly, The department of defense high level architecture, in: *Proceedings of the 29th Conference on Winter Simulation*, 2000, https://doi.org/10.1145/268437.268465.
[37] D. Wang, Q. Guo, Y. Song, K. Gao, A. Zhou, Cyber-physical security assessment and simulation based on graph database, in: *Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2017, pp. 1–6, https://doi.org/10.1109/EI2.2017.8245607.
[38] M. Ficco, G. Avolio, F. Palmieri, A. Castiglione, An HLA-based framework for simulation of large-scale critical systems, Concurr. Computat. Practice Experience 28 (2) (2016) 400–419, https://doi.org/10.1002/cpe.3472.
[39] F. Kuhl, R. Weatherly, J. Dahmann. Creating Computer Simulation Systems: An Introduction to the High Level Architecture, Prentice Hall; Book and CD-ROM edition, 1999.
[40] A. Jain, D. Robinson, B. Dilkina, R. Fujimoto, An approach to integrate inter-dependent simulations using HLA with applications to sustainable urban development, in: *Proceedings of the 2016 Winter Simulation Conference (WSC)*, 2016, pp. 1218–1229, https://doi.org/10.1109/WSC.2016.7822178.
[41] M. Wei, W. Wang, Greenbench: a benchmark for observing power grid vulnerability under data-centric threats, in: *Proceedings of the IEEE INFOCOM 2014 - IEEE Conference on Computer Communications*, 2014, pp. 2625–2633, https://doi.org/10.1109/INFOCOM.2014.6848210.
[42] D. Bhor, K. Angappan, K.M. Sivalingam, A co-simulation framework for Smart Grid wide-area monitoring networks, in: *Proceedings of the 2014 Sixth International Conference on Communication Systems and Networks (COMSNETS)*, 2014, pp. 1–8, https://doi.org/10.1109/COMSNETS.2014.6734880.
[43] E. Rome, P. Langeslag, A. Usov, Federated modelling and simulation for critical infrastructure protection, in: G. D'Agostino, A. Scala (Eds.), Networks of Networks: The Last Frontier of Complexity, Springer International Publishing, Cham, 2014, pp. 225–253.
[44] Birman Hopkinson, Coury Giovanini, EPOCHS: integrated commercial off-the-shelf software for agent-based electric power and communication simulation, in: *Proceedings of the 2003 Winter Simulation Conference*, IEEE, 2003, pp. 1158–1166, https://doi.org/10.1109/WSC.2003.1261545.
[45] R. Klein, E. Rome, C. Beyel, R. Linnemann, W. Reinhardt, A. Usov, Information modelling and simulation in large interdependent critical infrastructures in IRRIIS, in: R. Setola, S. Geretshuber (Eds.), Critical Information Infrastructure Security, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 36–47.
[46] E. Bagheri, H. Baghi, A.A. Ghorbani, A. Yari, An agent-based service-oriented simulation suite for critical infrastructure behaviour analysis, Int. J. Bus. Process Integrat. Manage. 2 (4) (2007) 312–326, https://doi.org/10.1504/IJBPIM.2007.017756.
[47] J. Marti, C. Ventura, J. Hollman, K. D. Srivastava, and H. Juárez García, I2SimModelling and Simulation Framework for Scenario Development, Training, and Real-Time Decision Support of Multiple Interdependent Critical Infrastructures during Large Emergencies, *RTA/MSG Conference on "How is Modelling and Simulation Meeting the Defence Challenges Out to 2015?" RTO-MP-MSG-060*, 2008.
[48] IEEE, IEEE Standard for Distributed Interactive Simulation–Application Protocols, IEEE Std 1278.1-2012 (Revision of IEEE Std 1278.1-1995) (2012) 1–747, https://doi.org/10.1109/IEEESTD.2012.6387564.
[49] J.B. Fitzgibbons, R.M. Fujimoto, D. Fellig, S.D. Kleban, A.J. Scholand, IDSim: an extensible framework for interoperable distributed simulation, in: *Proceedings of the IEEE International Conference on Web Services*, 2004, https://doi.org/10.1109/ICWS.2004.1314779.
[50] P.T. Grogan, O.L.d. Weck, Infrastructure system simulation interoperability using the high-level architecture, IEEE Syst. J. 12 (1) (2018) 103–114, https://doi.org/10.1109/JSYST.2015.2457433.
[51] E. Casalicchio, R. Setola, S. Bologna, A two-stage approach to simulate interdependent critical infrastructures, in: Proceedings of the 2010 Complexity in Engineering, 2010, pp. 76–78, https://doi.org/10.1109/COMPENG.2010.33.
[52] S. Bologna, E. Rome, E. Gelenbe, E. Luiijf, and V. Masucci, DIESIS - An Interoperable European Federated Simulation Network for Critical Infrastructures, *Simulation Interoperability Standards Organization: 2009 SISO European Simulation Interoperability Workshop (EURO SIW 2009)*, 2009.
[53] E. Casalicchio, E. Galli, S. Tucci, Federated agent-based modeling and simulation approach to study interdependencies in IT critical infrastructures, in: D. J. Roberts, G.K. Theodoropoulos, A. ElSaddik (Eds.), *Proceedings of the Ds-Rt 2007: 11th Ieee International Symposium on Distributed Simulation and Real-Time Applications, Proceedings*, IEEE Computer Soc, 2007, pp. 182–189, https://doi.org/10.1109/DS-RT.2007.11.

[54] C. Nan, I. Eusgeld, Adopting HLA standard for interdependency study, Reliab. Eng. Syst. Saf. 96 (1) (2011) 149–159, https://doi.org/10.1016/j.ress.2010.08.002.
[55] I. Eusgeld, C. Nan, S. Dietz, System-of-systems" approach for interdependent critical infrastructures, Reliab. Eng. Syst. Saf. 96 (6) (2011) 679–686, https://doi.org/10.1016/j.ress.2010.12.010.
[56] C. Nan, G. Sansavini, Developing an agent-based hierarchical modeling approach to assess human performance of infrastructure systems, Int. J. Ind. Ergon. 53 (2016) 340–354, https://doi.org/10.1016/j.ergon.2016.04.002.
[57] T. Pitch, *The HLA tutorial: a practical guide for developing distributed simulations*. 2012.
[58] S.J.E. Taylor, Distributed simulation: state-of-the-art and potential for operational research, Eur. J. Operat. Res. 273 (1) (2019) 1–19, https://doi.org/10.1016/j.ejor.2018.04.032.
[59] W. Huiskamp, T. van den Berg, Federated Simulations, in: R. Setola, V. Rosato, E. Kyriakides, E. Rome (Eds.), Managing the Complexity of Critical Infrastructures: A Modelling and Simulation Approach, Springer International Publishing, Cham, 2016, pp. 109–137.
[60] Z.H. Zhang, X.D. Chai, B.C. Hou, System security approach for web-enabled HLA/RTI in the cloud simulation environment, in: *Proceedings of the 2011 6th IEEE Conference on Industrial Electronics and Applications*, 2011, pp. 245–248, https://doi.org/10.1109/ICIEA.2011.5975588.
[61] P. Bieber, J. Cazin, P. Siron, and G. Zanon, "Security Extensions to ONERA HLA RTI Prototype," 1998.
[62] A. Elkins, J.W. Wilson, D. Gracanin, Security issues in high level architecture based distributed simulation, in: *Proceeding of the 2001 Winter Simulation Conference*, IEEE, 2001, pp. 818–826, https://doi.org/10.1109/WSC.2001.977372.
[63] R. Zimmerman, Decision-making and the vulnerability of interdependent critical infrastructure, in: *Proceedings of the 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583)* 5, 2004, pp. 4059–4063, https://doi.org/10.1109/ICSMC.2004.1401166.
[64] P. Trucco, E. Cagno, M. De Ambroggi, Dynamic functional modelling of vulnerability and interoperability of critical infrastructures, Reliab. Eng. Syst. Saf. 105 (2012) 51–63, https://doi.org/10.1016/j.ress.2011.12.003.
[65] S. De Porcellinis, R. Setola, S. Panzieri, G. Ulivi, Simulation of heterogeneous and interdependent critical infrastructures, Int. J. Crit. Infrastruct. 4 (1) (2008) 110–128, https://doi.org/10.1504/IJCIS.2008.016095.
[66] R. Fujimoto, R. Weatherly. Hla Time Management And DIS, *Interoperability of Distributed Simulations*, 1999.
[67] G. Lasnier, J. Cardoso, P. Siron, C. Pagetti, P. Derler, Distributed simulation of heterogeneous and real-time systems, in: *Proceedings of the 2013 IEEE/ACM 17th International Symposium on Distributed Simulation and Real Time Applications*, 2013, pp. 55–62, https://doi.org/10.1109/DS-RT.2013.14.
[68] Y. Wu, L. Fu, F. Ma, X. Hao, Cyber-physical co-simulation of shipboard integrated power system based on optimized event-driven synchronization, Electronics 9 (3) (2020), 540, https://doi.org/10.3390/electronics9030540 [Online]. Available:https://www.mdpi.com/2079-9292/9/3/540.
[69] IEEE, IEEE recommended practice for high level architecture (HLA) federation development and execution process (FEDEP), IEEE Std 1516.3-2003 (2003) 1–40, https://doi.org/10.1109/IEEESTD.2003.94251.
[70] S.E. Chang, H.A. Seligson, R.T. Eguchi, Estimation of the Economic Impact of Multiple Lifeline Disruption: Memphis Light, Gas and Water Division Case, in: National Center for Earthquake Engineering Research, 1996 [Online]. Available:https://www.eng.buffalo.edu/mceer-reports/96/96-0011.pdf.
[71] M. Shinozuka, A. Rose, and R. T. Eguchi, "Engineering and socioeconomic impacts of earthquakes: An analysis of electricity lifeline disruptions in the New Madrid area," United States, 1998. [Online]. Available: https://www.osti.gov/biblio/339696.
[72] N. Sharma, A. Tabandeh, P. Gardoni, Regional resilience analysis: a multiscale approach to optimize the resilience of interdependent infrastructure, Comput. Aided Civ. Infrastruct. Eng. 35 (12) (2020) 1315–1330, https://doi.org/10.1111/mice.12606.
[73] S.A. Lucas, P.J. Coombes, A.K. Sharma, The impact of diurnal water use patterns, demand management and rainwater tanks on water supply network design, Water Supply 10 (1) (2010) 69–80, https://doi.org/10.2166/ws.2010.840.
[74] L. Rossman and J. Van Zyl, *The open sourcing of EPANET*. 2010.
[75] L.C. Ribeiro, F.L. Vieira, B.D. Bonatto, A.C.Z. de Souza, P.F. Ribeiro. Chapter 5 - Modeling and simulation of active electrical distribution systems using the OpenDSS," in Decision Making Applications in Modern Power Systems, Academic Press, 2020, pp. 121–152.
[76] E. Noulard, J.-Y. Rousselot, and P. Siron, "CERTI, an Open Source RTI, why and how," 2009.
[77] F. Wang, J.J. Magoua, N. Li, D. Fang, Assessing the impact of systemic heterogeneity on failure propagation across interdependent critical infrastructure systems, Int. J. Disast. Risk Reduct. 50 (2020), 101818, https://doi.org/10.1016/j.ijdrr.2020.101818.
[78] T. Adachi, "Impact of Cascading Failures on Performance Assessment of Civil Infrastructure Systems," 2007 [Online]. Available: http://hdl.handle.net/1853/14543.
[79] N. Sharma, P. Gardoni, Mathematical modeling of interdependent infrastructure: an object-oriented approach for generalized network-system analysis, Reliab. Eng. Syst. Saf. 217 (2022), 108042, https://doi.org/10.1016/j.ress.2021.108042.
[80] A.D. González, L. Dueñas-Osorio, M. Sánchez-Silva, A.L. Medaglia, The interdependent network design problem for optimal infrastructure system restoration, Comput. Aided Civ. Infrastruct. Eng. 31 (5) (2016) 334–350, https://doi.org/10.1111/mice.12171.
[81] F. Wang, J.J. Magoua, N. Li, Modeling cascading failure of interdependent critical infrastructure systems using HLA-based co-simulation, Autom. Constr. 133 (2022), 104008, https://doi.org/10.1016/j.autcon.2021.104008.
[82] J.J. Magoua, F. Wang, N. Li, Towards HLA-based modeling of interdependent infrastructure systems, in: *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, 2021, https://doi.org/10.22260/ISARC2021/0038.