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Modeling cascading failure of interdependent critical infrastructure systems using HLA-based co-simulation

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ABSTRACT

Cascading failure modeling in interdependent critical infrastructure systems (CISs) is an important but challenging work that lays the foundation for disaster impact assessment and recovery planning. However, despite the increasing volume of studies that examine cascading failure across interdependent CISs, the majority of modeling approaches proposed in prior studies do not capture the complex heterogeneous nature and behavior of the CISs under disaster, limiting the ability of these approaches to detailly model the cascading failure process. To address the above limitation, this study proposes a high level architecture (HLA)-based co-simulation approach to integrate heterogeneous domain-specific CIS models and model the cross-domain interdependencies and failure propagation processes. Moreover, the approach provides a novel solution for modeling the dynamic impact of disaster on CISs and analyze its impact on the cascading failure of interdependent CISs. A case study of two interdependent power and water systems was conducted, which demonstrated the efficacy of the proposed approach. The results showed that the model developed using the proposed approach could provide granular data of the state and heterogeneous behaviors of the systems, capture the dynamic evolution of disaster impact on system components, and reveal the paths and mechanisms of failure propagation within and across the systems. The proposed modeling approach can overcome the drawbacks in current interdependent CISs cascading failure models, and provide a foundation for resilience assessment of CISs.

1. Introduction

Critical infrastructure systems (CISs), such as power and water supply systems, provide the basic needs and services that are essential to sustain human activities, good living standards, safety and economic security [1,2]. Although largely considered independent in their operations, CISs are directly or indirectly dependent on each other because of the services they exchange [3]. For example, the power supply system provides the electricity needed to power the pumping station of the water supply system, which in turn supplies the power system with cooling water needed by its power plant. Such dependencies among CISs create a complex system of systems with unpredictable behaviors and hidden feedback loops [4,5].

Cascading failure is a process by which a system component fails due to the failure of another component it depends on. This process can cause a local disturbance to propagate in an unusual and unpredictable manner through an entire system, which in the worst cases can lead to global failure of the system [6–9]. The propagation of failure within and across CISs is primarily due to their complex interactions and hidden feedback loops, and is difficult to be quantitatively analyzed using mathematical formulae [9]. Cascading failures can have devastating effects on interdependent CISs, as was the case in the events that led to the September 28, 2003 electric power blackout in Italy [10]. The shutdown of power stations led to the failures of multiple facilities of the power supply network and the internet and communication network, which in turn caused the further breakdown of other power stations. To prevent such events from reoccurring, further studies on the cascading failure of interdependent CISs need to be conducted to provide further insights into the disaster risk reduction and resilience enhancement of the CISs.

Modeling the cascading failure of interdependent CISs requires the comprehensive modeling of (1) the disaster scenarios and their dynamics; (2) the intra-system failure propagation process; and (3) the inter-system failure propagation process. Over the years, several different approaches have been proposed to model cascading failures in interdependent CISs. Among these approaches, the complex network-

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based (CNB) and network flow-based (NFB) approaches are the most widely adopted [6,11,12]. The CNB approach models cascading failure as the failure of all edges connected to a failed node and vice versa [6], whereas in the NFB approach, a component fails when the actual load reaching it exceeds its load capacity [13]. The primary limitation of these approaches is that they fail to capture the complex heterogeneous nature and behavior of the CISs. The heterogeneities in physical network features, transported material properties, operational characteristics, and disaster response mechanisms of the CISs are either not considered or not adequately accounted for [12]. Consequently, a significant amount of operational data and physics laws governing the dependencies among system components are lost, limiting the abilities of these approaches to model both the intra-system and inter-system failure propagation processes with sufficient details. In addition, component failure is modeled following the same principle for all CIS components, without considering their differences in tolerance to various disaster types and intensities. The cascading failure of CISs is a complex sequence of spontaneous responses of CIS components to changes in the state of, and services provided by, components they depend on. The universal, theoretical failure propagation principles adopted in existing approaches cannot reflect the intrinsic complexities of the real cascading failure process of CISs. Finally, the dynamic impact of the disaster events on the CISs is usually not reasonably modeled in previous studies. In reality, the direct damage of system components due to disaster events can be a sudden or progressive reduction in the functionality or structural integrity of the components [14]. The fragility of the system components may increase over stages as the disaster persists [14]. However, prior researches do not take into consideration this accumulation of partial damages and progressive increase in the fragility of CISs during disaster scenarios, which could significantly affect the disaster impact analyses results. Therefore, the connection between the disaster scenario and the updated state of CISs throughout the simulation of cascading failure should be considered to model the dynamic impact of disaster events.

The above limitations identified in previous studies may considerably affect the efficiency and reliability of the cascading failure models and the assessed disaster impact. Therefore, a more advanced approach for modeling cascading failures of interdependent CISs should be proposed to address these limitations. A possible solution to the limitations identified above is to adopt fine-grained domain-specific models of the CIS and disaster scenarios to simulate, with high fidelity, the disaster impact and failure propagation process. A domain-specific model adopts domain-specific knowledge to represent real-world objects in a domain field [15]. However, the main challenges of this approach are to achieve the interoperability and synchronization of the heterogeneous domain-specific models. Magoua et al. [16] demonstrated the efficacy of a High Level Architecture (HLA)-based co-simulation environment in addressing the above challenges, showcasing its ability to integrate, organize and manage multiple heterogeneous CIS models and simulation tools.

This study therefore aims to propose an HLA-based co-simulation approach for modeling the cascading failure of interdependent CISs. This approach leverages the domain knowledge of CISs and well-tested data, practices, and tools for modeling the CISs and disaster scenarios, to more detailly model the disaster impact and cascading failure process. The advantages and efficacy of the proposed approach were demonstrated in a case study of Shelby County's interdependent power and water systems under a hypothetical earthquake disaster scenario. The contribution of this work is that it proposes a novel approach for modeling the cascading failure process, which can help reveal the previously unforeseen chain of events, feedback loops, and behaviors of the interdependent CISs. This study therefore contributes to improving the existing knowledge on the modeling and simulation of cascading failure of interdependent CISs while providing useful information for the emergency response decisions of CISs managers.

The remainder of this paper is organized as follows: Section 2 presents related works and discusses current research gaps; Section 3 describes the methodology developed in this study; Sections 4 and 5 present a case study and the results, respectively, followed by Section 6 that discusses the findings as well as their theoretical and practical implications; Section 7 concludes the paper.

2. Related work

2.1. Approaches for modeling cascading failure of interdependent CISs

CISs are constantly exposed to adverse events such as natural and man-made disasters. In the event of a disaster, the cascading failure of system components may significantly increase the disaster impact on the CISs and potentially lead to global failure of the CISs. The accurate modeling of the failure propagation process is therefore of significant importance to disaster impact assessment and disaster risk reduction. Much attention has been paid to this issue in prior literature, with several approaches being proposed for modeling the cascading failure of CISs.

A vast majority of previous studies have adopted the complex network theory to model cascading failure in CISs since the interdependent CISs can easily be represented as interconnected networks of nodes and links. In the CNB approach, the intra- and inter-system failure propagation mechanisms are modeled identically. Failure of a node triggers the failure of all edges connected to it and vice versa [6]. A typical model based on this approach is the percolation model [17], which is widely adopted to analyze the topological failure of multilayered interdependent infrastructure networks. The network-based approach has been adopted in several studies to analyze the cascading failure of interdependent networks with different average degrees [18], and under various attack conditions (deliberate or random) [13,19]. The limitation of the pure network-based approach is that it only considers the topology of the CISs, leaving out the functional characteristics of the systems. In so doing, important information reflective of the systems' behavior under disaster scenarios such as flow values, component parameters, and so on, are overlooked in the modeling process. Consequently, the developed models do not provide a detailed representation of the CISs nor capture the systemic heterogeneities, and cannot simulate the system behaviors and cascading failure processes with sufficient detail.

To consider both the topological and functional characteristics of CISs, the concept of artificial flow index has been introduced in network models to describe the functional characteristics of the CISs [20–22]. Two commonly used artificial flow indices in the literature include betweenness [13] and the number of shortest paths [23]. Based on these artificial flow indices, several models that adopted the overload damage mechanism were proposed to simulate the failure propagation across interdependent CISs networks [24,25]. These models assume that every CIS network component has an optimal load capacity and would suffer overload failure when the actual load reaching the component exceeds this capacity. Failure of a network component would trigger the redistribution of flow throughout the interdependent networks, either by recalculating the flow index without considering the failed components or by proportionately redistributing the flow of the failed component to its adjacent components. The limitation of the artificial flow-based approach is that by abstracting the network flow, important flow-related information, such as the time-dependent variation of flow, the hydromechanical characteristics of real flow, and so on, are not captured. As a result, the developed models exhibit flow variations and trends that do not adequately reflect reality, and thus may significantly affect the accuracy of the modeled cascading failure process.

In more recent studies, researchers have attempted to use real flow indices, such as water flow rate and current flow rate, to describe the functional characteristics of CISs. In this approach, the failure propagation mechanism of each CIS is modeled differently. For example, in the power supply system, flow is calculated based on the Direct Current

(DC) power flow model [26], while in the gas supply system, flow is calculated based on the maximum network flow model [27]. In addition, several uncertainty factors can be considered in this approach, such as the uncertainty of interdependency strength [28], disaster scenarios [29], and so on. The limitation of this approach is that the developed models are oversimplified compared to reality, and cannot capture the nonlinearity and dynamics of flows within the CIS. For example, the DC power flow model was adopted to briefly analyze the power supply system with alternating current, hence not capturing system behaviors specific to alternating current flow. As a result, this approach cannot model the real intra-system failure propagation process of each CIS.

Another important issue when analyzing cascading failure is the modeling of the disaster impact on CIS. Existing approaches for modeling cascading failure have limited capabilities in modeling the dynamic impact of disaster events on the CISs. By developing overly abstracted CISs models, the information necessary to analyze and simulate the progressive damages endured by the system components is not made available. Hence, some previous studies had to rely on some statistical or empirical models to assess the dynamic impact of disaster events, instead of the actual evolutionary state of the simulated CISs [29].

In summary, although considerable progress has been made in modeling the cascading failures of interdependent CISs under disaster scenarios, the existing modeling approaches still exhibit several significant limitations. Among these limitations, the inabilities of these approaches to model the functional characteristics of the CISs with sufficient detail, to capture systemic heterogeneities among the CISs, and to model the dynamic impact of the disaster events, have the most significant impact on the accuracy of the modeled failure propagation process.

2.2. HLA-based co-simulation and its applications in modeling CIS

Co-simulation allows for the integration of multiple models to simulate large-scale systems or the division of large models into several sub-models that can be operated on separate computers. The advantages of the co-simulation approach include model reusability, interoperability, and data privacy [30–32]. Co-simulations were originally developed in the field of computer science [33], and have been widely used to evaluate the behavior of complex systems [34], such as human behavior in transportation systems [35], and information exchange in smart grid systems [36].

Several standards, such as HLA and Distributed Interactive Simulation (DIS), exist for developing co-simulation platforms [37,38]. Among these standards, the HLA standards are the most advanced and widely adopted in previous research [39,40]. The HLA standards were developed by the U.S. Department of Defense to guide the development of co-simulation platforms (known as federations) and improve the interoperability, modularity, and reusability of simulators (known as federates). The HLA standards include three essential parts [41], namely 1) the HLA framework and rules that define the behavior of the simulators during the simulation; 2) the Federate Object Model (FOM) that specifies the data format exchanged among the simulators; and 3) the interface specifications that describe the functions of the run-time infrastructure (RTI) middleware. The RTI is a software middleware that provides data and time management services to the federation by coordinating the publish and subscribe schemes of the federates.

Some of the advantages of the HLA-based co-simulation over alternative standards include [42,43]: 1) better simulation time management with the ability to synchronize time-stepped and event-based models; 2) faster data exchange rates when modeling large-scale system using multiple simulators; 3) improved interoperability between heterogeneous simulators by providing an object model template (OMT) to set the exchanged data formats.

With regard to the modeling and simulation of CISs, although no co-simulation approach for modeling cascading failure has been proposed in previous studies, a few studies have attempted to use the HLA-based simulation approach to model individual and interconnected CISs. For instance, Nan [36] examined the feasibility of adopting HLA standards to model interdependent CISs by conducting a case study of a power supply system and its SCADA (Supervisory Control and Data Acquisition) system. The study results showed that the developed interdependent model could effectively simulate the interdependencies between both models while maintaining relatively fast data transfer rates between them. Other studies adopted the HLA standards to develop models for vulnerability assessment [44], performance assessment [45], and interdependency modeling [46] of CISs. In addition, Casalicchio et al. [47] combined HLA standards and agent-based modeling to propose a federated agent-based modeling approach that considered several CIS simulators as agents that communicate via an RTI middleware. A shared limitation of the above-mentioned studies is that they focused primarily on understanding and modeling CISs interdependencies, and abstracted out most of the internal complexities of individual CISs. Much of the CISs domain knowledge was absent from the developed interdependent CISs models and only simple interactions were modeled when using heterogeneous CISs models.

The advantages of the HLA co-simulation approach can potentially improve the level of detail and granularity in modeling and simulating the cascading failure of interdependent CISs. The data exchange services provided by the RTI middleware can facilitate the integration and interoperability of CIS domain-specific models and simulation tools. In addition, the time management services offered by the RTI can ensure the synchronization of simulators and reflect the real-time course of events in the simulation progress. In sum, by integrating and coordinating the interactions between fine-grained CIS domain-specific models and disaster simulators within an HLA-based co-simulation environment, the cascading failure process of CISs under disaster scenarios can be simulated with more details and higher granularity.

3. Methodology

Motivated by the aforementioned gaps in the literature, this study proposes an HLA-based co-simulation approach for modeling the cascading failure of interdependent CISs. In this section, a federation architecture is proposed for developing the disaster-impacted interdependent CISs model, followed by a detailed description of the cascading failure simulation process.

3.1. HLA-based modeling of interdependent CISs subject to disaster impact

The disaster-impacted interdependent CISs model is developed by integrating several CIS domain-specific models and disaster simulators in an HLA federation following the IEEE 1516 standard. The federation architecture, illustrated in Fig. 1, consists of a disaster scenario module, several CIS modules, and the RTI middleware. A module is a group of associated federates (models or simulation tools) responsible for simulating a particular CIS, agent or factor. Each module in the federation architecture is explained in detail below.

The disaster scenario module includes federates that simulate a specific disaster and perform various disaster impact analyses of the systems, such as components' failure probability calculations, structural analysis of facilities, and so on. The data and information required, processed, or exchanged by federates in this module may include the disaster event information (such as the main disaster locations, magnitude, and propagation parameters), the CISs information (such as the components' locations and fragility parameters), as well as other relevant environmental or historical data (such as geological data, human mobility data and so on). The output of the disaster scenario module may include the probability of the system components suffering different levels and/or types of damages, a map of disaster-affected areas, failure probabilities of system components, and so on.

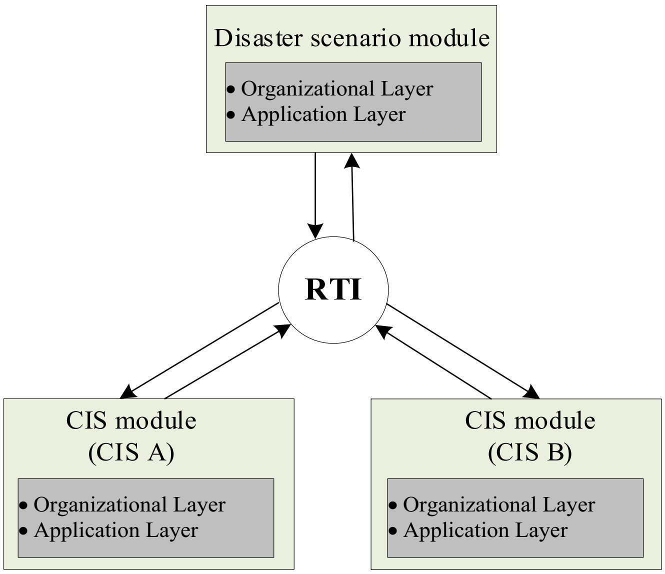


Fig. 1. Federation architecture for modeling interdependent CISs affected by a disaster.

A CIS module consists of the federates responsible for simulating and analyzing the functionalities, operations, and behavior of individual CISs. The data and information required, processed, or exchanged by the federates in this module may include the CISs information (such as the components' locations, functionality parameters, and the relationship between dependent agents/components), and the operational parameters under the defined simulation scenario (such as duration and sequence of simulation events). The output of a CIS module may include system performance values, components' functional state (functional or failed) and damage state (e.g. slight, moderate, extensive, complete), real-time variations in specific attributes of the components/agents, and so on.

Each federation module is composed of two layers, namely the application layer that contains the actual domain-specific CISs models or disaster simulators, and the organizational layer that is an additional computational layer necessary to improve the interoperability among the heterogeneous federates.

The application layer applies the HLA standards for representing a federate in which a federate is a set of *model objects,* each having a number of *attributes* that together describe the *status* of the object at each simulation timestep. The *model state* is a collection of all the model objects and their attributes at a particular simulation timestep. The *model input* is a set of all data necessary to update the model state, while the *model output* is a set of updated object attributes that are published to the federation or exported as the simulation output. The model states at each timestep are computed based on the logic or physics defined in the computational engine of the federates.

The organization layer of a module facilitates the communication between the federates of its application layer and the RTI. This layer consists of data processing units (DPUs) that interact with the RTI (publish/subscribe to data) by means of *RTI library functions*, invoke the federates using their respective *API functions,* and process the exchanged data when necessary using *dependency functions.* A DPU acts as a wrapper that can process calls and modify data passing between the RTI and the federates with little additional computation. The DPUs also retrieve model output to be published or exported for analysis.

Dependency functions are used when the subscribed data requires additional processing to generate model input (for example, the dependency function of a module can be used to randomly generate the states of system components based on the failure probability data subscribed from another module). API functions are specific to a software application and are used to interact with the federate of a module by editing the object attributes (e.g. "*setPump(x)Power(y)*" or "*addLink(x) Coord. (y)*"), executing a specific function (e.g. "*computeFlowAnalysis*" and "*runSimulationScenario(x)*"), and retrieving model output (e.g. "*getTank(x)Head*"). The RTI library functions consist of the federate ambassador and RTI ambassador that allow the RTI to manage calls and callbacks between the modules. Fig. 2: presents the data exchange and data processing mechanism of the federation.

The interdependent CISs federation can be developed following the federation development process described in [16], which is summarized in the following four steps:

(1) Objectives development: define the study objectives and required simulation output
(2) Conceptual design: develop the simulation scenario based on an appropriate real-world representation of the interactions between the disaster event and the interdependent CISs.
(3) Federation design: select the most suitable domain-specific models and simulation tools to model the CISs and disaster events, and design the publish-subscribe scheme between the selected federates to capture all existing dependencies.
(4) Federation Implementation: develop the FOM and necessary DPUs, then test and debug the federation.

3.2. Simulation of cascading failure

The cascading failure process is modeled as a cycle of information exchange between the different federation modules at every timestep of

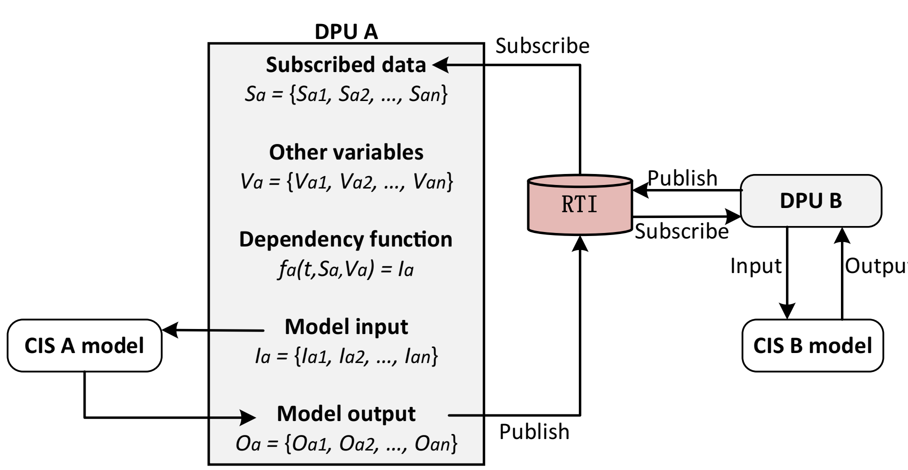


Fig. 2. The data exchange mechanism of the federation.

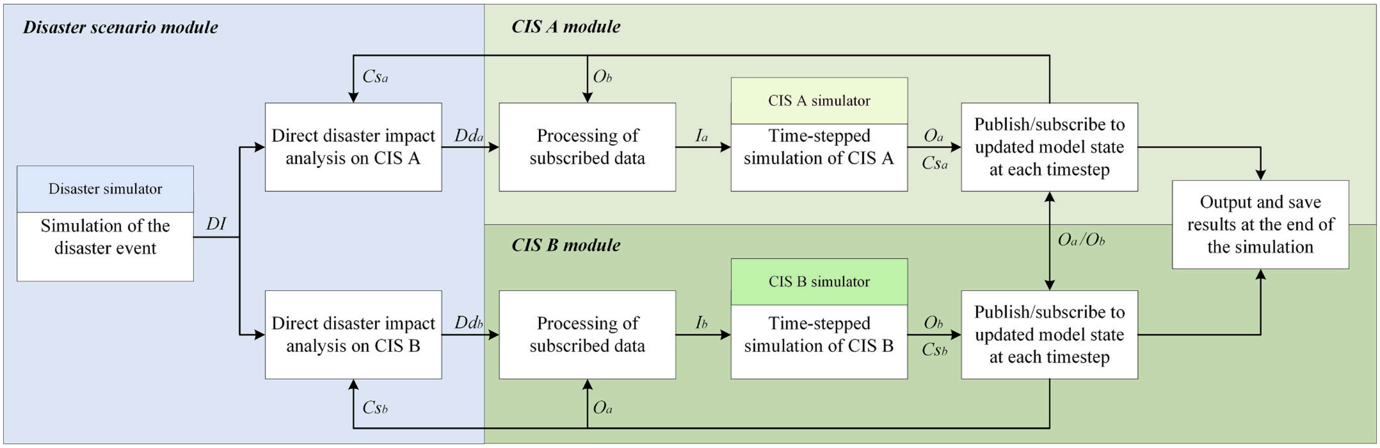


Fig. 3. The cascading failure simulation process.

the simulation. A timestep is the pre-defined time interval between two successive updates of a model's variables. Fig. 3 illustrates the cascading failure simulation process proposed in this study, highlighting the main simulation steps and information exchanged. Table 1 further describes the information exchanged during the simulation process.

The simulation of the disaster event, based on the scenario information defined by the modeler, initiates the entire cascading failure simulation process. Depending on the type of disaster being simulated, the disaster event simulator may provide static or dynamic information about the disaster, such as disaster intensities, for the affected area. For example, a flood simulator can provide the depth of water at different locations throughout the simulation period, while an earthquake simulator can provide PGA (Peak Ground Acceleration) values at different locations for the mainshock and aftershocks.

The disaster information is then published to the direct impact analysis federates that analyze the damages suffered by each CIS due to the direct action of the disaster. Each direct impact analysis federate contains the basic CIS information, such as components' location, type, present state, and structural parameters, that is necessary to complete the required analysis. Results of the direct impact analyses of each CIS (e.g., failure probabilities of the components, structural damages, and so on) are then published to their respective CIS module.

The DPU of each CIS module subscribes to the direct disaster impact results and performs any additional data processing to generate model input that can be assimilated by the selected CIS federate. For example, if direct impact analysis results are in the form of damage probabilities of components, the DPU can randomly generate multiple sets of components damage states (none, slight, moderate, extensive, complete) as model input. If no recovery action is considered, the damage state of components remains fixed after the simulated disaster event is completed. At the same time, data subscribed from other CIS modules (attributes from interdependent components) are processed as part of the CIS model input following the process described above.

Based on the model input at each simulation timestep, the CIS federates simulate the systems' functions, operations, and evolutionary behavior, making available the updated model state at the end of each timestep. The model state is published to the rest of the federation and used as input for the next simulation timestep. The set of updated object attributes is published to the interdependent CIS module, while the set of the updated functional state of system components is published to the direct impact analysis simulator.

The simulation cycle described above is automatically repeated until reaching the final timestep defined by the modeler.

Table 1
Information exchanged during the cascading failure simulation process.

Information	Description
DI	Intensity of the simulated disaster at all locations of interest
Dd_a/Dd_b	System damages directly induced by the simulated disaster
I_a/I_b	CISs model input at each timestep
O_a/O_b	Set of updated object attributes published to the interdependent CIS at each timestep
Cs_a/Cs_b	Updated functional state and damage state of system components

4. Case study

4.1. Case description

A case study of the interdependent water and power supply systems of the Shelby County, Tennessee (TN), United States, subjected to a simulated earthquake disaster, was conducted to test the efficacy of the proposed approach. Located on the east banks of the Mississippi River, Shelby County is the largest county in TN, both in terms of population and geographic area. The county's water and power supply systems 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. The data of the considered infrastructure systems and disaster parameters, which were primarily collected from prior studies, are described in the following subsections.

4.1.1. Power supply system

Based on the descriptions provided in [48,49], Shelby County's power network is equipped with eight gate stations that act as the county's main power sources. Substations and transmission lines distribute the electric power from the gate stations to the end users, as illustrated in Fig. 4. The system counts a total of seventeen 23kv and nineteen 12kv substations (numbered 1–36). The eight gate stations (numbered 37–44) were modeled as power generators independent of plants outside of the county. This was done so that the dependency of power generators on the water network could be represented in the interdependent CISs model.

4.1.2. Water supply system

According to the descriptions provided in [50,51], the Shelby County water supply system consists of nine pumping stations that draw water from an artesian aquifer and distribute it to six elevated storage tanks that supply the distribution nodes via buried pipes. The network consists of approximately 960 distribution nodes with elevations ranging between 63.6 m to 126.6 m, and 1300 pipes with diameters ranging from 16 cm to 122 cm. A simplified model of the water supply network, with 6 tanks, 9 pumps, 34 distributed nodes, and 71 links, was used in this study, as illustrated in Fig. 5.

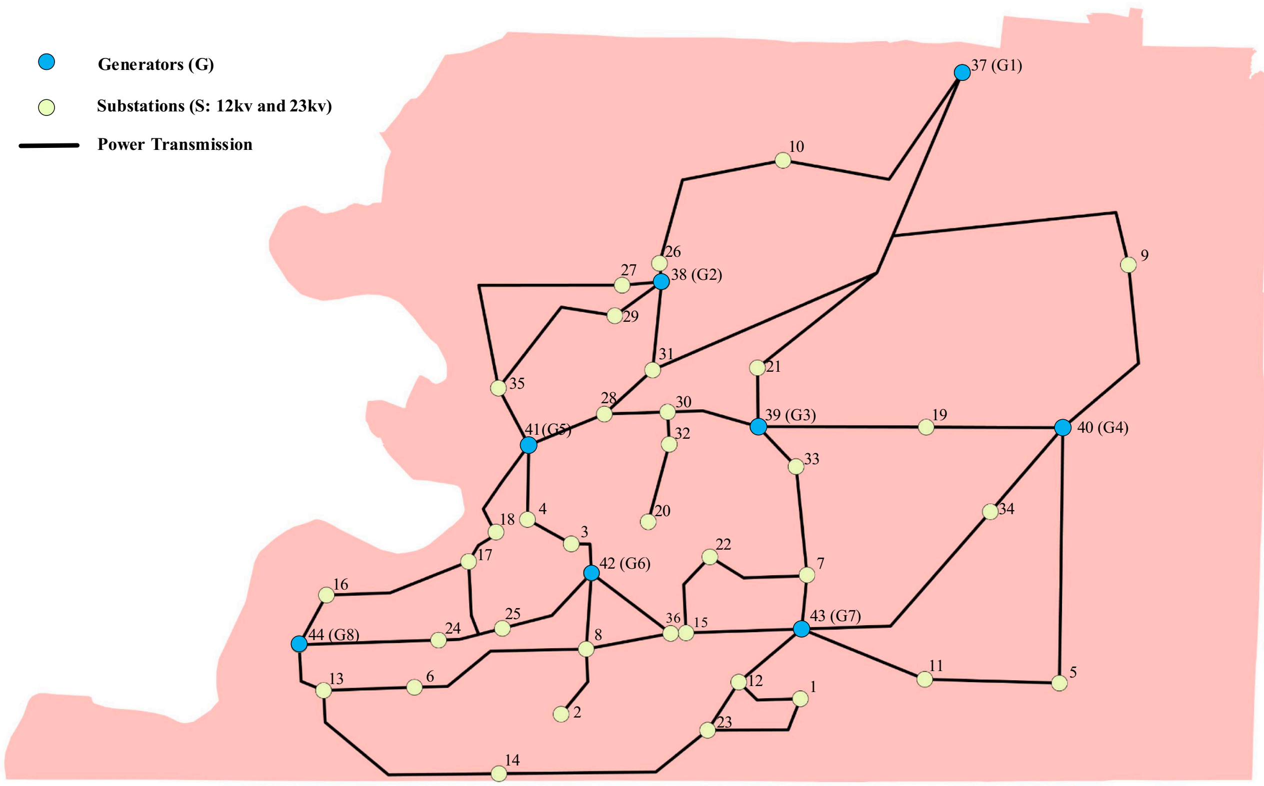


Fig. 4. Topology of the power supply system (not to scale, modified from [49]).

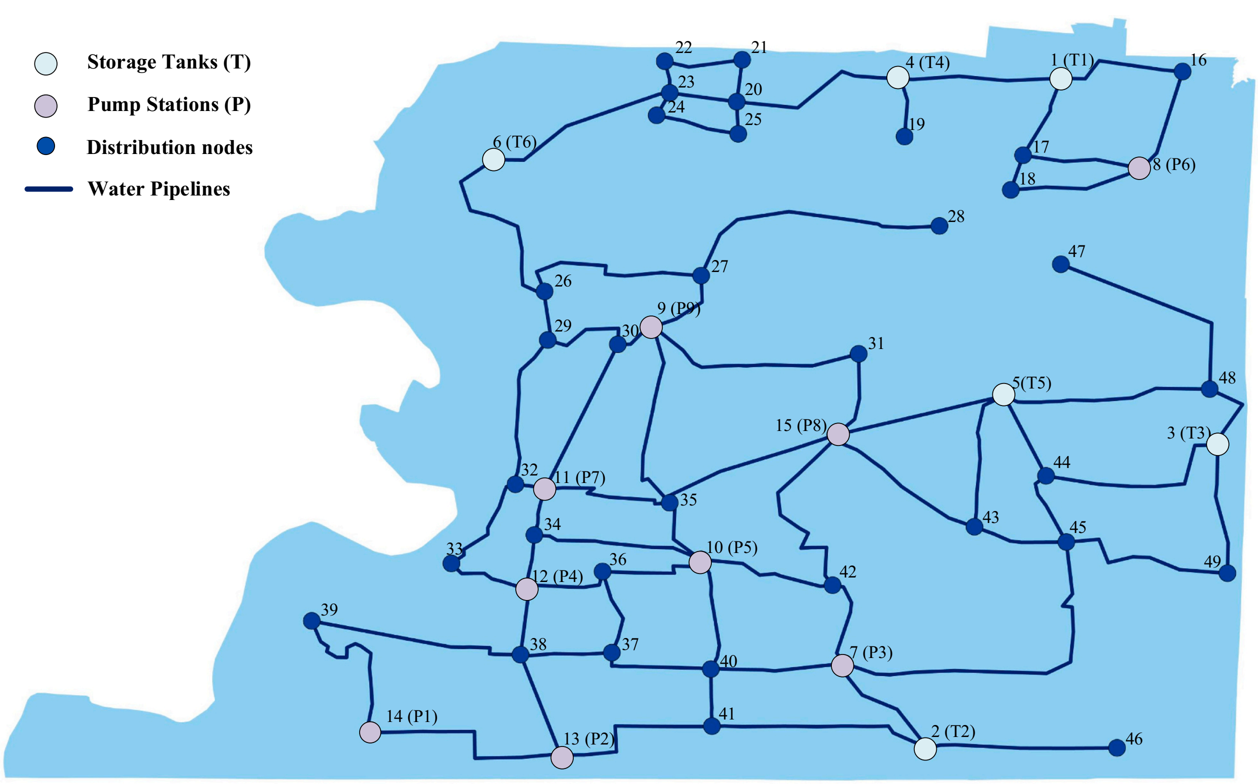


Fig. 5. Topology of the water supply system (not to scale, modified from [50]).

4.1.3. System interdependency

The dependencies between the power and water supply systems ensure their proper functioning. The pumping stations depend on the power supplied by the power substations, while the power generators depend on the cooling water supplied at the distribution nodes they are connected to. The interdependent component pairs of the water and power supply systems are summarized in Table 2.

The power consumption of the pump stations was modeled as loads on the power substations, while the cooling water consumption of the power generators was modeled as demand on the water distribution nodes. The power consumption of a pump station can be determined using the pump's performance curve or a constant horsepower. If this power demand is not met by the power substations, the pump's functionality is impaired.

The flow rate, temperature, and pressure of water reaching the power generators can significantly affect their operational level (OL) ($0 \leq OL \leq 1$). To demonstrate the applicability of the proposed approach in modeling the non-linear relationship between the generator OL and water supply, this case study adopts an adaptation of the relationship described in [52]. Two pressure thresholds, Sp1 and Sp2, were determined to describe the variation in generator OL with respect to water pressure. When the supplied water pressure is above Sp2, the OL of the generators is 100%. Between Sp1 and Sp2, the OL of the generators decreases proportionally to the difference between the Sp2 and the actual water pressure. Below Sp1, the OL of the generator is zero. To choose reasonable pressure threshold values for the case study, the water system model was first independently simulated to estimate the fluctuation limits of water pressure at the distribution nodes. Pressure threshold values were then selected to ensure observable fluctuations in the OL of the generators without considerably impairing their functionality. In this case, the two pressure thresholds, Sp1 and Sp2, were set as 20 m and 80 m, respectively.

4.2. Scenario description

The proposed modeling approach can be used for all types of disaster scenarios such as earthquakes, floods, and hurricanes. Without loss of generalizability, this study focuses on earthquake disasters, primarily because a large number of prior researches have studied earthquake disasters in Shelby County, providing a considerable amount of useful data for this study such as the seismic epicenter, seismic magnitude, and so on. In addition, by considering an earthquake event and its aftershock, the impact of a dynamic disaster event on the cascading failure of interdependent CISs can be revealed.

The earthquake's mainshock is set to happen at timestamp 5 mins of the simulation. The seismic epicenter is located at longitude −90.3 and latitude 35.3 [53], with a seismic magnitude $M = 5.0$. The attenuation equation proposed by[54] is used to generate the seismic intensity PGA at each component site.

An aftershock is set to hit the systems at timestamp 35 mins of the simulation. The seismic epicenter of the aftershock is also located at longitude −90.3 and latitude 35.3, with a seismic magnitude $M = 4.52$ determined based on the mainshock-aftershock relationship $M_{aftershock} = 0.5{*}M_{mainshock} + 2.02$, described in [55]. Other parameters are left unchanged.

The disaster simulation duration is set to one hour. The water demand at each distribution node is assumed to be constant during the short simulation duration.

Table 2
Interdependent component pairs of the water and power supply system.

Power – water		Water – power	
Substation	Pump station	Distribution node	Generator
13	P1	19	G1
2	P2	27	G2
12	P3	31	G3
25	P4	44	G4
22	P5	32	G5
9	P6	36	G6
4	P7	42	G7
20	P8	39	G8
31	P9		

4.3. Case model development

This section describes the main steps in the development of the case model using the proposed modeling approach.

4.3.1. Selection of the federates

Based on the scenario description, the federation developed in this paper consists of three modules, namely the water supply system module, power supply system module, and earthquake disaster module. The water supply system is modeled using the EPANET v2.2 software [56]. EPANET is a widely used software application for modeling and simulating water distribution systems that was developed by U.S. EPA (Environmental Protection Agency) in the 1990s, and can be used for many different types of applications in water distribution systems analysis. The power supply system is modeled using the OpenDSS v9.0 software [57]. OpenDSS is a comprehensive simulation tool for electric utility power distribution systems that has been used since 1997 in support of various research and consulting projects requiring distribution system analysis. The earthquake disaster and seismic impact analyses of the CISs are modeled using the IN_CORE (Interdependent Networked Community Resilience Modeling Environment) platform [58]. IN_CORE was developed under a project funded by the U.S. National Institute of Standards and Technology (NIST) aiming to develop a measurement science that supports community resilience assessment. IN-CORE can measure the earthquake intensity at each component location using the specified seismic epicenter, magnitude, attenuations, depth, and geologic information (such as soil liquefaction). The probability of five damage states (none, slight, moderate, extensive, complete) of each component can then be calculated based on the earthquake intensity and component's attributes (materials, type, installation methods). Table 3 summarizes the functionalities, input, and output data types of the selected federates, and Table 4 summarizes the object classes and attributes of the federates.

4.3.2. Implementation of the federation

Fig. 6 illustrates the layout and data exchange mechanism of the federation developed in this case study, in accordance with the data exchange mechanism presented in the methodology section. Each CISs module has one DPU responsible to process the damage probability data published by the earthquake disaster module and determine the components' damage states used as model input for the CIS federate. On the other hand, the earthquake disaster module has two DPUs, one to complete the disaster impact analysis for the water system (IN_CORE_WATER) and the other for the power system (IN_CORE_POWER). Both DPUs are designed to subscribe to the updated model state of their respective systems, invoke the IN_CORE platform to simulate the seismic shock, then calculate the damage probability of the functional components.

The CERTI middleware application is used to establish communication between the modules. 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 [59]. The DPU codes are developed using MATLAB v2019b and the MatlabHLA toolbox that is part of the CERTI package. The API function libraries of the federates are provided as part of their original software packages. Specifically, the API functions used in developing the case models include *getNodePressure, getNodeHydaulicHead, getLinkFlows* and *getLinkEnergy* for EPANET, and *DSSText.command, DSSObj.Text, DSSObj.ActiveCircuit* and *DSSCircuit.Solution* for OpenDSS.

Table 3
The functionalities and data types of the simulators.

System	Simulator	Functionalities	Input data types	Output data types
Water supply system	EPANET	• Design, analysis, and performance upgrade of hydraulic systems • Evaluation of water quality improvement strategies • Assessment of consumer exposure	Demand (lps) Pump power (hp) Pipe roughness Reservoir levels	Flow (m^3/h) Water head (m) Water pressure (m) Water quality Pump statuses Head loss (m/km) Flow velocity (m/s) Pump power consumption (kW)
Power supply system	OpenDSS	• Frequency domain (sinusoidal steady-state) analyses • Performance assessment of smart grids, grid modernizations, and renewable energy systems	Load (kW) Fuel refill Line resistance Repair hours	Power (kW) Voltage (kV) Current(A) Circuit loss
Water supply system &power supply system	IN_CORE	• Seismic damage analyses of system components • Mapping of vulnerability curves	Geological conditions Component materials Seismic epicenter Magnitude Attenuations Depth State of component	Intensity (g) Probabilities of component damage states

Table 4
List of object classes and their attributes.

System	Object class	Attributes
Water system	Pumps	Status (open or closed) Functional state[a] (failed or functional) Damage state[a] Damage probability[a] Performance curve Power consumption[a] Flow Elevation
	Junctions (distribution nodes)	Functional state[a] Damage state[a] Damage probability[a] Water demand Water pressure[a] Elevation
	Tanks	Functional state[a] Damage state[a] Damage probability[a] Volume Water levels[a]
	Pipes	Roughness Functional state[a] Failure probability[a] Dimensions Status Length Flow
Power system	Generators	Operational level (OL) Functional state[a] Damage state[a] Damage probability[a] Power output Status
	Substation load	Power supply[a]
	Transmission lines	Geometry Length Resistance Hours to repair
	Transformer (substation)	Functional state[a] Damage state[a] Damage probability[a] Voltages Status

[a] Data published and subscribed during simulation.

The FOM is developed as an XML file using a free FOM editor tool developed by MAK Technologies [16]. The FOM contains information about the datatypes of all the object attributes and interaction parameters exchanged during the simulation, as summarized in Table 5.

4.3.3. Federation execution

The federation is created by loading the FOM file to the RTI and setting a federation name. The federates then connect to the RTI, join the created federation, and declare the object attributes they will publish or subscribe to. The above process is done using the RTI library functions (*rti.publish* and *rti.subscribe*) invoked by the DPU. Once all the federates have declared their publish-subscribe scheme, the fully automated simulation process can be started. The simulation was performed on a computer with CPU specifications E5–2640 v3 @ 2.6GHz and 32 GB of RAM. The simulation process is summarized in Fig. 7 and explained below.

The CIS federates started the simulation process by loading the CIS information and generating the CISs models. Before the mainshock occurred at timestamp 5 mins, the CIS federates would exchange their model states (based on the publish-subscribe schemes) among each other via the RTI, simulating their interdependencies. Between timestamps 0 and 5 mins, the disaster scenario module did not take part in the simulation. At timestamp 5 mins, the disaster scenario module automatically simulated the earthquakes' mainshock. The earthquake intensity at each component location was calculated using the earthquake information defined on the IN_CORE platform. These intensities were then used to calculate the failure probability of water pipes, and the probabilities for the five damage states (none, slight, moderate, extensive, and complete) of the other system components.

The damage state probabilities and pipe failure probabilities data were then published to the CIS modules through the RTI. The DPU of each CIS module processed the damage state probabilities to determine the damage state and functional state of the system. Firstly, the DPUs sequentially generated binary damage states (true and false) for each damage state probability, from the "complete damage" to "slight damage". That is, if the "complete damage" state was true, the final damage state of the component would be "complete damage", otherwise if the "extensive damage" was true, the final damage state of the component would be "extensive damage", and so on. The above process was repeated until one damage state was true, and then the process stopped. If all four damage states were not true, this implied that the final damage state of the component was "none". Secondly, after the damage states of all the components were determined, the functional states of the components were determined under the assumption that the components would functionally fail when their damage states exceeded the "extensive damage" threshold. At the same time, the DPU of the water supply system processed the pipe failure probabilities to determine the functional state of each water pipe. If pipe failure was true, it was assumed that the pipe had functionally failed. The direct damage states and

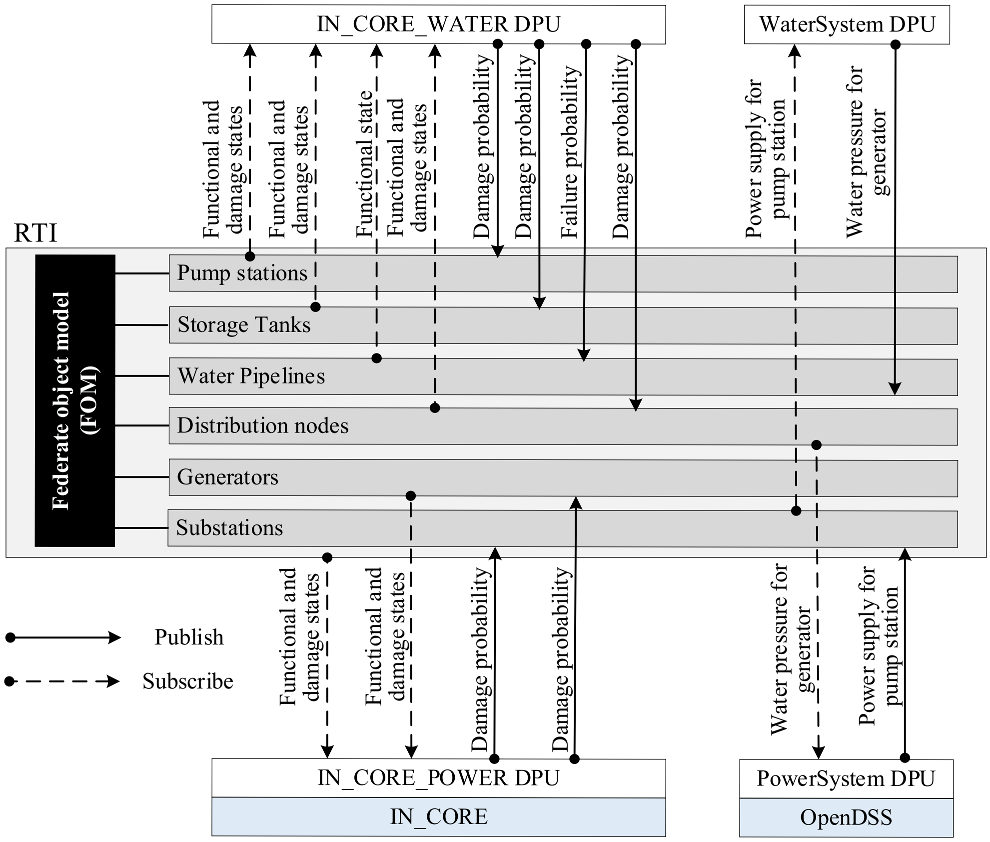


Fig. 6. Data exchange mechanism of the developed federation.

Table 5
Main content of the FOM.

	Class	Attribute/parameter	Data type
Objects	Pump	ID	HLAinteger32BE
		PowerConsumption	HLAfloat32BE
		DamageProbability	HLAfloat32BE
		DamageState	HLAfloat32BE
		FunctionalState	HLAboolean
	DistributionNode	ID	HLAinteger32BE
		DamageProbability	HLAfloat32BE
		DamageState	HLAfloat32BE
		FunctionalState	HLAboolean
		Pressure	HLAfloat32BE
	Tank	DamageProbability	HLAfloat32BE
		DamageState	HLAfloat32BE
		FunctionalState	HLAboolean
		Pressure	HLAfloat32BE
	Pipes	ID	HLAinteger32BE
		FailureProbability	HLAfloat32BE
		FunctionalState	HLAboolean
	SubstationPower	ID	HLAinteger32BE
		PowerSupply	HLAfloat32BE
	Generator	ID	HLAinteger32BE
		DamageProbability	HLAfloat32BE
		DamageState	HLAfloat32BE
		FunctionalState	HLAboolean
	Substations	ID	HLAinteger32BE
		DamageProbability	HLAfloat32BE
		DamageState	HLAfloat32BE
		FunctionalState	HLAboolean
Interactions	LoadScenario	ScenarioName	HLAunicodeString
		SimulationTime	HLAinteger32BE
	Start		
	PauseResume		

functional states of all the components were then used as input to update each CIS model. At every timestep of 1 min, between timestamps 5 and 35 mins, the CIS federates exchanged the object attribute values defined in their publish-subscribe schemes, allowing the disaster impact on one system to propagate to the other.

At timestamp 35 mins, the disaster scenario module subscribed to the updated states of both CIS models, and simulated the aftershock intensities at the location of functional components. The damage probability of each surviving component following the aftershock was dependent on the component's damage state following the mainshock. That is if the damage state of a component following the mainshock was "none", the damage probability of this component following the aftershock was normally calculated in IN_CORE using the information of aftershocks. Otherwise, if the damage state of a component following the mainshock was anything from "slight" to "extensive", the damage probabilities following the aftershock for the possible damage states (equal or more severe than the damage state following the mainshock) were averaged. For example, if the damage state of a component following the mainshock was "extensive", the damage state of this component following the aftershock could only be either "extensive" or "complete", with an equal probability of occurrence (0.5). Concerning the failure probability of water pipes, the pipe failure probability following the aftershock was dependent on the calculated pipe repair rate under the mainshock. The repair rate (repair number/km) is a critical parameter used to calculate the failure probabilities of pipes based on the wave passage, liquefaction, coseismic slip, afterslip, pipe material, joints and pipe diameter. To account for the accumulation of disaster impact on the water pipes when calculating the pipe failure probability following the aftershock, the repair rates due to the mainshock and aftershock were summed under the assumption that the pipe damage locations following both shocks were always different [60].

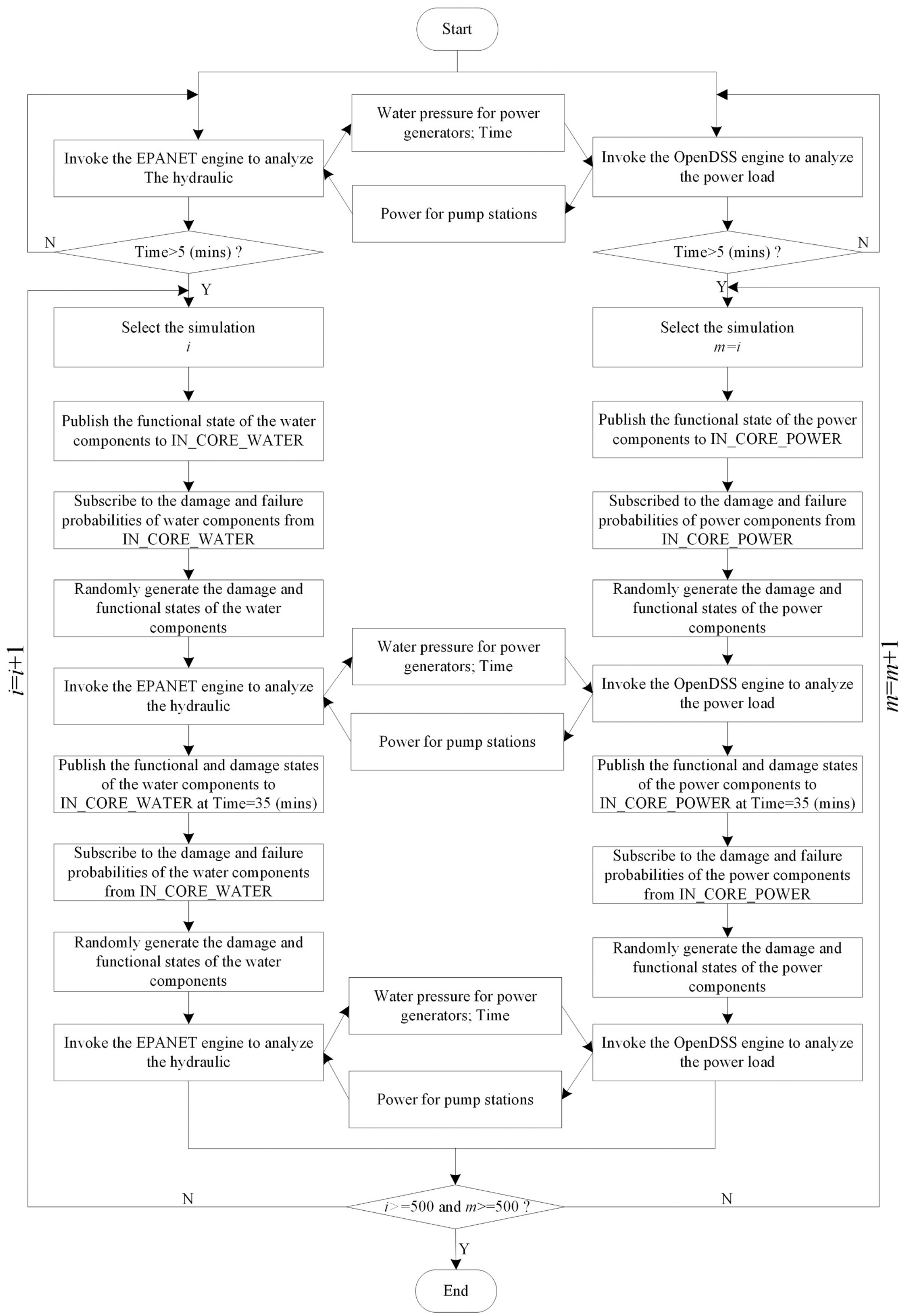


Fig. 7. Simulation flowchart of the studied case.

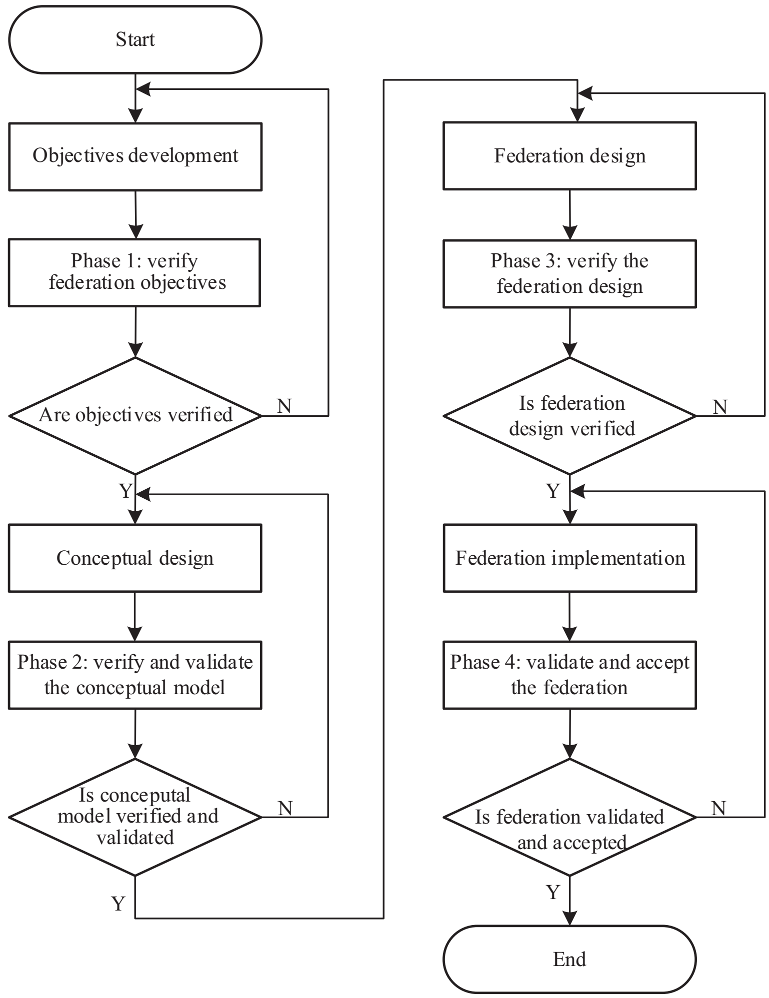


Fig. 8. Flowchart of the V&V process.

The damage and failure probabilities under the aftershock were subscribed and processed by the DPU of the CIS modules to generate the direct damage state and functional state of each component following the process described above. Data was repeatedly exchanged between the federates at every timestep for a total simulation duration of 65 mins. The simulation was repeated 500 times and the results were averaged for analysis.

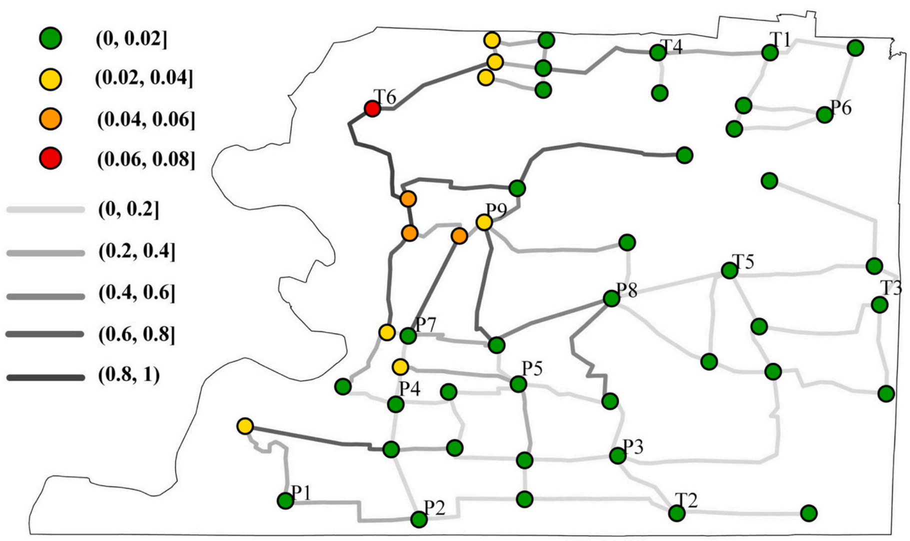
4.4. Model verification and validation

Model verification and validation (V&V) are essential aspects of the HLA federation development process. Following the IEEE recommended practice for the V&V of HLA federations [61] and the federation development process [16] adopted in this study, the V&V process followed in this case study consisted of four main phases, which are illustrated in Fig. 8 and explained below.

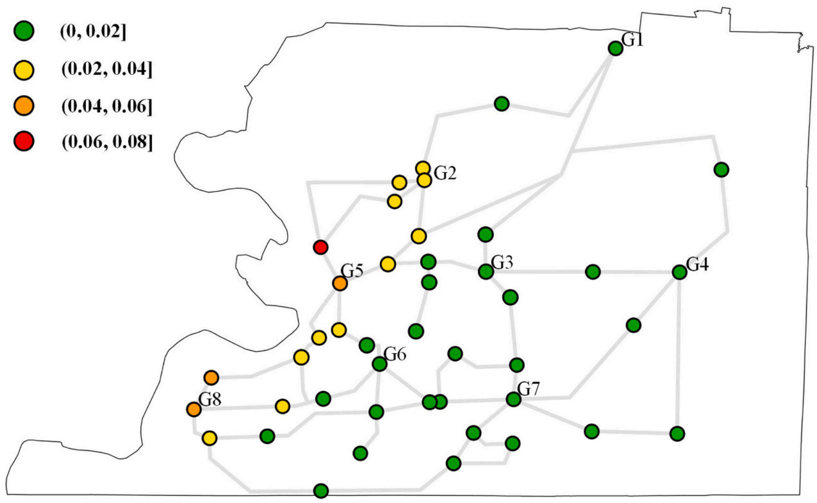
- Phase 1: verify the federation objectives. In this phase, the completeness, consistency, and correctness of the simulation objectives in this study were verified by the V&V team consisting of two federation developers, and four subject matter experts (SME). Four simulation objectives were defined, including: (1) demonstrate the efficacy of the proposed approach to model the systemic heterogeneities among the CISs; (2) demonstrate the efficacy of the proposed approach to model interdependencies among the CISs; (3) demonstrate the efficacy of the proposed approach to model the dynamic impact of disaster; and (4) demonstrate the efficacy of the proposed approach to detailly model the cascading failure process within and across the CISs. The V&V team then defined seven acceptability criteria (Table 6) to assess the acceptability of federation.
- Phase 2: verify and validate the conceptual model. In this phase, the simulation objectives defined above guided the development and validation of the conceptual model of the interdependent systems and the simulation scenarios. The V&V team first verified the model requirements and the characteristics of model entities, attributes, and entity interactions for each individual system. Then, the dependencies between the water and power supply systems were identified and verified by the V&V team, and a conceptual model of the interdependent CISs was developed. The conceptual model was then validated as an adequate representation of the systems and their interactions in reality.
- Phase 3: verify the federation design. In this phase, the V&V team first assisted the federation development team with developing and validating the models simulated by each federate. The appropriate domain-specific models and API packages for developing the water system and power system models were selected, and the system models were developed based on verified data of the case systems collected from multiple sources. The V&V team then verified the design of the FOM and DPU codes necessary to establish seamless communication and facilitate data exchange between the federates. The V&V team oversaw the federation design process to ensure the appropriateness of the simulation.
- Phase 4: validate and accept the federation. In this phase, the V&V team first verified and validated the federation implementation

Table 6
Summary of the acceptability assessment and conclusions.

Acceptability criteria	Assessment results and conclusion
(1) The difference in system susceptibility to overload damage should be captured.	The proportions of overload damaged components in the water and power systems were 0% and 13%, respectively, indicating that criterion (1) was satisfied.
(2) The difference in the locations of main physical damage should be captured.	The main physical damage occurred at nodal components and pipelines in the water system, whereas only nodal components suffered physical damage in the power system, indicating that criterion (2) was satisfied.
(3) The impact of system interdependencies should be manifested in the behavior of the interdependent CISs.	The simulation results showed that the OL of functional power generators changed synchronously with changes in water pressure at the depended distribution nodes in the water system, following the defined dependency function between the components, indicating that criterion (3) was satisfied.
(4) Seamless communication and data exchange should be established between the federates.	A total of 65 call and callback cycles were recorded between EPANET and OpenDSS, with one cycle completed at each timestep (1 min) of the simulation. For the interactions between IN_CORE_WATER and EPANET, and between IN_CORE_POWER and OpenDSS, two call and callback cycles were recorded between each pair (one during the seismic mainshock and one during the aftershock). The results indicated that criterion (4) was satisfied.
(5) The damage state of a component following the aftershock should not be lower than that following the mainshock.	The damage state of all components following the aftershock was larger than or the same as that following the mainshock, indicating that criterion (5) was satisfied.
(6) The final disaster impact on the systems should be larger than the direct earthquake damage because of the effect of cascading failures between the systems.	The head losses due to direct damage and whole disaster impact were 642.5 m and 869.8 m under the mainshock, respectively. The power losses because of direct damage and whole disaster impact were 0 and 1190 kw under the mainshock, respectively. The results indicated that criterion (6) was satisfied.
(7) The response behaviors of components, subsystems and interdependent CISs should be captured.	The variations in component attributes and subsystem outputs of both CISs were observable. The interdependencies between CISs were also captured. The results indicated that criterion (7) was satisfied.



(a) Water supply system (T: tank; P: pump station; Other: distribution node)



(b) Power supply system (G: generator; Other: substations)

Fig. 9. The failure probabilities of system components following the mainshock.

process and the scenario-specific datasets needed for federation execution. The V&V team then assisted the federation developers in the testing, debugging and execution of the federation. Finally, the simulation results were used to assess whether the acceptability criteria defined in Phase 1 were satisfied. The assessment results of acceptability criteria are presented at the end of the next section.

5. Simulation results and analyses

The simulation results were organized and analyzed under two analysis contexts.

In analysis context one, the results from all the 500 simulation instances were averaged to analyze the failure propagation path, performance, and flow of the interdependent CISs under the impact of the earthquake disaster. Two system performance indicators were selected including the *total head* and *total power output f*or the water and power systems, respectively. Two widely adopted flow indicators were selected for the water system (*water pressure* [62], *water flow* [63]) and one for the power system (*power output* [27]).

In analysis context two, a single simulation instance was randomly selected to analyze the failure propagation process of the interdependent CISs at a components level and highlight the advantages of the proposed approach. The selection was made to observe an uninterrupted sequence of events within the systems, which would not be possible when averaging all the simulation instances.

5.1. Analysis context one

Fig. 9 shows the failure probabilities of the components of the systems following the mainshock. For node components, the failure probabilities were equal to probabilities for "extensive damage" because one adopted assumption in this study was that the components would functionally fail when their damage state exceeded the "extensive damage" threshold. It can be observed from the figure that the highest values of failure probability were recorded at the components located in the northwest region of the county (closer to the epicenter), maxing out at about 0.06. The failure probabilities then gradually decreased going southeast, with the majority of the components in both systems having a

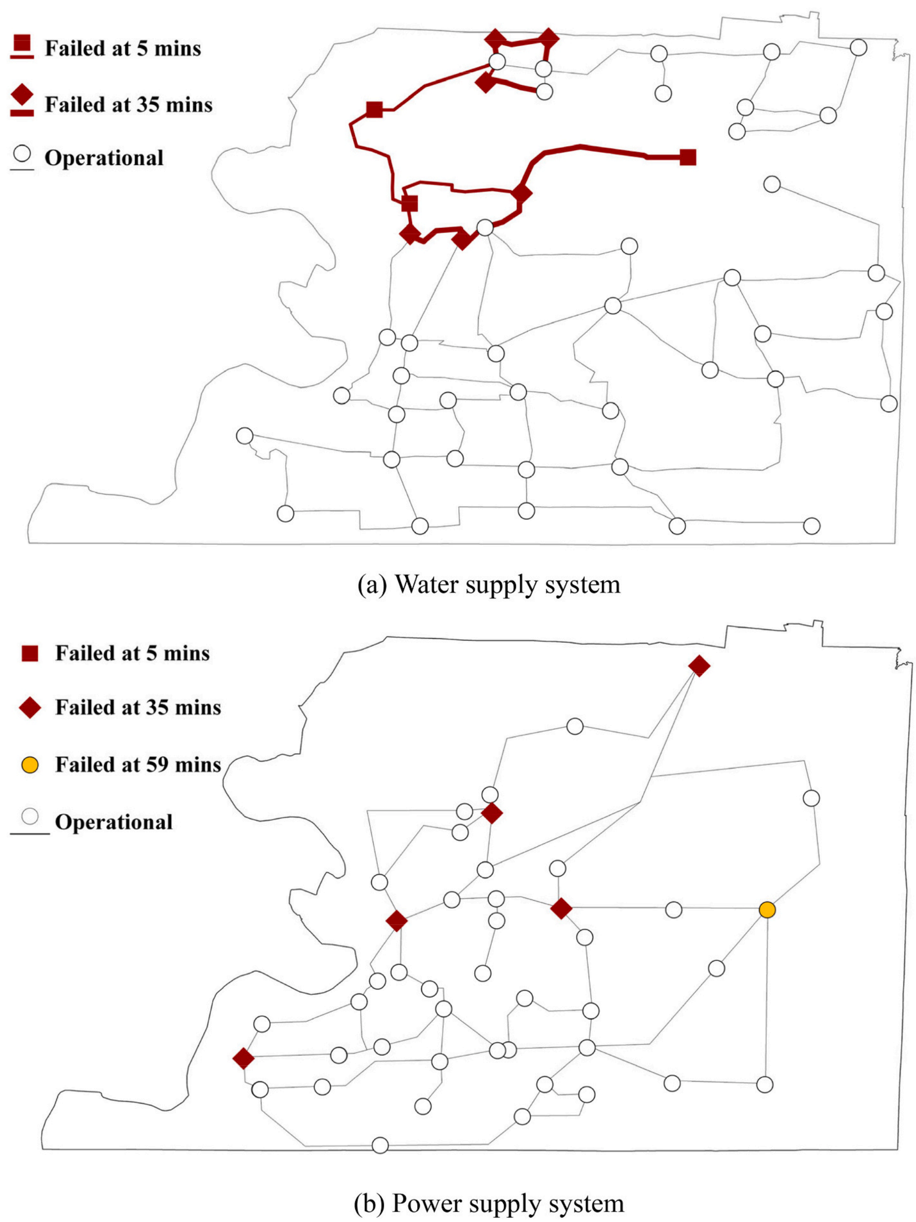


Fig. 10. The averaged locations and time of component failures.

relatively low failure probability below 0.02. These results highlighted the effect of seismic attenuation due to the increasing distance from the epicenter.

When observing components within a small geographical area of the systems, the difference in failure probability among different component types was significant. For example, Fig. 9(b) shows that generator G5 had a considerable different failure probability than the surrounding substations. Similarly, some power system components had higher failure probabilities than the water system components located in similar areas. For example, generator G5 and pump P7, which are relatively close to each other, show significant differences in failure probabilities (G5 above 0.04; P7 below 0.02). These observations revealed the influence of component properties and systemic heterogeneities on the estimated failure probabilities of the components.

Fig. 10(a) and (b) show the averaged locations and time of component failures in the water system and power system, respectively. In the water system, the number of components that failed due to the mainshock and aftershock were close, and the failed components were concentrated in the northwest region of the county. In contrast, in the power supply system, all the components failed following the aftershock, with no component failure due to the mainshock. The failed components in the power supply system were observed at dispersed locations all over the county. These results indicated that, unlike the water system in which most component failures were directly induced by the earthquake, the failure of components in the power system was mainly induced by cascading failure phenomena such as overload damages and the dynamic impact of the disaster.

Fig. 11 shows the variations in the total head (a) and total power output (b) of the water and power systems, respectively. It can be observed from Fig. 11 that both systems experienced a more significant loss in performance following the aftershock ($M = 4.52$) than that following mainshock ($M = 5$). These results indicate that an aftershock of lower seismic magnitude could induce more system damages than the mainshock due to the accumulation of disaster impact.

Fig. 12 below shows the variations in the three selected flow indicators ((a) water pressure, (b) water flow, and (c) power levels) throughout the simulation. One common observation in all three subfigures is that all the indicators were mainly impacted at the moment of the mainshock and aftershock, and settled at new balance levels after the seismic shocks. Major disruptions in the patterns of the indicators could be observed immediately following the seismic shocks as the systems attempted to redistribute flow and stabilize.

5.2. Analysis context two

For the randomly selected simulation instance in analysis context two, Fig. 13(a) and (b) show the damage states and functional states of the water supply system components following the mainshock and aftershock, respectively. Fig. 14(a) and (b) show the damage states and functional states of the power supply system components following the mainshock and aftershock, respectively.

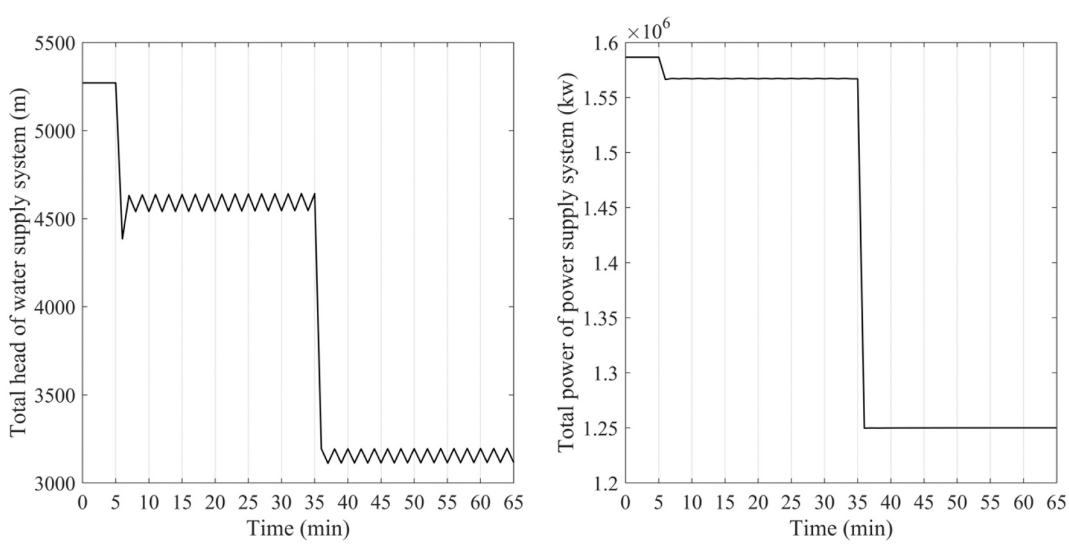
Figs. 13 and 14 reveal that the damage states and functional states of components in both systems considerably changed from mainshock to aftershock. For example, the damage state and functional state of distribution node 31 (that serves G3) in the water supply system increased from "moderate" (functional) to "extensive" (failed). If the damage caused by the mainshock was not considered while simulating the aftershock, the damage state of node 31 under the aftershock of lower seismic magnitude would have been similar or lower than the one recorded following the mainshock. The results indicate that the proposed modeling approach can model the dynamic impact of disaster events.

Fig. 15 shows the failure propagation path of the water system and power system, respectively, under the selected simulation instance. Fig. 16 shows the water pressure at the distribution nodes supplying the power generators and the OL of the generators. Fig. 17 shows the maximum available power at the substations supplying the pump stations.

It can be observed from Fig. 15(a) that distribution nodes 18, and fourteen pipes were damaged by the mainshock at timestamp 5 mins. Failure of the above-mentioned components caused tank 6 and distribution nodes 20, 21, 22, 23, 24, 25, 26, 29 and 30 to be disconnected from the network, resulting in a cluster of nonfunctional components in the region closer to the seismic epicenter. No component was damaged in the power supply system following the mainshock.

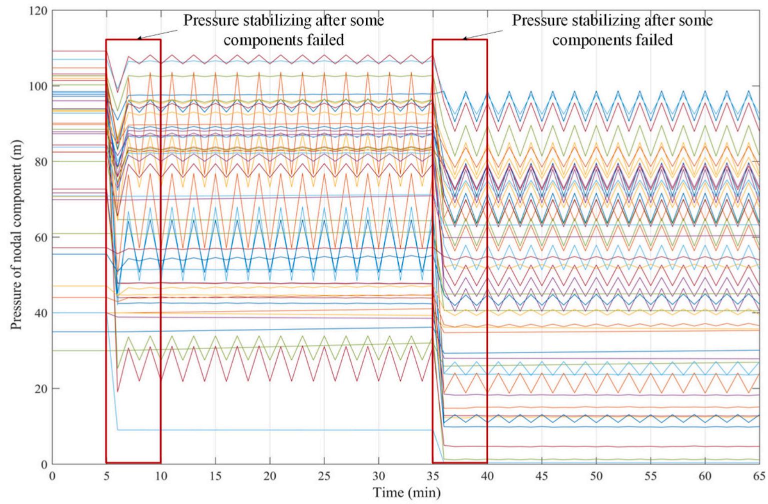
The disruptions incurred by the water system due to the mainshock caused the water pressure levels at the distribution nodes supplying water to the generators to drop, and subsequently, the OL of the still functional generators were negatively impacted as shown in Fig. 16(b), (c) and (d). For example, following the mainshock, the pressure of distribution node 44 dropped from 94.04 m to 41.83 m (between Sp1 and Sp2) at timestamp 6 mins, causing the OL of generator 4 to drop from 1 to 0.5229.

The perturbations in the OL of the functional generators caused a significant drop in the maximum power available at the substations, as

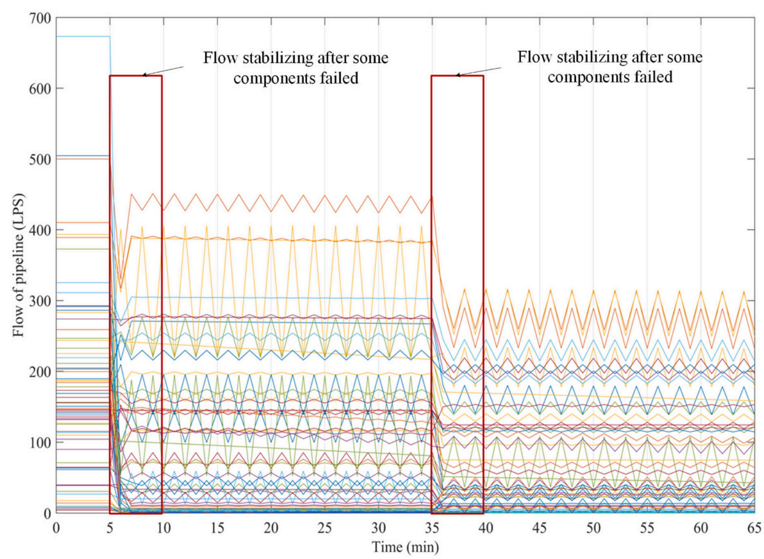


(a)Water supply system (b) power supply system

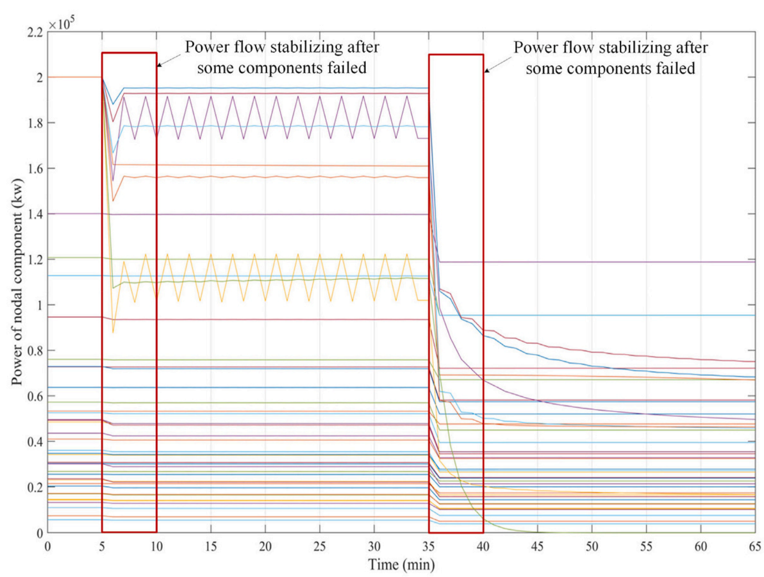
Fig. 11. Total system output.



(a) Water pressure at the nodal components of the water supply system



(b) Water flow in the pipes of the water supply system



(c) Power supply at the nodal components of the power supply system

Fig. 12. The variation of flow indicators.

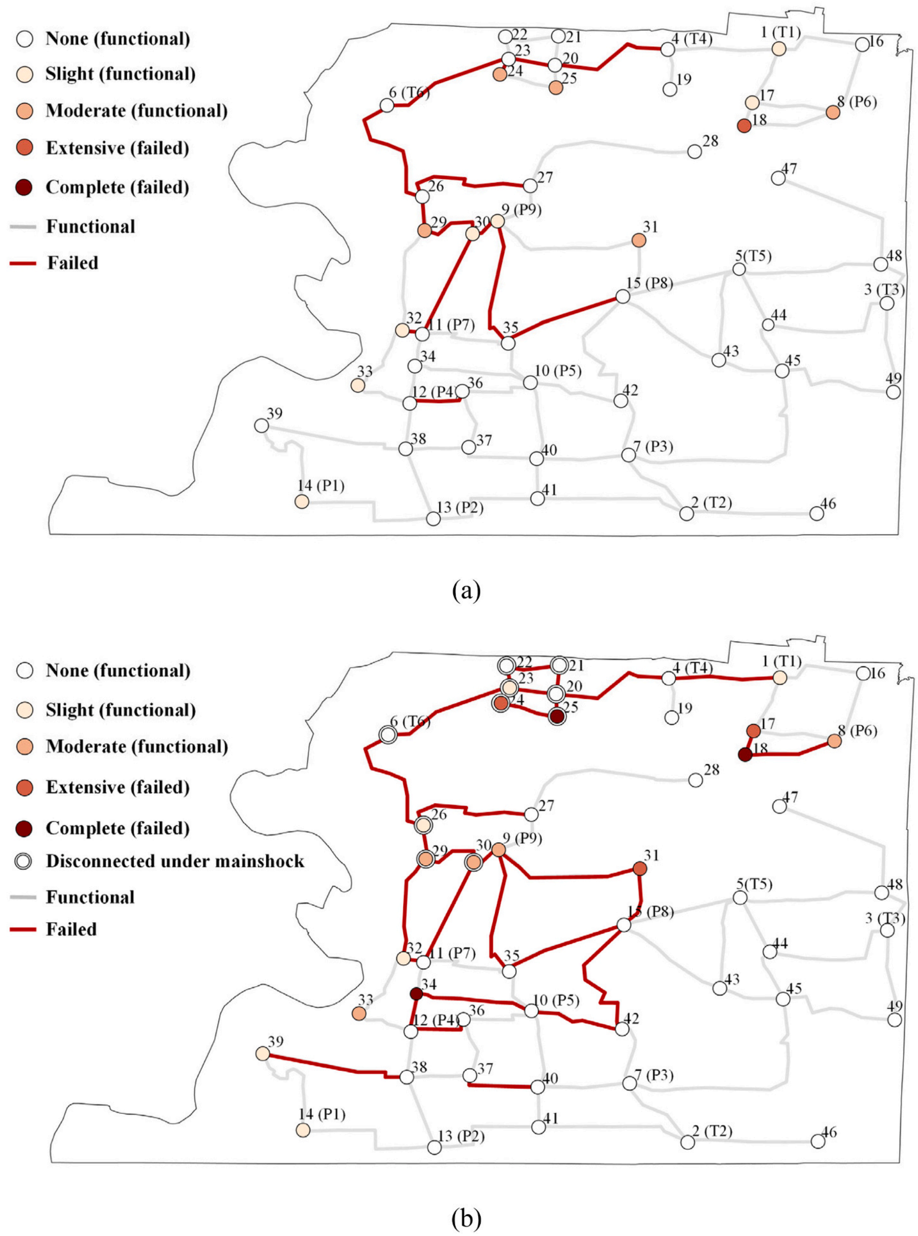


Fig. 13. The damage states and functional states of the water supply system components under the mainshock (a) and the aftershock (b).

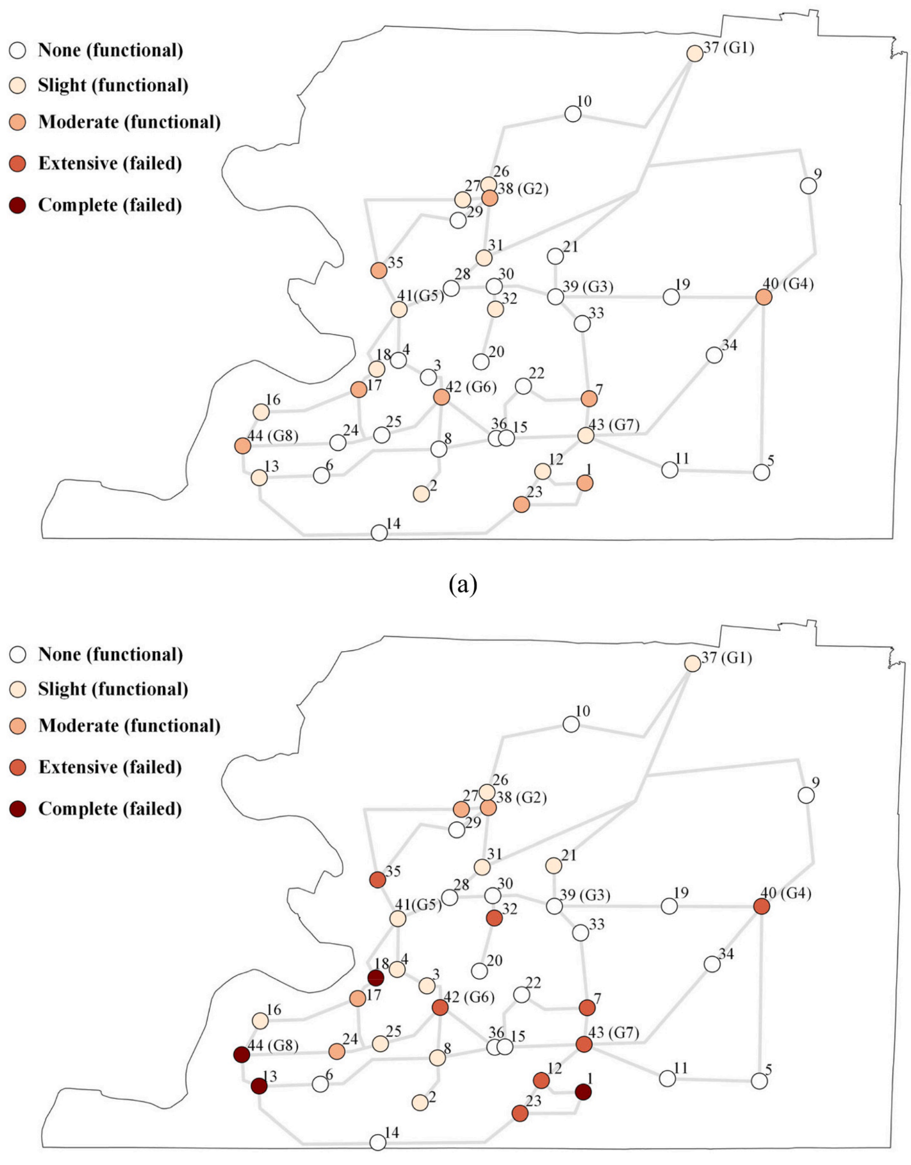


Fig. 14. The damage state and functional state of the power supply system components under the mainshock (a) and the aftershock (b).

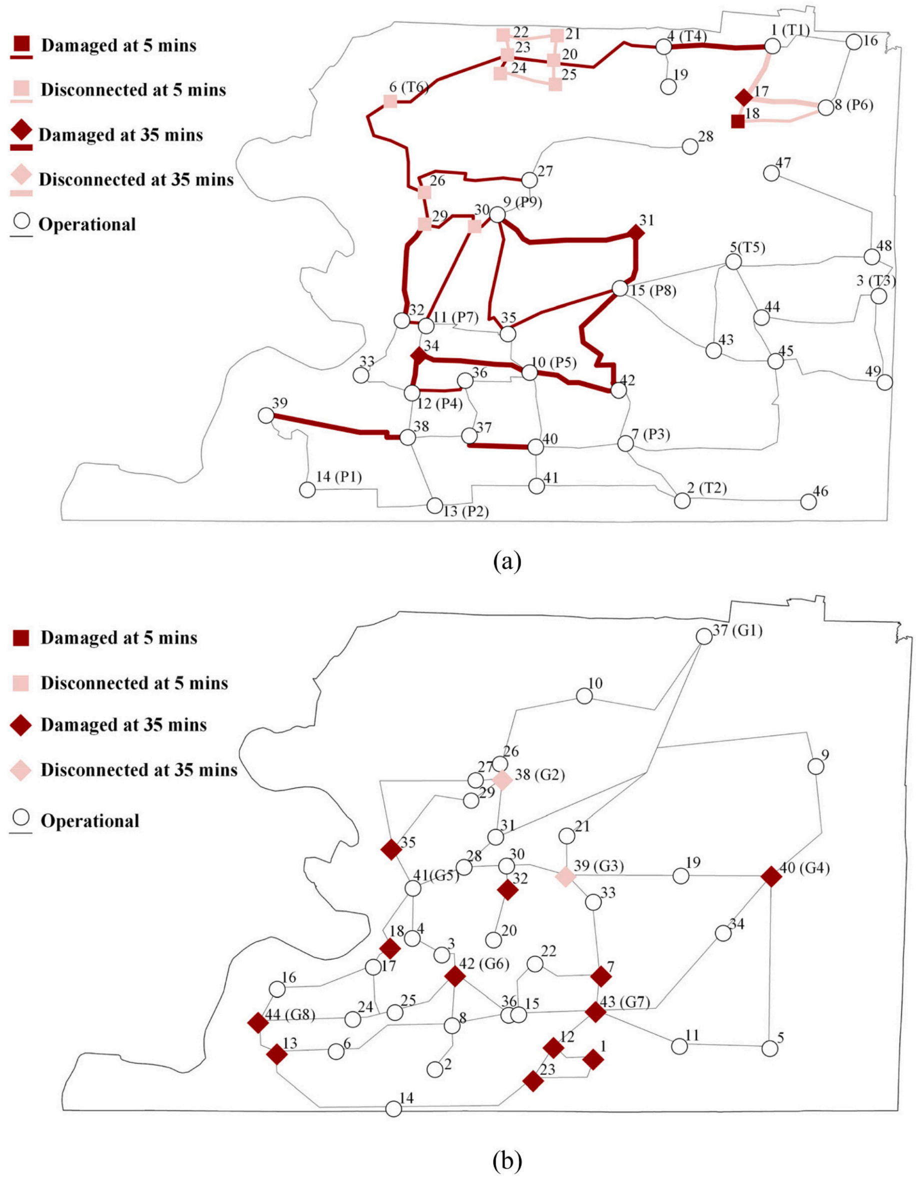


Fig. 15. The failure propagation path of (a) water supply system and (b) power supply system.

shown in Fig. 17. This drop in power supplied to the water pumps prevented them from operating at much higher efficiencies, explaining why the initial pressure levels in some distribution nodes could not be fully recovered.

Due to the aftershock at timestamp 35 mins, distribution nodes 17, 31 and 34 were damaged, and no distribution nodes were disconnected. At the same time, generators G4, G6, G7 and G8 and substations 1, 7, 12, 13, 18, 23, 32 and 35 were damaged, and the power redistribution in the power system caused the failure of generators G2 and G3. Also, the failure of substations 12 and 13 caused the power supply at pumps P3 and P1, respectively, to be cut off, as shown in Fig. 17(c) and (a). Following this sequence of events, both systems finally reached new stable states at timestamp 36 min and the simulation was completed at timestamp 65 mins.

Lastly, the acceptability of the federation was assessed using the results of simulation context two and based on the acceptability criteria defined in phase 1 of the aforementioned model V&V process. The assessment results and conclusions are summarized in Table 6. The conclusions showed that the developed federation was acceptable.

6. Discussions

The water supply system and power supply system are two heterogeneous systems that show significant differences in their physical, functional, and operational characteristics. Systemic heterogeneity is the main cause behind the difference in failure propagation mechanisms among CISs [64]. Unlike the majority of prior studies in which the failure pattern of the modeled interdependent CISs are identical [6,21], the results from the present study were in line with the above proposition. The considered CISs were simulated using heterogeneous CISs domain-specific models, capturing a variety of systemic heterogeneities among the CIS. The simulation results revealed significant differences in the component failure probabilities, the failure propagation path, and the overall behavior of the two CISs.

The propagation of failure across interdependent CISs is directly related to the functional and operational behavior of each system [12]. This suggests that the ability of the proposed approach to model inter-system cascading failures depends on the level of details and granularity in the modeling of intra-system interactions and cascading failures. Results from the case study revealed that the approach proposed in

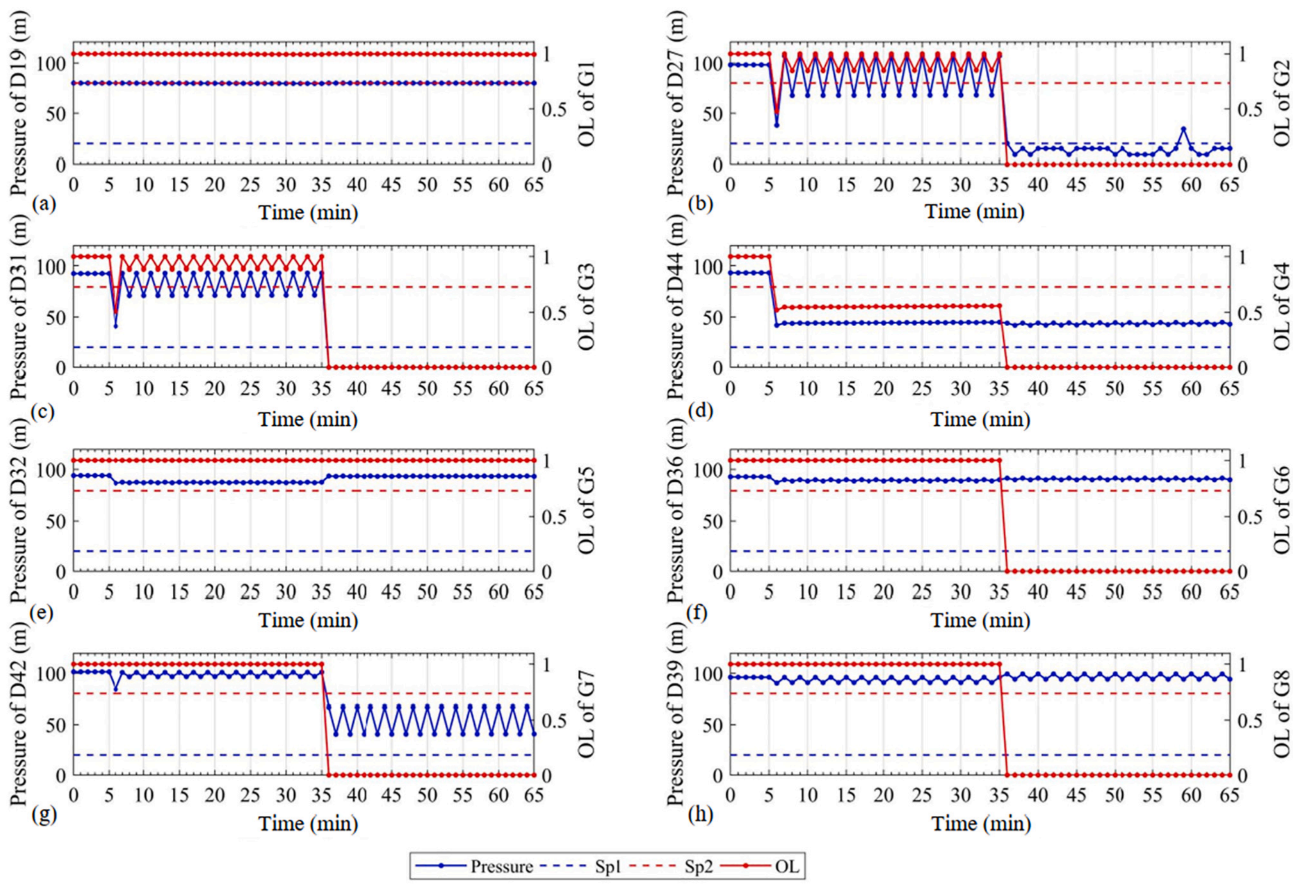


Fig. 16. The relationship between the pressure of distribution nodes and OL of generators in the selected instance: (a) distribution node 19 and generator 1; (b) distribution node 27 and generator 2; (c) distribution node 31 and generator 3; (d) distribution node 44 and generator 4; (e) distribution node 32 and generator 5; (f) distribution node 36 and generator 6; (g) distribution node 42 and generator 7; (h) distribution node 39 and generator 8.

this study can effectively be used to model and analyze interdependent CISs with high granularity while applying CISs domain-specific knowledge to model intra-system interactions and cascading failure processes. The dynamic functional characteristics of the CISs such as the power consumption of pump stations, water pressure at distribution nodes, and actual power distribution at substations, were captured by the proposed model and significantly impacted the simulated failure propagation across the CISs. For example, the OL of the power generators was negatively impacted when water pressure levels at the corresponding distribution nodes dropped due to system damages incurred by the earthquake. The ability of the proposed approach to capture such level of detail in the intra- and inter-systems cascading failure process is a significant improvement compared to existing approaches in which only the functional state of interdependent components is considered.

An important observation in the results of analysis context two is that although the aftershock was of lower seismic magnitude than the mainshock, the damage states of system components following the aftershock were significantly higher than after the mainshock, and consequently, more components failed due to the aftershock. An example of a similar observation in real-life was the Wenchuan earthquake, during which the structural integrity of numerous partially damaged dams and reservoirs considerably worsened during the sequential aftershocks [65]. This shows that the susceptibility to component failure of the system had significantly increased following the earthquake's mainshock, demonstrating the ability of the proposed approach to model the dynamic impact of disaster events on CISs.

The demonstrated advantages of the proposed approach over other existing approaches make it adequate for a variety of practical applications. Firstly, the proposed approach can be used for disaster impact assessments for which detailed and specific values of system performance indicators are required. Secondly, the proposed approach can be used by CISs decision-makers to investigate the most likely failure propagation paths of the systems under disaster scenarios and select the most effective disaster prevention measures and disaster response strategies. Thirdly, the proposed approach could be used for assessing the impact of some factors (such as interdependency, heterogeneity) on the cascading failure process to support the optimization of CISs design.

7. Conclusions

Modern CISs are becoming increasingly dependent on each other's functionalities to ensure their reliable performance. Cascading failure is a process in which the failure of a system component causes the failure of the components that depend on it, amplifying the impact of a disaster to the entire interdependent CISs. Uncovering the mechanism behind the cascading failure of CISs is very important for disaster management, impact prediction, and emergency decision–making. This study aimed at developing and testing an HLA-based co-simulation approach for modeling the cascading failure of interdependent CISs. The case study results demonstrated the capabilities of the HLA-based cascading failure modeling approach to incorporate the domain knowledge specific to each CIS and capture various systemic heterogeneities among the CISs, resulting in a more detailed simulation of cascading failure.

One limitation of the proposed approach is that when integrating multiple models with high granularity and multiple complex interactions, the computational cost of the proposed approach becomes considerably larger than other available approaches. In future work, more efficient DPUs for each domain-specific model should be designed to save the computational cost and improve the computational efficiency of the proposed approach.

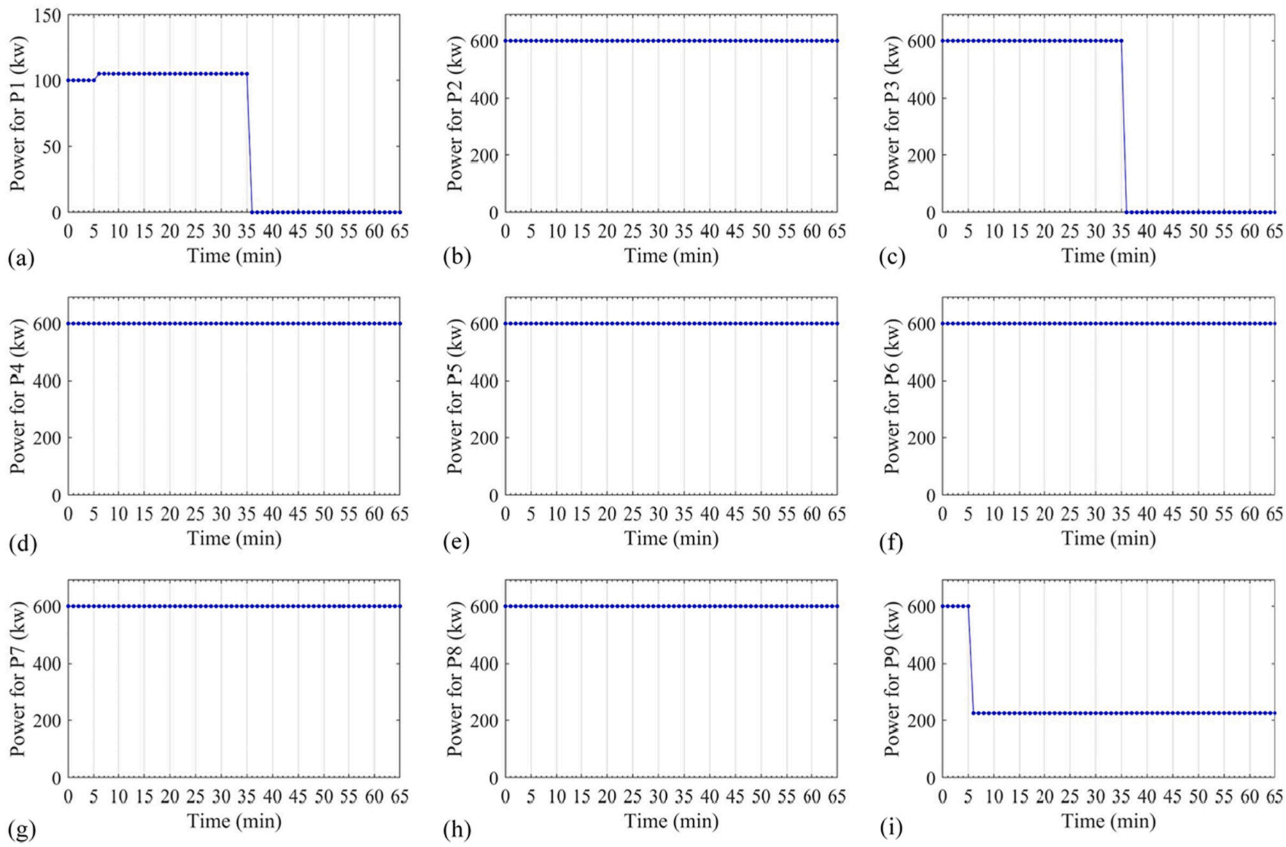


Fig. 17. The power supplied by the power substations to the water pump stations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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