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HIGH LEVEL ARCHITECTURE (HLA) COMPLIANT DISTRIBUTED SIMULATION PLATFORM FOR DISASTER PREPAREDNESS AND RESPONSE IN FACILITY MANAGEMENT

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ABSTRACT

By imitating chaotic disaster situations in risk-free settings, disaster-related simulation can be helpful for training of response participation, damage evaluation, and recovery planning. However, each single simulation needs to interact with others because different simulation combinations are required due to numerous disasters and their complex effects on facilities, and diverse response efforts. We therefore developed a distributed simulation platform for disaster response management by using the High Level Architecture (HLA) (IEEE 1516) to promote its future extendibility. With a focus on the facility damage after an earthquake and fire, disaster response simulations—including evacuation, emergency recovery, and restoration—interact with a seismic data feeds, and structural response and building fire simulations. This base platform can provide information on possible damages and response situations to reduce confusions in disaster responses. With the strongest features of HLA, which is reusability and extendibility, additional disaster simulators could be coupled for all-time disaster management.

1 INTRODUCTION

In a complex and chaotic disaster situation, insufficient information on damage and responses causes difficulties in rapidly implementing efficient response and recovery planning (Olshansky et al. 2012). Due to the ability of the computer simulation to manage greater complexity and uncertainty (Harrison et al. 2007), computer simulation techniques have been widely applied in disaster management (e.g., the training of response participation, damage evaluation, and response and recovery planning of facilities) by imitating complex and chaotic disaster situations in a low cost and risk-free setting. Despite the emergence of numerous amounts of advanced disaster-related simulations and technologies, individual ones still have following limitations to be utilized for disaster response and recovery management: (a) consideration on diverse damage patterns according to the types of disasters, and their serial and complex effects on facilities; (b) incorporation of diverse response and recovery efforts; and (c) analysis on a disaster situation change over time according to a disaster management cycle (Hu et al. 2009, Yotsukura and Takahashi 2009). Therefore, each single simulation for analyzing disaster, damage, and response situations needs to interact with others because various disaster situations require different combinations of simulations. To alleviate this problem, a distributed disaster simulation approach can be employed with a new interoperable environment where different simulations interact with each other (Yotsukura and Takahashi 2009). With regard to such issues, this paper focuses on describing how to combine disaster simulators and techniques with different analysis purposes using the High Level Architecture (HLA) compliant distributed simulation platform. The principles of the HLA, which was standardized by the Institute of Electrical and Electronics Engineers (IEEE 1516), provide interoperability, reusability, and extendibility among each simulations by its general rules for distributed simulation environments (Zhang et al. 2011). For the purpose of more comprehensively analyzing complex disaster response and recovery situations of facilities, this research develops a distributed disaster simulation platform for multiple disaster management with different disasters (i.e., earthquake and fire) and diverse response efforts (i.e., building evacuation, functional recovery and structural restoration). Based on the platform, this research further develops a disaster preparedness and response system (DPRS) for facility management which not only has interoperability among different simulations but also has extendibility and reusability for the future.

2 THE NEED FOR HLA-COMPLIANT DISTRIBUTED SIMULATION

The areas of disaster management using computer simulations include the disaster predictions and intensity analyses (e.g., earthquakes, hurricanes, and tsunami), damage estimations (e.g., fire, structural damage, and non-structural damage), and disaster responses (e.g., evacuation, rescue, and recovery efforts) (HallQuist 2000, McKenna et al. 2000, Pachakis and Kiremidjian 2004, Imamura 2006, Vickery et al. 2006, Chu et al. 2012, USGS 2014). Despite these advanced simulation techniques and models that have different abilities, the simultaneous use of multiple simulations is required to incorporate both a disaster intensity analysis and a damage assessment into disaster responses. However, a gap exists between each simulation technique with regard to the target, level, scope, and purpose of the analysis. For instance, specific disaster prediction and damage simulations have limited capabilities in including numerous types of disasters and damage patterns as well as in supporting response planning. Due to a specific purpose of each technique, a single simulation is difficult to satisfy all the functional needs for a comprehensive analysis of disaster responses. In this situation, a distributed simulation can concurrently utilize diverse simulation systems and incoming data streams for their own purposes (Yotsukura and Takahashi 2009). Therefore, the distributed simulation has been applied to disaster management areas including complex disaster analysis, damage mitigation, evacuation planning, rescue planning, and emergency relief efforts (Koto and Takeuchi 2003, Currion et al. 2007, Hu et al. 2009, Yotsukura and Takahashi 2009, Dimakis et al. 2010). When considering various types of disasters, damage patterns, and responses, a synthetic environment for disaster-related simulation components enables comprehensive disaster management in the future. For the purpose of promoting reusability and extendibility of the distributed simulation, the HLA was developed by the U.S. Department of Defense (DoD) (IEEE 1516) (Kuhl et al. 2000). The HLA is an approach that provides collection of general rules and standards for different types of separate simulation components (i.e., federates) to build a distributed simulation environment while maintaining interoperability among federates (AbouRizk 2010). HLA enables computer simulation to exchange information, coordinate operation, and synchronize simulation action regardless of their technical implementation (AbouRizk 2010, Menassa et al. 2014). With a consideration of fully distributed environment in the future, it is found that the CERTI HLA implementation can be effectively applied to design the distributed simulation platform because CERTI HLA, developed since 1996 by ONERA, the French Aerospace Lab, is open-source and platform/programming language independent by providing the flexibility in the simulation interactions (Noulard et al. 2009, Menassa et al. 2014). CERTI HLA RTI follows the IEEE 1516 standard and provides total controls over source code because CERTI is fully opened with the general public license. It also allows users to construct federations from a set of communicating components according to the needs of simulations (Noulard et al. 2009). Therefore, the use of CERTI HLA implementation in disaster simulation is expected to facilitate the integration of other new and existing simulation techniques into the developed platform according to further requirements for the analysis of different damage and response situations.

3 OVERVIEW OF SYSTEM DEVELOPMENT

To investigate the impact of disasters on the facility, a significant number of simulators for disaster prediction, intensity analysis, damage estimation, and response has been introduced to provide meaningful outcomes. However, this research mainly focuses on the disaster responses with the damage from earthquake and fire at a facility level because complex damage patterns after an earthquake as well as spreads of a fire over time may significantly affect facility disaster responses.

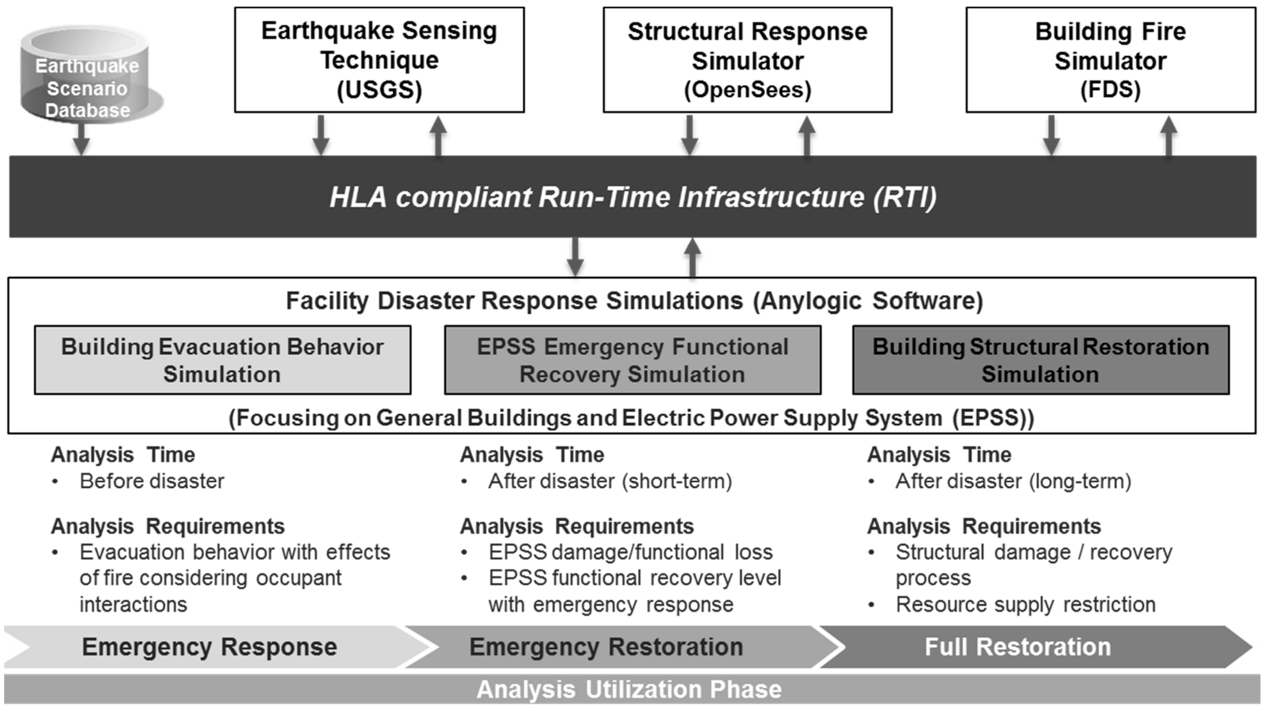


Figure 1: The scope and roles of disaster preparedness and response system.

Figure 1 describes an overview of DPRS system in a HLA-compliant distributed simulation environment. Among a number of advanced techniques, this research uses a data retrieval technique to receive seismic information provided by the U.S. Geological Survey (USGS) real-time data feeds. By using the technique, a query which contains information about a particular earthquake event for an analysis is requested to the USGS server and relevant seismic data is received if the server contains the information on the event of interest (USGS 2014). In addition, the OpenSees for structural response simulation is used to analyze possible structural damage and displacement at each of the key nodes of the building after an earthquake based on the subscribed seismic data (e.g., acceleration-based ground motions) and facility's structural information (McKenna et al. 2000). For a case of a fire event, the Fire Dynamic Simulator (FDS) is in charge of estimating the concentration levels of toxic gases which impair the evacuation ability of occupants inside the building (McGrattan et al. 2013).

After estimating disaster damage by the OpenSees or the FDS, analysis on various types of disaster responses at a facility level should be followed for an effective and fast facility management. To achieve this purpose, three different types of facility disaster response simulations are developed in this research; a building evacuation behavior simulation using agent-based modeling (ABM), an emergency functional recovery simulation using ABM and discrete event simulations (DES), and a building structural restoration simulation using DES. These three different simulations are handled effectively here with the Anylogic 7 software that provides a multi-method simulation platform for developing both ABM and DES simulations.

The building evacuation behavior simulation, which aims to analyze the evacuation behavior of occupants after an event of disaster in the building, consists of two modules; fractional effective dose (FED) calculation and occupant evacuation behavior simulation modules. FED calculation module imports fire gases data from the FDS and calculates FED level of each occupant (Purser 2006), whereas occupant behavior simulation module investigates possible changes in the movement and decision-making process of the occupants with the effects of fire. The various fire evacuation scenarios can be applied for the simulation at normalcy for disaster response preparation, and the analysis outcome can be utilized at the break of disaster for fast response.

In order to evaluate the non-structural damage such as electric power shortage after an earthquake, an emergency functional recovery simulation is developed focusing on the electric power supply system (EPSS). The simulation model is divided into two modules; damage assessment module and emergency operation/restoration analysis module for EPSS. The damage assessment module calculates the ratio of expected probability of EPSS's malfunctioning based on the peak ground acceleration values from the seismic data retrieval technique and related damage functions (FEMA 2003). The emergency operation/restoration analysis module using DES and ABM methods describes the operational state of EPSS—normal, shutdown, emergency operation, and safety inspection—and the number of blackout households in the disaster area. The model simulates the restoration process of EPSS with different resource allocation plans, and it enables to minimize the restoration time and to mitigate restoration delays of other facilities due to electric power shortage at the emergency restoration phase.

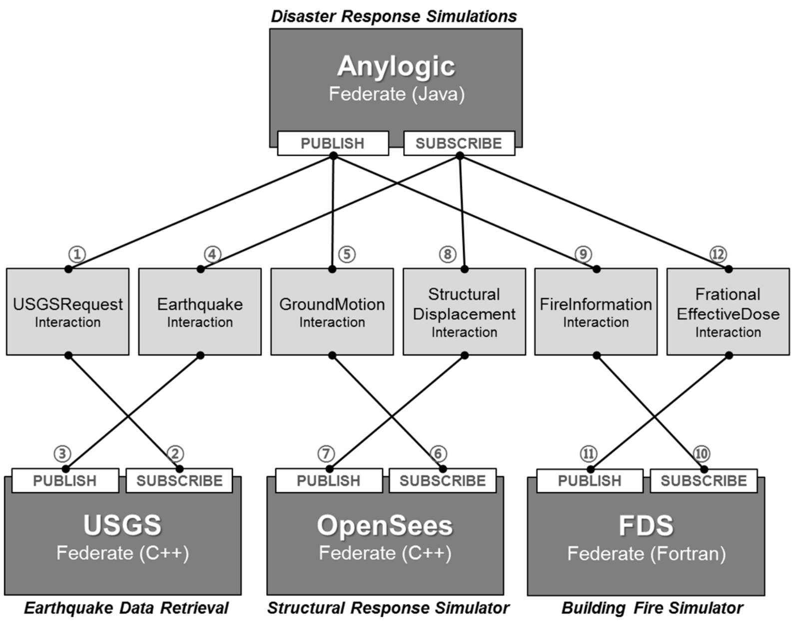
Finally, the building structural restoration simulation with damage assessment and restoration operation analysis modules is built to estimate the possible structural damage and restoration process of the building. The damage assessment module requests the seismic data to the USGS server and utilizes the received data to estimate ground motion for the OpenSees to publish structural response data. Based on the aspects of expected damage on the building, the restoration operation analysis module runs a simulation of restoring the building's structural damage caused by an earthquake. This module could be utilized at the full restoration phase, a few months after the event of disaster.

Further, to conduct a comprehensive analysis on disaster response and recovery situations of facilities with above mentioned technique and simulators, an HLA-compliant disaster simulation is designed. One of the distinguishable features of HLA is that it incorporates a run-time infrastructure (RTI) which enables data exchange between federates. The data exchanges are accomplished by interactions which refer to a collection of non-persisting data fields in the simulation that can be published and/or subscribed to by any number of federates (Kuhl et al. 2000). By utilizing these main principles of the HLA, four federates are integrated in the platform to fulfill their analysis purpose at different phases of disaster (i.e., emergency response, emergency restoration, and full restoration). To consider both structural and non-structural damage (e.g., electric power shortage), in particular, the system is based on both general buildings and the electric power supply system (EPSS).

4 DISASTER PREPAREDNESS AND MANAGEMENT SYSTEM (DPRS)

To establish a distributed simulation platform for the DPRS, it is essential for four federates—the USGS, the OpenSees, the FDS, and the Anylogic federates—to communicate with each other through interactions in the HLA RTI. Interactions containing specific parameters for data exchange include the *USGSRequest*, *Earthquake*, *GroundMotion*, *StructuralDisplacement*, *FireInformation*, and *FractionalEffectiveDose*. Furthermore, these interactions are included in the Federation Object Model (FOM) which standardizes names of federate elements for cross-federate access. The table in Figure 2 summarizes the contents of FOM files with different parameters for each interaction.

In this platform, the API handles all of the RTI function calls necessary for creating or joining a federation, the collection of federates integrated via the HLA, publishing or subscribing interactions, and sending and receiving data updates. Because the DPRS in this study requires multiple language bindings according to the uses of various simulation techniques such as C++ (e.g., OpenSees), JAVA (e.g., Anylogic), and Fortran (e.g., FDS), the open source CERTI HLA RTI with multiple language bindings can be effectively applied to develop seamless distributed environment. With the development of HLA compliant distributed simulation platform, interactive data exchange among various disaster simulators and incoming data streams are accomplished as shown in Figure 2. Based on this platform, a developed DPRS can assist immediate and robust planning and response activities for facility managers in general buildings and EPSSs during and after an unexpected disaster.

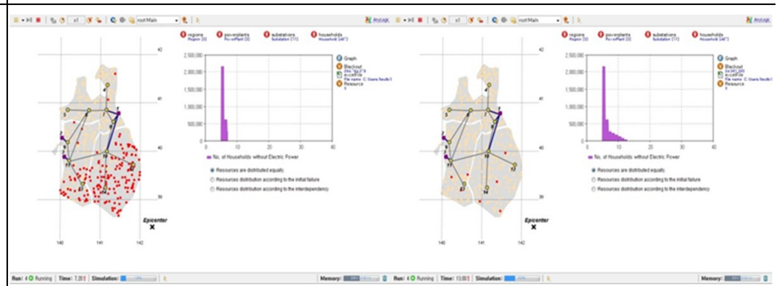
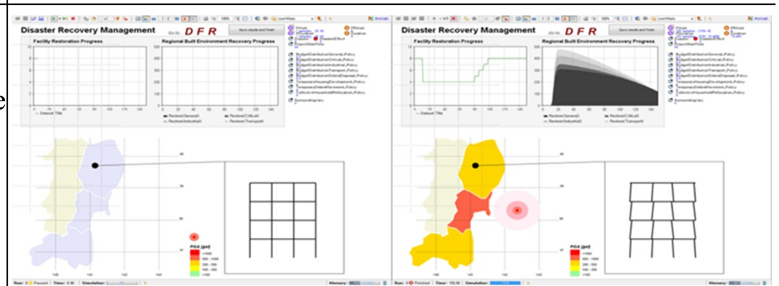
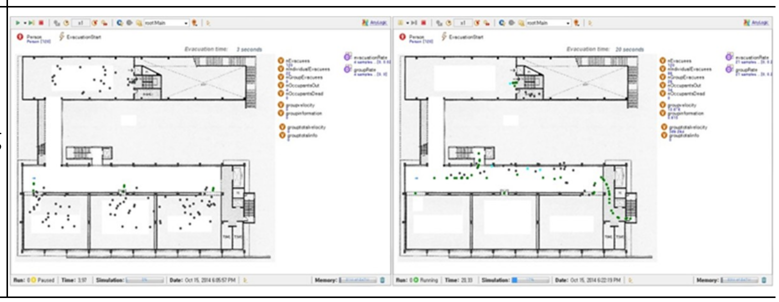


Interactions (Parameters)	Earthquake Data Retrieval (USGS)	Structural Response Simulator (OpenSees)	Building Fire Simulator (FDS)	Disaster Response Simulations (Anylogic)
USGSRequest				
• StartTime	Subscribe			Publish
• EndTime	Subscribe			Publish
• MinMagnitude	Subscribe			Publish
• MinLatitude	Subscribe			Publish
• MaxLatitude	Subscribe			Publish
• MinLongitude	Subscribe			Publish
• MaxLongitude	Subscribe			Publish
Earthquake				
• EventID	Publish			Subscribe
• Time	Publish			Subscribe
• Longitude	Publish			Subscribe
• Latitude	Publish			Subscribe
• Depth	Publish			Subscribe
• Magnitude	Publish			Subscribe
GroundMotion				
• Scale Factor		Subscribe		Publish
• AccelerationFile		Subscribe		Publish
StructuralDisplacement				
• Displacements		Publish		Subscribe
FireInformation				
• IgnitionPoint			Subscribe	Publish
• HeatReleaseRate			Subscribe	Publish
FractionalEffectiveDose				
• FDSSimulationTime			Publish	Subscribe
• CarbonMonoxide			Publish	Subscribe
• CarbonDioxide			Publish	Subscribe
• Oxygen			Publish	Subscribe
• GasVelocity			Publish	Subscribe

Figure 2: Data map of disaster preparedness and management system (DPRS).

Number ① to ⑧ in Figure 2 demonstrate the sequential process of utilizing earthquake and facility damage data for EPSS recovery and building restoration. The Anylogic federate, which is a subset of disaster response simulations, publishes input data containing a specific scope of the earthquake event to request to the USGS federate through the *USGSRequest* interaction. The input data includes start and end times of an event, min/max latitudes and longitudes of the target region, and minimum value of magnitude. The USGS federate then provides seismic information relevant to requested query from the USGS server, including event time, epicentral location (e.g., latitude and longitude), and focal depth of a current earthquake event. Once the information on the event of interest is obtained, the *Earthquake* interaction transfer the data to the Anylogic federate for calculating ground motion (e.g., scale factor and acceleration file), and sends the results to the OpenSees federate through *GroundMotion* interaction. Finally, OpenSees software uses the data received to calculate structural displacement of the target facility and sends the results (i.e., *StructuralDisplacement* interaction*)* to the Anylogic federate for the disaster response analysis. As mentioned earlier, the analysis with the seismic data could be utilized for both EPSS emergency functional recovery simulation and building structural restoration simulation as two different combinations—EPSS recovery and building restoration federations—depending on analysis purposes as described in Table 1. The use of distributed disaster simulation platform allows the disaster response simulations in each federation to instantly utilize both the non-structural or structural damage based on the near real-time seismic and structure response data. The damage information is helpful to determine the scope of recovery efforts, and consequently to analyze the EPSS's recovery and building's restoration process in a more rapid and reliable manner during the early recovery phase. Furthermore, the automatic requests of seismic data based on the time interval settings in the Anylogic federate seem to make it possible to detect and prepare the possibility of aftershocks on the facilities.

Table 1: Descriptions for simulation federations in the DPRS.

Federation	Federates	Utilization	Simulation execution
EPSS recovery federation	USGS–Anylogic	Instant use of seismic data to analyze the functional loss and recovery process of EPSS	
Building restoration federation	USGS–OpenSees–Anylogic	Instant use of seismic and structure response data to analyze the structural damage and facility recovery process	
Building evacuation federation	FDS–Anylogic	Use of fire toxic gases data to analyze changing evacuation behavior under fire in building	

On the other hand, number ⑨ to ⑫ in Figure 2 form another combination−building evacuation federation−which focuses on the event of fire and deals with the toxic gases information for building evacuation analysis as shown in Table 1. The detailed simulation process for building evacuation is described in Figure 3.

By passing input values (i.e., ignition point and hear release rate) of ignition point from the building evacuation behavior simulation through the *FireInformation* interaction, the FDS federate runs a fire simulation that analyze the amount of toxic gases including carbon dioxide, carbon monoxide, and oxygen at the ignition point at every second. Along with the fire gases data, the FDS federate publishes simulation time and gas velocity values and *FractionalEffectiveDose* interaction simultaneously sends out five types of data (i.e., level of carbon dioxide/carbon monoxide/oxygen, simulation time, and gas movement velocity) changing in each time step to the building evacuation behavior simulation. Based on the published data from the FDS federate, the building evacuation behavior simulation calculates FED level at the ignition point and FED level for individual occupants using the distance of x, y coordinates between the origin of fire and occupant's location at each time. Being separated from the previously federations, this process does not include a use of the seismic data retrieval technique. Instead, this could be utilized based on various fire evacuation scenarios in the building with different ignition points and occupants behavior before a fire event for examining evacuation safety of a building or training purposes. The integration of the FDS federate and building evacuation simulation under proposed platform enables to simulate the harmful effects (i.e., changes in movement and decision-making) of toxic gases on occupants inside the building during fire evacuation. The analysis outcome can be utilized at the break of disaster for fast responses to figure out the crowded areas, which can be helpful for decision making in rescue efforts.

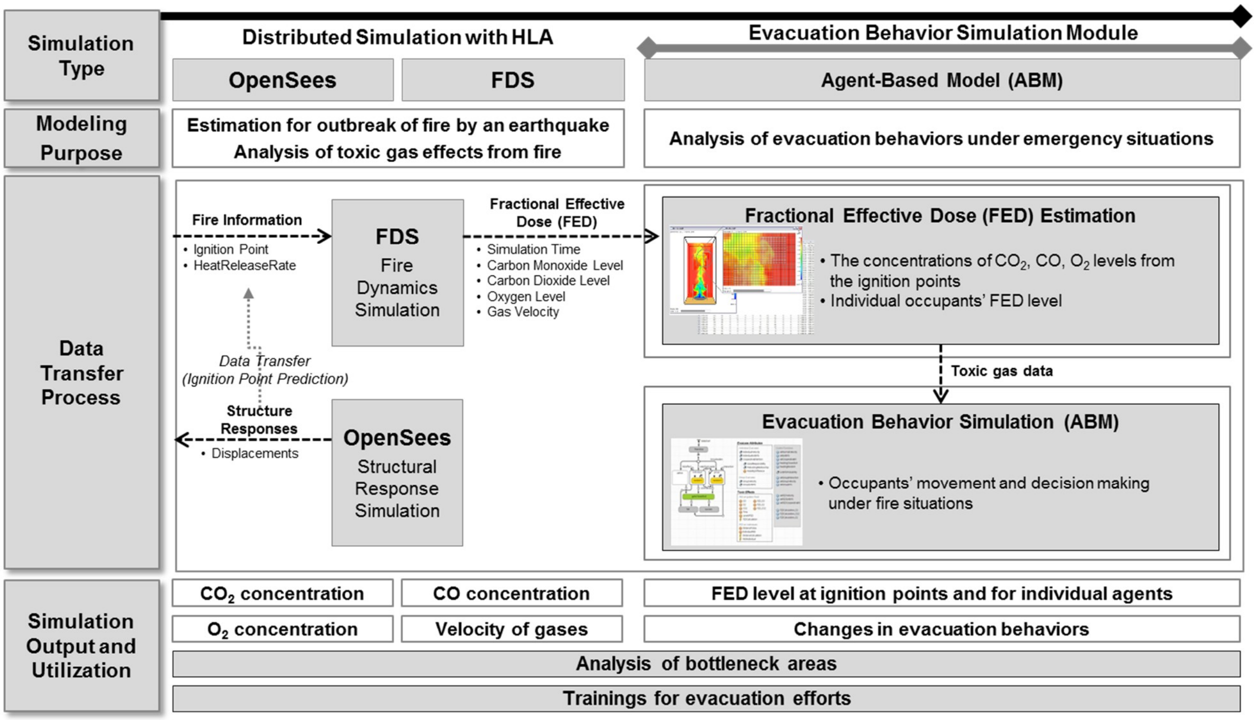


Figure 3: Application example: Evacuation behavior simulation.

After the development of the DPRS, a verification of the proposed system has been conducted to check the stability of seamless data incoming/outgoing between federates. Each disaster response simulation model's validity has been tested and presented in the authors' previous works (Choi et al. 2013, Park et al. 2013) and thus, we focus on the verification which demonstrates the distributed system is built right. The verification examines the performance of dynamic data exchanges with six interactions containing 23 parameters based on the numbers of successful subscription and publication of required data as shown in Figure 2. With the use of distributed simulation platform, the interoperability among different simulations was successfully tested by demonstrating that all of 23 parameters both subscribe data from and publish data to other federates as intended.

However, additional efforts will be needed in the future to reduce time delays when retrieving the seismic data from the USGS server. An advanced time management functionality of the HLA-compliant distributed simulation should thus be supplemented to promote interactions between federates at the proper time. By doing this, the integration of diverse types of disaster-related simulations can extend the range of uses of the developed platform according to its reusability and extendibility. For instance, the developed distributed disaster simulation can be applied in the post-hurricane situation by simply connecting hurricane intensity analysis or sensing modules into the platform because the OpenSees simulation is used to lateral load analysis of structures. Also, a disaster sensing techniques can be directly interacted with the disaster simulation to more accurately incorporate disaster intensity. For example, in the case that the ground shaking of a facility can be directly detected by using an accelerometer—which is a device for real-time measurement of seismic accelerations—and then input to the distributed simulation, this ground shaking data can be utilized for the structural response analysis on a real-time basis without detecting other earthquake information (e.g., magnitude). With the future work described above, the developed system can have the potential to be applied to real-world disaster management by more accurately reflecting reality.

5 CONCLUSIONS

To establish an integrated and a comprehensive disaster response and recovery management, this research proposed a base platform of the DPRS using the HLA compliant distributed simulation which interconnects various types of disaster-related simulators and techniques. A comprehensive analysis including building occupant evacuation, EPSS emergency functional recovery, and building structural restoration after disasters (i.e., earthquake and fire) could be implemented under an interoperable simulation environment. By conducting fire scenario based evacuation simulation, the facility managers could search more efficient and reliable source for evacuation planning and training in different types of building. On the other hand, the seismic data retrieval technique will enable EPSSs to establish faster and more accurate functional recovery plans whose functionality is critical to the regions depending on it. Also, facility restoration based on actual seismic data and structural response simulations will assist facility managers in project scoping and scheduling after an earthquake. As a result, the base platform of a distributed simulation for a facility's disaster management can be utilized to provide information on possible damages and response situations through the generation of serial and complex disasters—both artificial and actual—into the simulation. This information can be helpful for reducing possible confusions in disaster response as well as assisting immediate and robust disaster response planning.

So far, this research provides a distributed simulation system for disaster management limited to earthquake and fire situation. However, utilizing HLA compliant distributed simulation's the strongest features, which is reusability and extendibility, additional disaster simulators or techniques could be supplemented in the future for all-time disaster management including disaster forecast, occupant rescue, and waste disposal in various types of disasters (e.g., landslides, hurricanes, or floods).

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