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A Prototype of Distributed Simulation for Facility Restoration Operation Analysis through Incorporation of Immediate Damage Assessment

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***Abstract:** To rapidly recover ceased functionality of a facility after a catastrophic seismic event, critical decisions on facility repair works are made within a limited period of time. However, prolonged damage assessment of facilities, due to massive damage in the surrounding region and the complicated damage judgment procedures, may impede restoration planning. To assist reliable structural damage estimation without a deep knowledge and rapid interactive analysis among facility damage and restoration operations during the approximate restoration project planning phase, we developed a prototype of distributed facility restoration simulations through the use of high-level architecture (HLA) (IEEE 1516). The simulation prototype, in which three different simulations (including a seismic data retrieval technique, a structural response simulator, and a restoration simulation module) interact with each other, enables immediate damage estimation by promptly detecting earthquake intensity and the restoration operation analysis according to estimated damage. By conducting case simulations and experiments, research outcomes provide key insights into post-disaster restoration planning, including the extent to which facility damage varies according to disaster severity, facility location, and structures. Additional insights arise regarding the extent to which different facility damage patterns impact a project's performance, especially when facility damage is hard to estimate by observation. In particular, an understanding of required type and amount of repair activities (e.g., demolition works, structural reinforcement, frame installation, or finishing works) is expected to support project managers in approximate work scheduling or resource procurement plans.*

***Keywords:** Distributed simulation; Earthquakes; High-level architecture; Project planning; Restoration*

I. INTRODUCTION

In the aftermath of a catastrophic earthquake, critical decisions on facility repair and reconstruction are made within a limited time due to urgent needs for recovery of interrupted facility's functionality [1]. To assist rapid and reliable construction (including repair/reconstruction) planning, Discrete Event Simulation (DES) has been successfully applied to construction operation analysis with its powerful ability to handle the complex and uncertain nature of construction processes [2]. Despite the advantages of DES, in the post-disaster situation the accurate and immediate assessment of facility damage is essential for approximately determining the amount of required repair/reconstruction works and consequently examining restoration operation changes according to damage, prior to implementing restoration plans such as work scheduling and construction resource procurement [3]. However, when a wide range of area is excessively damaged, a lack of skilled engineers who conduct damage assessment causes lengthy duration of damage judgments. If these assessments are performed by non-expert damage assessors who have a limited knowledge of earthquakes and facility structures, inaccurate damage estimation can be made, especially when damage severity is difficult to determine by observation. This causes invalid facility restoration planning [4]. Therefore, it is obvious that post-disaster restoration planning should not only analyze facility repair/reconstruction operations but also properly consider facility's damage as soon as possible.

To assist reliable structural damage estimation without a deep knowledge during the approximate restoration project planning phase, there exist available technologies, tools, and systems for rapidly analyzing structure responses by only using earthquake information (e.g., ground motions) and facility information (e.g., structures). Our challenges thus include both the immediate damage estimation by promptly detecting earthquake information and the restoration operation analysis according to estimated damage, in order to support project managers in rapidly implementing valid restoration plans. For the purpose of interactive and prompt analysis among seismic intensity, facility damage, and restoration operations, we develop a prototype of distributed facility restoration simulations through the use of high-level architecture (HLA) (IEEE 1516), that is capable of synchronizing different simulation models or incoming data streams [5]. By using a hypothetical case example of a common building, we present the behaviors of the prototype as well as identify the effectiveness of the distributed simulation in post-earthquake facility restoration management.

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II. OPPORTUNITIES AND TECHNICAL HURDLES OF RELATED WORK

DES is regarded as an effective tool for construction process analysis due to its advantages in describing operational details, with a consideration of stochastic durations and resource inputs to reproduce system events [3,6]. In the post-earthquake situation, however, it is hard for DES to be solely applied in restoration operation analysis because the amount and type of required construction activities can vary according to seismic intensities and consequent structural damage patterns. Therefore, the integration of seismic intensity analysis, damage simulation, and restoration operation simulation (i.e., DES) can be more effective in post-earthquake restoration planning. Although numerous tools for seismic intensity analysis and structural damage simulation exist, the OpenSees—which has been focused on providing an advanced finite-element computational tool for analyzing nonlinear responses of structural systems subjected to seismic excitations [7]—is identified as an effective tool for structure response analysis required for facility damage assessment. In addition, web-based real-time earthquake data feeds by the U.S. Geological Survey (USGS) can be effectively utilized to analyze seismic intensities in near real-time because earthquake information for worldwide events can be provided using query methods for requesting interest magnitude, location, and time of an event.

Although each single simulation needs to interact with others for post-earthquake facility restoration planning with a consideration of structural damage, interoperation among simulations can be hindered because of different technical implementation and platforms among simulation techniques. In this situation, HLA-compliant distributed disaster simulation approach alleviates these problems via a new distributed simulation platform where different simulations interact with each other. It can make use of diverse systems that are used or have been developed for their own purposes at the same time [8]. The HLA was first developed by the U.S. Department of Defense (DoD) to provide interoperability and reusability among each simulation by its general rules for distributed simulation environments. The HLA enables computer simulation to seamlessly interact with each other because it provides standards for building the individual federates (i.e., federate is an individual simulation component such as single simulation model and incoming data stream) of such environments by different developers while maintaining interoperability between them [9]. Based on the abilities of HLA-compliant distributed simulation in promoting flexibility and future extendibility, we develop a distributed simulation for post-disaster facility restoration planning, through the incorporation of an USGS seismic data retrieval, an OpenSees structural response simulation, and a DES restoration operation simulation. In particular, we utilize Anylogic 7 software (Anylogic Company) for DES modeling because multi-method simulations in the Anylogic can provide future extendibility to diverse restoration management.

III. DISTRIBUTED SIMULATION FRAMEWORK FOR RESTORATION PLANNING

Based on the in-depth investigation of relevant simulation techniques, Fig. 1 offers the distributed simulation framework for post-earthquake restoration planning. In the distributed simulation environment, HLA RunTime Infrastructure (RTI) provides functions for exchanging data and synchronizing simulation action among required sub-simulations which can be referred to "federate". In the HLA-compliant simulation platform, three federates—including a seismic data retrieval using USGS real-time data feeds (i.e., USGS federate), a structural engineering using OpenSees (i.e., OpenSees federate), and a DES restoration simulation using Anylogic software (i.e., Anylogic federate)—are able to interact.

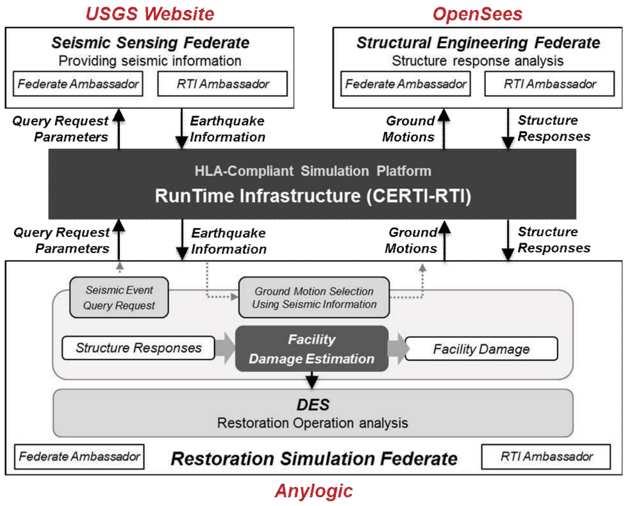

FIGURE I
DISTRIBUTED FACILITY RESTORATION SIMULATION FRAMEWORK

First, the USGS federate communicates with a USGS server to retrieve earthquake and seismic event data for the region in which the facility resides in near-real time. To detect a seismic event of interest, the USGS federate requires query information that includes the event time, the latitude and longitude in the target region, the minimum value of a magnitude of interest seismic events. The earthquake data provided (i.e. location, depth, and magnitude of the event) by the USGS is used for computing ground motion from which structural displacements and facility damage are assessed. Second, the OpenSees federate is used to generate a 2-D model of the facility and calculate the structural responses (e.g., displacement) at each of the key nodes during a seismic event. This data is utilized for estimating the structural damage incurred during an earthquake. By inputting model parameters such as a size and material information of structures, diverse facilities can be easily modeled for a structural response analysis. Third and finally, the Anylogic federate simulates structural damage based on the structural response data. This data is shared with the facility restoration operation simulation which represents the core functionality of the HLA-compliant distributed simulation. In other word, the Anylogic performs not only the DES restoration simulation but also damage assessment of facility's structures. In addition, for the purpose of rapid restoration simulation, the Anylogic also has functionality to request earthquake information to the USGS server by generating query parameters for a target seismic event. This information is newly updated at every time step and sent to the USGS federate that provide real-time data feeds within 30-minutes for worldwide seismic events [10]. After the USGS federate send earthquake information such as the magnitude and epicenter, the damage estimation and restoration simulation of a facility are activated.

In general, structure response analysis using the OpenSees requires ground motion and shaking data (i.e., accelerograms) at the damaged point. when the ground shaking of a facility can be directly detected using an accelerometer (i.e., accelerometer is a device for real-time measurement of seismic accelerations) this ground shaking data can solely be utilized for a structure response analysis without sensing other earthquake information. However, it is hard for common facilities to obtain accelerograms because only critical facilities or strong motion stations are equipped with accelerometers. Therefore, there exist numerous ground motion databases for the purpose of analyzing structure responses using the historical data and empirical approach. The most suitable accelerograms for target facility can be selected from this database and then scaled with a consideration of differences between the magnitude and epicentral distances both of current event and past event [11]. In this procedure, only moment magnitude and epicentral distance of a notable seismic event are employed as the most common parameters for the simplest ground motion selection and scaling.

Based on this procedure, the Anylogic federate converts earthquake information from USGS into ground motion data in order to send it to the OpenSees federate. Then, the OpenSees simulates structural responses of the target facilities, by using the ground motion data and scale factor as input values. As a prototype, this simulation model mainly utilizes structural displacement information as a main element for estimating structure damage. By using this structural response data from the OpenSees, the Anylogic federate estimates facility damage status based on the structural design standards [12]. By determining the required amount and type of repair/reconstruction works in facility restoration projects, a DES model in the Anylogic can finally show to what extent the structural damage has an impact on overall facility restoration processes and project performances (e.g., project duration) using input values in DES such as the amount of resources and the duration for initiating each activity.

With a consideration of fully distributed environment in the future, we utilize CERTI HLA RTI, which is an open source HLA RTI developed since 1996 by ONERA, the French Aerospace Lab [13], because the CERTI has multiple language bindings such as C++ (e.g., OpenSees), JAVA (e.g., Anylogic). In the framework, the CERTI HLA RTI coordinates the synchronization and transfer of data between federates. In this distributed simulation platform, each sub-simulation process (i.e., federate) interacts locally with an RTI ambassador process (RTIA). The RTIA always listens to both the federate (i.e., federate ambassador) and the RTI (i.e., RTI gateway (RTIG)), which controls publication and subscription of data. When a message for data transfer is received from a given RTIA to the RTIG, the RTIG delivers it to the other interested RTIAs. Then, interested federate can conduct simulation based on the subscribed data. For instance, if the USGS federate creates earthquake information and then sends it to the RTIG and if Anylogic federate informs RTIG of its interest to earthquake information, the RTIG delivers this information to the RTIA of Anylogic federate.

IV. FEDERATION DESIGN

TABLE I
DESCRIPTION OF INTERACTIONS IN THE RESTORATION SIMULATION

Interactions and Parameters	Explanations (Data Type)
USGSRequest	
Start Time	Minimum (Min.) time for events to download (long)
End Time	Maximum (Max.) time for events to download (long)
MinMagnitude	Min. magnitude for events to download (double)
MinLatitude	Min. origin latitude of events to download (double)
MaxLatitude	Max.origin latitude of events to download (double)
MinLongitude	Min. origin longitude of events to download (double)
MaxLongitude	Max. origin longitude of events to download (double)
Earthquake	
Time	The time at which the event occurred (long)
Longitude	The longitudinal location of the event's origin (double)
Latitude	The latitudinal location of the event's origin (double)
Depth	Depth from ground level of the event's origin (integer)
Magnitude	The magnitude of the event (double)
GroundMotion	
Scale Factor	A scaling factor for normalizing data between damage federate and OpenSees federate (double)
Acceleration FilePath	The file path for an appropriate acceleration file determined by Damage (string)
Structural Disp.	
Displacements	Nodal displacements (C++: vector<double> Java: ArrayList<double>)

Based on the federate interactions determined previously, the restoration simulation federation (i.e., the federation is the collection of federates in the distributed simulations that are integrated via HLA) is designed and developed. In this prototype, the API handles all of the CERTI HLA RTI function calls necessary for creating or joining a federation, publishing or subscribing objects and interactions, sending and receiving data update. In the HLA-compliant simulation, *Interactions* in the RTI refers a collection of non-persisting data fields (i.e. an event) in the simulation that can be published and/or subscribed to by any number of federates. Each *Interaction* Class has a single data field called parameter [14]. In the distributed restoration simulation, four interactions are used for the communication between federates occurred via HLA, including the *USGSRequest*, *Earthquake*, *GroundMotion*, and *StructuralDisplacement* interactions. Table 1 offers a detailed description of interactions and their parameters.

Fig. 2 shows the HLA-based communication architecture of the distributed facility restoration simulation, including three federates, interactions, and publishing/subscribing schemes. During a federation execution, the Anylogic federate increments the simulation time by one week [(1) in Fig. 2], and creates and sends queries for earthquake information (i.e., *USGSRequest* interaction) which are used as an input data for the USGS federate [(2) in Fig. 2]. In the *USGSRequest*, the *StartTime* and *EndTime* parameters can be represented as previous simulation time and current simulation time respectively, while other parameters are static. After the USGS federate subscribes the *USGSRequest* interaction and after seismic data conforming to the parameters in *USGSRequest* is found [(3) in Fig. 2], the USGS federate publishes earthquake information (i.e., *Earthquake* interaction) [(4) in Fig. 2]. Then, the Anylogic subscribes the *Earthquake* [(5) in Fig. 2], and then publishes estimated facility ground motion data (i.e., *GroundMotion* interaction) required for the OpenSees federate [(6) in Fig. 2]. After the OpenSees federate subscribes the *GroundMotion* [(7) in Fig. 2], the OpenSees federate computes and publishes structure response data (i.e., *StructuralDisplacement* interaction) [(8) in Fig. 2], which are subscribed by the Anylogic federate to compute facility damage [(9) in Fig. 2], and to simulate the facility restoration progress [(10) in Fig. 2].

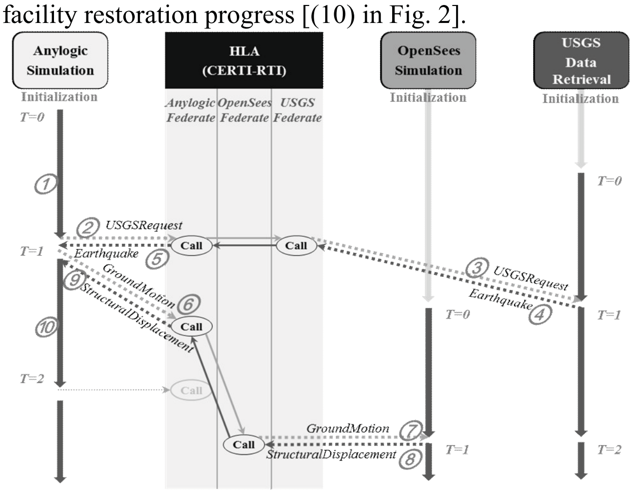

FIGURE II
DATA EXCHANGE DURING FEDERATION EXECUTION

V. CASE SIMULATION

Based on the developed prototype and the actual data of a past disaster case of the M 9.0 2011 earthquake of Tohoku, we conduct a case study of facility restoration projects to examine the effects of different damage patterns on the facility restoration project and to show the effectiveness of distributed simulation in the restoration planning. By the interaction with the USGS and OpenSees federate, the DES facility restoration simulation can be utilized to restoration planning after a disaster by rapidly assessing facility damage. General assumptions are set for case simulations, as the disaster event takes place 10 weeks after the simulation start time, and when the hypothetical case of the reconstruction project for a damaged building—including a site preparation, an interior/external material demolition, a structural reinforcement, a frame and a deck installation, and a curtain wall installation for a 8-story building—starts 20 weeks after the simulation start time. In addition, the simulations are conducted based on the assumption that facility's structural damage is hard to determine with observation while the full damage of the facility's exterior (e.g., curtain walls) is easily identified. Therefore, we focus on several facilities in different locations with different disaster intensities.

As shown in Table 2, the case simulation is implemented by three scenarios with three hypothetical facilities located in different area with different damage levels: (a) facility restoration in the severely damaged area that full damage of structures is estimated (Case 1: Graph A in Fig. 3); (b) restoration in the less severely damaged area where partial damage of structures is estimated (Case 2: Graph B in Fig. 3); and (c) restoration in the slightly damaged area where only exterior damage is estimated (Case 3: Graph C in Fig. 3). The three cases for the experiment of post-earthquake facility restoration projects consider the different structural damage of facilities in the DES restoration operation simulation. Since the Case 1 simulates restoration operations of fully damaged buildings that 100% of structural damage is estimated, the simulation results correspond to the results of only DES simulation. On the other hand, Case 2 and 3 for partially damaged building restorations represent the simulation results from the distributed facility restoration simulation through interactions with the USGS seismic data retrieval and the OpenSees structural response/damage simulation.

TABLE II
CASE SIMULATION SCENARIOS

Cases	Explanations (Data Type)	Locations
Case 1 (Base Case)	Fully damaged building restoration (100% structure damage estimated with fully damaged exteriors)	In severely damaged area (Lat.: 38.9; Long.:141.5)
Case 2	Partially damaged building restoration (50% structure damage estimated with damaged exteriors)	In less severely damaged area (Lat.: 39.7; Long.:141.2)
Case 3	Only-exterior damaged building restoration (0% structure damage with damaged exteriors)	In slightly damaged area (Lat.: 37.1; Lo ng.:139.4)

Graph (A) of Fig. 3 (Case 1) displays reconstruction works of a fully damaged facility completed in 48 weeks after the project's commencement. On the other hand, Graph (B) of Fig. 3 (Case 2) displays reconstruction works for a partially damaged facility may be completed approximately 10 weeks before completion of the fully damaged facility due to less damage and a consequent less amount of restoration works. This information of expected project duration according to different facility damage can be effective for implementing a valid restoration plan in an early stage especially when the facility damage is hard to estimate with an observation, and when damage assessment requires lengthy duration because of the massive amount of damaged facilities in the whole region that await deliberate structure examination by lacking skilled engineers.

The information of different project durations according to different damage patterns can be also found in Graph (C) of Fig. 3 (Case 3) that shows the restoration operations of the building where only exteriors are damaged. As shown in this result, the detailed analysis of post-disaster facility restoration operations according to structural damage can provide the information of what kinds of restoration activities are required and how each activity progresses. In particular, Graph (C) of Fig. 3 shows only curtain wall installation work is required because no structural damage is estimated, in which approximately 20 weeks earlier project completion compared to fully damage facility restoration can be expected.

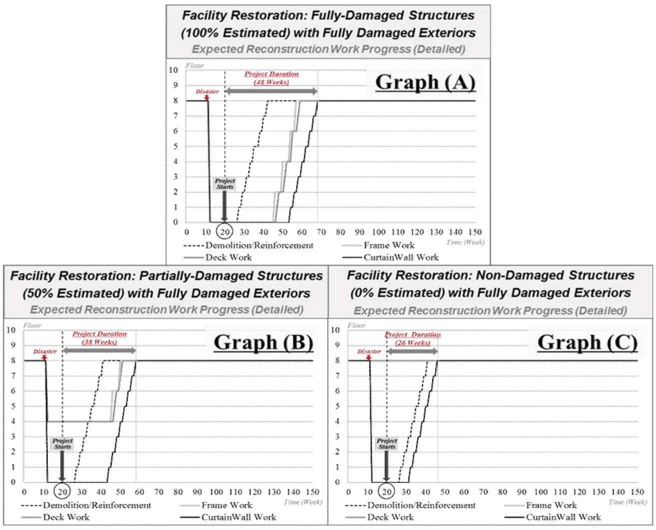

FIGURE III
SIMULATION RESULTS FOR DETAILED RESTORATION OPERATIONS OF A FACILITY ACCORDING TO DIFFERENT DAMAGE PATTERNS

As a result, due to the uncertain and complex post-earthquake situation, immediate assessments of facility damage are essential for rapid and robust project planning during the approximate project planning phase. Both the approximate and rapid assessment of facility damage patterns and the determination of the amount and the type of required repair/reconstruction works (e.g., demolition works, structural reinforcement, frame installation, or finishing works) using distributed facility restoration simulation can support project planners in project scheduling and project work scope decisions.

VI. CONCLUSIONS

We developed a distributed simulation prototype for more rapid and appropriate post-earthquake facility restoration management in an uncertain disaster situation, by enabling rapid interactive analysis among disaster intensity, facility damage, and restoration works. Simulation results for facility restoration using distributed simulation implied that facility restoration projects tend to be highly variable in a post-disaster situation, according to facility's damage patterns. In particular, this study's outcomes can provide key insights into post-disaster restoration planning and management, including to what extent the facility damage is different according to disaster severity and facility's locations and structures, and to what extent different facility damages impact a project's performance in a post-earthquake situation.

Therefore, by accurate and immediate assessment of facility damage, an analysis of restoration project's performance in an early time assists the project manager in immediate and appropriate project planning in the conceptual planning phase, such as project work scope decisions and approximate scheduling. In particular, required types and amounts of repair activities (e.g., demolition works, structural reinforcement, frame installation, or finishing works) can be approximately understood, which can be useful for future detailed work scheduling or resource procurement plans.

The distributed facility restoration simulation provided a base technology for disaster-related simulation and restoration management. By integrating seismic intensity, structural damage, and restoration operation analysis of a facility, this prototype can be further utilized to analyze diverse damage and restoration situations when serial and complex disasters are generated (e.g., aftershocks), and when different types of disasters occur (e.g., hurricanes).

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REFERENCES

[1] Stephens, J. E., and Yao, J. T. P. " Damage Assessment Using Response Measurements." *Journal of Structural Engineering*, ASCE, 113(4), 787–801, 1987.
[2] Law, A., and Kelton, W. D. *Simulation Modeling and Analysis*, 3th, McGraw-Hill, New York, NY., 2006.
[3] Ma, T. Yang, H. T., and Chang, C. " Structural Damage Diagnosis and Assessment under Seismic Excitations." *Journal of Engineering and Mechanics*, 131(10), 1036–1045, 2005.
[4] Anil, E. B., Akinci, B., Garrett, J. H., and Kurc, O. "Representation of Damage Information for Post-Earthquake Damage Assessment of Reinforced Concrete Frames." In *Proceedings of Computing in Civil Engineering*, ASCE, Reston, VA, 825–832, 2013.
[5] Schulze, T., Strasburger, S., and Klein, U. "Migration of HLA into Civil Domains: Solutions and Prototypes for Transportation Applications." Simulation, 73(5), 296–303, 1999.
[6] AbouRizk, S., Halpin, D., Mohamed, Y., and Hermann, U. "Research in Modeling and Simulation for Improving Construction Engineering Operations." *Journal of Construction Engineering and Management*, ASCE, 137(10), 843–852, 2011.
[7] Jiang, J., Jiang, L., Kotsovinos, P., Zhang, J., Usmani, A., McKenna, F., and Li, G. Q. "Opensees Software Architecture for the Analysis of Structures in Fire." *Journal of Computing in Civil Engineering*, ASCE, 29(1), 2015.
[8] Yotsukura, S., and Takahashi, T. "Framework of an Emergency Management System Using Different Rescue Simulators." *Advanced Robotics*, 23(9), 1233–1246, 2009.
[9] AbouRizk, S. "Role of Simulation in Construction Engineering and Management." *Journal of Construction Engineering and Management*, ASCE, 136(10), 1140–1153., 2010.
[10] U.S. Geological Survey (USGS) website: http://earthquake.usgs.gov/earthquakes/?source=sitenav
[11] Katsanos, E. I., Sextos, A. G., and Manolis, G. D. "Selection of Earthquake Ground Motion Records: A State-of-the-art Review from a Structural Engineering Perspective." *Soil Dynamics and Earthquake Engineering*, 30(4), 157–169, 2010.
[12] Taranath, B. S. *Wind and Earthquake Resistant Buildings: Structural Analysis and Design, Drift Limitation*, CRC Press Taylor and Francis Group, Boca Raton, FL., 2005.
[13] Noulard, E., Rousselot, J., and Siron, P. "CERTI, an Open Source RTI, Why and How." *Spring Simulation Interoperability Workshop*, 23–27, 2009.
[14] Kuhl, F., Dahmann, J., and Weatherly, R. *Creating Computer Simulation Systems: An Introduction to the High Level Architecture*. Prentice Hall PTR, Upper Saddle River, NJ, 2000.