Review on Modeling and Simulation of Large-scale and Complex Disaster Scenarios

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Abstract

Recent large-scale and complex disasters, such as the Japan earthquake and tsunami in 2011, left devastating damage to our society. The damage is particularly amplified because of the interdependencies of the infrastructure in the society. For instance, a mixture of a short power outrage and a tsunami threatened to induce a nuclear reactor meltdown in the Japan case. To prevent this consequence, some researchers have modeled, simulated and analyzed the complex structure of our infrastructure systems and the relations to the disaster effect. This review introduces such effort as well as found commonalities in the modeling frameworks.

1. INTRODUCTION

Recent large-scale and complex disasters [1, 2, 3] call for further research on the modeling and simulation of disasters. In 2010 and 2011, there were a number of large-scale and complex disasters: the epidemic of H1N1 Influenza [4], the Pakistan floods [5], the Japan earthquake and tsunami [2], the land sliding in Seoul [6], the Newzealand earthquake [7], and etc. Some analysts expect that the number of such devastating incidents is increasing due to the weather change [8]. Also, others claim that the consequence of the disasters is now much more devastating because of complexity in the infrastructure of our societies [9, 10]. One common conclusion is that we need to strengthen our capability in the disaster modeling and simulation.

The recent disasters have resulted in large and complex consequences. For instance, the Japan earthquake and tsunami was destructive by itself, but its effect was amplified because it was accompanied by an accident of a nuclear power plant located in the disaster area. The epidemic of H1N1 spread rapidly around the world because of our globalized societies, which was not seen in the Spanish flu in 1918 [11]. These incidents are large-scale because our society is more tightly coupled with outside world as well as infrastructure systems. Additionally, various infrastructure systems of communication, gas, electricity, traffic, and government systems are all interconnected, so a failure in one system easily propagates to other systems [12, 13]. Therefore, today's disaster often leaves a large-scale consequence which is emerged from our complex society and infrastructures.

Due to this research demand, there also have been research efforts to model and simulate the disasters that impact the complex infrastructure in the large scale [14, 15, 16, 17, 18, 19, 20]. This paper is a brief introduction of such modeling and simulation research. First, we review the disaster modeling and simulation in general. Next, we analyze the difference between the past disaster modeling and simulations and the modern large-scale and complex efforts. Finally, we review specific large-scale and complex disaster modeling and simulations, such as the works from National Infrastructure Simulation and Analysis Center, or NISAC [15, 16] as well as from Critical Infrastructure Modeling Simulation, or CIMS [17, 18, 19, 20]. We expect that this review might inform the researchers where we are and inspire the growing demand in the area of the disaster modeling and simulation.

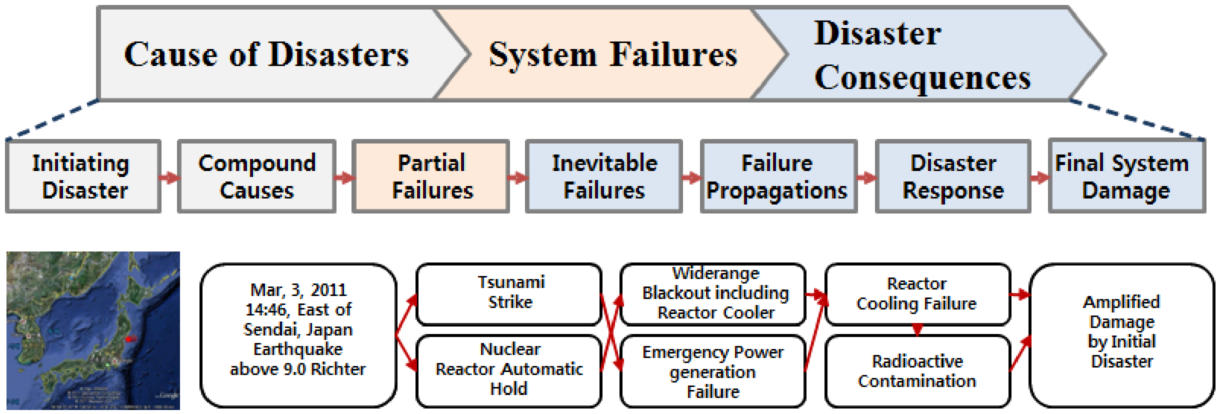

Figure 1. The progress of large-scale and complex disasters, the case of the Japan earthquake and tsunami

2. DISASTER MODELING AND SIMULATION OF SINGLE ASPECT

To move the discussion of large-scale and complex disaster modeling and simulation, we have to define the nature of the large-scale and the complex. Some simulations model a large population to estimate the spread of epidemic. The models might run for a long time in a large-size machine, yet the size of the simulation would not guarantee that such models are large-scale from my viewpoint. If a model handles a large size of population with a single aspect of disasters, such as evacuation, supply chain, search and rescue, the simulation is a large repetition of the modeled aspect, not a model with many interconnected aspects of disasters. Having said that the single aspect models may not be the large-scale and complex models that are the interests of this paper, such single aspect models are often the basis of the complex models that we will discuss later.

From the beginning of modeling and simulation, disasters have been a recurring domain for modeling. Early examples include the wild-fire spread [21, 22], the epidemic spread [23, 24], and the resident evacuation in a building [25, 26]. These models often focus on either detailed description of the disasters or detailed behavior of the affected population. The target system without detailed description is abstracted as a simple parameter or a simple model.

The wild-fire spread [21, 22] is one example of a single aspect disaster models. The model of wild-fire spreads have been developed from the extensive usage of cellular automata in the modeling and simulation. There has been extensive research on the state and the transition function modeling the fire spread from one cell to another. However, the research is mainly modeling hypothetical plain terrain, and only some models simulating with the real world geography in the mountain or the plain areas. Hence, there has been little research on what could be the effect of the wild-fire to the infrastructure. Similar to the wild-fire research, the flooding is often limited to the estimation of the elevation of the water surface, not the affected complex infrastructure and the consequence of the infrastructure failure.

The pandemic breakout [23, 24] is another example of a single aspect disaster models. Whereas the wild-fire models focus on modeling the disaster itself, the pandemic models often focus on modeling the population. The pandemic models simulate the population that are in either susceptible, infected or recovery, or (SIR) stages [27, 28], and the interactions between these compartments of the population are modeled.

3. MULTIPLE ASPECTS OF COMPLEX DISASTERS

Recent disasters have frequently left extensive damage in the infrastructure of the area and have lead to the failure of the infrastructure. The difference from the past is that the local failure of the infrastructure propagates to the interconnected systems and becomes the failure of the national level with a good chance. We call this propagation of disaster damage and the failure of the national level infrastructure caused by a local failure as the large-scale and complex disasters.

The Japan earthquake and tsunami is a typical example of such large-scale and complex disasters.

Table 1. Interoperating models from Urban Infrastructure Suite, or UIS, developed by National Infrastructure Simulation Analysis Center

Model name	Modeled Area	Brief model description
Urban Population Mobility Simulation Technologies (UPMoST)	Population	A common interface for the flow of information between UIS sector models, The data storage of the synthetic population and urban elements
Transportation Analysis Simulation System (TRANSIMS)	Traffic	The cellular automata based micro-simulation with synthetic population. The output is the mobility of population that is calibrated to the demographic information
Multi-Scale Integrated Information and Telecommunications System (MIITS)	Information	Peer-to-peer communication system model. A type of an agent based simulation modeling the individual packets, devices, connections, etc
Epidemiological Simulation Systems (EpiSims)	Health care	A contact-based approach for evaluating the spread of disease among a population. The interactions and contacts are modeled by the TRANSIM's mobility estimation.
Interdependant Energy Infrastructure Simulation System (IEISS)	Energy	The electric power flow model that simulates service and outrage areas, outrage duration, critical system components, and restoration strategy
Water Infrastructure Simulation Environment (WISE)	Water	The integration of geographic information systems with a wide range of infrastructure analysis tools including industry standard hydraulic simulation engines, i.e. EPANET and SWMM

Described in Figure 1, the start of the Japan earthquake and tsunami was devastating, yet limited to the north-east area of Japan. Given this local start, the effect of the tsunami propagated to the failure of the local electricity system and eventually the failure of the nuclear power plant safety system due to lack of the electricity supply. The nuclear power plant has a back-up generator to negotiate the power shortage in the disaster, but when the tsunami hit, the back-up generator was also ruined by the tsunami. Once the nuclear power plant becomes unstable, the national disaster relief effort was concentrated on resolving the nuclear crisis, which left less supply and relief to the evacuated people and the search and rescue operations. This chain of failures is the result of the interconnected infrastructure and the interdependent disaster management systems. Because the interconnection and the interdependence are key characteristics of the infrastructure and the disaster management systems today, the analysis of such chains is imperative in preventing the example of the Japan earthquake and tsunami. Particularly, the analysis requires a joint and interoperating model of diverse aspects of the disasters, the management systems, and the infrastructures.

4. DISASTER MODELING AND SIMULATION OF MULTIPLE ASPECT

As the today's interconnection and inter-dependence require the joint and interoperating model, some models have emerged to simulate the large-scale and complex disasters. We review the models briefly in this section.

4.1. National Infrastructure Simulation and Analysis Center (NISAC)

The Korea government recently funded a modeling and simulation research project for large-scale and complex disasters, which was motivated by the Japan earthquake and tsunami. Participating the project, we performed a review of models for large-scale and complex disasters at various levels. From the review, one outstanding research institute in the complex disaster modeling is National Infrastructure Simulation and Analysis Center, or NISAC [15, 16], in the U.S. NISAC is a modeling and simulation research center operated by Sandia National Laboratory and Los Alamos National Laboratory, and NISAC is a part of Department of Homeland Security. The goal of NISAC is becoming a "source of national expertise to address critical infrastructure protection" research and analysis.

To provide the key analysis to protect the national infrastructure, NISAC has developed various models of infrastructure, i.e. transportation, telecommunications, banking and finance, energy, population; as well as models of diverse disasters, i.e. spill of chemical and hazard materials, influenza, hurricane, crude oil supply disruption, etc. By observing the enumerated modeling areas, NISAC is not just a modeling center for a natural disaster, but for any types of disasters caused by either human error, natural disaster, or international relation.

Among these various models, what we found interesting is a collection of interoperating simulation models for the complex disaster in urban areas. This model collection, or the interoperation framework, is Urban Infrastructure Suite, or UIS. UIS includes the models listed in Table 1. As the table describes, each model in the UIS is a detailed model in a specific area, yet they collectively represent the urban complex infrastructure in disasters. Figure 2 shows how the models are interoperating. UPMoST is the model of the urban population mobility, and it is the center of the UIS interoperation framework. UPMoST provides the common interface for the flow of information between multiple UIS domain-specific models. This means that the other UIS models follow the UPMoST interoperation framework. Having said this, to my knowledge, UIS is not following any standard protocol for simulation interoperations such as HLA/RTI.

While UPMoST is the center of the information flow between the models, the initial scenario generation, such as creating instances of population and urban environment, is the responsibility of TRANSIMS that is the model of transportation analysis. Therefore, the initial operation of the UIS is the sequence of executing the TRANSIMS's entity creations and the UPMoST's entity information distribution. After the initial setup, UPMoST becomes the data repository, and a simulation progresses by updating the entities in the repository with the request of interoperating models.

Compared to other disaster modeling and simulations, the models from NISAC are collectively an extensive model of the infrastructure. Whereas some previous models focused on the progress of the disaster, the models in NISAC focus on the chain reaction that the disaster initiates. Because such chain reaction from one infrastructure area to another is difficult to be modeled by a single modeler, eventually, the NISAC developed the common interface that different modelers from different domains can share in the process of modeling.

Besides of the common interface, the NISAC models rely on *the generic cities project* that aims to replicate a selected city or region in the models. Given the need to instantiate the population and the urban environment, it is important to replicate them realistically to utilize the model in the real world. Therefore, the generic cities project aims to provide a hypothetical population and urban environment which are not real, yet have the approximately identical statistics when the population and the environment are aggregated across the modeled region.

4.2. Critical Infrastructure Modeling Simulation (CIMS)

Similar to the NISAC's effort, the Idaho National Laboratory also developed the Critical Infrastructure Modeling Simulation (CIMS) framework [17, 18, 19, 20]. The objective of CIMS is providing the common interface that different infrastructure modelers can utilize for their own modeling purposes. The fundamental model of the CIMS is the mixture of network representations and agent based simulations. The assets of the infrastructure are represented as nodes, and the interdependencies of the assets are represented as edges. One interesting feature of CIMS is the utilization of sensory data. While the other models simulate the behavior that the modelers implemented, the models of CIMS are

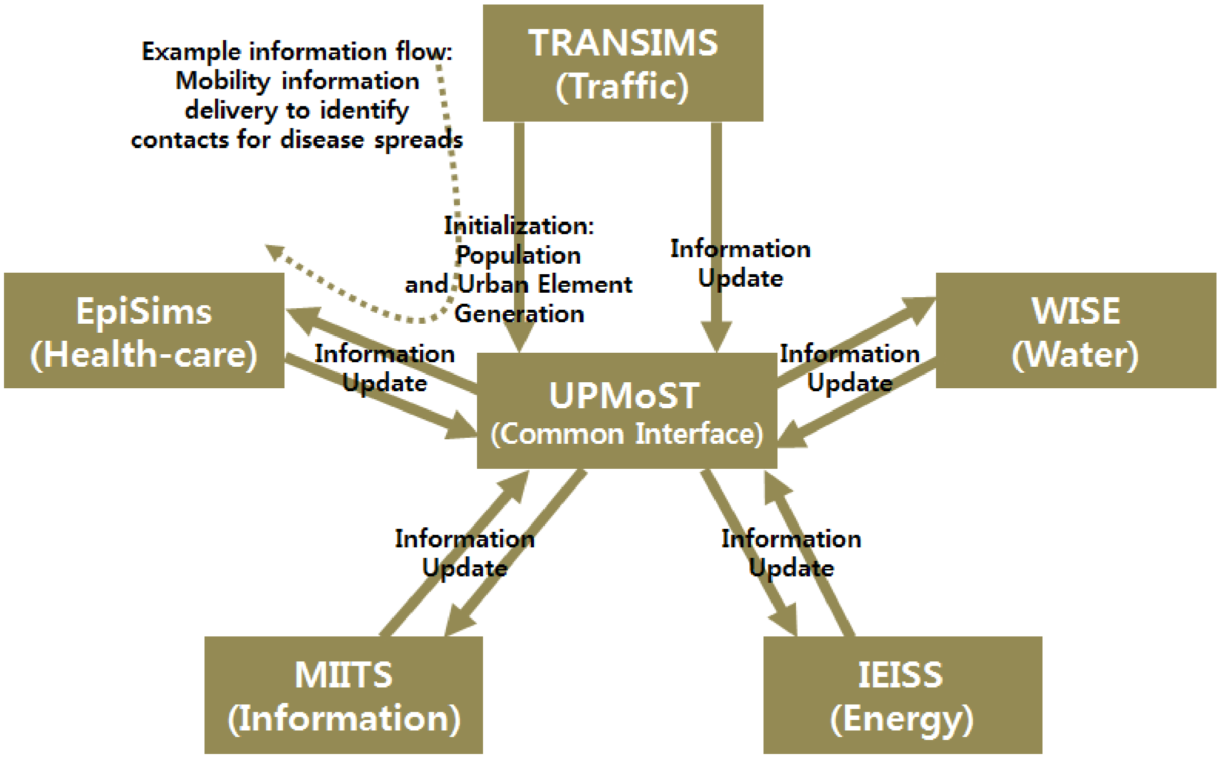

Figure 2. The structure of Urban Infrastructure Suite, or UIS, from National Infrastructure Simulation and Analysis Center, or NISAC. UIS is a collection of multiple models from different infrastructure domains, yet the models share the simulation data through common interface named Urban Population Mobility Simulation Technologies, or UPMoST.

capable of mimicking the behavior captured by the sensory data.

Maybe because of the influence from the funding agency that is the U.S. Air Force Research Laboratory, CIMS uses multiple military features. Firstly, the CIMS is adapt in using the geographical data, such as GIS data, aerial images, scanned images, and map images. Moreover, the asset nodes modeled as an infrastructure network have geospatial coordinates. Additionally, CIMS provides advanced visualization of modeled assets and their relations through various commercial and open toolkits, such as Google Earth. Secondly, the CIMS approaches the disaster relief operation in the military analytic ways. Political, Military, Economic, Social, Information, and Infrastructure, or PMESII, aspects are enumerated to identify the key dimensions of the disaster relief operations. Particularly, the identified elements in the PMESII [29] dimensions are modeled as the networks.

5. CONCLUSION

As the climate change becomes more severe and our infrastructure become more complex, our society will potentially face more devastating, large-scale and complex disasters. Such disasters are difficult to weather because one infrastructure failure caused by a local disaster might induce a systematic failure throughout the entire infrastructure systems. To prevent this systematic failure, we have to better inform the disaster management organizations with more extensive what-if scenarios. To provide these scenarios, we have to expand our single aspect disaster models to a holistic disaster model. The works from NISAC and CIMS are the examples of such holistic models.

As we review the works from NISAC and CIMS, we found a number of common features to accomplish the holistic disaster models. First, the holistic disaster models are the collection of models from different modelers with different expertise. Hence, the models are aggregated through a common interface, i.e. the UPMoST model interface in NISAC. This brings up an old research venue of the modeling and simulation discipline, which is the standardization of our modeling and simulation methodologies. Second, we found projects of generating a hypothetical city from a descriptive statistics over the population and the environment in the area of interests. Again, this also opens up a recurring research topic in the modeling and simulation area, which is a parameter calibration of models.

Eventually, we expect that the modeling and simulation community will require a framework that supports more standardized modeling approaches as well as more calibrated simulations.

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BIOGRAPHY

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Taesik Lee is an assistant professor in the Dept. of Industrial and Systems Engineering at KAIST. He obtained his M.S. and Ph.D in Mechanical Engineering at MIT. Before joining KAIST, he worked as an assistant director at Park Center for Complex Systems at MIT, where he carried out system design and analysis research for aerospace systems and healthcare systems. His current research focus is on operations management of healthcare delivery system. He has been working on a variety of healthcare system problems including patient flow analysis, emergency medical service system design, national trauma care system design, modeling and simulation of pandemic disease spread, and disaster response.