Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

A STRUCTURED APPROACH FOR CONSTRUCTING HIGH FIDELITY ED SIMULATION

Wonjun Lee
Kyohong Shin
Hyun-Rok Lee
Hayong Shin
Taesik Lee

Department of Industrial and Systems engineering
Korea Advanced Institute of Science and Technology(KAIST)
291 Daehak-ro, Yuseong-gu
Daejeon, 305-701, REPUBLIC OF KOREA

ABSTRACT

This paper presents a structured approach to building a high-fidelity simulation for an emergency department. Our approach has three key features. First, we use the concept of modules as a building block for modeling. A module is a minimum unit that has clinical or administrative meanings in ED operation, and it consists of low level operational activities. Second, we use a structured template to formally represent modules, and we adopt notations and grammars from the business process modeling notation. This provides an enhanced clarity and transparency, which proves very useful in extracting necessary data from a hospital database or from interviewing ED staff. Finally, we define an interface, specifically data structure and handler, for converting information represented in the modules into simulation languages. This interface makes it possible to seamlessly link the modeling process to the implementation process in the simulation construction.

1 INTRODUCTION

Improving an emergency department (ED) for better patient care requires solutions for a wide range of problems. Such solutions typically involve human resource scheduling (Rossetti, Trzcinski and Syverud 1999; EL-Rifai et al. 2015), bed capacity adjustment (Ahmed and Alkhamis. 2009; Zeinali, Mahootchi and Sepehri 2015), and streamlining discharge process (Khare et al. 2009; Powell et al. 2012; Shi, Dai and Ding 2015). While solution strategies in general are well known, designing and implementing specifics of these solutions is never straightforward due to the complexity of operational environment of ED. Trial-and-error is not a desirable approach since introducing changes in an operating ED can be quite costly(Jun et al. 1999); introducing changes that turn out ineffective could cost resources invested for the changes, but more than that, it could mean loss of opportunities for saving lives. Thus, it is critical to have reasonable prediction on the effects of a solution to be implemented before actually implementing it.

Simulation is a natural tool to answer to those what-if questions, as evidenced by many prior literature on ED simulation studies. Paul, Reddy and DeFlitch (2010) offer an excellent surveys on the studies that use simulation models for solving problems in EDs. Simulation models offer a great deal of flexibility and rich details so that complexity of an ED can be captured. By conducting simulation experiments, we can test many things that cannot be easily tested in a real ED without incurring cost or risks accompanying real-world experiments. Of course, a fundamental premise is that a simulation model that we use for such experiments behaves as close to the real-world ED as possible; it has to be a precise replica of the ED that we intend to study (Sargent 2005). We must construct a high-fidelity simulation model of a target ED system. While specific requirements for a high-fidelity ED simulation can vary, it may be characterized by detailed descriptions of actual ED operations such as immense diversity in patient pathways, realistic resource activities, spatial trajectories of patients and caregivers, and detailed level of care processes, etc.

To construct a high fidelity simulation is a challenging task both in terms of modeling and implementation into a simulation program. First of all, it is difficult to extract sufficient and relevant information on a target ED system. Communication between simulation modelers and ED staff can be ineffective and inefficient due to differences in their background as well as the nature of specialized knowledge. In addition to the commitment from higher-level management, which is often cited in the ED simulation literature as a critical success factor for a simulation project, a systemic framework is needed to more effectively engage all parties involved. Second, unstructured information obtained from surveys and interviews often contain large amount of information irrelevant to simulation modeling. Even information from an electronic medical record (EMR) system requires substantial efforts for data cleaning and deciphering. Data from an ED EMR system does not simply produce a nice and clean time-stamped patient flow information because they are not developed to serve such purpose. It is most likely that we need to combine data from an EMR system and the estimates and judgment from ED staff. This problem becomes more severe as we incorporate higher level of details in a simulation model. Third, in its implementation phase, we need an efficient means to transfer large amount of information captured in a reference model to a simulation model.

Based on our most recent experience of building an ED simulation model, this paper introduces a structured approach for constructing high fidelity ED simulation. Our approach has three key features. First, we use the concept of modules as a building block for modeling. A module is a minimum unit that has clinical or administrative meanings in ED operation, and it consists of low level operational activities. Since a module can be understood in the clinical or operational context, communication is made much easier and clearer. Second, we use a structured template to formally represent modules, and we adopt notations and grammars from the business process modeling notation (BPMN). The formal representation include specifications for which information will be obtained from ED EMR system or staff knowledge. This provides an enhanced clarity and transparency, which proves very useful in extracting necessary data from a hospital database or from interviewing ED staff. Finally, we define an interface, specifically data structure and handler, for converting information represented in the modules into simulation languages. This interface makes it possible to seamlessly link the modeling process to the implementation process in the simulation construction.

2 COMPONENTS IN THE PROPOSED APPROACH

2.1 Module

A module is defined as a minimum unit for clinical or administrative tasks in an ED – e.g., registration, triage, intubation, and X-ray. A patient's pathway is a chain of administrative and clinical processes, and thus by defining modules, a patient's pathway can be described by linking relevant modules. A module itself consists of a series of low-level activities. Figure 1 shows an example of X-ray module.

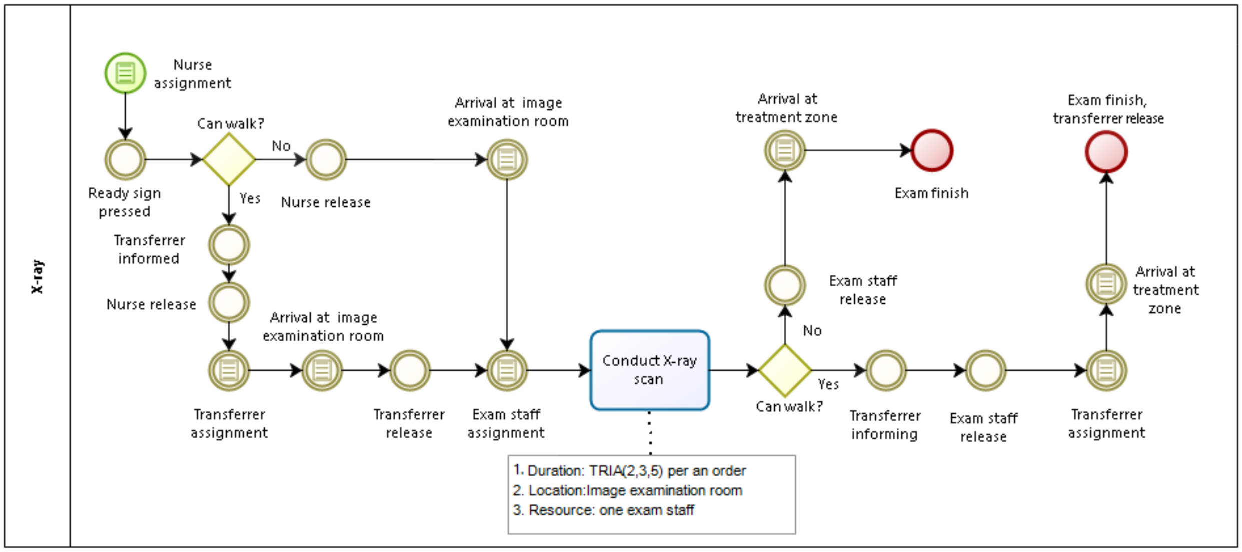


Figure 1: Example of X-ray module.

It should be noted that a module, while being the minimum unit, contains rich details and complicated set of activities by doctors, nurses, patients, and others involved in the task. Figure 1 shows an example of a module where the low-level activities required to complete the task are large in number and complicated in structure.

A patient's pathway of {Registration} – {Triage} – {MD-first-diagnosis} – {X-ray} – {Disposition} – {Discharge} may look the same on surface in two different EDs, but exactly how and by whom each of these tasks is carried out can be quite different. To achieve high fidelity in a simulation model, it is important to capture such low level details below the module level representation; modeling a task of taking X-ray involves much more than specifying the process time for X-ray by using a triangular distribution.

On the other hand, it is also important to maintain a simplified view to patient's pathways with lowest level details obscured by proper abstraction. This is especially necessary for helping both modelers and ED staff to avoid being overwhelmed by too much details and complexity, thereby losing focus in their communication. Having a clearly defined modules allows the team to zoom in and out the complex picture of ED operation as needed. As such, we find that a module-based representation makes it much more effective to exchange information between modelers and ED staff.

To define modules, we first worked with the ED staff to identify a list of modules that represent 53 tasks. It is an vastly expanded list of tasks from the 19 modules that was identified in an earlier simulation modeling project that the authors carried out with the same hospital in 2012 (Jang et al. 2012). In the 2012 study, the list of 19 modules were identified by a top-down approach, where the patient pathways of 23 most frequent disease groups are first analyzed and the common operational tasks are extracted to form modules. With a goal of achieving higher level of fidelity, the team, ED staff in particular, expands the list by a bottom-up approach this time to develop 53 modules as shown in Table 1. Given that emergency medicine builds on the common medical knowledge and principles, we believe Table 1 provides a comprehensive and general list of modules necessary to represent operations of an ED and patient pathways in it.

Table 1 : The list of 53 modules.

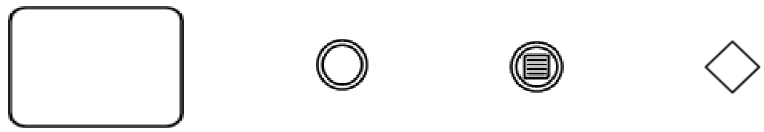
Antibiotic injection	Colonoscopy	Expire	Registration
Angiography	Culture	First diagnosis	Sigmoidoscopy
Arterial blood gas analysis	Dead on arrival	Foley catheter insertion	Spinal tapping
Arterial line insertion	Discharge	Foreign body removal	Splint
Bone marrow biopsy	Dressing	Hospitalization	Suture
Cancellation	Duplex ultra sound	Intubation	Symptom control
Cardiopulmonary resuscitation-ED	Echo ultra sound	Laboratory test	Thoracentesis
Cardiopulmonary resuscitation-Outside	Electrocardiography	L-tube insertion	Transfer
Central line insertion	Embolization	Magnetic resonance imaging	Triage
Chest tube insertion	Emergency Dialysis	Paracentesis	Ultra sound
Computed tomography	Emergency Severity Index-1 early treatment	Portable X-ray	X-ray
Consult-ED	Endoscopic retrograde cholangiopancreatography	Pulmonary function test	
Consult-ophthalmology	Enema	Re-diagnosis	
Consult-otorhinolaryngology	Esophago-gastro-duodenoscopy	Reduction	

Each of the 53 module is investigated further to define its detailed description. This is done by the ED staff, and informal flowcharts and written description for each module is produced. This information shows how each task (module) is carried out with the details including low-level activities and their sequence, required human and equipment/facility resources, decisions involved, and duration of activities. Initial drafts are created by an ED physician and a few nurses, and reviewed by a larger group of ED staff to get a final approval. We then take this information and transform it to a more formal representation, which will be discussed in next section.

2.2 Formal representation of modules

The module definition documents produced by ED staff do not have a standard structure and contain verbal description. For example, {anti-biotic injection} module is comprised of 3 sentences, 'nurse goes to a patient', 'nurse injects anti-biotic to the patient' and 'nurse returns'. They are not suitable to use directly for simulation modeling, and a more formal representation of modules is needed to facilitate data acquisition and constructing a simulation model. Business Process Modeling Notation (BPMN) has been suggested as a framework to represent conceptual agent based modeling (Onggo and Karpat 2011, Onggo 2012). BPMN contains a set of different types of components to represent business processes graphically (Dumas et al. 2013, Object Management Group 2016). Using BPMN, rules for processing each task in a business process can be easily and clearly expressed. We employ the framework and notations from BPMN, and make some modification and simplification to suit the context of our information.

We classified the low level processes contained in modules according to their characteristics, and there are three types of the low level processes. They are 1) consume resources and time, 2) execute immediately, and 3) make decision or branch. It turns out that with these three types of processes, we are able to present every low level process. We adopt three notations from BPMN for each of the three processes: activity, event, and gateway (Figure 2).



(a) (b) (c) (d)

Figure 2. BPMN symbols for (a) Activity (b) Event (c) Conditional event (d) Gateway.

Event component is used to represent immediate happenings. <call a nurses>, <assign a bed to a patient> and <release resources> are examples of an event component; a particular event happens immediately. Activity component is used to express work that consumes time and resources. Required resources and time duration should be specified for an activity component. For example, for <Anti-biotic injection> activity, one nurse is needed and it takes 3 minutes for the nurse to complete the activity. Gateway component represents a decision or branching process. An example of a gateway component is that when taking the X-ray, patients who can't walk is escorted by a medical staff member, and those who can walks to an X ray room by him/herself.

Using these notations and symbols, the informal module documentation has been transformed to a standard, structured representation for all 53 modules. In the next section we explain how to implement this information into a simulation model.

2.3 Data structure for modules

In section 2.2, we present a formal representation framework for low level process flows in a module. With all modules formally represented, our next step is to use them as a reference model to construct a simulation model. To make the transition efficient, we intend to directly link the module representation to simulation modeling. In this process, the first thing is to make a data structure that can import the information captured in modules. The well-structured representation of a module provide a natural model, which is a network data structure with nodes and arcs. We define Activity, Event and Gateway as a node, and sequence flows are presented as an arc. The proposed network data structure is shown in Figure 3.

Activity node seizes the required resources and target patients for a specified duration. Examples of activity nodes include <Diagnosis>, <Acting> and <Intubation>. The type of resources required and activity duration are specified in the node as its parameters. There are some activity nodes that do not relate to any specific patient. For example, when a nurse (resource) types in administrative information on a computer, this "activity" takes a finite duration during which a resource is occupied. For this type of activity, we use different name to define additional node, and we call it a task node.

Event node presents an immediate occurrence of an event, and it may or may not require resources. Event Node contains information about event to be executed such as "AssignResources", "ReleaseResources", "AssignBeds" and "goToDestination". Event node does not need any parameters. Gateway node determines which path in the process flows in the module to follow. It specifies condition information that describes the decision criteria at the gateway. There are two types of Gateway node: exclusive gateway and parallel gateway. An exclusive gateway corresponds to a decision process where only one of outgoing paths is selected. A parallel gateway depicts a branching process, and it is used to represent multiple processes being carried out in parallel.

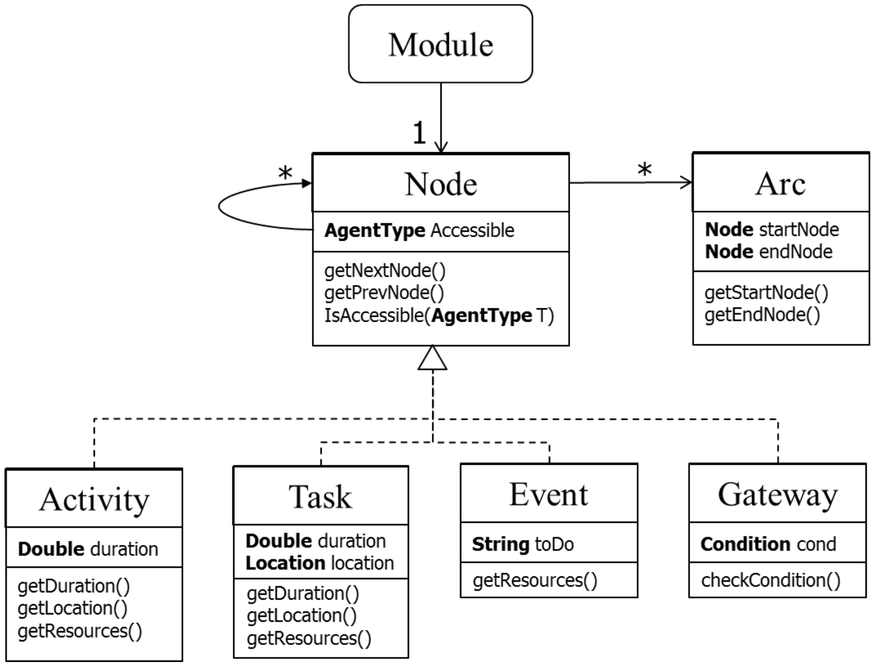


Figure 3 : Simple class diagram of data structure.

The four nodes described above inherits a parent class, Node. The Node class has a parameter that defines which agent type has an access to it. This parameter is referred to as "accessible". This is necessary to prevent logical errors in determining behaviors of agents. For instance, an injection activity must be conducted by a nurse. But if we do not specify which agent can conduct the injection activity, there is a possibility that a patient does it by himself.

With this data structure, our simulation model is now able to import information contained in the modules. This data structure thus is an interface between the module documents and a simulation model. Modules stored in the data structure format can be reused in a simulation model repeatedly.

2.4 Module handler for agent based simulation implementation

We choose agent based modeling (ABM) as an implementation platform. In ABM simulation, each agent interacts with other agents and the environment based on their behavior logics. In our case, the behavior logics for patients, nurses, doctors and other agents are already encoded in the modules. Thus, what an agent needs to do for their decision making is to read from the modules relevant actions and decision. To implement such functions in the ABM simulation, we develop a concept of module handler (Figure 4).

Every agent in the model has modules associated with it. A patient agent is assigned a sequence of several modules that defines her pathway in an ED. This sequence of modules tells which tasks a patent needs to go through, and the low level process information in each module dictates the detailed pathway during her stay in an ED. As a patient agent proceeds per her defined pathway, required resources are dispatched. Doctors and nurses are also assigned a set of schedules, and their schedule which may not be directly related to individual patient pathways. For example, entering medical and administrative records on a computer system or attending other duties are incorporated in their schedule data for a doctor agent. The schedules for resource agents are handled by the module handler the same way patient agent's modules are handled.

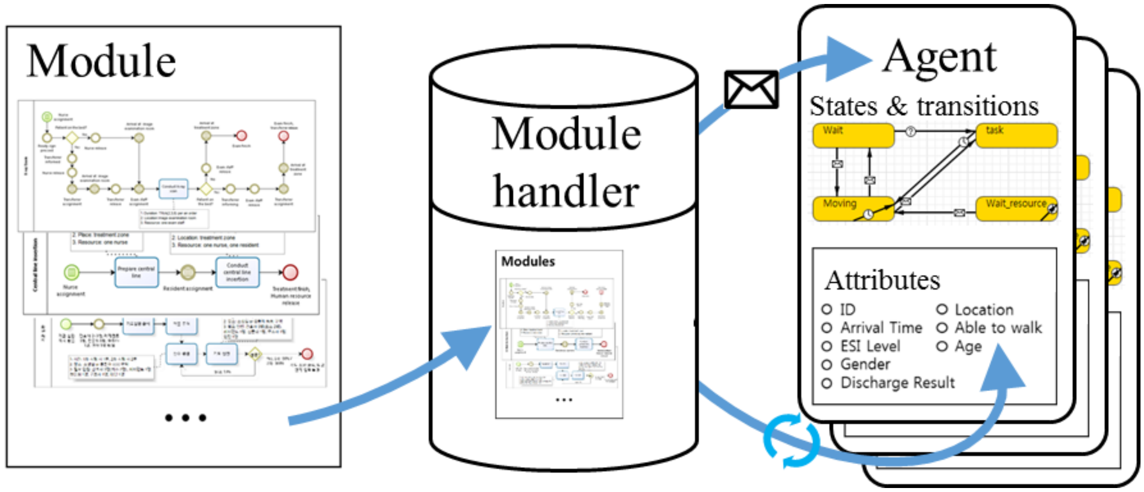


Figure 4 : Functions of a module handler.

Every agent has a module handler to interpret the modules. A module handler reads the low level process data which is represented as nodes in the modules. As it reads the information from modules, it performs a few functions: message delivery, state transition and attribute update for an agent. For example, a patient is on a node “Nurse assignment” in “X-ray” module in Figure 1. Being on the “Nurse assignment” node indicates that a nurse has been assigned to the patient. The module handler sends the assigned nurse a message which contains relevant information about the patient. Then, the module handler reads the next node in the module, and conducts similar procedure repeatedly.

With the module handlers, patient agents and resource agents make decisions and acts according to their pathway and schedules. In an ED, each patient has his or her own pathway, and each resource agent has their own schedule. Each agent acts on the decisions produced by its module handler.

2.5 Section summary

In this section, we summarize the concepts explained in the previous sections in the context of the overall simulation modeling procedure.

The very first step in ED simulation modeling is to define a list of modules. In section 2.1, we present 53 modules that we defined out of this study. We believe these 53 modules are comprehensively representative of process units that a modern ED is dealing with. Then, each module is defined further for its detailed lower level processes. While 53 modules are representative of a general ED process, the specifics contained in each module will possibly vary for individual hospital. These first two steps are primarily done by the ED staff. This information is then translated into a formal representation by using notations that we adopt from BPMN. We use four components in particular – activity, event, conditional event, and gateway. Symbolic notations allow a structured, graphical representation of a complicated patient care processes. Once constructed, the module documents are reviewed in collaboration to ensure that they are accurate reference model for ED processes.

Then, the information in the module documents are extracted and stored in a format of the network data structure. The data structure has four nodes and an arc. The four nodes are <Activity>, <Task>, <Event>, and <Gateway>. Each component in the module document corresponds to one of the four types of nodes in the data structure. For example, <Conduct X-ray scan> node in Figure 1 is an “activity” according to the BPMN formalism and it contains duration and resources information. This information is “hand-written”, and we need to encode this information in certain data structure so that it can be read directly by the simulation model. This is done by defining a corresponding data structure, <Activity> node, which has variables for duration and resources.

Finally, an agent based simulation model is constructed. There are mainly five agents in an ED model: patient, doctor, nurse, escort, and monitor. Each agent is associated with a set of modules or schedules. For a patient, a series of modules define the patient's pathway. A pathway should present all administrative and clinical procedures that should take place from the moment of patient arrival till her exit. For other resource agents, they are assigned a set of schedules. Schedules for the resource agents are a set of activities that they have to do outside their involvement in patient care processes. A key feature in this step is the module handler. Each agent has a module handler, and it translates information contained in the module to determine actions and decisions for an agent. In simulation, every agent will follow what the module handler indicates. Figure 5 is a screen shot of the ED simulation model developed in AnyLogic 7.2.0 environment.

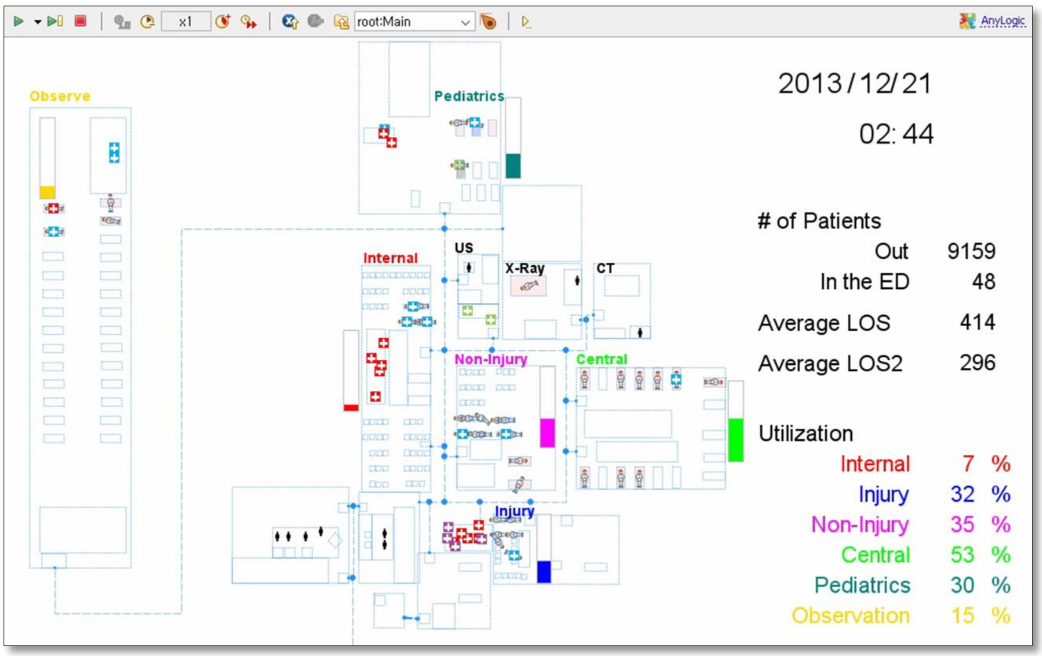


Figure 5 : Sample implementation in AnyLogic 7.2.0.

3 DISCUSSION

There are advantages that we found our approach offers. First, defining ED processes in terms of modules proves very helpful in collaborating with the ED staff. With modules, the team can obscure or delve into the details of complex care processes as necessary. This helps both modelers and ED staff to stay focused in the team communication. Also, it helps the team to gauge its progress in the model construction as it gives a quantitative measure for the progress. In addition to the benefit in communication aspect, the module-based approach offers extensibility and reusability.

Second, we develop a structured representation for modules by using modified Business Process Modeling Notation. This formal representation allows to explicitly identify necessary data hence facilitating data acquisition from the hospital database. We can easily figure out what information is needed and which is meaningful data located inside an EMR system, which is a critical challenge in a data acquisition process. Furthermore, the well-structured representation of modules naturally leads to a corresponding data structure so the information from the module documents are directly imported in a format that can be used in a simulation model.

The concept of module handler is an effective way to connect the patient pathway and care process information in the modules with the agent's behavior and actions in an ABM simulation. Its functions include reading information from modules, passing messages and changing states and variables. The concept and functions of a module handler are fairly simple and yet effective. With a module handler, each agent, patient and resource agents alike, behaves as an active decision making unit while being consistent with the specified pathways and care processes.

These advantages contribute to constructing an ED simulation with high fidelity. The first and foremost challenge in building a high-fidelity ED simulation is to extract sufficient and relevant information to generate a quality reference model. By providing a structured procedures with a module-based approach, information exchange between simulation modelers and ED staff is made effective and efficient. A formal representation of module-based reference model resolves the difficulty in information acquisition from surveys and interviews as well as the hospital electronic medical record (EMR) system. Finally, the concept of module handler along with the proposed data structure in the ABM simulation framework offers practical convenience for transferring a reference model into a simulation model.

4 CONCLUSION

To construct a high fidelity simulation is a challenging task both in terms of modeling a reference system and implementing it into a simulation program. This paper introduces a structured approach for constructing high fidelity ED simulation. Key features of the proposed approach are 1) module-based reference model construction, 2) structured representation of modules, and 3) the concept of module handler and its implementation architecture in an ABM framework. Our contributions are twofold. A module-based approach, specifically with 53 generally applicable modules defined, offers a useful aid for a future simulation study on an ED. These modules are well-defined with a formal representation, which facilitates their incorporation into a simulation model. Next, the concept of module handler along with the data architecture makes it convenient to implement the information contained in the modules in a simulation model.

We found in our most recent experience of an ED simulation study that the approach is effective in addressing the modeling and implementation challenges for building high-fidelity ED simulation.

REFERENCES

Ahmed, M. A. and T. M. Alkhamis. 2009. “Simulation Optimization for an Emergency Department Healthcare Unit in Kuwait.” *European Journal of Operational Research* 198(3): 936-942.

Connelly, L. G., and Bair, A. E. 2004. “Discrete Event Simulation of Emergency Department Activity: A Platform for System-level Operations Research.” *Academic Emergency Medicine*, 11(11): 1177-1185.

Dumas, M., M. La Rosa, J. Mendling, and H. A. Reijers. 2013. *Fundamentals of Business Process Management*. Heidelberg: Springer.

EL-Rifai, O., T. Garaix, V. Augusto, and X. Xie. 2015. “A Stochastic Optimization for Shift Scheduling in Emergency Departments.” *Health Care Management Science* 18(3): 289-302.

Espinoza, C., J. Pascual, F. Ramis, D. Bórquez, and J. A. Sepúlveda. 2014. “Real-time Simulation as a Way to Improve Daily Operations in an Emergency Room.” In *Proceedings of the 2014 Winter Simulation Conference*, A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1445-1456. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Jang, H., T. Lee, Y. Kim, and WC. Cha, 2012. “A Framework for Building a Simulation Model to Study Overcrowding in ED.” Paper presented at *2012 KIIE Annual Fall Conference*, Ansan, Korea, November 2, 2012.

Jun, J. B., S. H. Jacobson, and J. R. Swisher. 1999. “Application of Discrete-Event Simulation in Health Care Clinics: A Survey.” *Journal of the operational research society*, 50(2): 109-123.

Khare, R. K., E. S. Powell, G, Reinhardt, and M. Lucenti. 2009. “Adding More Beds to the Emergency Department or Reducing Admitted Patient Boarding Times: Which Has a More Significant Influence on Emergency Department Congestion?” *Annals of emergency medicine*, 53(5): 575-585.

Onggo, B. S. S., and O. Karpat. 2011. "Agent-Based Conceptual Model Representation using BPMN." In *Proceedings of the 2011 Winter Simulation Conference*, edited by S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, and M. Fu, 671-682. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Onggo, B. S. S. 2012. "BPMN Pattern for Agent-Based Simulation Model Representation." In *Proceedings of the 2012 Winter Simulation Conference*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Object Management Group. 2016. Business Process Model and Notation. Accessed April 3, 2016. http://www.bpmn.org/.

Paul, S. A., M. C. Reddy, and C. J. DeFlitch. 2010. “A Systematic Review of Simulation Studies Investigating Emergency Department Overcrowding.” *Simulation* 86(8-9): 559-571.

Powell, E. S., R. K. Khare, A. K. Venkatesh, B. D. Van Roo, J. G. Adams, and G. Reinhardt. 2012. “The Relationship between Inpatient Discharge Timing and Emergency Department Boarding.” The *Journal of emergency medicine*, 42(2): 186-196.

Rossetti, M. D., G. F. Trzcinski, and S. A. Syverud. 1999. “Emergency Department Simulation and Determination of Optimal Attending Physician Staffing Schedules.” In *Proceedings of the 1999 Winter Simulation Conference*, edited by P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, 1532–1540. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Sargent, R. G. 2005. “Verification and Validation of Simulation Models.” In *Proceedings of the 2005 Winter Simulation Conference*, edited by M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 130–143. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Shi, P., M. C. Chou, J. G. Dai, D. Ding, and J. Sim. 2015. “Models and Insights for Hospital Inpatient Operations: Time-dependent ED Boarding Time.” *Management Science*, 62(1): 1-28.

Zeinali, F., M. Mahootchi, and M. M. Sepehri. 2015. "Resource Planning in the Emergency Departments: A Simulation-based Metamodeling Approach." *Simulation Modelling Practice and Theory* 53: 123-138.

AUTHOR BIOGRAPHIES

WONJUN LEE is a Ph.D. student in the department of Industrial and Systems Engineering at KAIST, Republic of Korea. His current research interest focus on modeling & simulation and machine learning . His email address is yj20005237@kaist.ac.kr.

KYOHONG SHIN is a Ph.D. student in the department of Industrial and Systems Engineering at KAIST, Republic of Korea. His current research interest focus on modeling and simulation of emergency medical service system. His email address is hong906@kaist.ac.kr.

HYUN-ROK LEE is a Ph.D. student in Industrial & Systems Engineering Department at KAIST. His research interests included modeling and simulation. His email address is hyunrok@kaist.ac.kr.
HAYONG SHIN is a professor in the Department of Industrial Engineering at KAIST (Korea Advanced Institute of Science and Technology). Before joining KAIST, He worked for DaimlerChrysler Corp., CubicTek Co. and LG Electronics, developing commercial and in-house engineering software solutions. He received a BS from Seoul National University in 1985, an MS and a PhD from KAIST in 1987 and 1991, all in industrial engineering. His recent research interests are in the area of geometric modeling, simulation, and machine learning for system problems. He can be reached at hyshin@kaist.ac.kr

TAESIK LEE is an associate professor of Industrial & Systems Engineering Department at KAIST, Korea. His research interests include system design, modeling and simulation. For the past few years, he has been working on designing various aspects of healthcare delivery systems. Dr. Lee obtained his MS and PhD degree from MIT in the Dept. of Mechanical Engineering. His email address is taesik.lee@kaist.edu.