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A Discrete-Event and Agent-Based Hybrid Simulation Approach for Healthcare Systems Modeling and Analysis

Mohammed Abdelghany[1], Amr B. Eltawil[2]
Industrial Engineering and Systems Management,
Egypt-Japan University of Science and Technology (E-JUST),
Alexandria, Egypt
[1] mohammed.abdelgalil@ejust.edu.eg
[2] eltawil@ejust.edu.eg

Sameh F. Abdou
S.F Radiology Center
Alexandria, Egypt
samehfa@hotmail.com

***Abstract*—Simulation modeling is becoming a very familiar tool used for handling healthcare systems' problems and issues. Most applications considered using individual simulation methods only. The complexity of healthcare systems is derived from its complex structure consisting of queues and flows concept, and human behaviors and decision making. Individual methods are incapable of capturing all of these elements in one paradigm. In such cases, the more model assumptions are used, the less realistic models may result. However, discrete event simulation and agent based simulation methods together may be capable of capturing such concepts and details. In this paper, a discrete event – agent based hybrid approach for modeling healthcare systems is proposed. Then a description and validation of a case study for a Radiology Center is presented.**

Keywords—integrated simulation; hybrid simulation; healthcare; discrete-event simulation; agent-based simulation; radiology

I. INTRODUCTION

Simulation has been used to analyze many issues in the healthcare sector for over 40 years [1]. Such issues that have been addressed by simulation include, but not limited to; improving patients' workflows and throughput time, reducing waiting times, resources allocation and optimization, staff scheduling and development of decision support systems (DSS). Discrete Event Simulation (DES), Agent Based Simulation (ABS) and System Dynamics are the main simulation methods that have been used for healthcare systems' modelling and analysis [2]. Although each of these methods has its own capabilities, they exhibit some limitations [3]. Table 1 summaries some of the capabilities and limitations of DES and ABS methods in healthcare applications.

Recently, several hybrid/integrated simulation models have been introduced. In such approach, multiple simulation methods are combined in one model. This combination/ integration of individual methods enables the symbiotic realization of the strengths of individual methods, while reducing their limitations [4].

Chahal and Eldabi [5], [6] identified three different formats for the integration between DES and SD: Hierarchical format (data passes between two distinct paradigms), Process-environment format (two distinct paradigms, one sits inside the other), and Integrated format (one hybrid paradigm with no clear distinction between the discrete and continuous parts). Such formats can be used to represent the integration format between any couple of the individual methods (DES, ABS and SD).

Modeling human behaviors in any system such as healthcare where humans make decisions or perform activities is very important, as it affects the system performance [7]. Although DES is not capable of modeling such human behaviors ABS does. As ABS models take longer to be built and require more data and knowledge of decision rules, a hybrid DES-ABS model would be a better representative. Instead of representing the whole system using ABS, a DES paradigm can be used to represent the overall system and ABS paradigms can be used to represent the effected human behaviors only. Kaushal et al. [8] argued that emergency departments can be modeled using DES to capture patient flow and ABS for modeling human decision-making, as the DES can provide an environment where agents and rules can work.

It is worth mentioning that there were many challenges that faced researchers in developing such hybrid models. Challenges include deciding between simulation methods to select which method is more suitable to represent which part of the system. In addition to, linking the integrated models together which is quite challenging, especially if the models were developed in different software packages. In such case, a third party tool is needed to link the two models together.

However recently, a multi-methods simulation software tool "AnyLogic" has been developed. It is claimed to be the first tool that brings together discrete event, agent based and system dynamics methods within one modeling language and one model

Table 1: DES and ABS methods' capabilities and limitations

Individual method	Capabilities	Limitations
DES	▪ Queues are a key element. ▪ Top-down modeling approach. ▪ Focus on modeling the system in detail.	▪ Neglecting indirect patient-related tasks and staff members' interactions. ▪ Unable to consider the side effects of a facility changes/ redesign. ▪ Unable to model interaction between entities (staff, patient, etc.).
ABS	▪ Bottom-up modelling approach. ▪ Focus on modelling the entities and interactions between them.	▪ The concepts of queues and flows that exist in healthcare systems is not addressed. ▪ Models take longer time to build and require more data and knowledge of the decision rules.

development environment [9]. Such a tool encourages more research and applications for hybrid approaches, as it facilitates the integration process by saving efforts that were spent in linking models.

Most healthcare systems imply a concept of flows and queues, in addition to the humans' decisions and interactions. From the comparison provided in Table 1, neither the DES method nor the ABS method is capable to capture such details and complexity in healthcare systems on its own. However, both methods together may be capable of capturing these details. In this paper, a framework for a novel DES-ABS hybrid approach for modeling healthcare systems is proposed with the aim to enable modeling of the complexity of healthcare systems considering the concepts of flows and queues, and also humans' decisions and interactions. Then, a case study for one of the famous radiology centers in Alexandria, Egypt is provided.

II. LITERATURE REVIEW

In 2010, an integrated model of DES and ABS for Emergency Medical Services (EMS) was developed with the aim to design a general and flexible simulation model for EMS management, Aringhieri [10]. The DES paradigm was used to model the workflow of the EMS to help identifying system bottlenecks. An ABS paradigm integrated with a Geographic Information System (GIS) was used to model ambulances movements and their interactions with the Operation Centre. The model was used to assess the impact of some ambulance management policies. The authors argue that the model enabled repeated relocation of ambulances through the day and helped improving the number of urgent missions served.

In 2013, another distributed hybrid ABS-DES model for EMS was developed by Anagnostou et al. [11]. The model consisted of an ambulance services system as an ABS model and several Accident and Emergency (A&E) departments as DES models. Using a distributed simulation; various simulations can run in different CPUs and communicate through a network or run on the same CPU. The authors argue that such a distributed hybrid model can be a valuable tool for EMS management and for performing what-if analysis.

In 2014, Fakhimi et al. presented an integrated model of ABS and DES for analyzing sustainable planning strategies for EMS [12]. The ABS paradigm was used to model the ambulance services (emergency call center, vehicles and crews) taking into consideration environmental, social and financial factors for sustainability modeling. While the DES paradigm was used to analyze the resulting data of the ABS paradigm. The authors argue that this is a novel approach of integrated ABS-DES modeling which may have an enormous impact on the way simulation analytics is applied.

According to the review, those are the only three studies – conference papers – that considered a hybrid ABS-DES models in healthcare sector. This is confirmed by Brailsford statement in 2014, that there are very few studies that describe a hybrid ABS-DES models, and most of them also are conference papers [7]. In general, this hybrid approach is relatively new escpicially in the healthcare sector.

III. THE PROPOSED HYBRID MODEL FRAMEWORK

Using both DES and ABS methods, the complexity of healthcare systems can be captured. In order to integrate these two methods, an integration approach is proposed in Fig. 1. The upper part of the figure represents the DES paradigm which capture the patients' flows through the system. The lower parts represent multiple ABS paradigms that capture different resources' activities. While the dashed lines between the upper and lower parts represent interactions between the DES and ABS paradigms.

The entity (patient) goes through the DES paradigm and the interaction occurs as follows:

1) When the entity reaches to Process 1, a request is sent to Resource #1. Based on receiving the request, the resource starts to execute a group of defined activities to finish the process.

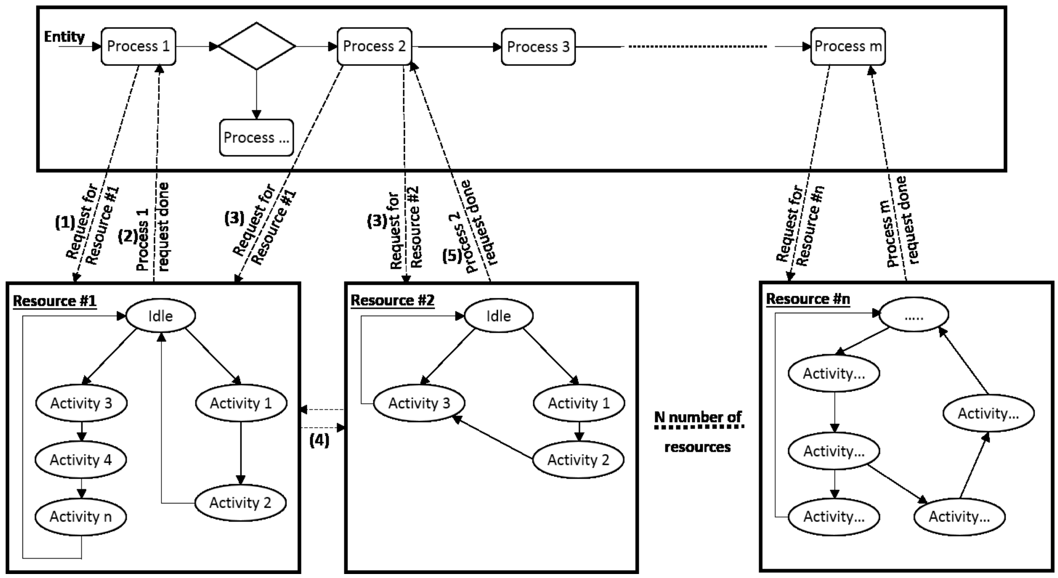

Figure 1: The integrated DES-ABS model framework

2) When Resource #1 finishes its activities, a message is sent to Process 1 declaring that the process has ended, therefore the entity can pass to the next process.
3) If the process require two different types of resources, such as Process 2, a request is sent to both resources Resource #1 and Resource #2. Then both resources start their defined activities.
4) Information is exchanged between the two resources for confirming that each one has finished its activities.
5) After the two resources finish their activities, a message is sent to Process 2 declaring that the process has ended and the entity can pass to the next process.

The model may contain *m* number of processes in the DES paradigm and *n* number of resources in the ABS paradigms. Each resource may have different groups of predefined activities that would be executed based on a specific process request.

IV. Radiology Center Case Study

A. Model Description

The proposed framework was used for modeling a radiology center in Alexandria, Egypt. The Center is working for thirteen hours daily, six days per week. The center provides a variety of services including Ultrasonic imaging, mammography, Computerized Tomography (CT) scan, dental panoramic X-Rays, laser imaging, minor operations, examinations and follow-up. The center provides its services for two categories of patients; regular/private patients and public health insurance patients. The center receives on average 250-300 patients weekly. The hybrid DES-ABS model was developed using the multi-methods simulation environment AnyLogic [9].

- *The Discrete Event Simulation Paradigm*

DES was used to model the patient flow through the center as shown in the model snapshot in Fig. 2. Firstly, after a patient arrival, he/she passes through the registration process. Four main different patient flows have been identified. First option is to go through Facility (A); where services such as examinations, follow-up, Ultrasonic imaging and mammography are provided. Second option is for Facility (B); which provide a Computerized Tomography (CT) scan and dental panoramic X-Rays services. Third option is for Facility (C); where minor operations are performed. Last option is for laser imaging services - Facility (D).

- *Agent Based Simulation Paradigms*

ABS method was used to model the different resources activities/states. There were many different resource types that have been considered including humans and major facilities. For each resource, a statechart has been developed to capture its different activities/states as shown in Fig.3 from (a) to (d). Each resource has groups of predefined activities/states that based on a certain request, a group of activities will be executed. For example, as shown in Fig. 3 (c), the default state of a physician is to be “idle”. Based on receiving a certain request either from Facility (A) or Facility (C), the physician will go from the “idle” state to the composite state "facilityA" or "minorOperation" state respectively. If the request is for "facilityA", then the physician will go to "facilityA" composite state, and based on a predefined probability, he/she will go through "US_Mammo" or "examinationFollowUp" groups of activities.

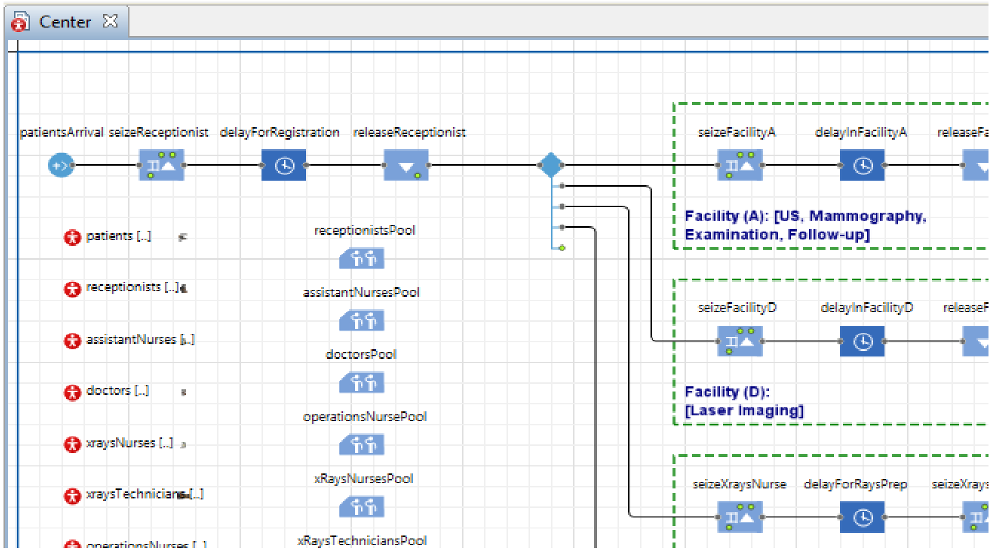

Fig. 2. Snapshot of the Radiology Center - Discrete Event Simulation paradigm

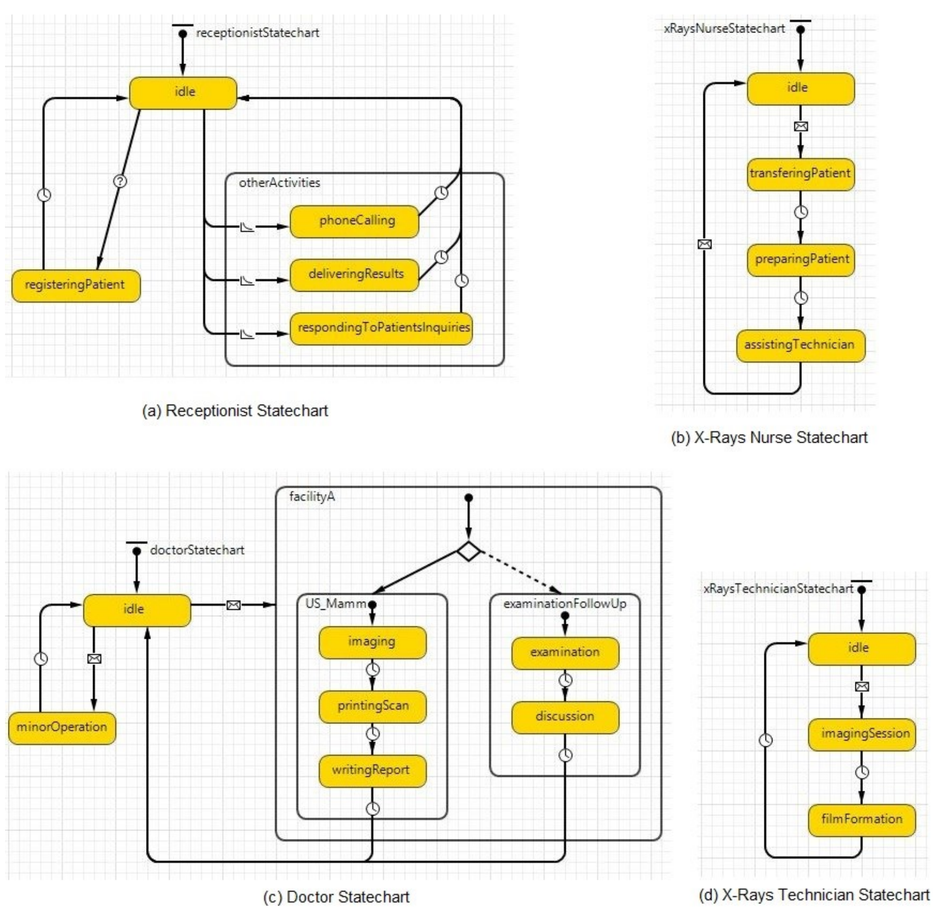

Fig. 3. Snapshots of Resources - Agent Based Simulation Paradigms

- *Data collection and analysis*

The data used for model development have been collected from different sources. Data such as patients' arrival patterns has been derived from a database of the electronic registration system. In order to figure out the patients' arrival patterns, an analysis for the daily number of arrivals for the period from July 2014 to June 2015 has been done. A sample of the analysis is shown in Fig. 4. The main conclusion of the analysis is that there is a weekly peak days for number of arrivals. These peaks usually occur on Tuesday and sometimes Sunday. These peaks were justified by the center's administrators as the public health insurance patients are scheduled to be on Sunday, Tuesday and Thursday. In addition to, the follow-up service is scheduled for insurance patients on Tuesday only. More deep analysis was done to get the arrival patterns during each day of the week. Fig. 5 summarizes these arrival patterns.

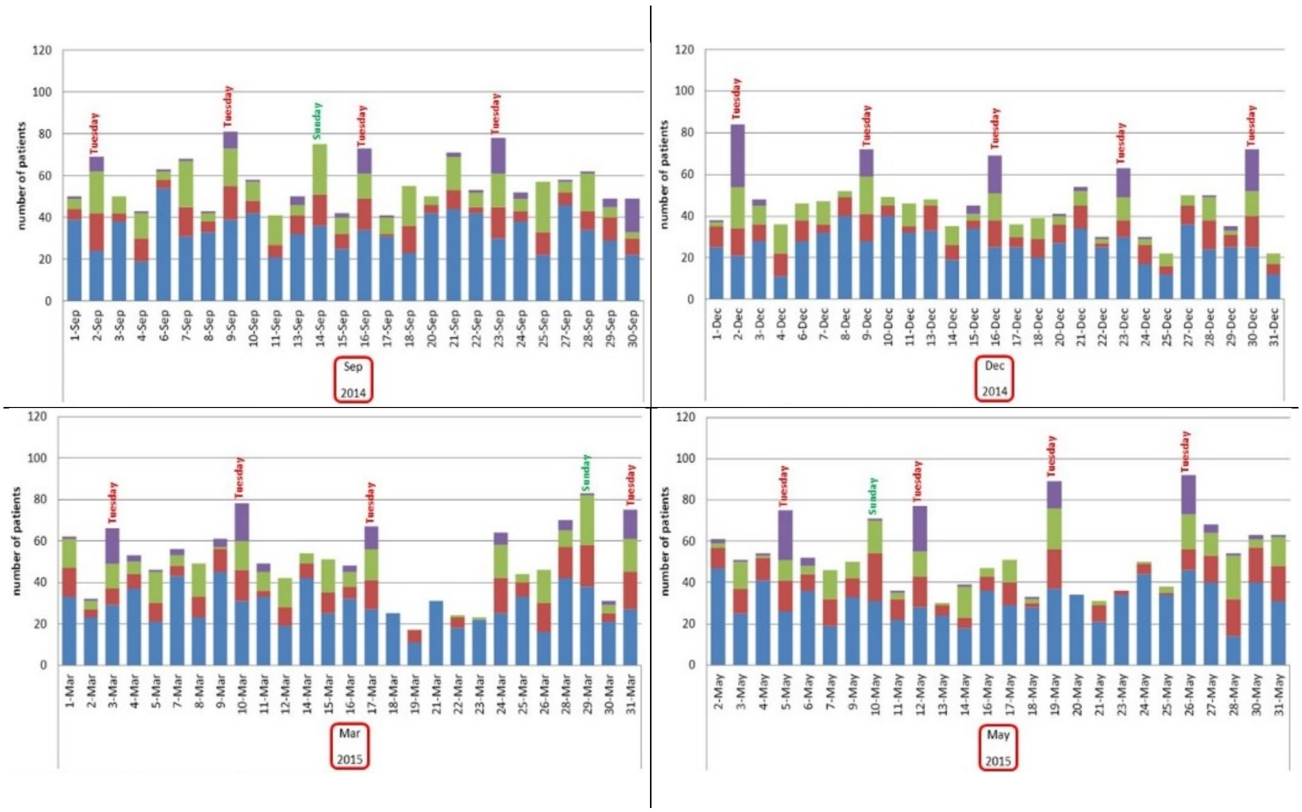

Fig. 4. Analysis of the daily number of arrivals

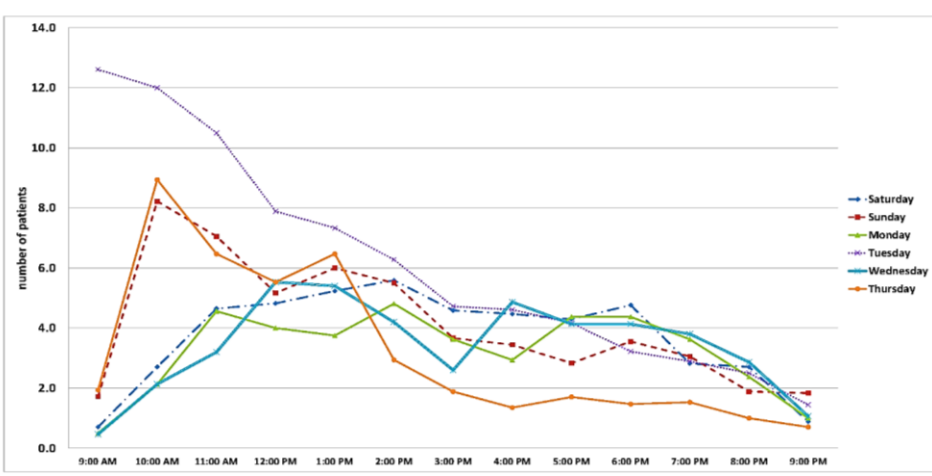

Fig. 5. Patient arrivals patterns (hourly number of arrivals per each day of a week)

The major patient flows have been identified through monitoring the system and interviews with the center's administrators. Fig. 6 shows the daily average percentage of patients for each flow of the four main patient flows. These percentages have been derived from data collected using data collection sheets.

Other data collection sheets were designed and used to record different resources activities and their durations. Table 2 summarize the major resources activities and their durations.

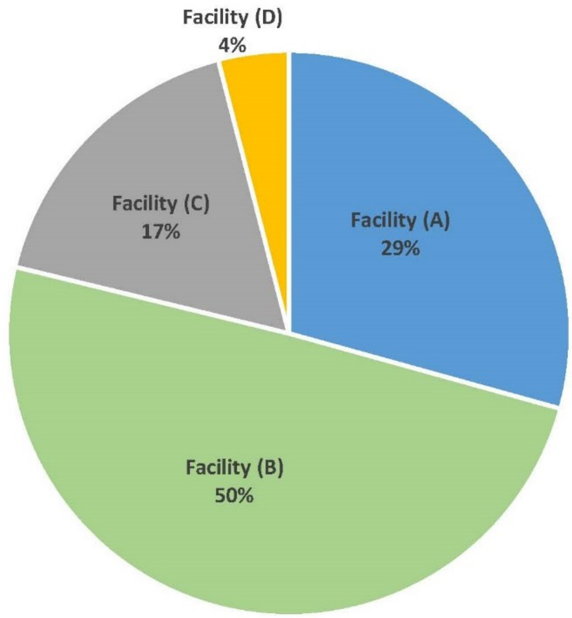

Fig. 6. Average percentage for the daily number of patients for different flows

Table 2: Major resources activities and their process time durations (minutes)

Receptionist (2 resources per shift)	
- Registering patient	Exponential (2.82)
- Phone calling	2.64 * Beta (1.33, 3.22)
- Delivering results	Uniform (1.0, 2.0)
- Responding to patients inquiries	Lognormal (1.49, 0.3)
Doctor (2 resources per shift)	
- Performing minor operation	9.5 + 66 * Beta (0.469, 1.32)
- Patient examination	Uniform (2.5, 20.5)
- Discussions with patient and relatives	0.5 + 11 * Beta (0.366, 0.661)
- Radiology imaging/scan	1.5 + Erlang (7.11, 1)
- Printing/preparing scan	0.5 + Exponential (1.56)
- Writing report	0.5 + Exponential (3.83)
X-Rays Nurse (1 resource per shift)	
- Transferring patient from reception	Triangular (0.45, 0.615, 1.0)
- Preparing patient for imaging	Triangular (0.0, 1.0, 5.5)
X-Rays Technician (1 resource per shift)	
- Imaging session	0.5 + Exponential (2.76)
- Film formation	0.5 + Exponential (2.66)
Internal Ward Nurse (2 resources per shift)	
- Preparing patient for operation	4.5 + Weibull (8.91, 1.29)
Laser Technician (1 resource per shift)	
- Service time	24.5 + Exponential (9.88)
Internal Ward Beds (4 beds)	
Operating Rooms (2 beds)	
Assistant Nurse (1 resource)	
Others	
- Patient recovering period (after operation)	Normal (34, 24.5)

B. Model verification and validation

- *Model verification*

The model was run several times without any errors. All DES and ABS paradigms' objects were checked during the run and confirmed that all objects are working well. The DES model was presented to the center's administrators who verified that the model logic complies with the actual patients' flows. The center's administrators also reviewed the logic of the resources – ABS paradigms and confirmed their conformity with reality. The patients' arrival patterns were also examined and confirmed that these patterns capture what occurs in reality.

- *Model validation*

The model was run for a complete week. Results for patient Length Of Stay (LOS) for the four patient flows were collected and compared with actual data collected from the real system. The LOS is calculated from patient registration till patient departure. A two-sample t -test was used for comparing LOS for actual data and model results. Table 3 summarizes the validation results for the average patient LOS. The results show that there is no significant difference between the mean of the actual LOS and the resulting model patient LOS.

In addition, another comparison was performed between actual and model daily number of arrival. The model was run for a replication length of a complete month and results was compared with an actual data of a month. The comparison also shown at the bottom of Table 3 showed that there is no significant difference between actual arrival data and model arrivals.

Table 3: Model validation results by comparing the actual data and model results

		Actual data	Model Results	95% CI	P-value
LOS Facility (A)	Mean:	14.318	18.190	(-8.0333, 0.29039)	0.068
	Standard deviation:	8.063	11.278		
LOS Facility (B)	Mean:	18.6	16.034	(-1.8878, 7.0201)	0.256
	Standard deviation:	12.144	10.208		
LOS Facility (C)	Mean:	105.57	78.774	(-5.9458, 59.541)	0.103
	Standard deviation:	52.915	24.507		
LOS Facility (D)	Mean:	39.625	33.250	(-5.9545, 18.704)	0.282
	Standard deviation:	13.125	9.1599		
Daily # of arrivals	Mean:	53.12	53.72	(-10.614, 9.2163)	0.903
	Standard deviation:	16.650	16.844		

V. CONCLUSION

Discrete event simulation and Agent based simulation have their own individual capabilities and limitations. DES and ABS methods are argued to be complementary for each other. Most of healthcare systems are based on two major elements; the concept of queues and flows and the human behaviors and decision making. DES models are able to consider the concept of queues and flows, while ABS models are able to capture human behaviors and decision making in healthcare systems. A framework for a hybrid model of DES and ABS was proposed to capture both major elements of healthcare systems. Using the proposed hybrid approach, a more realistic and detailed models can be developed easily. Accurate resources utilization can be figured out by considering all resource activities including direct and indirect patient related activities. Better improvement decisions related to resource tasks and activities can be taken. A case study for the proposed approach was shown and validated. As a future work, more statistical analysis and modeling scenarios will be investigated. Studying the feasibility of incorporating the third simulation method – system dynamics – to the approach is a next step.

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BIOGRAPHY

Mohammed Abdelghany is an MSc candidate at department of Industrial Engineering and Systems Management at Egypt-Japan University of Science and Technology (E-JUST). He received his BSc in Industrial Engineering from Fayoum University in 2011. His research interests include simulation modeling and analysis and healthcare systems planning and management.

Amr B. Eltawil is a Professor and acting chairperson of the Department of Industrial Engineering and Systems Management at Egypt-Japan University of Science and Technology (E-JUST). His research interests include supply chain design, simulation modelling and analysis, healthcare planning and management, production planning and container terminal planning.