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# Exploring Systems Performance Using Modeling and Simulation – Project-based Study and Teaching

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## Abstract

Modeling and Simulation (M&S) provides a risk-free environment allowing the users to experiment in a computer-generated virtual platform and analyze the what-if scenarios for effective decision support systems. Due to its pervasive usefulness, the concept of M&S is widely used across many sectors, including manufacturing, warehouse operations, supply chain, logistics, transportation, mining, and many more. The field of M&S requires computer-intensive and software-based training, which is very different from teaching in a regular classroom setting. Hence, we develop a three-stage (mimic-guide-scaffold) project-based teaching strategy to enhance students learning experience in M&S education. Here, students first follow the instructor to understand basics of simulation and become familiar with AnyLogic software. Second, the students work on a group project under the passive supervision of the instructor to enhance their problem-solving capability. In the third step, students work independently on a similar but extensive project to scaffold their knowledge. The project was designed to answer three high-level key research questions for a hospital system including systems throughput, resource utilization, and patients' length of stay reduction. We performed a thorough evaluation using an anonymous survey, where thirty-one students participated to provide their feedback. This paper provides a detailed description of the projects including problem statements, learning objectives, evaluation rubrics, data collection criteria, and evaluation outcomes with detailed discussion.



*Keywords:* Modeling and Simulation, healthcare simulation, systems throughput, resource utilization, and performance analysis


## 1 Introduction

Computer-based modeling and simulation have gradually been replacing the traditional, laborious hand calculations, drafting, physical testing and model building approach to many design tasks. The term 'model' encompasses a simplified description of observed behavior. Simulation provides a suitable analogy and the manipulation of parameters articulated in a model to ask 'what if' questions for investigating any situation [1]. Over recent years, this technology has significantly expanded its capabilities, aided by more powerful processors, greater visualization capacities, and more sophisticated software. In addition, it can explore operational efficiencies, systems utilization, bottleneck analysis, etc., using combinations of readily available computer software packages, such as SIMIO, FlexSim, AnyLogic, spreadsheets and other visualizations tools [2, 3]. The huge popularity of M&S can be seen in the wide set of application areas such as manufacturing, transportation, government, and healthcare, along with its ability to drive increasingly high-quality animation, helping practitioners in appropriate decision-making [4]. In recent years, the use of M&S has increased greatly among leading modern organizations [5, 6]. Their adoption is forcing many organizations to reconsider the way they conduct and manage innovative activities. Successful companies need to ensure that the costs associated with time, equipment and other investments are being considered and optimized. M&S is an inexpensive, risk-free way to test any hypothetical situation, it can help the organization in meeting their goals at the lowest possible cost. Unlike spreadsheet-based analysis and forecasting, M&S offers a quick and efficient method to adjust parameters and get results faster. When large-scale changes are considered, good modeling and simulation approach can accurately predict the consequences of the change, so poor decisions can be eliminated [7, 8]. Thus, today's industries, service companies, federal, defense industries, and many other organizations greatly benefit from concepts and application of M&S.

Industrial and Systems Engineering (ISE) is a critical discipline that examines how to construct and analyze decision-making scenarios by reviewing production schedules, engineering specifications, process flow, and other information in manufacturing and services. Industrial and systems engineers find ways to deliver services with maximum efficiency and develop effective management control systems [9]. They also developed quality control systems to coordinate activities and production planning to ensure that product/service meets quality standards, and, thus, mitigate production problems and minimize costs. To fulfil these tasks, engineers need to validate different process and operations before starting the actual production or running a large-scale operation system, where M&S can play an important role in understanding complex systems in both general and specific scenarios [10-12]. Thus, M&S has become a critical tool for industrial and systems engineers aiding in the design, modification, and evaluation of many complex systems and interdependent decisions.

Realizing the above-mentioned importance, the IMSE Department at UTEP creates an ample opportunity for the students to enhance their compatibility in M&S. However, M&S is a highly technical field, which requires hands-on learning using simulation software. In such a field, classroom teaching only is not sufficient for effective learning, rather demands project-based activities with appropriate pedagogy. Hence, we developed a three-phase learning strategy, where students get the opportunity to learn by solving a set of near-world problems in the healthcare domain. The details of the project, learning phases, students learning outcomes, and evaluations are demonstrated in the following sections.

## 2 Project Design and Implementation

Nowadays, simulation tools are widely used in healthcare management systems [13,14]. The project is designed to explore a healthcare system using a hypothetical case study on hospital emergency department (ED). The purpose to perform this project is to explore an ED for three key issues – 1) determining the best strategy to assign beds to patients for patients' length of stay reduction; 2) identify the resource utilization under different settings; and 3) to identify the optimal resources for better decision making. The entire project is divided into three sub-projects, which are accomplished in three learning phases as described in the following sub sections.

### 2.1 Phase I (Mimic)

This project represents the hospital's bed management problem for a hypothetical Emergency Department (ED). To solve this problem, we consider five top-label processes to model the emergency department: 1) Check-in, 2) registration, 3) triage, 4) bed assignment, 5) treatment delay, and 6) discharge. This project aims to optimize the bed assignment while reducing the patient's length of stay (LOS) or waiting time in the system. The patients arrive at the ED with three conditions: 1) walk-in in non-severe condition, 2) walk-in with a severe condition (i.e., serious bleeding, major strike, etc.), and 3) using an ambulance (i.e., heart attack, brain stroke, etc.). Given the conditions, the patient flows within the ED according to the flow diagram shown in Figure 1.

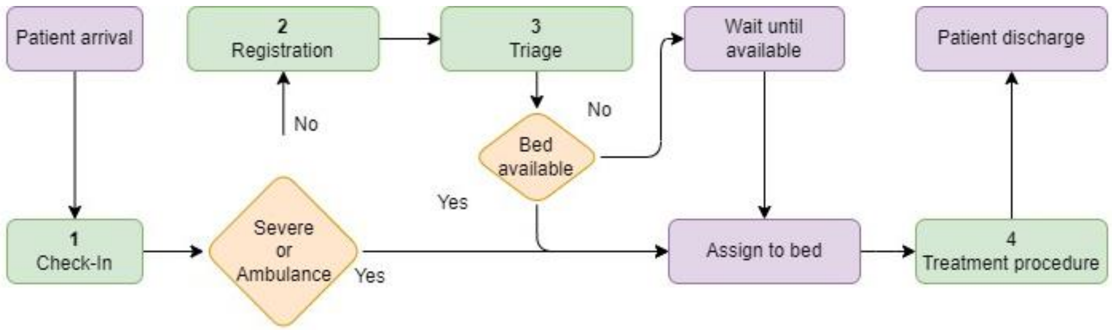


Figure 1. Patient flow within the emergency department

The ED operates 24 hours a day, and it is observed that the hourly patient arrival rate varies during the day and night shifts. According to the previous history, the hourly patient arrival (PA) rate is averaged and rounded up in Table 1.

Table 1. Average patent arrival rate

| **Hour** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PA | 0.28 | 0.056 | 0.196 | 0.2 | 0.192 | 0.1 | 0.324 | 0.7 | 1.356 | 3.488 | 2.912 | 4.984 |
| **Hour** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** |
| PA | 3.976 | 2.756 | 2.018 | 2.068 | 2.433 | 2.153 | 2.044 | 1.92 | 1.018 | 1.6 | 0.56 | 0.361 |

As the patients move through the system, they may wait for different services of the emergency department. The waiting times differ mostly depending on the patient's health conditions, availability of staff, doctors, equipment, beds, and other resources related to the treatment plan. These parameters result in an uncertain delay in the patient's end-to-end stay (commonly known as length of stay) within the ED. To complete the sub-project in Phase-I, let's consider four simple processes (as numbered in Figure 1 with process ID from 1 to 4). We assume that each of the processes follows a distribution according to a $uniform\ (a, b)$ and $traingular(a, b, c)$, where $a$, $b$, and $c$ are the minimum, maximum, and model delay time, respectively.  The specific time distribution (in minutes) of each of these processes is mentioned in Table 2.

Table 2. Services time distribution in the ED process

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $uniform\ (3, 6)$ | $triangular\ (5, 10, 7)$ | $triangular\ (6, 13, 8)$ | $triangular\ (50, 90, 70)$ |

The emergency department has eight (8) beds. Given the availability, patients are assigned to the bed on a first come, first serve basis. Due to the high patient arrival rate volume, the ED must carefully assign beds and be strategic to reduce patients' waiting time. Hence the ED sets two strategies to observe bed utilization and patients' mean LOS.

- Strategy 1 – Among the eight beds, the ED decides to reserve two beds for severe and ambulance patients, i.e., the regular walk-in patients will not be assigned to these beds. The rest of the six beds will be used for walk-in patients.
- Strategy 2 - Patients with severe conditions or who arrive in ambulances are given priority over walk-in patients, i.e., if any severe or ambulance patients check in to the system, they will be assigned to bed first and then the walk-in patients.

Given the above scenario, the emergency department wants to - 1) identify bed utilization for both strategies, 2) identify the optimal number of beds to limit the patient's LOS below 2.5 hours, and 3) identify the number of beds to ensure an overall bed utilization below 85%.

## 2.2 Phase II (Guide)

This project focuses on the treatment process after the bed assignment in extension of Phase-I. Notice that in Phase-I, the treatment process was assumed delay time as a whole. In this phase of the project, the treatment process is expanded based on the patient's conditions, treatment plan, and availability of nurses and doctors according to the patient-follow model shown in Figure 2.

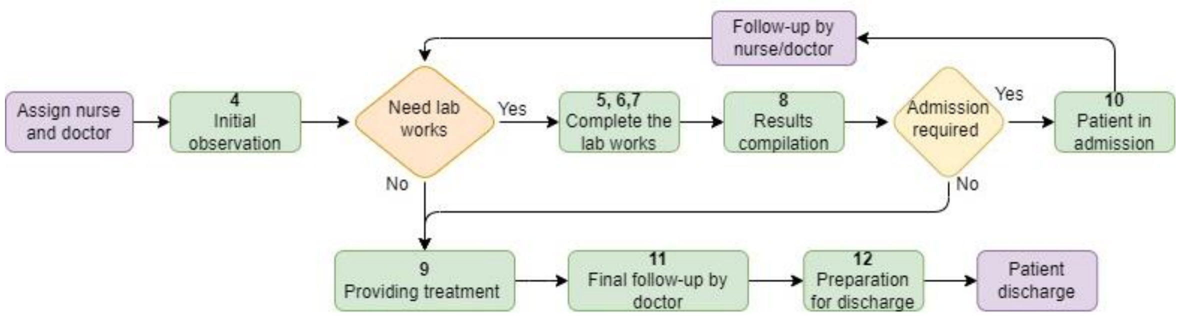


Figure 2. Treatment process after bed assignment in the emergency department

Once the patient is assigned to the bed, a nurse and doctor perform an initial observation of the patient to determine if the patient needs any examinations (blood test, X-ray, MRI, CT, etc) for diagnosis purposes. If the patient does not require any examination, the nurse provides the treatment according to the doctor's suggestion. As such cases could be very minimal in the emergency department, we assume that there are only 20% of the walk-in patients for this route of service. The rest of the patients will require medical examinations for the treatment plan. Here, we considered three examinations, including blood tests, X-Ray, and MRI/CR. For example, the doctor may suggest doing a chest X-Ray and CT scans. In that case, we will consider the delay time for these two tests to determine patients' length of stay. The corresponding delay times of the three tests are listed in Table 3. After performing all the required tests, a nurse first compiles all the test results, and later, a doctor evaluates the results. Based on the evaluation, the doctor decides if a patient needs to be admitted to the emergency room for an elongated period and treatment follow-up. Otherwise, a nurse provides the final treatment according to the doctor's prescription. Later, a registrar prepares the patient discharge process. In the end, the patient is discharged, and the assigned bed is released and prepared for the next patient.

The expanded treatment process comprises nine (9) time-consuming events, as indicated in process ID (PID) from 4 to 12 in Figure 2. Let's assume that each of the processes follows a distribution according to a $uniform\ (a, b)$ and $traingular(a, b, c)$, where $a$, $b$, and $c$ are the minimum, maximum, and model delay time, respectively. The specific time distribution (in minutes) of each of these processes are mentioned in Table 3.

Table 3. Time distribution of the different event of treatment process

| TP ID | Distribution | TP ID | Distribution |
|---|---|---|---|
| 4 | $traingular(8{,}15{,}12)$ | 9 | $traingular(10{,}20{,}15)$ |
| 5 | $traingular(10{,}15{,}12)$ | 10 | $traingular(4, 6, 5)$ |
| 6 | $traingular(7{,}13{,}10)$ | 11 | $traingular(7{,}12{,}9)$ |
| 7 | $traingular(10{,}20{,}15)$ | 12 | $traingular(5, 8, 6)$ |
| 8 | $traingular(3{,}6{,}4)$ | | |

* The distribution time for delay in case admitted patients is in hours.

The ED process deploys five types of resources, such as beds (emergency rooms), nurses, doctors, technicians, diagnosis equipment (X-ray machine, MRI, CT, etc.). We consider a simple schedule to assign the number of nurses and doctors. Due to the high number of patients during the daytime (from 7 AM to 8 PM), the ED assigns six full-time nurses and four doctors. However, during the night time (8 PM to 7 AM), the number of nurses and doctors decreased to half of the day time. Notice that, at this phase, we skipped the number of the other resources, such as diagnosis equipment, staff, etc., and consider that they will be available upon request. Thus, there are no delays (waiting) in the queue to get those services.

The objective of this model is to expand the model on top of Phase-I and complete the simulation model of the above mention treatment process to explore four useful performance criteria of the end-to-end ED process – 1) the LOS distribution of the severe/ambulance check in patients, 2) the LOS distribution of the walk-in patients, 3) the utilization of the ER beds, nurses, and doctors, 4) to determine the systems throughputs for a timeframe of seven days.

### 2.3 Phase III (Scaffolding)

This phase is designed to perform experiments based on the simulation completed in Phases-I and II. The statistical outputs of Phase-II indicate that the duration of patients' LOS is significantly higher, which may result in negative experiences for the patients. Hence, the ED authority wants to improve the patients' experience by reducing the LOS duration to its tolerable limit. The main reasons of high LOS are the limitations of the resources, such as the number of beds (emergency rooms), available doctors and nurses, and delays in different service points. As the service delay cannot be avoided, the ED authority wants to experiment with number of beds, doctors, and nurses to see their effect on the system performance. After careful consideration, the authority identified that the number of beds (emergency) can be increased to 10. After observing the patient-arrival history and the schedule of doctors/nurse, the ED authority sets four shifts (each shift with six hours) to allocate the doctor/nurse. The existing (Curr.), minimum required (MinR), and maximum available (MaxA) available doctors/nurses are listed in Table 4.

Table 4. The number of available doctors and nurses per shift

| Doctors | Curr. | MinR | MaxA | Nurses | Curr. | MinR | MaxA |
|---|---|---|---|---|---|---|---|
| 12.00 AM – 6.00 AM | 2 | 2 | 4 | 12.00 AM – 6.00 AM | 3 | 2 | 5 |
| 6.00 AM – 12.00 PM | 4 | 2 | 6 | 6.00 AM – 12.00 PM | 5 | 2 | 8 |
| 12.00 PM – 6.00 PM | 5 | 2 | 8 | 12.00 PM – 6.00 PM | 6 | 2 | 10 |
| 6.00 PM – 12.00 AM | 2 | 2 | 5 | 6.00 PM – 12.00 AM | 3 | 2 | 6 |

Given the information in Table 4, the authority is interested in exploring the two basic decision models, as described below:

- Model 1: The objective of the first model is to minimize patients' length of stay within the ED. However, due to budget limitations, the authority wants to limit the daily allocation of doctors and patients to a maximum number of 15 and 20. In addition, to avoid the high workload, the ED wants to keep the doctor/nurse utilization below 75 %.
- Model 2: The authority observes that the average length of stay of their competitor's ED is less than seven hours. To gain a positive patient experience, the ED authority set the target to decrease the LOS to below seven hours. Hence, the objective of this decision model is to determine the optimal number of doctors, nurses, and beds to keep the LOS below the targeted hour. The ED still considers 75% of doctor/nurse utilization.

## 3 Methodology

The above-mentioned three sub-projects were designed and deployed in three phases. Each of the phases has a set of learning outcomes as in Figure 3. Students completed the project in a group of two members. In the first phase, the instructor demonstrates the problem and shows the students to model the problem using AnyLogic simulation software. Students follow the instructor to complete this phase of learning. The second phase is an extension of the Phase-I with more process variants and a larger system. Students leverage their learning from Phase-I to complete this Phase-II. In this phase, instructor plays the role of a supervisor to observe students progress and provide guidance as required. Students completed the third phase of the project independently to scaffold their knowledge. Students understand how to apply the concept of modeling and simulation for resource utilization and effective decision-making.

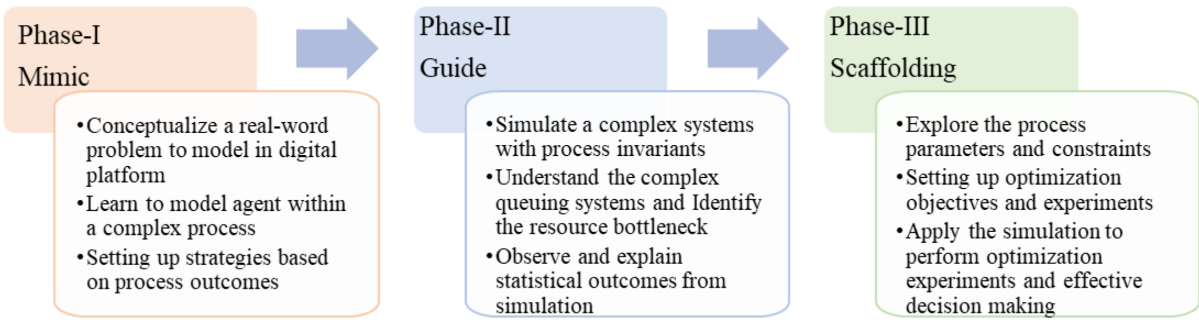


Figure 3. Learning objectives of the three different project phases

The learning outcomes were thoroughly evaluated using an anonymous questionnaire. The questionnaire has five different sections to evaluate the overall course design. Among them, Sections 1, 2, and 3 specifically focus on the three phases of learning with a project-based approach as shown in Table 5. Each of the Sections had a set of questions to collect students' response in scale of 1 to 4 as the lowest and highest possible rating, respectively. The questionnaire has a total of 17 questions allowing the highest rating of 68 and minimum of 17 points. From the feedback, we quantitatively evaluated students learning progress under four categories such as advanced proficient (56-68), proficient (45-55), developing (35-44), and novice (0-34). Students who perceived the advanced proficient learning can demonstrate deeper understanding of simulation and modeling theories and practices for systemic, equitable, and student improvement. Proficient students can demonstrate good working and background understanding of simulation and modeling theories and practices for improvement of situation. Students of the developing category have a working knowledge and skills of simulation and modeling theories and practices for improvement of situation. Novice students have incomplete or wrong understanding of simulation and modeling theories and practices for improvement of situation. The evaluation rubric and data collection criteria for Phases-I, II, and III are shown in Tables 5 and 6, respectively.

Table 5: Data collection and evaluation rubric for learning assessment

| **Evaluation rubric scoring levels** | **Score** | **Scoring scale** | **Total** |
|---|---|---|---|
| Strongly agree/Very positive/High rating | 4 | Advanced Proficient | 56 – 68 |
| Agree/Positive/Moderate rating | 3 | Proficient | 45 – 55 |
| Neutral/Average rating | 2 | Developing | 35 – 45 |
| Negative/ Low rating | 1 | Novice | 0 – 34 |

Table 6: Evaluation criteria for three phases of leaning.

| Phases | Criteria ID | Criteria description |
|---|---|---|
| I | C1 | Student got sufficient exposure to practice examples |
| | C2 | The practice examples cover the fundamentals of the M&S |
| | C3 | Able to follow the practice example with the instructor |
| | C4 | Examples were designed to stimulate students' interest in M&S |
| II | C5 | Able to complete in-class exercise with instructor's guidance |
| | C6 | Able to simulate different real-world scenarios |
| | C7 | Learn statistical analysis and visualization through simulation |
| | C8 | Able to adjust, modify, and expand simulation models |
| III | C9 | Able to decompose a complex problem |
| | C10 | Feel confident about applying simulation for new situations |
| | C11 | Able to work independently with simulation modeling |

## 4 Results and Discussions:

Students completed the three phases in a timeframe of a regular semester. From the beginning of semester, students started making progress towards completion of the project according to design of the project. At the end of completion of the projects students learn to develop a complete simulation for a complex system, explore the performance with existing setup, identify the caveats in the systems to set the improvement strategies, perform if-then/optimization experiments on the systems, observe systems outputs, and analyze them to take strategic decisions with proper judgment. The outcome of the simulated project is shown in Figure 4.


Figure 4: Dashboard of the simulation outcome for the emergency department.

At the end of the semester, we conducted a student-survey using the rubric shown in Tables 5 and 6. Thirty-one (31) students from the Industrial Systems Simulation courses (IE 4353) participated in this survey. The survey was anonymous to avoid bias in collecting students' feedback. The collected data was analyzed for two major purposes –1) to understand student learning on individual phases of the project and 2) to understand the student overall learning from this course.

(a) (b)

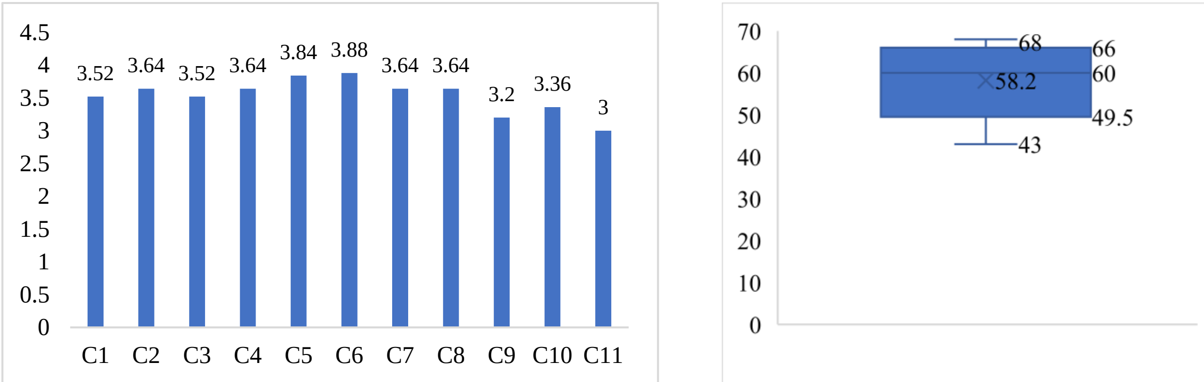


Figure 5. Students' learning outcome evaluation (a) average rating on the evaluation criteria and (b) the five-number summary of the total evaluation points.

As we can see from Figure 5, students provide the highest rating on criterion C5-C8, which are associated with Phase-II. It indicates that students had a great learning experience with the guidance of instructors. Students also gain positive learning in Phase-I where they directly copy the instructor to understand the basic concepts. Surprisingly, the learning curve shows a downward trend in Phase-III. This may happen since students worked independently on more complex problems with less supervision of instructor. The five-number summary shows that the average rating of 58.2 indicating an overall learning category as advanced proficient. However, the average rating value lies at the border of "advanced proficient" and "proficient". Obviously, there is more scope to improve student learning outcomes, especially in Phase-III, when students act independently to apply the acquired knowledge on similar but new environments.

## 5 Conclusions:

This paper presents a project-based learning approach implemented for the "Industrial Systems Simulation" course offered in the Industrial, Manufacturing and Systems Engineering (IMSE) Department at The University of Texas at El Paso. The project was divided into three sub-projects and completed in three learning phases. The students' learning outcomes were thoroughly evaluated using an anonymous questionnaire with seventeen (17) evaluation criteria. A total of thirty-one students participated in this survey to provide their feedback on the project design. The evaluation outcome was discretized into four evaluation categories – Advanced proficient, proficient, developing, and novice. We observed an average rating of 58.2, which is in the range of advanced proficient. However, there are still some opportunities to improve the students' learning outcomes as the average rating lies in the border of "advanced proficient" and "proficient". Moreover, the low rating on Phase-III learning provides another major concern. In this study, we only considered the quantitative evaluation on the student learning criteria, however, we did not perform the investigation the reason of high/low rating. In future, we will try to understand the reason on comparatively low learning outcomes in knowledge scaffolding phase with qualitative analysis.

**Acknowledgements**

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