The Effectiveness of an Interactive Simulation-Based WDPP Tool in Fostering Student Comprehension of Complex Problem Solving

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https://doi.org/10.24191/ajue.v19i1.21229

Received: 21 September 2022
Accepted: 10 December 2022
Date Published Online: 31 January 2023
Published: 31 January 2023

Abstract: Complex problem solving is regarded as one of engineering's central activities. However, students consistently find complex interactions involving multiple parameters to be tedious and perplexing in the classroom. Hence, an interactive simulation tool based on the Wolfram Demonstration Project platform (WDPP), which was adopted from www.learncheme.com, is used as a teaching aid to enlighten students about the complex interactions of multiple parameters in engineering calculations in a simple and engaging manner. This interactive simulation tool was implemented in selected chapters of the Separation Processes course as a pilot test to evaluate its effectiveness as a new and alternative teaching aid in the classroom based on actual student attainment of course outcome (CO) and questionnaires. The two (2) COs include the attribute of i) applying engineering knowledge and/or fundamentals (CO1, PO1) and ii) solving complex engineering problems (CO2, PO2). Analysis of the assessment data revealed that, the average student attainment for CO1 and CO2 was 81.43% and 81.13%, respectively, for the chapters in which interactive simulation was used. In contrast, the average CO1 and CO2 attainment for non-adopted chapters was 75.40% and 81.99%, respectively. These results suggest that the student's achievement improved decently based on coherent data of students' actual attainment in both CO average and CO density when the interactive simulation-based WDPP was used in the class. In addition, 92.59% of students agreed that the use of interactive simulations in classroom was useful, interesting, and engaging. These results shed new insight on the use of interactive simulation-based WDPP as an alternative teaching aid or learning platform for enhancing the content and delivery of the curriculum.

Keywords: Complex engineering, Course outcome, Interactive simulation, Teaching aid, WDPP

1. Introduction

Malaysia, as part of the International Engineering Alliance (IEA), has signed the Washington Accord (WA) since 2019, which consists of the statutes for the recognition or accreditation of engineering programs at the tertiary level (International Engineering Alliance, 2014; Isa et al., 2021a). WA is one of the important aspects in the accreditation of engineering programs in Malaysia, as required by the Engineering Accreditation Council (EAC), Board of Engineers Malaysia (BEM) (Board of Engineers Malaysia, 2020). The WA stipulates that students' ability to solve complex engineering problems must be the primary focus, which indirectly meets the accreditation standards (International Engineering Alliance, 2014).

Complex Engineering Problems (CEP) involves students' competence in understanding in-depth engineering knowledge to solve complex technical, engineering, and other problems. Burkholder et al. (2021) investigated the importance of chemical engineering students' problem-solving skills at two institutions in the United States of America (USA). The results suggest that incorporating extensive problem-solving decision-making experiences into the curriculum could lead students to graduate with skills more similar and closer to those of experienced engineers. The engineering education curriculum places great emphasis on students' ability to comprehend complex engineering problems. Therefore, engineering educators need to be able to use proper approaches in facilitating the learning process (Phang et al., 2018). To date, several advanced tools have been developed and used in the classroom to improve the quality of learning. These include the use of augmented reality (AR) (Enzai et al., 2021), the use of interactive e-book (Lim et al., 2020), the game-based learning approach (Runniza et al., 2021), and the use of interactive simulation (Ameerbakhsh, 2018). Among the available approaches, the use of interactive simulation tools as teaching aids have attracted decent interest.

The introduction of interactive simulations into engineering curriculum represents new paradigm shift in the educational system. Interactive simulations allow students to manipulate variables and receive immediate feedback on how the changes might affect the system/process, allowing the students to develop their personal insight (Falconer, 2019). Ansaf and Jaksic (2020) reported that an interactive simulation tool has the potential to improve both students' motivation and performance by combining active student learning experiences. This would improve the ability of visual learners to comprehend complex engineering problems, rather than undergoing the teaching-centric approach. A survey by Wieman et al. (2008) found that, about 80% of the students who performed an interactive simulation exercise understood the ideas on the summative assessments better than the students who performed a normal exercise on the same topics. An interactive simulation was also implemented by Chernikova et al. (2020), which resulted in positive feedback that facilitated students comprehension in complex problem solving.

The interactive simulation tool, based on the Wolfram Demonstration Project platform (WDPP), was developed by Falconer and his team for several chemical engineering courses (Falconer et al., 2018; Falconer, 2019; Falconer and Nicodemus, 2014, 2015). The interactive simulation-based WDPP application allows students to manipulate process variables through an interface to which they receive an immediate response of how changing the variable affects the system (Falconer et al., 2018). For instance, Falconer and Nicodemus (2014) conducted a survey on the effectiveness of this interactive simulation-based WDPP in a fluid mechanics course. The positive results of the survey showed that 90% of the students preferred to use the simulation tool in another course to improve their understanding rather than relying solely on the textbook. Based on these results, the use of the interactive simulation-based WDPP in the classroom can promote student engagement to learn more about the interaction of multiple variables in complex processes.

According to the engineering accreditation council Malaysia (EAC) standard (Board of Engineers Malaysia, 2020), seven (7) program outcomes (POs) are described that emphasise the inclusion of CEP in the engineering curriculum. Isa et al. (2021a) conducted a study on the implementation of CEP in engineering programs of 25 universities in Malaysia that focused on effective continuous quality improvement (CQI) activities. The results showed that the weightage 20-40% of CEP skills were practiced by the majority of the programs, justifying the need for appropriate CQI activities to further improve students' understanding of complex problem solving. The implementation of CEP in the Bachelor of Chemical Engineering (Environment) with Honours (EH225) program (Table 1) in various types of assessments resulted in numerous challenges to continuously improve student performance in each semester. Therefore, an interactive simulation approach was incorporated into one (1) selected course as a pilot study to evaluate its potential towards students' performance.

The aim of this study is to evaluate the effectiveness of interactive simulation-based WDPP as a new and alternative teaching tool in the Separation Process (CEV501) course as part of the CQI activity to improve the student's comprehension in complex problem solving. Its effectiveness was evaluated based on students' actual attainment of the course outcome (CO), programme outcome (PO) and students' reflection through questionnaires. The following research questions are addressed in depth in this study:

1. How was the effectiveness of the interactive simulation-based WDPP measured in terms of improving student understanding in solving complex engineering problems in the CEV501 course?
2. Which chapters (simulation or non-simulation) have an impact on student performance/ attainment and grade based on the assessments assessed?
3. Overall, how do students rate the use of the interactive simulation-based WDPP in the CEV501 course?

Table 1. EH255 program outcomes (POs) mapping to CEP (Board of Engineers Malaysia, 2020)

POs	POs Descriptions	Graduate Attributes	CEP
PO1	Ability to apply knowledge of mathematics, science, engineering fundamentals to solve complex engineering problems in chemical and environmental engineering.	Engineering Knowledge	√
PO2	Ability to identify, formulate, analyze and solve complex chemical and environmental engineering problems using the principles of mathematics, applied science and engineering.	Problem Analysis	√
PO3	Ability to design component, system and process for complex chemical and environmental engineering problems with an appropriate consideration on health, safety, society and environment.	Design/Development of Solutions	√
PO4	Ability to conduct complex chemical and environmental investigation using research-based knowledge and method including design of experiment, analysis and interpretation of data to provide valid conclusion.	Investigation	√
PO5	Ability to utilize modern science, engineering or IT tools and systems to solve complex chemical and environmental engineering problems.	Modern Tool Usage	√
PO6	Ability to assess safety, health, legal and cultural issues in engineering scenarios that affect society.	The Engineer and Society	√
PO7	Ability to demonstrate professional engineering solution in societal and environmental contexts for sustainable development.	Environment and Sustainability	√
PO8	Ability to recognize the ethical principles and apply the professional conducts in engineering practice.	Ethics	-
PO9	Ability to communicate effectively not only with engineers but also with the community at large.	Communication	-
PO10	Ability to function effectively as an individual as well as in a group with the capacity to be a resourceful person, leader and an effective team member.	Individual and Teamwork	-
PO11	Ability to engage in independent and life-long learning.	Lifelong Learning	-
PO12	Ability to manage projects related to chemical and environmental engineering, and/or entrepreneurial business that involve multidisciplinary roles.	Project Management and Finance	-

2. Methods

2.1 Research Framework

The conceptual research framework for this study is shown in Fig. 1. The development of the framework represents the entire process flow that was required to conduct the research based on the standard analytical research approach. First, the problems and research gaps were identified before the scope of work was planned. This included selecting of the target respondents, course, chapters and type of assessments. Once the decision was made, the planning was implemented using the interactive simulation-based WDPP in the CEV501 course. Once the data collection was completed (COs attainments and questionnaires survey), a quantitative approach to data collection and analysis was adopted. Both descriptive and statistical approaches were adopted for data analysis. The details of the research design, data collection, and data analysis are described in the following sections.

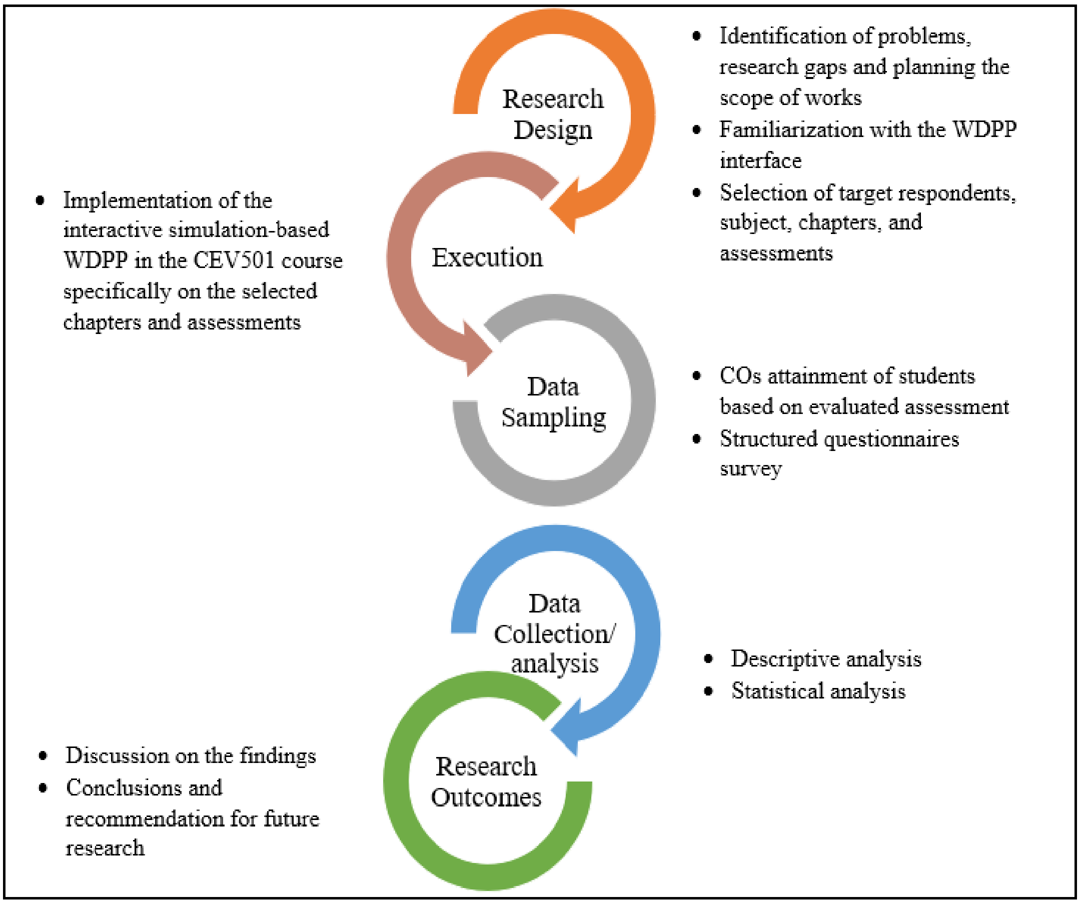

Fig. 1 Research framework

2.2 Research Design - Interactive Simulation-based WDPP

The interactive simulation tool used was adapted from the Wolfram Demonstration Project platform (WDPP), which uses a *Mathematica*-based simulation (Falconer and Nicodemus, 2015). This simulation was used as a teaching tool to facilitate students about the complex interactions of multiple parameters in engineering calculations in a simple and engaging way. The WDPP simulation was obtained from the LearnChemE website (www.learncheme.com), where more than 275 interactive simulation-based WDPP on chemical engineering courses can be found (*LearnChemE*, n.d.). One (1) selected course - Separation Process (CEV501) was used to assess the performance of enrolled students in solving complex engineering problems. Table 2 shows the COs and POs mapping for the CEV501 course. Two (2) of four (4) chapters used the interactive simulation-based WDPP during the lecture, as shown in Table 3. Examples of the interactive simulation-based WDPP are shown in Fig. 2. In these simulations, calculations are performed in real time once the selected parameters are entered in using user friendly controls that are converted into graphical output.

Table 2. CEV501 course outcomes (COs) to POs mapping (AiMS UiTM, 2019)

COs	COs Descriptions	PO1	PO2
CO1	Apply separation process principles of unit operation in solving chemical/environmental engineering problems.	√	
CO2	Explain the solutions of complex chemical/environmental engineering problems using separation process principles.		√

Table 3. List of chapters in CEV501 course that adapt the interactive simulation-based WDPP

Chapter	Topic	Simulation	Non-Simulation
Chapter 1	Distillation	√	-
Chapter 2	Liquid-liquid Extraction	-	√
Chapter 3	Leaching	-	√
Chapter 4	Membrane Separation	√	-

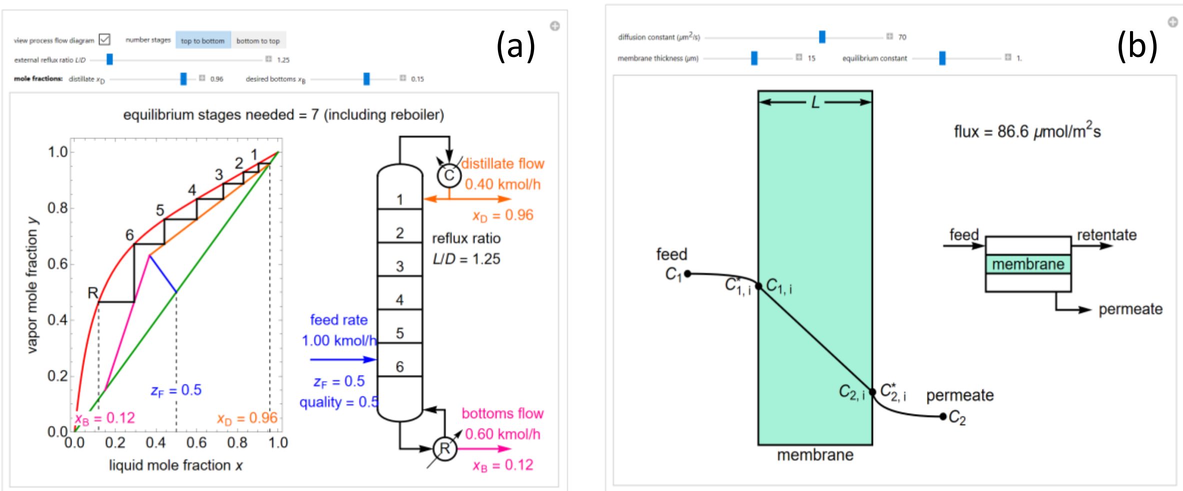

Fig. 2 Example of Wolfram Interface for McCabe-Thiele method for (a) fractional distillation (Chapter 1) and (b) membrane concentration profile (Chapter 4)

2.3 Data Analysis - Course Outcome (CO) Assessment Evaluation

The effectiveness of the interactive simulation-based WDPP was evaluated based on actual student attainment of the course outcomes (COs) for each assessment and on students' reflection through survey on questionnaires. The mapping of the assessments is presented in Table 4. For all assessments, student cognitive abilities were measured based on Bloom's taxonomy. The overall COs average and COs density for all assessments were calculated, respectively.

Table 4. CEV501 mapping of COs versus assessments

COs	Simulation			Non-Simulation		
	Assignment	**Test 1**	**Test 2**	**Assignment**	**Test 1**	**Test 2**
CO1	√	√		√		√
CO2	√	√	√	√		√

The overall CO average and CO density for all assessments were calculated according to Equations (1) and (2), respectively. The Key Perfomance Index (KPI) for CO density indicator is shown in Table 5. The COs were also analysed based on the grade as shown in Table 6.

$$\text{CO Average} = \frac{\Sigma \text{ CO Score}}{\text{N}} \tag{1}$$

$$\text{CO Density} = \frac{\text{S} \geq 75}{\text{N}} \times 100\% \tag{2}$$

where S ≥ 75 indicates number of students obtained CO's score more than 75% and N is the total number of students sample. The students are expected to achieve CO density at least 75% of CO score in each evaluated CO.

Table 5. Key Performance Index (KPI) for COs density indicator (Idris et al., 2018)

KPI RANKING	
Benchmarking (%)	**Level**
0 – 74	NC: Non-compliance
75 – 100	C: Compliance

Table 6. Grade-based on the COs score from all assessments (UiTM, 2018)

Final grade	**A+**	**A**	**A-**	**B+**	**B**	**B-**	**C+**	**C**	**C-**	**D+**	**D**	**E**	**F**
Total marks	90-100	80-89	75-79	70-74	65-69	60-64	55-59	50-54	47-49	44-45	40-43	30-39	0-29

2.4 Data Sampling via Questionnaires

A student reflection survey was conducted through the Google Form platform. A total of 30 students enrolled in the CEV501 course (semester: September 2021-February 2022) participated this survey. Table 7 lists the survey criteria and evaluation indicators that students used to self-assess their experience on the effectiveness of the interactive simulation-based WDPP in the CEV501 course. These data were analysed using IBM SPSS statistic software (Ver. 28.0.0.0 (190)).

Table 7. Rating Indicators of Each Survey Criteria on interactive simulation-based WDPP Experience

Survey Criteria	**Rating Indicator**
General	1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree
Learning Process	1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree
Students' Experience	1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree
Overall Rating	1- completely disagree to 10- completely agree

3. Results and Discussion

3.1 COs Attainment

Students' actual attainment on the COs was analyzed in two different categories: i) assessments related to the interactive simulation-based WDPP and ii) assessments not related to the interactive simulation-based WDPP. Fig. 3 shows a comparison of the CO average and CO density for the evaluated assessments in each category.

The analysis of the assessment data exhibited that average student attainment for CO1 and CO2 was 81.43% and 81.13% for chapters that adapted interactive simulation-based WDPP. In terms of CO density, 85.19% of students achieved an assessment score greater than 75% (key performance index (KPI) target) for both COs. In contrast, the average student attainment of CO1 and CO2 for non-adopted chapters was 75.40% and 81.99%, respectively. The density of CO1 and CO2 for non-adopted chapters was 77.78% and 92.59%. The student attainment on CO1 improved moderately, while CO2 attainment remained unchanged. These results suggest that the student's achievement improved decently based on coherent data of students' actual attainment in both CO average and CO density when the interactive simulation-based WDPP was used in the classroom.

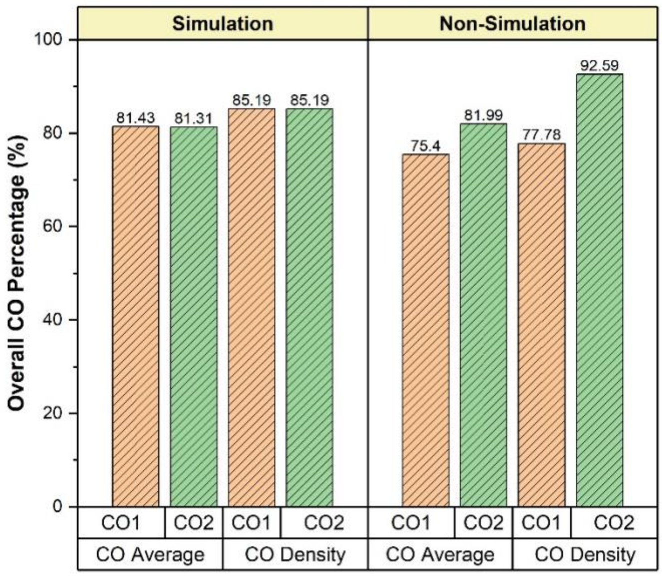

Fig. 3 Comparison of CO Average and CO Density of simulation and non-simulation COs attainment

The results of the COs were further analysed by grade level to determine individual student performance as well as to evaluate the effectiveness of simulation-based WDPP as teaching tool in improving students' comprehension to solve complex problems. From the data presented in Fig. 4, it is evident that there is a very significant difference in the student performance between the simulation-based WDPP and non-simulation one. Most students acquired grades of A+ and A for assessments where the simulation-based WDPP concepts were adapted compared to A and A- grade for non-simulation for CO1. Meanwhile, the grades for CO2 are comparable for both approaches. These findings confirm the effective role of simulation-based WDPP as an alternative teaching tool, as the grade analysis improved by 50%, especially for CO1. Therefore, it can be concluded that this grade distribution for all COs is a good indicator of the use of interactive simulation-based WDPP in CEV501 course.

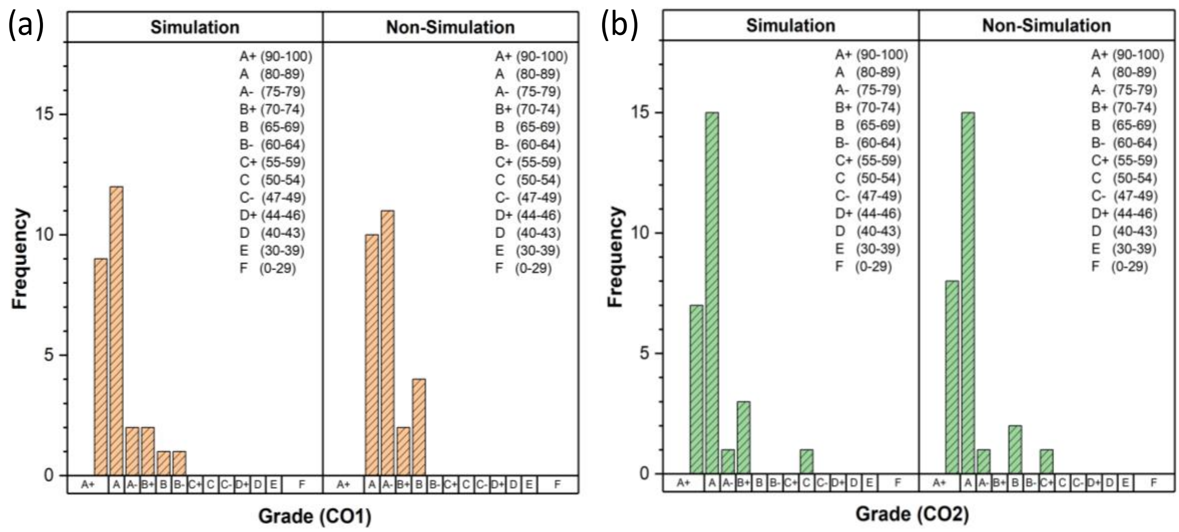

Fig. 4 COs Attainment based on Grades for a) WDPP Simulation and b) non-simulation

The improved student performance on both COs attainment and grades indicates that the use of simulation-based WDPP activities in the classroom had a large positive impact on improving student's understanding of complex problem-solving activities. These findings are consistent with those of Chernikova et al. (2020) and Falconer and Nicodemus (2014, 2015), who concluded that simulation-based learning activities are among the most effective approaches for promoting the development of higher-order cognitive skills that enable students to think holistically when solving complex problems or challenges. In fact, simulation-based activities often provide unique and interactive information feedback that has a greater and positive impact on complex learning activities (Grossman et al., 2009).

3.2 Student Reflections

Fig. 5 shows the distribution analysis of students' general opinion about the use of interactive simulation-based WDPP in classroom. The pattern of distribution analysis was centred at approximately of 4.5, which corresponds to a range between agreement and strongly agreement with standard deviation of almost 0.5. The majority of students (>95%) found that the use of simulation activities was interesting, engaging and could promote further understanding of complex problem-solving during class.

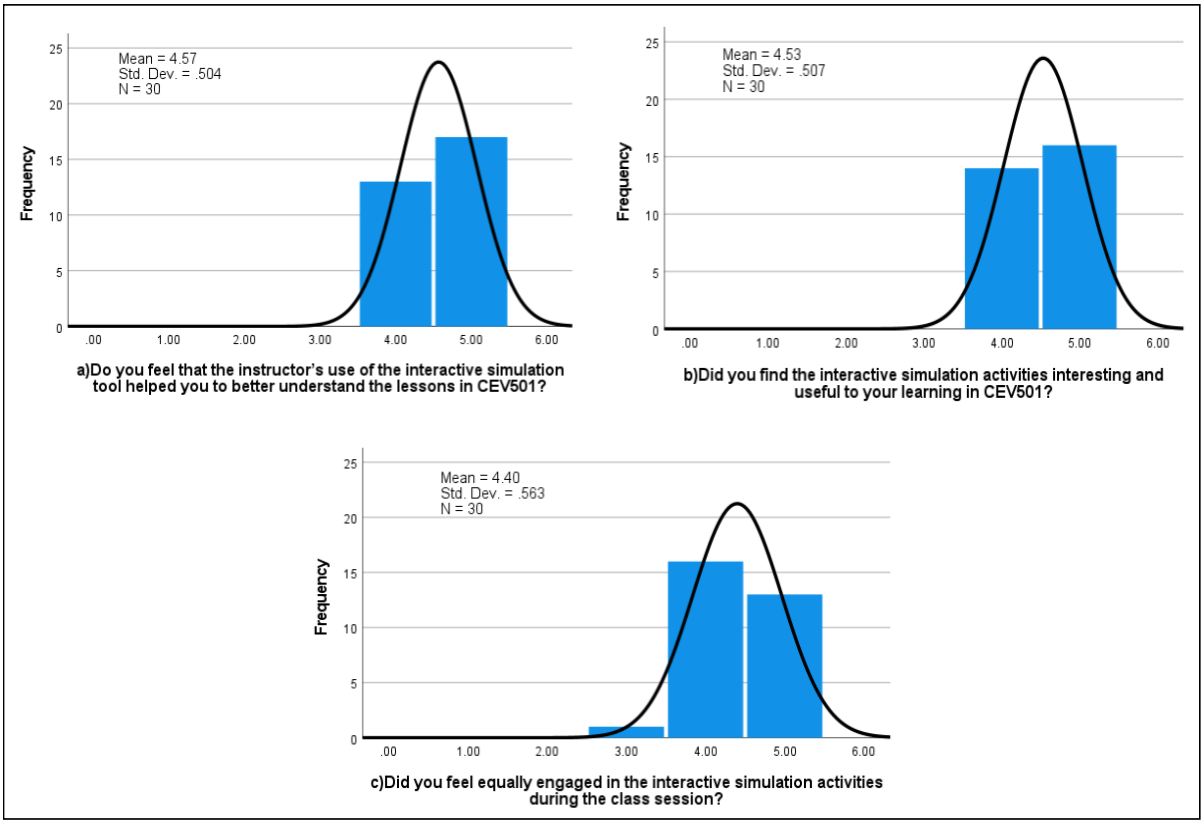

Fig. 5 Distribution Analysis based on Students' Response on General Questions. Note: 1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree

A further examination of the students' reflections on the effectiveness of interactive simulation in facilitating their learning process and activities, particularly to the assigned assessment of selected chapter is shown in Fig. 6. It was found that the students' responses ware highly consistent with the mean value of 4.40 and 4.5 for chapter 4 and chapter 1, respectively. Interestingly, the variance was very low, and it was in the range of 0.56 – 0.57 deviation. These results confirm that most students are in well agreement that the simulation activities enable student to comprehend the principles fundamentals of the assigned chapters. In facts, such findings can well be corroborated with the students' actual attainment on CO and grades as well.

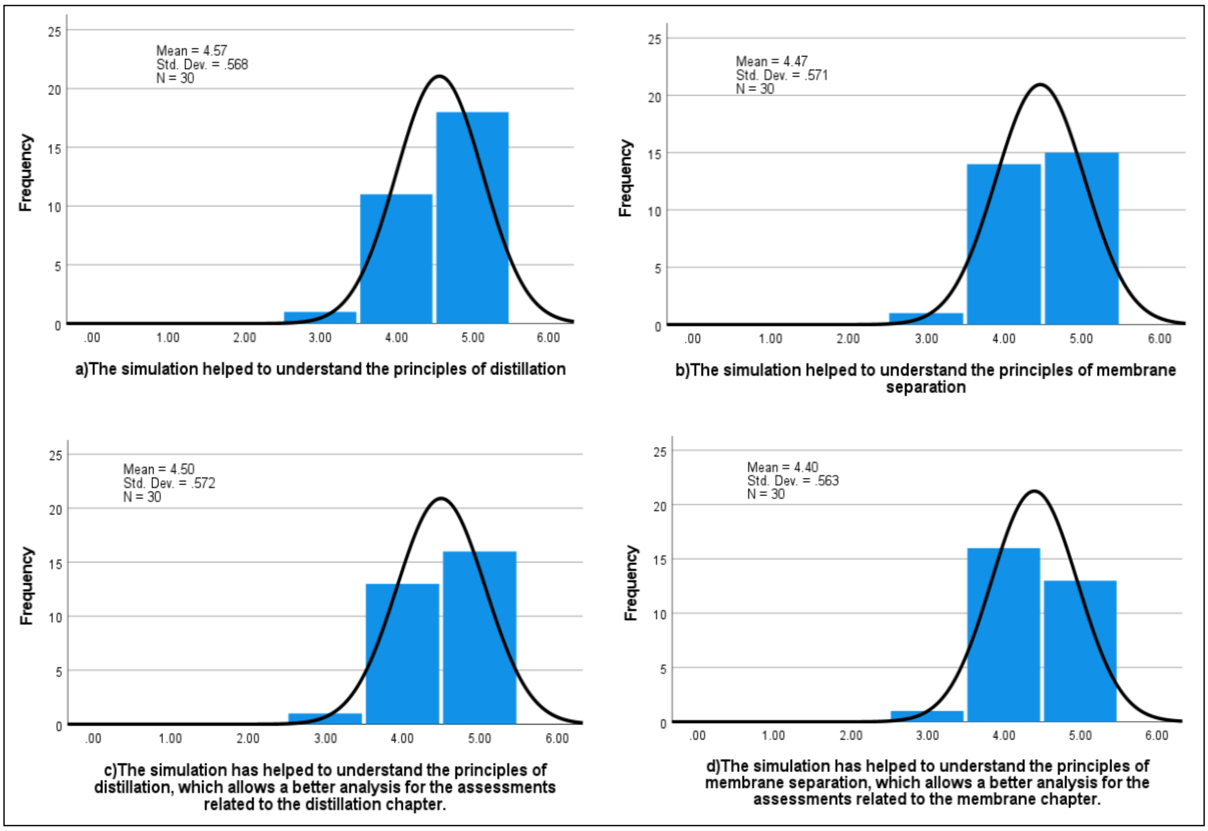

Fig. 6 Distribution Analysis based on Students' Response on Learning Process Questions.
Note: 1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree

Detailed analysis of the students' experience indicated that the interactive simulation activities had a positive impact on students' understanding. The mean distribution was found to be at 4.5 with a variance of 0.5-0.6 as illustrated in Fig. 7. Interestingly, almost 57% of the students felt that this interactive tool could be used in other courses as well. This positive input proves the effectiveness of interactive simulation activities as one of the alternative teaching tools that can be used as one of continuous quality improvement (CQI) activities for CEP.

In addition, students' positive attitudes towards the use of simulation-based WDPP in the classroom were found to significantly influence their engagement in learning activities. These findings are in tandem with previous research by Putit et al. (2022) and Ng & Fong (2020) who reported that attitude has a statistically significant impact on students' behavioural engagement in Malaysian universities.

Moreover, the students' feedbacks show that they have acquired better knowledge and thinking skills about the subject matter through the facilitation of simulation-based WDPP activities. Such responses are consistent with the improved student performances, which suggests the plausible attainment of higher cognitive domains in solving complex engineering problems (CEP). This finding indirectly supports the need for effective implementation of CEP in Malaysian engineering curricula as highlighted by Isa et al. (2021a; 2021b).

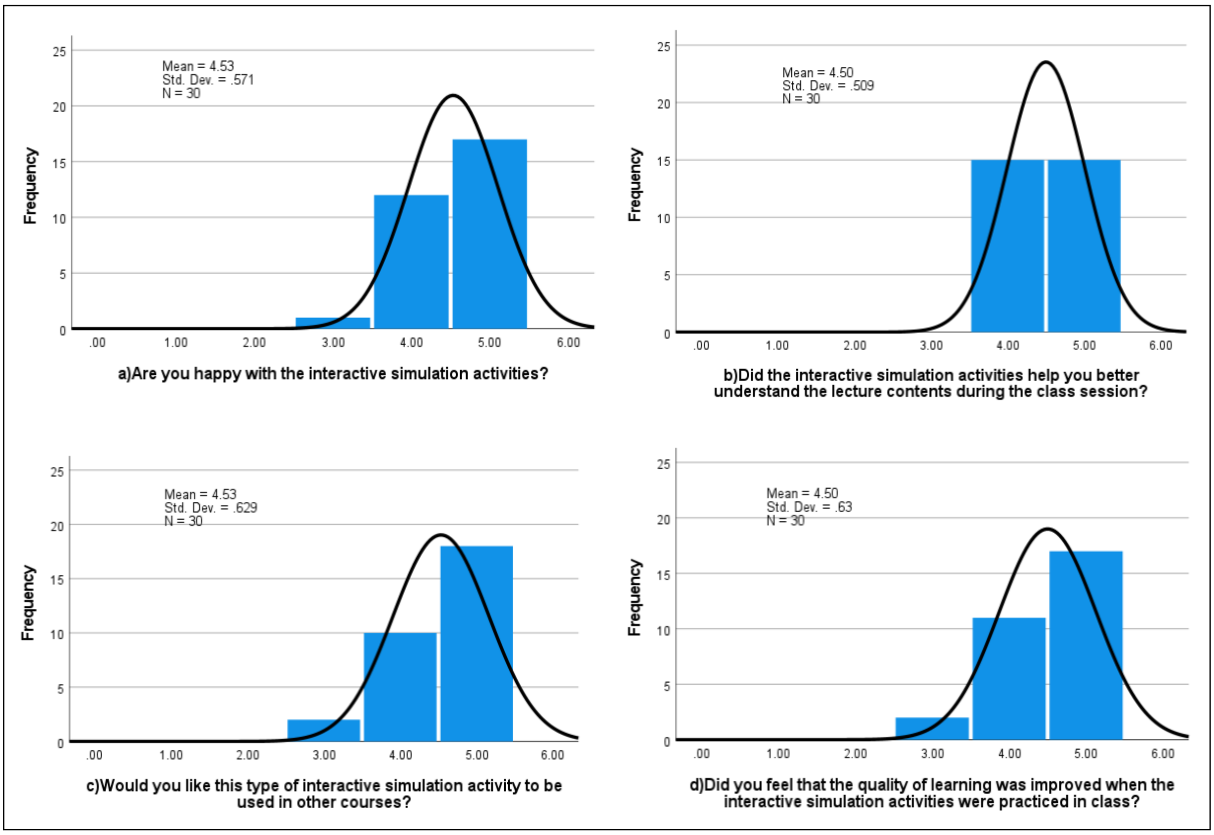

Fig. 7 Distribution Analysis based on Students' Response on Students' Experience Questions.
Note: 1 - Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, 5 - Strongly Agree

Fig. 8 shows that the distribution data for overall students' reflection that are centered at average of 9.2 with a variance of 0.7-0.8. Analysis of students' overall reflection revealed that more than 90% (with an average rating scale of 9 out of 10) of students found that the use of the interactive simulation-based WDPP in the selected chapters to be useful, interesting, and engaging. They also felt that the quality of learning was improved when the interactive simulation activities were integrated into the lessons. These findings suggest that the use of interactive simulation-based WDPP in teaching and learning activities is useful and important to holistically support learning activities and outcomes.

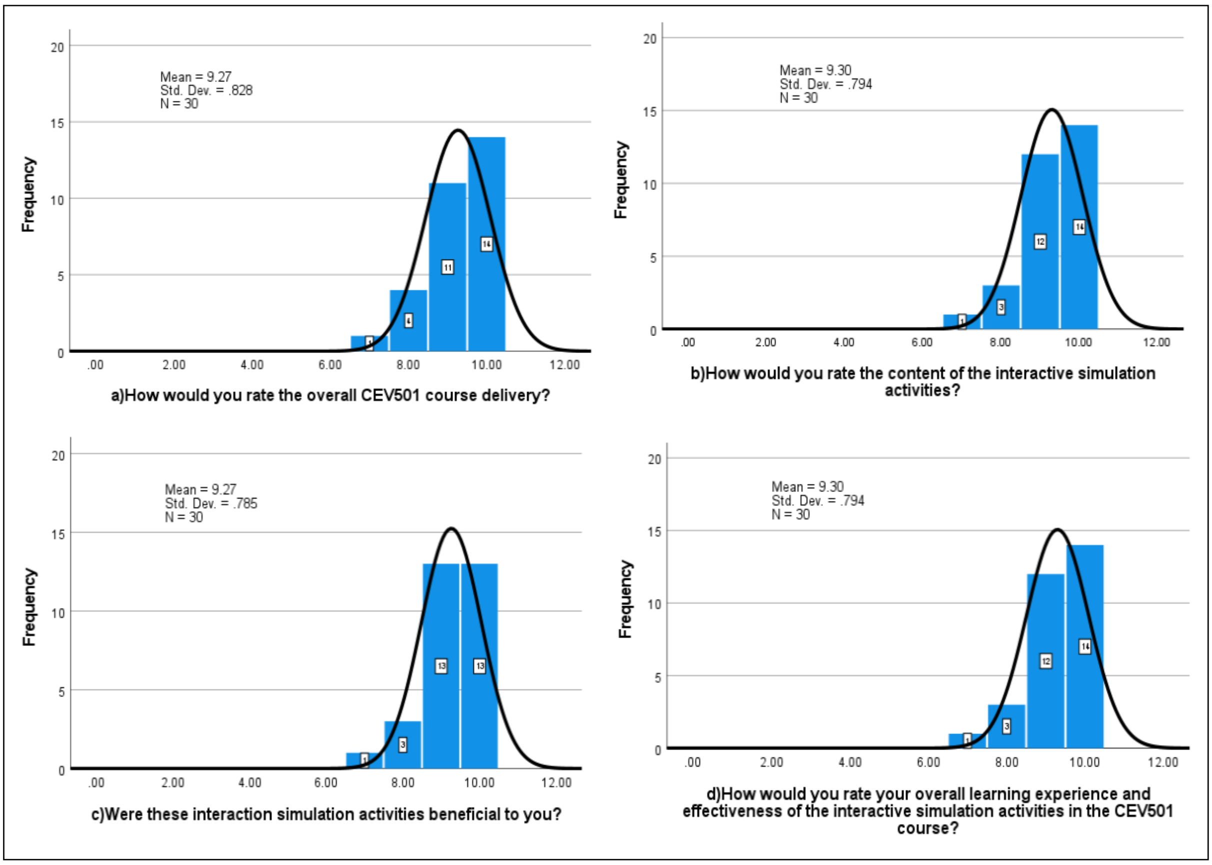

Fig. 8 Distribution Analysis based on Students' Response on Overall Rating Questions.
Note: 1- completely disagree to 10- completely agree

4. Conclusions and Suggestions for Future Research

The effectiveness of the interactive simulation-based WDPP is evident from the coherent data of both CO1 and CO2 to the assigned chapters. These findings align with the analysis of the students' reflections survey that unanimously indicated that the use of interactive simulations in the class was found to be useful, interesting, and engaging, which enable to foster their learning process and complex problem-solving activities as well. In conclusion, the results of this work provide new insights into the use of interactive simulation-based WDPP as an alternative teaching tool or learning platform to enhance the content and delivery of the curriculum dealing with complex engineering problems. This positive contribution proves the effectiveness of interactive simulation activities as one of the alternative teaching tools that can be used as one of the continuous quality improvements (CQI) activities to further enhance students' understanding of complex problem solving. It is recommended that further research be conducted on other fundamental and critical engineering courses in the EH225 program as part of the CQI to improve teaching and learning activities.

5. Co-Author Contribution

The authors declare that there is no conflict of interest affecting the content of this article. Both authors are equally involved in the design of the research framework, data collection and analysis, writing and reviewing the manuscript.

6. Acknowledgements

The authors are grateful for free access to use the interactive simulation-based WDPP developed by the LearnChemE team (www.learncheme.com). The authors gratefully acknowledge the support of the students from the Centre of Chemical Engineering Studies, Universiti Teknologi MARA Cawangan Pulau Pinang who participated in the questionnaire survey.

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