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Using Engineering Design Software to Motivate Student Learning for Math-Based Material in Biotechnology Courses*

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This paper explores the implementation of process engineering design software, specifically UniSim®, as a vehicle to investigate student interest, engagement, and confidence in learning engineering design and their experiences of group work. This research gathered information about student's perception and experience about (1) the role of engineering design software as a motivator for learning engineering design calculation and (2) the importance of group work in engineering education. This paper outlines the results of a pilot project concerning second- and third-year biotechnology students' experiences in learning engineering design concepts using simulation software. The process design software was found to be an excellent complement to traditional classroom teaching as it facilitated learning via repeated practice allowing students to perform engineering design calculation of problems with various levels of difficulty while the complete solutions of the problems were generated by the software. Problem solving using the software not only helped students to confirm their hand calculations but also allowed them to better focus on comprehending and analyzing the results of complex problems. According to survey results, over 70% of students commented that the simulation-based learning modules increased their interest in learning math-based concepts in the process engineering design and therefore facilitated their understanding of the course materials. Students also commented higher performance working in groups due to idea sharing and troubleshooting together. This survey could serve as a basis for instructors intending to further implement software-based learning at their respective institutions.

Keywords: biotechnology; level of interest; engineering design; UniSim®; group work

1. Introduction

Several researchers have argued for the importance of including process simulation software in engineering curriculum [1–9]. Jimènez et al. (2004), for example, argued for the pedagogical benefits of simulation software as a means to improve students' understanding of theory and promote the development of soft skills, such as team-based problem solving and group work techniques [2] while Taher and Khan (2016) discussed the importance of simulation software to reduce the gap between learning environment and real environment [3]. Lim (2017) developed a design software to expose students to repeated practice approach in engineering design calculation [4]. He found that the design software could be utilized as a tool to enhance students' ability to learn independently by providing an opportunity for students not only to design their own questions with various levels of difficulty but also to generate the complete solutions [4]. Wankat et al. (2002) demonstrated the importance of process simulation software as a motivator for student learning [5]. They used simulation software to facilitate a problem-based learning approach [5]. In their research, the authors found that students were more motivated to learn the lecture materials as well as the simulation software. Similar to Wanket et al. (2002), Ruiz-Ramos et al. (2017) found that utilizing commercial design software, such as Aspen Plus® to study local and regional research topics fosters student's interests to learn engineering design calculation [10]. In 1957, Atkinson developed the expectancy-value theory to further understand and study how motivation leads to greater achievements [11]. According to the expectancy-value theory, students' performance is affected by their expectancies for a successful outcome as well as the level of value they assign to tasks. These expectancies which are directly proportional to students' engagement and academic accomplishments [12] refer to how confident the students are in their own capacity, whereas the task value refers to how valuable and important students think the tasks will be. Komulainen et al. (2012) found that the introduction of software made

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the course more interesting and students were better able to relate the simulation exercises to the lecture materials [7].

Bioprocess engineering design concepts are complex, and the biotechnology curriculum focuses more on students' ability to react to events in the context of bioprocess engineering rather than learn all aspects of theoretical and math-based concepts related to engineering design. Therefore, this paper and pilot project sought to explore the ways in which biotechnology programs could incorporate simulation software into unique courses that would not only provide students with a holistic overview of the biochemical processes and simulation software but also, to motivate students to engage with complex concepts that they are not expected to explore theoretically. Specifically, the focus of this paper is to measure the impact of the introduction of engineering design software on undergraduate biotechnology students' interest, engagement, confidence and experiences of in-class group work rather than detail execution of the simulation labs. This study investigated students' perceptions about the role of engineering design software as a motivator for learning math-based concepts in engineering design education. The expectancy value theory was used in this study to describe the application of the process simulation software as a motivator to provide students with a holistic overview of the bioprocess engineering design allowing them (1) to understand the value of the engineering design concepts by gaining experience with a real-world tool and (2) to fine-tune their expectations of a successful outcome in order to improve their engagement with the course content and therefore their performance in the course.

2. Background

2.1 Program and Course Background

The Bachelor of Technology Program (B.Tech) in the W. Booth School of Engineering Practice and Technology under the Faculty of Engineering at McMaster University emphases "hands-on" learning driven by industrial needs. The program has three streams: Biotechnology, Automation Engineering Technology, and Automotive Engineering Technology. Twenty percent of B.Tech's curriculum includes management and business skill courses to complement students' technical knowledge and heighten graduates' advancement once in industry. The course material lends itself to experiential and problem-based learning through active-learning activities to engender motivation and level of interest for students who wish to gain a more holistic understanding of the course material.

Biotechnology students at the School of Engineering Practice and Technology take several process engineering-related courses such as Chemical Engineering Concepts (level II), Bioprocess Control & Dynamics (Level III), and Bioreactor Processes & Design (Level III). In their second year, Biotechnology students take the Chemical Engineering Concepts course, which covers the concept of material and energy balances. Laboratory experiments include distillation, heat exchanger, evaporator, continuous stirred tank reactor (CSTRs), neutralization, and membrane filtration. Students then take a Bioprocess Control & Dynamics in their third year, which builds off the concepts learned in the Chemical Engineering Concepts course. This level III course covers the concepts of dynamic modeling of chemical and biochemical processes, actuators and sensor systems, and basic control theory.

Both Chemical Engineering Concepts and Bioprocess Control & Dynamics courses have received mixed reviews from students in the past, i.e. before the introduction of UniSim® software into their courses. Based on instructor's anecdotal experience, the students appreciated the course content for its usefulness and applicability to industry, but they were less enthusiastic about the required mathematics component. To bolster students' interest and attitude toward complex mathematical concepts, the course instructor (the first author) incorporated the engineering design software into the Chemical Engineering Concepts and Bioprocess Control & Dynamics courses to give students the ability to better engage with the course content based on expectancy value theory discussed earlier in a manner that suited a greater diversity of learners. By providing students access to an up-to-date software platform, students could walk away with a broader skillset and level of comfort. This paper provides an overview of how the instructor integrated UniSim® software into Chemical Engineering Concepts and Bioprocess Control & Dynamics courses and, the results of two course-based surveys to explore how, if at all, students' level of interest to learn engineering design components in the biotechnology program changed, following the introduction of problem-based instruction involving software. While, students in the Chemical Engineering Concepts course were introduced to UniSim® through one workshop solely to perform mass and energy balances calculations, students in the Bioprocess Control & Dynamics course experienced the in-depth application of the software in the bioprocess design through four simulation labs.

2.2 Structure of Process Simulation Labs

The Bioprocess Control & Dynamics course has three hours of classroom instruction per week and three-hour labs every other week. There were two lab sections for the course, allowing the instructor to assist a smaller number of students (approximately 20 students per section). One semester included thirteen weeks of classes. In the three-hour lab of the first two weeks of the term, students visited a local water and wastewater treatment plant, Woodward Treatment Plant, where students were able to visit the site and the control room and examine various components of a control system. UniSim®-based labs were introduced every other week for the remaining eight weeks (four labs per section) with an extra two weeks to account for a Fall reading week and potential of inclement weather. From the beginning, students were asked to work in pairs during lab time for the duration of the semester. This set up encouraged peer interaction that required students to practice group work skills. The instructor used an integrated approach to teach group work skills, that is, learning about group work skills in parallel to learning disciplinary knowledge [13]; Practicing and developing professional teamwork skills are a program level learning outcome in the B.Tech program. Aside from student-to-student interaction, this course also strengthened student-instructor interaction by having lab sizes that were small enough to facilitate the interactions. In this case, the instructor acted as a facilitator in the transition between classroom theory and simulation labs. Table 1 outlines the topic of each simulation lab and their learning objectives.

Each lab consisted of two parts: Part 1 was a tutorial with detail and step-by-step instructions on setting up specific equipment in UniSim®; Part 2 involved students applying learned materials in the tutorial and their theoretical knowledge to simulate a chemical/biochemical processing unit. These tutorials allowed the students to use a trial and error method. The trial and error method stimulated the student's senses to use their curiosity so that they became more familiar with the UniSim® at their own pace while the lab itself was used as a tool to evaluate the student's understanding of the process design and their critical thinking ability.

The first lab was an introduction to UniSim® and included the basics for using the software, such as creating a case, selecting components and fluid packages, and adding simple unit operation such as mixers, pumps, and heat exchangers to the process flow diagram (PFD). Students learned about fluid packages, material streams, compositions, connections, and more. The introduction also covered designing a Continuously Stirred Tank Reactor (CSTR) in the tutorial part followed by the actual lab surrounding the production of propylene glycol in a CSTR using propylene oxide and water. The lab was adapted from UniSim® tutorial manual. Students first read an introduction to the lab, including details of the industrial applications of CSTR's, then applied the basics of UniSim® learnt in the introduction to build their systems in the actual lab. Finally, they completed a lab report by answering questions about their processing unit, stream compositions, and explained how and why change occurred, for example, how and why manipulated variables, such as temperature, affected the responding variables, such as production of propylene glycol. In the second lab period, the tutorial gave students a basic understanding of design and optimization principles of distillation columns. The optimization of the distillation column was performed by investigating the effect of manipulating variables on percent yield and purity of the distillate. The tutorial portion of the lab manual walked students through setting up a distillation column, entering specifications for the feed stream, and describing how they would run the simulation. The tutorial was followed by a lab activity which incorporated a distillation column

Table 1. A summary of simulation labs and their learning objectives

Lab	Topic	Learning Objectives	Actions in UniSim®
1	Introduction	Familiarize with UniSim® software	Components, fluid packages, streams, unit operations, workbook
	CSTR (Continuously Stirred Tank Reactor)	Demonstrate production of propylene glycol using a CSTR	Setting up a reactor, defining reaction, creating reaction sets and making them available to fluid package
2	Distillation Column	Understanding the design principles of a distillation column	Setting up a column, specifying feed streams, specifying required number of trays in the separation column
3	PID (Proportional-Integral-Derivative) Controller	Setting up PID controller in system	Controller design, dynamic simulation, transient calculations, feedback control, controller tune-up
4	Biodiesel Production	Designing a transesterification plant and process optimization	Using aspects from all previous labs (mixers, reactors, distillation and separation columns, heat exchangers, etc.)

and a Continually Stirred Tank Reactor (CSTR) which students had already designed in the previous lab to produce propylene glycol. The goal of the lab was to design a distillation column to purify the product stream leaving the reactor in Lab 1 and recycle the unreacted materials to the reactor to help economics of the process. In contrast with the tutorial part, the lab activity had minimum instructions and students were asked to set-up their distillation column based on the concepts learned from the tutorial portion of the manual. This was where the collaborative effort of group work became active. Students submitted screenshots of their final Process Flow Diagram (PFD), as well as answers to questions about changing compositions, temperatures, mass flowrate, and number of trays in the distillation column. These questions allowed the instructor to check if students were on the right path and if the class learning objectives were being met. Lab 3 focused on dynamic simulation and setting up and tuning Proportional-Integral-Derivative (PID) controllers. To give further insight into the simulation labs, a detailed outline of lab 3 surrounding the topic of PID controllers is given in this section. Fig. 1, a screenshot of the tutorial part in lab 3, demonstrates the process flow diagram, an integrator which was used to set-up the control action, and the strip charts to record how the manipulated and controlled variables change with time. To investigate the dynamic behaviour of the controller and liquid level in the tank, the process was subjected to a change in the inlet flowrate by creating an "event scheduler" in Unisim®. Students were asked to tune the controller using computational search method by adjusting the proportional, integral, and derivative parameters of the controller that best satisfied the design criteria. The tutorial helped students to understand how control parameters in a single-loop control system affected the controlled variables and the stability of the system.

The PID tutorial lab was followed by a more complex process with less guidance. The process flow diagram of the system consisting of two tanks a heat exchanger is shown in Fig. 2. The students were asked to utilize controllers to control the liquid level in the tanks as well as the temperature in stream 8. Students were encouraged to use their knowledge of the concepts but were also allowed to review the tutorial during the lab period. Students were asked to change the set-point of the temperature controller, record the dynamic behaviour of the system, and tune the controllers using trial and error approach.

This approach allowed students to use trial and error to make calculated guesses as to the effect of multiple variables on one another and within the larger process, allowing to better understand the

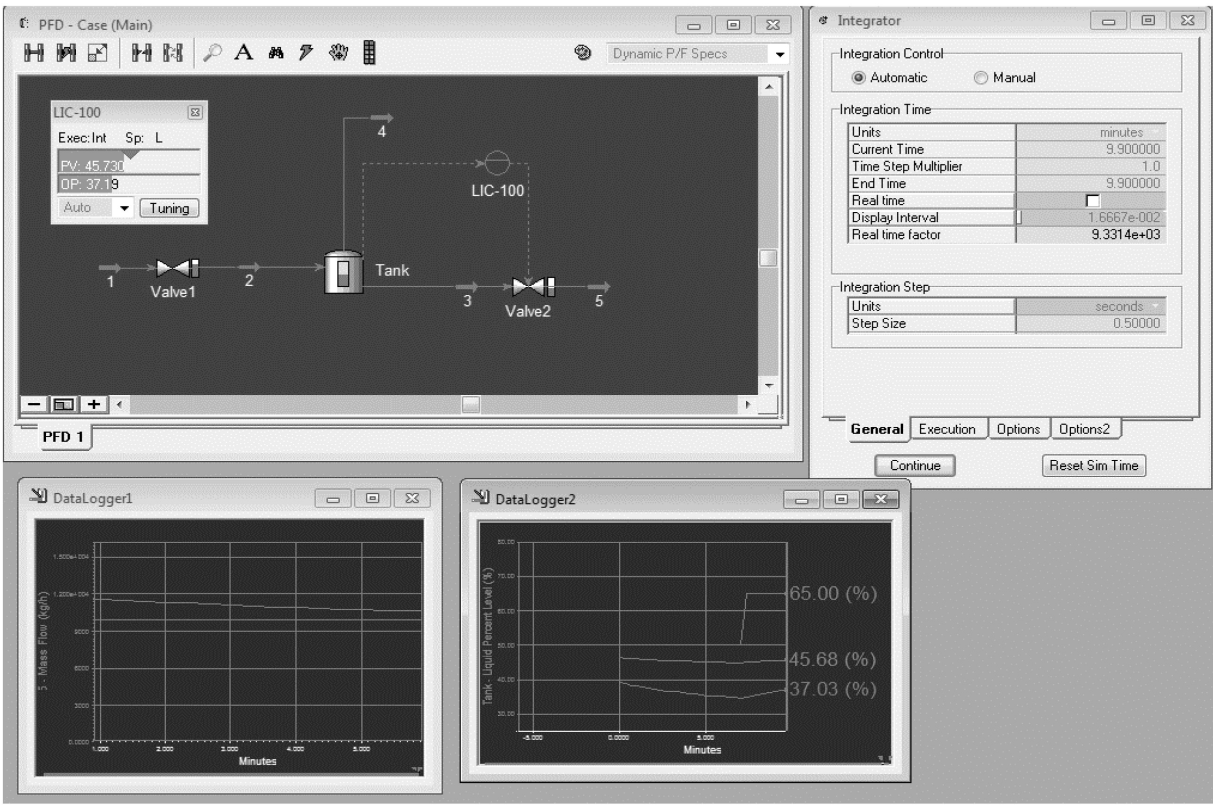

Fig. 1. A screenshot of the tutorial part in lab 3 showing the flow diagram, an integrator and strip charts.

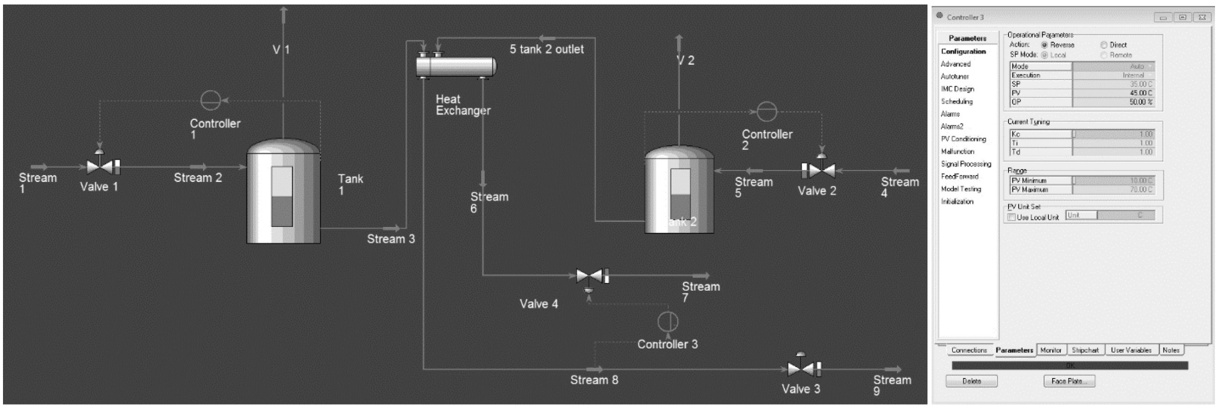

Fig. 2. PID lab activity including two level and one temperature controllers.

effects of manipulated variables on the dynamic behaviour of the system. When students tried different parameters to study their effects on the behaviour of the system, they were using their curiosity to guide their learning. In the lab report, students demonstrated their understanding of the controller tuning and dynamic simulation by reflecting and commenting on the performance of their simulated process. This allowed the instructor to analyze students' understanding of the topic.

Finally, lab 4 included an open-end problem where students were responsible for simulating a biodiesel production plant by applying their knowledge of pumps, tanks, mixers, heat exchangers, reactors, separation columns and other available processing equipment. With the aim of letting students problem solve through trial and error, the instructor provided the required processing parameters, a schematic of a biodiesel production plant, and the kinetics of the transesterification reaction with minimum guidance on how to set-up the whole processing plant. As described above, in order to meet the course learning objective of motivating students to learn mathematic components in their Bioprocess Control & Dynamics course, the instructor allocated lab time for students to complete partner-based problem-solving tasks using UniSim® software.

3. Methodology

In order to better understand student level of interest in learning process design component, students were given surveys at two points; after brief introduction of UniSim® in the Chemical Engineering Concept course (Level II) in 2016 and after UniSim® labs in Bioprocess Control and Dynamics course (Level III) in 2017. As courses involved in this study are mandatory and only offered once a year, most students are enrolled in both courses.

The 2016 survey included questions mostly surrounding previous engineering design practice and group work experiences. The 2017 survey included most of the questions from the 2016 survey, but also asked about UniSim® labs the students had just completed. In the 2016 survey, students (total of 46 students, 20 females) were given a paper-based survey and no incentive while during the 2017 survey, students (total of 40 students, 24 males) were sent an e-mail to their school accounts and were asked to complete an online survey. If they did so, they were entered in a draw to win 1 of 3 $100 gift cards to the student bookstore. Table 2 summarizes the 2017 UniSim® related survey questions which was launched online.

4. Results and Discussion

Students were given surveys in their second-year course in 2016 (paper-based survey) after they were introduced to UniSim® through mass and energy balances, and again after the UniSim® labs in their third-year course in 2017 (online survey). In the second-year course (2016 survey) where students were introduced to UniSim® through one workshop, students indicated a high interest in learning about engineering design in the classroom. Approximately 90% of students indicated they were either fairly interested or very interested in learning about design engineering, as seen in Fig. 3A. Results also showed that students preferred using UniSim® to learn about engineering design, showing at least some level of engagement in using UniSim®, and most students showed interest in learning more about UniSim® (Fig. 3B & C). These positive results encouraged the instructor to incorporate UniSim®-based engineering design labs in their third-year course in 2017. Although 2016 students had only been given a brief workshop of UniSim® in their second-year course, 81% of them concluded that it would be of much or extreme value to continue to learn UniSim® over many semesters.

Table 2. Summary of 2017 online survey questions

• How has the use of (UniSim®) software affected your level of interest in learning about math-based concepts in the engineering design process (check one)?	Decreased my interest greatly	Decreased my interest somewhat	No difference to my level of interest	Increased my interest somewhat	Increased my interest greatly	Unsure
• Why?						
• How do you prefer to learn about math-based concepts in the process engineering design in our courses?	Independent study	Group study				
• Why did you choose the learning preference you did?						
• Identify how competent you are at learning math-based concepts in the process engineering design:	Not at all competent	Somewhat competent	Uncertain	Competent	Highly Competent	
• Identify how comfortable you are in using the UniSim® software to learn about in the process engineering design:	Not at all comfortable	Somewhat comfortable	Uncertain	Comfortable	Very Comfortable	
• Please explain:						
• You will be asked to work in the same groups across two courses: (1) bioprocess control and dynamics and (2) bioreactor processes and design. you will be asked to use UniSim® for these group projects. how valuable is it to work with the same team over many semesters (check one)?	No value	Limited value	Average value	Much value	Extreme value	Unsure/not applicable
• Why did you assign the approach to teamwork the level of value you did?						
• How valuable do you think it is to learn using different software applications for your future employment (check one)	No value	Limited value	Average value	Much value	Extreme value	Unsure/not applicable
• How valuable do you think it is to learn about teamwork for your future employment (check one)?	No value	Limited value	Average value	Much value	Extreme value	Unsure/not applicable
• When you encountered an issue using the software application (UniSim®), who did you ask for help? (check all that apply)	No one	Group member	Peer outside my group	Teaching staff (faculty or TA)	Not applicable	

In 2017, the same students were surveyed after completing the four UniSim® labs (summarized in Table 1) in their third-year course, results of their survey are shown in Fig. 4. According to 2017 survey, over 70% of third-year students indicated the use of UniSim® increased their interest at least somewhat in learning math-based concepts in the process engineering design (Fig. 4A). Similar results were obtained by Richmond and Chen (2012) showing that their model predictive control package which was implemented in an undergraduate course stimulated student interest and laid down a foundation for future learning in technology [14]. Furthermore, 73% of students who participated in the 2017 survey felt competent at learning math-based concepts in process engineering design which, according to expectancy-value theory, was consistent with the first survey question concluding that using UniSim® increased their interest in continuing to learn math-based concepts in the process engineering design. According to the expectancy-value theory, students' performance and therefore their competencies are affected by their interest in the subjects and their expectancies for a successful outcome. Some students thought the use of software made the problems feel more real, but others expressed their frustration with using the software. Morscheidt et al. (2013) showed similar results when implementing software laboratories, as some students appreciated the real and concrete context while others saw the software as a restraint [15]. Students also commented that UniSim® allowed them not only to solve the problems especially the complex ones faster but also to spend more time on analyzing the results which helped them to foster their understanding of the concepts. Similarly, Duch et al., (2010), commented that the students' understanding of a subject and their critical thinking skill could be enhanced using real-life simulation software [16].

Survey results revealed that although 73% of third-year students felt that UniSim® increased their interests in learning math-based concepts in process engineering design and at the same time 73%

of them felt competent of learning math-based concepts in engineering design, only 50% of students felt comfortable using UniSim® to learn about the same concepts while 30% felt somewhat comfortable, and 20% felt not at all comfortable. The authors define competent as "fit" or "having requisite or adequate abilities" and comfortable as "free from vexation or doubt" (Merriam-Webster Dictionary, 2019). It is important to gauge both levels in students because students' competency does not necessarily result in students' comfort. For example, a student could receive a high mark in the course and feel competent about the course materials but wouldn't feel comfortable using what was learnt in the workplace. It is likely that students felt competent of learning math-based concepts in engineering design because they were able to successfully use UniSim® to construct a simulation model while their lack of comfort in using UniSim® could be attributed to their not fully understanding the theoretical background or the design principles. This observation aligns with the results obtained by Dahm, Hesketh, and Savelski (2002) who discussed the pedagogical drawback of simulation packages [17]. They warned that simulation software might allow students to successfully construct and use simulation models without really understanding the physical phenomena. In the survey, students also commented that although it took practice to become familiar with the software, the 3-hour lab was long enough to understand the concept being taught on that specific day and "to get things done".

Students who did not feel the same level of comfort also reflected that UniSim® was difficult to use and that it was hard for them to successfully construct a simulation model and analyze the results. Since ease-of-use promotes learning [3], it is believed that students will feel more comfortable using UniSim® to learn about math-based concepts in process engineering design once they become more familiar with the software. This also relates back to the expectancy-value theory. According to Wigfield and Eccles (2000), people are more inclined to try any activity if they know they can excel at it [18]. Therefore, it is believed that students who

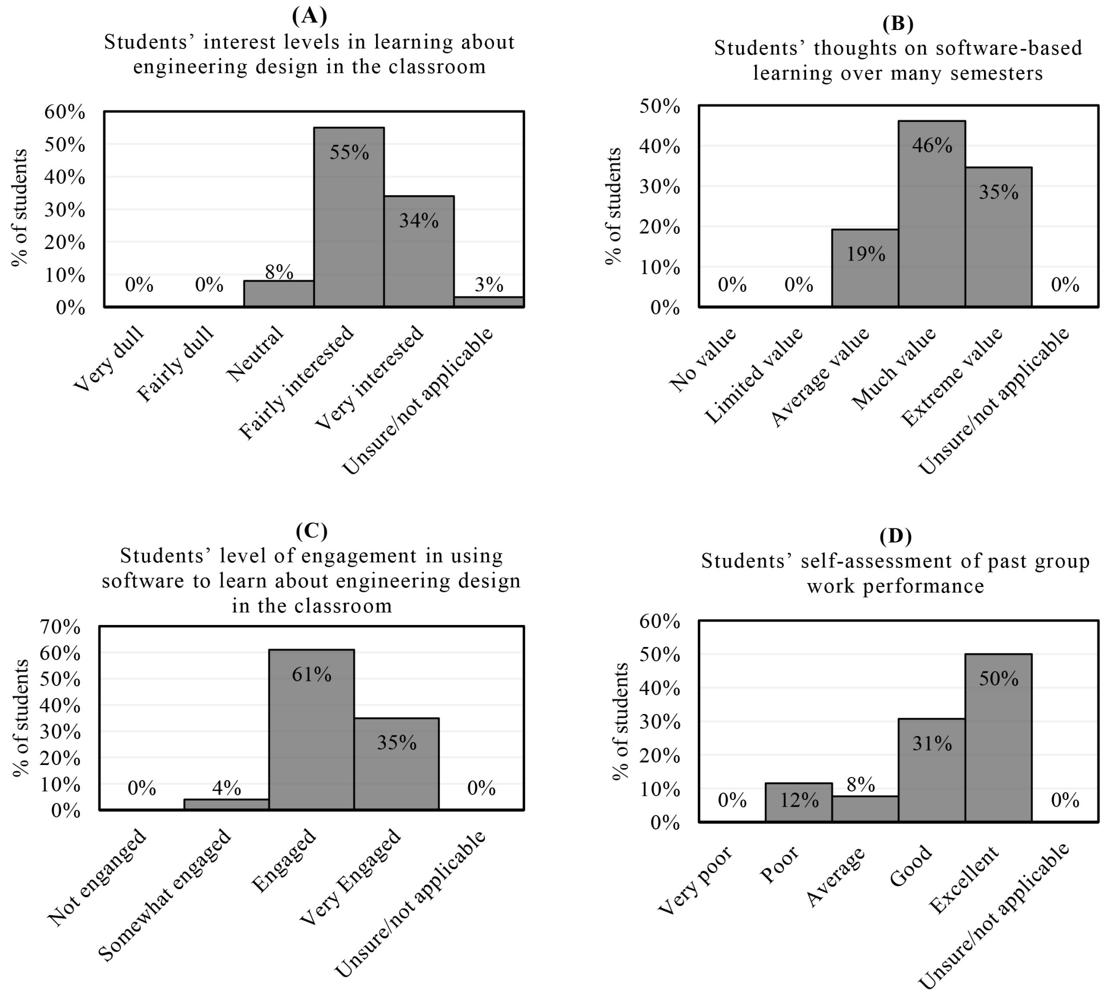

Fig. 3. Results of 2016 survey (second year students).

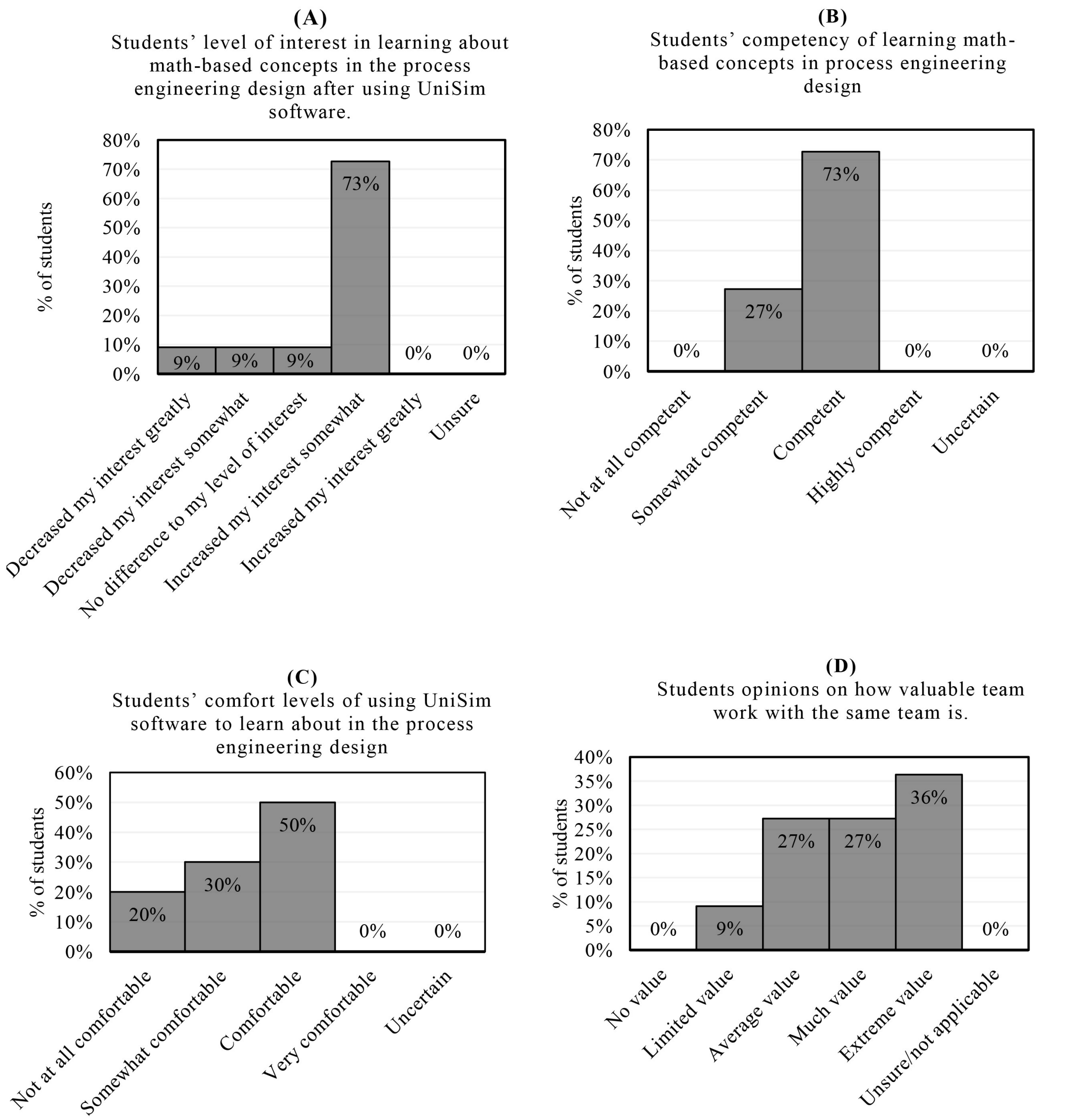

Fig. 4. Results of 2017 survey (third year students).

familiarized themselves with UniSim® felt more comfortable using it because they believed they could excel at it. Similar results were reported by Li and Huang (2017) where they found that students' experiences became more positive as they became more familiar with MATLAB software and the inverted-classroom style they were using [19].

As group work was such an important facet of these tasks, these surveys also included questions about students' experience problem-solving while in teams. Using a Likert scale question, students were asked to rate their performance when it came to group-work in the past while taking into consideration their level of interest and engagement in the group-work assignment. Approximately 80% of second-year students (survey 2016, Fig. 3D) felt that their group work experiences were good and excellent. Results of the 2017 survey showed that only 63% of third-year students (Fig. 4D) felt that there is much and extreme value in working with the same group over time. Third-year students' willingness to work with the same group was likely because students became familiar with their colleagues' work habit, strength, and weakness which helped them to develop a tolerance toward the diversity and adjust themselves to work effectively in the group [20]. Students explained that working with the same group in various projects allowed them to build trust with their group members and avoid conflicts. The remaining 37% of third-year students felt there is limited and average value in

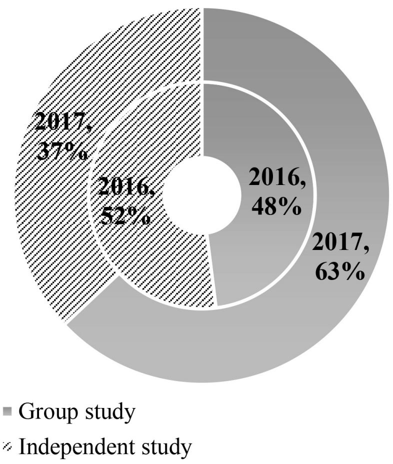

Fig. 5. Second- and third-year students' learning preference.

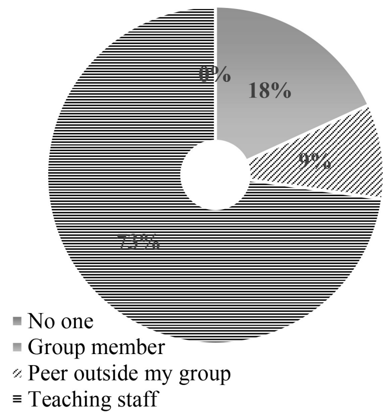

Fig. 6. Third-year students' preference on who to ask for help in labs.

working with the same group over time likely because of their poor group work experience. In a separate study by the first three authors, conflict between group members due to different personalities, ideas or work methods proved to be the greatest drawback to collaborating with peers for group work. The same authors also reported that third-year students rated their performance higher than second-year students' performance likely due to students becoming more comfortable with their role in a team.

One question posed in both surveys asked whether students preferred learning independently or in groups. Results from the survey (Fig. 5) showed that 48% and 63% of second-year students (2016 survey) and third-year students (2017 survey), respectively, preferred working in groups. The results aligns with the results showed in Fig. 4, that 63% of third-year students felt that there is much and extreme value in working with the same group over time suggesting the strong correlation between students' preferred learning method (independently or in groups) and their feeling about the value of working with the same groups over time. Some of the reasoning for working in groups included helping each other and sharing ideas which consequently enhance students' interest levels in the subject matter according to Humphreys et al (2001), while reasons to work alone included going at one's own pace or not needing to depend on other students [21]. Multiple students who preferred working alone specified that after initially learning at their own pace, they can incorporate and apply their knowledge in a group. Students also commented that group work allowed them to adapt themselves to other's working style in order to work more efficiently with least conflict. The results from this survey align with the results obtained by Othman et al. (2012) where they found that upper-year students were more comfortable to work in a group as they gave more commitment to the group work and tried to adapt better with the environment [22].

Fig. 6 shows that 72% of students prefer asking an instructor for help during simulation labs while 28% prefer to ask either someone in their group or a member of another group. The authors hope this number will change especially with the further implementation of group work related activities within the biotechnology program.

Second year students were also asked to rank their preferred learning methods for learning about process engineering design in the classroom, results are shown in Fig. 7. Their options were lab experiments and reports, problems and case studies, design software, and in-class problem solving. Survey results showed that design software and in-class problem solving were the most and least, respectively, preferred choices for students to learn about engineering design which confirm the results shown in Fig. 3.

5. Limitations and Future Work

Some limitations recognized by the researchers include the small sample sizes used for the survey. There were 26 participants in the in-class survey, which made up 60% of the second-year class. There were only 11 participants for the online survey the following year after the Bioprocess class 30%. The authors understand that these sample sizes are small, particularly for the second online survey. Despite the small sample sizes, the information acquired introduces us to students' thoughts and opinions on the software. This data can be used in the future to give researchers a baseline. The survey delivery method will be reconsidered, as there were more participants when the survey was given in-class on paper as opposed to online. It is the hope to expand the software further into the second-year

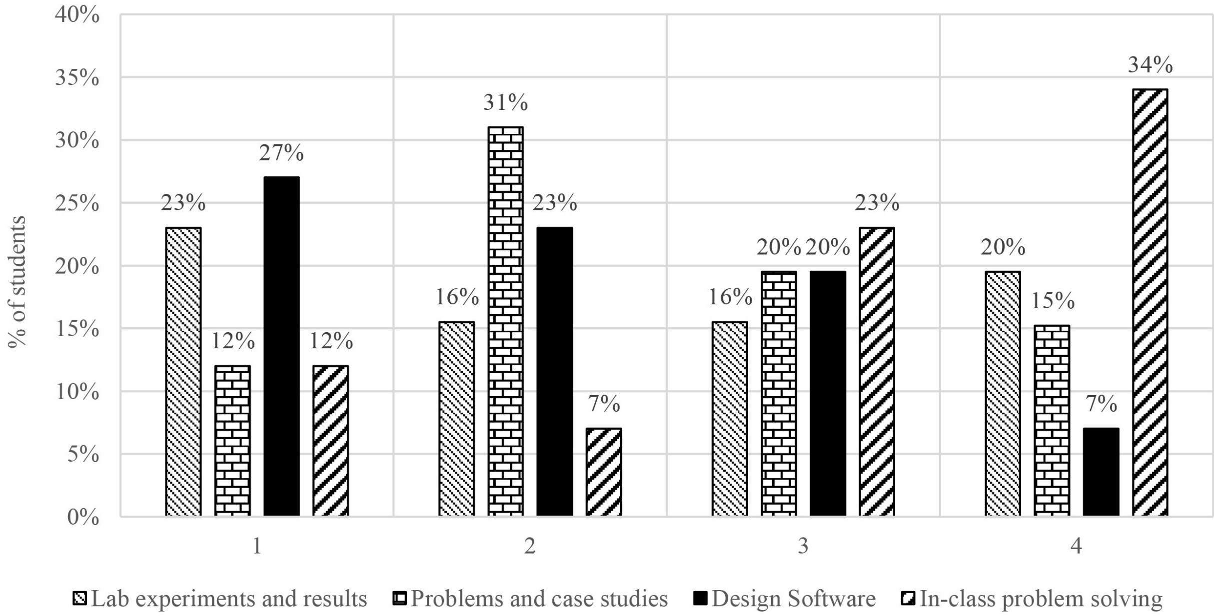

Fig. 7. Second year students' preferred learning method.

course, giving students more time using the software. This will ideally allow students to feel more comfortable using the software over time.

6. Conclusions

This paper presented the successful integration of software-based learning, specifically UniSim®, to teach the concepts of process engineering design in the Biotechnology curriculum. The success was defined as to whether students self-identified as being more engaged with the course material to learn engineering design concept. Students were surveyed after brief introduction of UniSim® in the Chemical Engineering Concept course (Level II) in 2016 and after UniSim® labs in Bioprocess Control and Dynamics course (Level III) in 2017. Survey results showed that although 73% of third-year students felt that UniSim® increased their interests in learning math-based concepts in process engineering design. Results showed that students felt competent of learning math-based concepts in engineering design because they were able to successfully use UniSim® to construct a simulation model while their lack of comfort in using UniSim® was likely because they didn't fully understand the theoretical background and the design principles. The results presented in this work suggested a strong correlation between students' preferred learning method (independently or in groups) and their feeling about the value of working with the same groups over time. Upper-years students showed higher preference in working in groups specially working with the same group over time.

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