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Use Of The Triple-Bottom Line Framework To Examine The Design Tendencies Of First Year Engineering Students

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ABSTRACT

Engineering design often requires the examination of multiple different factors and a design selection based on compromise between these factors. An engineer's preexisting values and experiences can influence design decisions. Therefore, knowing and understanding these design tendencies can prove valuable in guiding engineering students with their future design selections. The purpose of the project is to examine the design tendencies of first year engineering students using an interactive web-based virtual reality (VR) module focused on the triple-bottom line framework. The triple bottom line sustainability framework measures design in three key areas: people, profit and planet. The course for which the interactive module has

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been developed is a first-year engineering course called Chemistry of Natural and Engineered Systems. The activity is based around the chemical production of 6-aminopenicllianic acid through hydrolysis of Penicillin-G. This paper presents an explanation of the interactive web-based VR module, explores student design tendencies before an optimization problem, evaluates their design selections while completing the optimization problem and analyzes student reflections. Determining students design tendencies before the VR activity will help the teaching team gain insight into student thinking process about engineering design and determine the extent of variability of first year student design tendencies. We also envision this project as the first step of a longitudinal project to investigate the influence of undergraduate engineering education on student design tendencies.

1 INTRODUCTION

Engineering design can be defined as an iterative, systematic process for solving problems that involves creativity, experience, and accumulated disciplinary knowledge (National Assessment Governing Board, n.d.). For most undergraduate engineering programs, the design process and the elements of complex problem solving along with “engineering science” are introduced to students in the first and second year of their programs and then applied in senior undergraduate courses (Dym et al., 2005). This is based on the notion that students require discipline specific knowledge and experience before they can appropriately apply the design process. A delay in introducing discipline specific design activities can be seen as an obstacle but it also presents an opportunity to study pre-existing design tendencies. Therefore, the first-year undergraduate engineering would be an ideal time to examine student design tendencies given we, as educators, have not provided them with design guidance and instruction that might influence their propensities.

Engineering design also requires knowledge beyond technical knowledge such as sustainability. Sustainability has become an integral part of engineering education (Abd-Elwahed & Al-Bahi 2021), given the United Nations 2030 agenda for sustainable development goals (Tseng et al., 2020). Watson et al., (2013) has distinguished two types of sustainability integration into the curriculum: vertical and horizontal. Adding a specifica sustainability course to the curriculum woud be an example of vertical integration, while horizontal integration involves including sustainability topics across several courses. Active learning pedagogies, including problem based learning, role plays and case studies has been identified as effective approaches to teach sustainability (Segalàs et al., 2010). For example, in a study by Von Blottnitz et al., (2015) a new first-year core course was designed for chemical engineering focusing on sustainable development. A focus of the course is on ‘natural foundations’ which introduces nature not just as the source of raw materials but also as ‘mentors and models’. The course involves both theory delivered through lectures as well as group projects and writing assignments.

A critisim associated with integrating sustainability in the curriculum is the exclusion of the social and economic dimensions by focusing only on environmental dimensions (Watson et al., 2013). To address all those dimensions, the triple bottom line framework first proposed by Elkington (1997) could be used which attempts to find compromise and sustainability between planet, people and profit. Triple bottom line was redefined by Carter and Rogers (2008) as follows: “sustainability should hold economic performance, the natural environment and society at a broader level, and the intersection of social, environmental and economic activities can help organizations become engaged in activities that not only positively affect the natural environment and society but that also result in long-term economic benefits and competitive advantage for the firms.”

The purpose of the project is to examine the design tendencies of first year engineering students using an interactive module based on the triple-bottom line sustainability framework. The triple bottom line framework was selected for this study given its ease of understanding/applying and the strong emphasis on sustainability in engineering and engineering education. The aim is to help students become aware of their design tendencies and complete one of their first design experiences in the form of an optimization scenario, while introducing the concept of sustainability. The interactive module includes a desktop Virtual Reality (VR) chemical plant where students can change variables for the chemical production of a compound. The use of VR provides an immersive and interactive learning environment for students and provides a means to easily change the variables and observe the effect on outcomes of the reaction. In this study we defined design tendencies as the degree to which students focus on people, or planet or profit in an engineering design. The VR was used as a tool to embed sustainability in the course and hence not the focus of the study.

2 METHODOLOGY

2.1 Course setting

The course for which the interactive module has been developed is a first-year engineering course called Chemistry of Natural and Engineered Systems at Queen’s University. The course introduces thermodynamics, chemical process dynamics, and electrochemistry in the context of sustainable engineering design. The course is delivered face-to-face through lectures and tutorials to over 700 students.

2.2 Triple bottom line interactive module: description

The triple bottom line interactive module is an extension and complementary to an assignment completed earlier in the semester. The assignment is based around the chemical production of 6-aminopenicllianic acid (6-APA) through hydrolysis of Penicillin-G (Pen-G) shown in Figure 1. The students are asked to generate an expression for the rate of Pen-G hydrolysis as a function or reagent concentrations. Next, students are asked to use their rate expression to predict the time in hours that is required to achieve 50%, 95%, and 99.9% conversion of Pen-G to 6-APA. The aim of this assignment was to provide students with some background knowledge about the reaction and the variables affecting the reaction outcomes.

The assignment is followed by an interactive module hosted on Articulate RISE 360, and includes explanation of relevant concepts, a web-based Virtual Reality (VR) exercise for the chemical process of 6-APA and reflection questions. More specifically, the module begins with a description of the exercises and learning objectives, an overview of the chemical process including the reaction, and process block flow. Students are then presented with a description of independent variables for the reaction such as pH, temperature and catalysts which can affect the outcome variables such as rate constant, mass of product and energy consumption, with the latter contributing to people, planet, profit variables. The module provides the students with a review of the concepts used for earlier calculations in the completed assignment. A process well known to the students was selected so that they were not required to learn new material and could focus on the optimization problem.

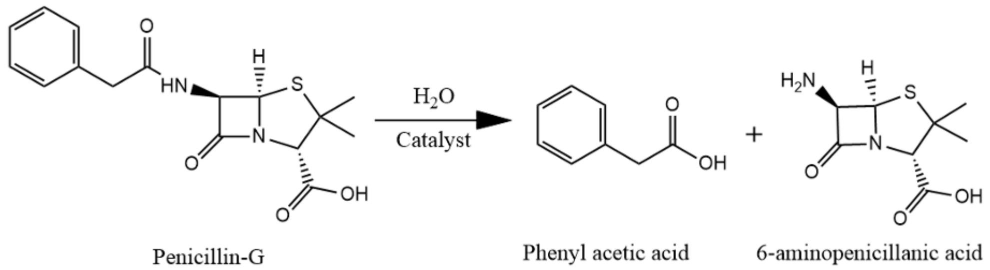

Fig. 1. Chemical reaction for production of 6-amino-penicillianic acid

A short description of the triple bottom line framework is then provided, followed by variables used to calculate a sustainability index in the VR. Examples of the variables include process hazard index (people variable), equivalance CO_2 emissions and volume of aquoues waste (planet variable), and cost of reagents, heating and utilities (profit variables). Students then complete a survey where they are asked to examine their design tendencies by allocating points to people, planet and profit, and providing a brief explanation for their rationale. This is referred to as the pre-VR survey throughout the paper.

Next, students are instructed to download the VR application on their desktop. Once in the VR environment, they have the opportunity to first tour the chemical plant (Figure 2), and are guided to find specific unit operations inside the plant which are relevant to the production of 6-APA. Students can then enter the control room where they can examine the structure of the product (Figure 2).

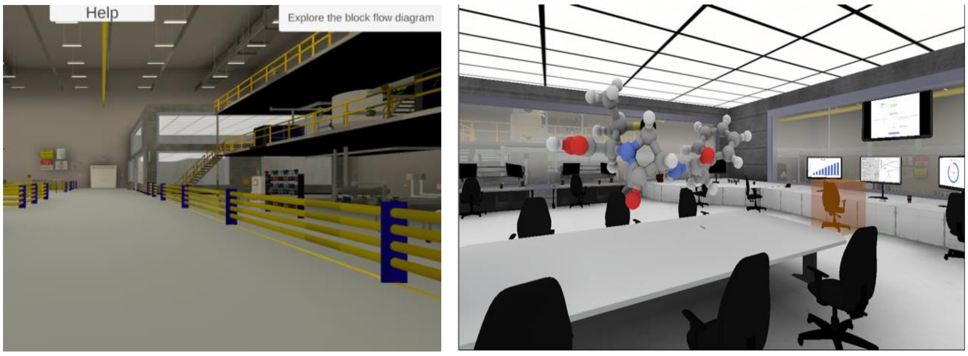

Fig. 2. Tour of chemical plant (left) and chemical plant control room (right) within the virtual reality environment

Next, students are asked to enter the variables obtained in their earlier assignment to understand how they affect the triple bottom line sustainability score. For this module, the semi-quantitative methodology developed by Penn & Fields (2017) was adapted which rates a design for each of the 3Ps using a radar chart as below (Figure 3). Each of the 3Ps is given a value from 0 to 100 which forms a triangle representing the relative values of each P. Any imbalance among the 3Ps will be apparent in the radar chart.

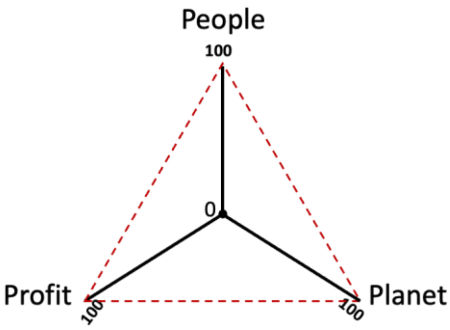

Fig. 3. Triple bottom line radar chart. Adopted from Penn & Fields (2017)

A sustainability index score can then be calculated as follows (Penn & Fields, 2017):

SI = [sum of 3Ps – (maximum of 3Ps – minimum of 3Ps)],

- 0: completely unsustainable
- 100: Moderately unsustainable
- 200: Moderately sustainable
- 300: Fully sustainable

Students are then instructed to optimize the chemical production of 6-aminopenicillianic acid based on their own design tendencies. They can observe the effect of changing each variable on people, planet, profit and the overall sustainability index (Figure 4). The module ends by asking students to write a short reflection for their rationale in choosing those variables, and two Likert scale questions about their design tendencies and the future use of this information.

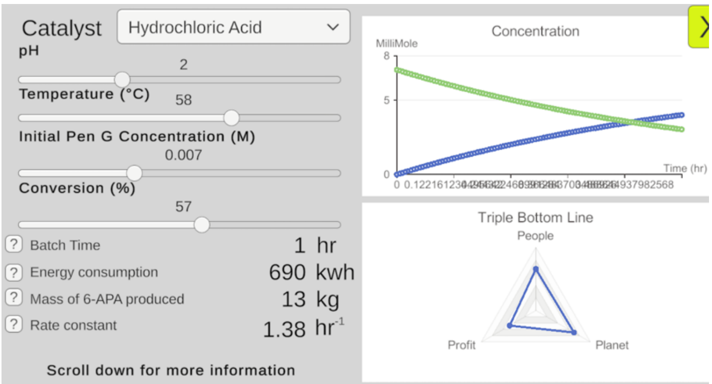

Fig. 4. VR control room triple bottom line display and user interface

3 RESULTS

At the beginning of the RISE module students were presented with a consent form to use their data for research. 356 students provided consent. 292 students filled out both the pre-VR survey and the VR exercise. In the pre-VR survey, students were asked to allocate 100 points to people, planet and profit. 13 responses were removed because the scores students provided did not add to 100.Table 1 shows the average score for each of these variables: People and planet almost scored the same, with profit having the lowest score. In the VR exercise, students were asked to optimize the people, planet, profit variables for the chemical production of 6-APA based on their own design tendencies. Interestingly, profit had the highest score with planet having the lowest score (Table 1). The last column shows the change in average scores and is calculated by subtracting pre-survey scores from the VR exercise scores. As shown, profit has the largest positive change given it had the highest score in VR. This indicates that students might have a pre-existing tendency to consider profit as not as important as other variables; however, when applying the triple bottom line framework to this optimaization problem profit played a larger role in sustainability.

Table 1. Students' triple-bottom line scores for pre-VR survey and VR optimization exercise(N=279)

	PreVR Survey		VR Exercise		Difference (VR - preVR survey)
	M	SD	M	SD	
People	37.46	6.44	33.66	3.06	-3.80
Planet	35.97	6.62	32.36	1.61	-3.61
Proft	26.96	8.01	35.36	4.03	+8.40

The aim was for students to choose the VR variables based on their own design tendencies. However, the open-ended responses related to student justification indicate that students might not have relied completely on their own tendencies. Most students commented that that they aimed for a balanced radar chart and a high sustainability index score. The radar chart visualization (Figure 4) might have affected student decisions and guided them to create an equilateral triangle. Thus, the pre-VR survey might be more indicative of students' design tendencies.

Students were also asked to rate two Likert scale questions on the effect of the module in helping them understand their design tendencies and the use of their design tendencies to inform their future design activities. Table 2 shows the response percentages with over 70% of students agreeing to both statements (N=186). While acknowledging the limitations of this survey given the limited number of questions asked, it provided encouraging results for follow-up studies to develop a more robust survey instrument and/or conduct longitudinal studies to explore student design tendencies as they move through the undergraduate engineering education.

Table 2. Students' responses to two Likert scale survey statements (N=186)

	Strongly agree/Agree	Neutral	Strongly disagree/disagree
The triple bottom line module (the background information, reflection questions, VR design activity) provided me with insight into my design tendencies.	71%	24%	5%
I will use the knowledge regarding my design tendencies to inform my future design activities	73%	26%	2%

Students were also asked to explain their answer for the use of the design tendencies in their future design. The majority of students indicated that they would use the triple bottom line framework and would consider its variables in their design to aim for a sustainable design. This was a more superficial response focused on the VR experience whereas the instructional team was interested in a deeper reflection. This could have been because of the statement wording or that it might be difficult for students to comment on their future deign tendencies given that they don't have extensive design experience. However, a few interesting themes were observed. One was awareness of bias; a number of students indicated that they will be more aware of their bias in their future design activities . For example, one student mentioned:

"*Knowing how I consider design, I can move forward with design activities with my own bias in mind."*

While another student commented:

"*My future design choices will be led by a more thorough and thoughtful approach to the benefits and disadvantages of design decisions. I feel as though I better* *understand my own way of thinking, and I can use this knowledge to prevent personal bias from interfering in decisions pertaining to engineering."*

Bias has been observed in engineering design industry and specifically is associated in idea selection step (Onarheim and Christensen 2012; Toh et al. 2015), and this understanding and evaluating personal bias is important for engineering students. One such bias is the ownership bias which is preferences for one's own ideas compared to other people's ideas (Toh et al. 2015). In a study by Cooper et al. (2002) it was found that design companies face challengues during idea screening and selection because of designers' bias, which could impact the final design and success of design (Hambali et al. 2009). Though different than ownership bias, the module appeared to have helped students become aware of their bias with respect to the triple bottom line framework.

Some students also indicated that in the future they will be more aware that all decisions and factors will have an impact and outcome. For example:

"*I was shown how small tweaks in a project parameter can have a great impact on the environment, people and also the profit of the project."*

Other interesting responses included consideration of "*multiple difference methods prior to creating a design," "to always consider the ethical concerns," "to orient my design towards the betterment of society,"* and *"I now know that when making a design it does not always happen correctly on the first try. "*

4 CONCLUSION AND FUTURE WORK

An interactive module based on triple bottom line was developed and implemented in a first-year undergraduate engineering course to examine student design tendencies. The module complemented an earlier assignment in the course on chemical kinetics. The interactive modules included a desktop VR environment which provided a simulated environment to easily adjust variables to optimize a chemical reaction based on the triple bottom line framework. Results indicated differences in student initial design tendencies and in the optimization scenario. Students also indicated the module helped them in understanding their design tendencies and that they will use this knowledge in the future.

Our future plans include using the themes from the student open-responses and literature to create an instrument on design tendencies to study and examine it in a more systematic way. Investigating student optimization responses with and without visualizing the radar chart and using qualitative data such as think-aloud or focus groups will also help us to design a more effective module. A longitudinal study tracking student design tendencies as they move through the 4-year undergraduate engineering education would help us to examine the effect of the program on student design tendencies.

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