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Develop the Mindset of Engineering for One Planet in Chemical Process Control

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Abstract: It is important to incorporate environmental, economic, and social considerations when we design control systems. While fossil energy will be used up in the future, converting solar energy to electric energy provides one potential solution to sustain the growth of the world population. The batteries play an essential role in electric energy storage, especially for electric vehicles (e.g., Tesla EV). The switch from traditional energy resources to renewable energy brings challenges and opportunities to chemical engineers who generally work in the oil & gas industry. To make students aware of these challenges and opportunities, a project was developed in the course of Chemical Process Control, which is the last required course taken by senior students in Chemical and Biological Engineering, to develop the mindset of Engineering for One Planet (EOP) in students. In this project, lectures were given to students on the nine core values of EOP, including Systems Thinking, Environmental Literacy, Social Responsibility, Responsible Business and Economy, Environmental Impact Measurement, Materials Choice, Design Mindsets, Critical Thinking, and Communication and Teamwork. After students were given the training materials on EOP Framework after the midterm, including handouts, videos and one lecture on the core concepts of EOP, three students formed a team to provide a two-page proposal on the scope of the project and the alignment of the proposed project with the nine core values of EOP. On the basis of the instructor's feedback, each team started to work on the project and submitted a report summarizing the obtained results by the end of the semester. An anonymous survey was given in class to collect students' feedback through multiple-choice questions on "how the EOP project helps students in learning process control" and "the effectiveness of the project in building the EOP mindset for students". Personal conversations between the instructor and students were conducted to collect information on "the advantages and drawbacks of the EOP project" were also included in the survey. Both the instructor's evaluation and students' self-evaluation indicated that students generally learned and applied the EOP mindsets in their EOP projects. However, they were reluctant to recommend the EOP projects to other students, as students needed to learn EOP techniques like environmental sustainability and life cycle analysis that are not directly related to the focus of Chemical Process Control. Additional instruction videos/materials on EOP may be helpful. In addition, there should be multiple courses in the curriculum to introduce EOP mindset. It is challenging to convince students to learn and use EOP skills just in one course.

Introduction

Global warming has been a significant threat to humans living on the earth. Extensive research has been conducted on switching fossil energy to renewable energy, as this is regarded as been one of the potential solutions to the global warming threat [1], [2]. For example, California will ban the sale of new gas-powered cars by 2035 [3], and governments all over the world design policies to promote electric vehicle deployment [4]. Since oil & gas companies have been one of the major employers of college students in chemical engineering majors, the core courses in chemical engineering are mostly focused on fossil-fuel driven processes. For example, Chemical Process Control is a common core course in chemical engineering for designing controllers to optimize the operation of chemical reactors and prevent accidents in chemical plants [5], [6]. This course mainly deals with refinery processes, storage and transport and mixing of liquids and gases, heat exchangers, batch/fed batch/CSTR reactors and chemical reactions. Few of these processes are directly related to renewable energy. Since the trend to substitute traditional energy with renewable energy is irreversible, it is necessary to warn chemical engineering students of the challenges or opportunities for this transition.

Engineering for One Planet (EOP) is an initiative catalyzed by The Lemelson Foundation and VentureWel to incorporate fundamental skills and principles of social and environmental sustainability in engineering education [7]. In particular, EOP develops a framework to equip students with the following nine core values: Systems Thinking, Environmental Literacy, Social Responsibility, Responsible Business and Economy, Environmental Impact Measurement, Materials Choice, Design Mindsets, Critical Thinking, and Communication and Teamwork. Since five ABET outcomes (especially, Outcomes 2&4) can be directly addressed by the EOP framework, quite a few universities in the U.S. participated in the EOP initiative. Therefore resources, such as publications, websites, and teaching examples, have been accumulating to encourage more faculty participants. Since Chemical Process Control integrates all components in the system in the format of feedback loop, it is essentially in line with the EOP core value of Systems Thinking. Chemical Process Control techniques can be used to reduce environmental pollution and increase the productivity. Therefore, there an organic niche in Chemical Process Control to incorporate the EOP mindsets.

In this work, the EOP concepts were introduced in the course Chemical Process Control for senior students in their last semester. A team project was assigned to three students so that each research team identified a project in which students applied the process control skills, such as feedback loop and controller design, to solve real-world problems related to social and environmental sustainability. Each research team submitted a detailed project report. An anonymous survey was given in class to collect students' feedback through multiple-choice questions on "how the EOP project helps students in learning process control" and "the effectiveness of the project in building the EOP mindset for students". Open-ended questions like "the advantages and drawbacks of the EOP project" were also included in the survey. The surveys from 49 students were then analyzed.

Materials and Methods

The instruction approaches

A 75-minute lecture was given to students about the nine EOP core values, i.e., Systems Thinking, Environmental Literacy, Social Responsibility, Responsible Business and Economy, Environmental Impact Measurement, Materials Choice, Design Mindsets, Critical Thinking, and Communication and Teamwork. References/websites were given by the instructor to the students on EOP mindsets (https://www.lemelson.org/our-work/entrepreneurship/us-education-entrepreneurship/engineering-for-one-planet/) and tools for design and sustainability (https://venturewell.org/tools_for_design/introduction/).

Three students were selected according to the alphabet order of their last names to form a team for a project to design control strategies for renewable energy systems and write a detailed report on their approaches. The following two tasks were assigned to each team.

- Task 1 (40 points, email the instructor of the research proposal): conduct a systems-level comparison between traditional energy (i.e., crude oil) and renewable energy (i.e., solar energy) from the perspectives of environmental literacy, social responsibility, responsible business and economy, life-cycle hazards, and materials choice. The elements for each of these perspectives are listed below. In this task, each team is suggested to present the results in the format of loop diagrams, basic life-cycle analysis. The research team should first check the document “Handout for Engineering for One Planet” for examples of analysis. More technical details for Engineering for One Planet (EOP) can be found in the document.

- Task 2 (60 points, email the instructor of the research report): explore the chances of process control techniques that can be used to design a sustainable energy system. For example, a good control system can enhance the conversion and storage of solar energy into electric energy. A literature review should be helpful for the team in creating the design ideas.

It was mentioned in the project assignment that the nine EOP core values should be reflected in the project proposal and report. These core values were provided by the EOP website. It was mentioned to students that their scores of their projects depend on how much their projects reflected the objectives associated with the nine EOP core values (listed on https://www.lemelson.org/our-work/entrepreneurship/us-education-entrepreneurship/engineering-for-one-planet/)

1. Systems Thinking Core Value
    - Demonstrates whole system awareness with the ability to identify and understand interconnectedness (intersecting, related and/or connected systems; synergies and rebound effects) and how all human-made designs rely upon and are embedded within ecological systems.
    - Is able to consider and understand tradeoffs and identifies impacts between different parts of the system (i.e., environmental, economic and social considerations).
    - Demonstrates awareness that all work is connected to other disciplines and understand when and how to collaborate and consult with others.
2. Environmental Literacy Core Value
    - Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change, water use, scarcity and pollution, air quality, waste management, toxicity, etc.).
3. Social Responsibility Core Value
    - Is able to articulate and understands how engineering activities directly and indirectly cause positive and negative social/cultural impacts throughout the design life cycle, both to workers producing the products (i.e., labor practices, livelihood, health, etc.) and to communities and society (i.e., resources acquisition, waste production and management, traditional/cultural methodologies, etc.), and is aware that communities have historically been negatively impacted and/or minoritized.
4. Responsible Business and Economy Core Value
    - Is able to forecast the near- and long-term costs and value of their work to the environment and society through the efficient use of resources (e.g., efficient for whom?) and socially/culturally responsible engagement with stakeholders.
    - Is aware of the risks and opportunities related to changing environments in their work (e.g., extended costs, value, trade-offs, partnerships, regulations, policies, etc.).
5. Environmental Impact Measurement Core Value
    - Is familiar with high-level environmental impact measurements (e.g., basic life-cycle assessments and life cycle hazards, i.e., how they work, what information they require, how to incorporate their findings into their work).

6. Materials Choice
   - Is aware of the potential impacts of the materials through the supply chain – from raw material extraction through manufacturing, use, reuse/recycling and end of life – with a focus on minimizing negative impacts to the planet and all people (i.e., considering impacts to minoritized groups).
7. Design Core
   - Is able to set design goals and use technical analyses to choose strategies that minimize environmental impact.
8. Critical Thinking
   - Is able to define problems comprehensively with consideration of consequences, unintended and intended.
9. Communication and Teamwork
   - Communicates through audience-specific written, graphical/visual, oral and interpersonal communication skills.

The project evaluation approach

Students' projects were evaluated by the instructor on how much their project proposals and reports reflected the aforementioned 9 core EOP values. A rubric was created for each EOP core value so that the students of each team were assigned one of the following assessments:

- Category of "Excellent": complete mastery of the concept with no to very minor (e.g. non conceptual) errors – you would rate this selection of student work as an "A".
- Category of "Good": Mastery of the concept with minor errors – you would rate this selection of student work as an "B".
- Category of "Average": Satisfactory attainment of the concept with some errors – you would rate this selection of student work as an "C".
- Category of "Below Average": Limited attainment of the concept – multiple errors – you would rate this selection of student work as an "D".
- Category of "Unsatisfactory": Unsatisfactory attainment of the concept – many grave errors – you would rate this selection of student work as an "F".

In addition to the evaluation of the instructor on students' projects, an anonymous survey was sent to each student who participated in the EOP projects. The questionnaire includes two sections: the first one is used to evaluate whether the EOP project helps students in learning the course Chemical Process Control (Table 1), while the second section deals with students' self-evaluation of their EOP skills (Table 2). The questions in Table 2 are directly related to the thirteen objectives associated with the nine EOP core values (as shown in the previous subsection, i.e., the instruction approaches). The questionnaire shown in Tables 1 and 2 was designed on the basis of those from the literature [6], [8]. The mean value of each item was then presented to visualize the results.

Table 1, Questions in the survey on whether the EOP project facilitates students' learning in chemical process control.

Please evaluate how the "Engineering for One Planet (EOP)" project helps you in learning process control

Please rank the effectiveness of these training materials in enhancing your learning experience in process control. "1" means the project is not helpful at all, while "5" means the oppositive.	Strongly disagree Strongly agree
(1) The term project helps you understand the concepts in process control.	① ② ③ ④ ⑤
(2) The term project allows you to implement process control in real-life scenarios.	① ② ③ ④ ⑤
(3) The term project makes you aware of your responsibility in engineering for one planet.	① ② ③ ④ ⑤
(4) You will keep EOP mindsets in your future careers.	① ② ③ ④ ⑤
(5) Your future work is related to engineering.	① ② ③ ④ ⑤
(6) You recommend this project for future students in process control	① ② ③ ④ ⑤

Table 2, Questions in the survey on students' self-evaluation of their EOP mindset after the EOP projects

Please evaluate the effectiveness of the project in building the "Engineering for One Planet (EOP)" mindset for you

Please rank the effectiveness of the term project in enhancing your learning experience in the EOP core values. "1" means the project does not help you build the EOP mindset at all, while "5" means this project helps you build a strong EOP mindset.	Strongly disagree Strongly agree
(1) Demonstrates whole system awareness with the ability to identify and understand interconnectedness	① ② ③ ④ ⑤
(2) Is able to consider and understand tradeoffs and identifies impacts between different parts of the system (i.e., environmental, economic and social considerations)	① ② ③ ④ ⑤
(3) Demonstrates awareness that all work is connected to other disciplines	① ② ③ ④ ⑤
(4) Understand when and how to collaborate and consult with others	① ② ③ ④ ⑤
(5) Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change)	① ② ③ ④ ⑤
(6) Is able to articulate and understands how engineering activities directly and indirectly cause positive and negative social/cultural impacts throughout the design life-cycle, both to workers producing the products	① ② ③ ④ ⑤
(7) Is able to forecast the near- and long-term costs and value of their work to the environment and society through the efficient use of resources	① ② ③ ④ ⑤
(8) Is aware of the risks and opportunities related to changing environments on their work (e.g., extended costs, value, trade-offs, partnerships, regulations, policies, etc.)	① ② ③ ④ ⑤
(9) Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change)	① ② ③ ④ ⑤
(10) Is familiar with high-level environmental impact measurements (e.g., basic life-cycle assessments and life-cycle hazards)	① ② ③ ④ ⑤
(11) Is aware of the potential impacts of the materials through the supply chain – from raw material extraction through manufacturing, use, reuse/recycling and end of life	① ② ③ ④ ⑤
(12) Is able to set design goals and use technical analyses to choose strategies that minimize environmental impact	① ② ③ ④ ⑤
(13) Is able to define problems comprehensively with consideration of consequences, unintended and intended	① ② ③ ④ ⑤

Results

There were 16 projects done by the 49 students, with three students in 15 teams and four students in one team. The topics of these projects included but were not limited to the process control and analysis for processes for nuclear fission, wind turbines, photovoltaic systems, hydroelectric power plants, battery systems, and renewable bioenergy. Students' performance for the nine EOP core values (or outcomes) was evaluated by the instructor. As shown in Table 3, none of students had scores below average (i.e., 60 points) or unsatisfactory. According to the percentage of students with excellent performance, students showed the best performance in "Environmental Literacy" (100%) and "Design Mindsets" (100%), which were followed by "Environmental Impact Measurement" (79%), "Critical Thinking" (79%), "Systems Thinking" (64%), "Materials Choice" (62%), "Social Responsibility" (47%), "Communication and Teamwork" (45%), and "Responsible Business and Economy" (19%). The core values with lower percentages with excellent performance generally returned higher percentage with good performance.

Table 3, The instructor's evaluation of student performance in the nine EOP core values from their project proposals and reports.

EOP Outcomes	% of students scoring excellent	% of students scoring good	% of students scoring average	% of students scoring below average	% of students scoring unsatisfactory
Systems Thinking	64%	30%	6%	0%	0%
Environmental Literacy	100%	0%	0%	0%	0%
Social Responsibility	47%	32%	21%	0%	0%
Responsible Business and Economy	19%	68%	13%	0%	0%
Environmental Impact Measurement	79%	21%	0%	0%	0%
Materials Choice	62%	26%	13%	0%	0%
Design Mindsets	100%	0%	0%	0%	0%
Critical Thinking	79%	21%	0%	0%	0%
Communication and Teamwork	45%	49%	6%	0%	0%

In addition to the instructor's evaluation of the nine EOP values reflected in students' project proposals and reports, an anonymous survey was distributed to students for their self-evaluation on how the EOP project facilitated their learning in chemical process control and how much they mastered the EOP mindset. Table 4 shows the average scores for each question shown in Table 1. As for "Q1 - The term project helps you understand the concepts in process control", an average score of 2.74 was obtained. An average score of 3.18 was obtained for "Q2 - The term project allows you to implement process control in real-life scenarios". Students evaluated their projects with higher scores for "Q3 - The term project makes you aware of your responsibility in engineering for one planet" (an average score of 3.59), "Q4 - You will keep EOP mindsets in your future careers" (an average score of 3.69), and "Q5 - Your future work is related to engineering" (an average score of 3.97). Surprisingly, a low score of 2.82 was obtained for "Q6 - You recommend this project for future students in process control".

Table 4, Students' self-evaluation on how the EOP projects facilitated their learning in chemical process control

Questions on how the EOP projects facilitated their learning in chemical process control	Average Score
(1) The term project helps you understand the concepts in process control.	2.74
(2) The term project allows you to implement process control in real-life scenarios.	3.18
(3) The term project makes you aware of your responsibility in engineering for one planet.	3.59
(4) You will keep EOP mindsets in your future careers.	3.69
(5) Your future work is related to engineering.	3.97
(6) You recommend this project for future students in process control	2.82

All students responded to the survey, as it was conducted in person before students took the final exam. In the second section of the questionnaire, students evaluated their EOP skills. The average scores for each question shown in Table 2 are shown in Table 5 below. In most cases, the average score is above or around 3.5.

Table 5, students' self-evaluation scores of the EOP skills that correspond to the objectives shown in Table 2.

Questions	Average Score
(1) Demonstrates whole system awareness with the ability to identify and understand interconnectedness	3.51
(2) Is able to consider and understand tradeoffs and identifies impacts between different parts of the system (i.e., environmental, economic and social considerations)	3.74
(3) Demonstrates awareness that all work is connected to other disciplines	3.85
(4) Understand when and how to collaborate and consult with others	3.72
(5) Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change)	3.45
(6) Is able to articulate and understands how engineering activities directly and indirectly cause positive and negative social/cultural impacts throughout the design life-cycle, both to workers producing the products	3.72
(7) Is able to forecast the near- and long-term costs and value of their work to the environment and society through the efficient use of resources	3.49
(8) Is aware of the risks and opportunities related to changing environments on their work (e.g., extended costs, value, trade-offs, partnerships, regulations, policies, etc.)	3.51
(9) Demonstrates knowledge of the basic facts and ability to quantify data about important (current/past/future and local/regional/global) environmental issues (e.g., climate change)	3.56
(10) Is familiar with high-level environmental impact measurements (e.g., basic life-cycle assessments and life-cycle hazards)	3.64
(11) Is aware of the potential impacts of the materials through the supply chain – from raw material extraction through manufacturing, use, reuse/recycling and end of life	3.59
(12) Is able to set design goals and use technical analyses to choose strategies that minimize environmental impact	3.54
(13) Is able to define problems comprehensively with consideration of consequences, unintended and intended	3.64

Discussion and Conclusion

In Chemical Process Control, the system engineering concepts, such as negative feedback loops and PID controllers, were introduced before the introduction of the EOP framework. While students were asked to design control systems for new energy processes or systems, the control system design was mainly in the format of diagrams, with limited mathematical model or controller information. This may explain that an average score of 2.74 for "Q1 - The term project helps you understand the concepts in process control" in Table 4. Students had to spend time in learning and applying EOP concepts that were not directly related to process control, such as environmental impact measurements and life cycle analysis. Few students had learned these concepts from other courses. The instructor realized this via students' feedback on open-ended questions. This may explain an average score of 2.82 "Q6 - You recommend this project for future students in process control".

The evaluation from both the instructor and the students indicates the students generally learned and used EOP concepts via the EOP projects. Feedback from open-ended questions implied that students would appreciate any training videos or materials they can learn more about EOP. A 75-minute lecture and provided websites may not provide sufficient support to students as the EOP concepts are not the focus introduced in the course Chemical Process Control. It is challenging for students to pick up the EOP mindsets just through one course. Students would be more motivated if the EOP mindset was introduced in multiple courses before this last course (i.e., chemical process control) in the curriculum.

EOP concepts and projects were introduced to 49 senior students in the course of Chemical Process Control in Spring 2022. While students showed EOP mindsets or skills in their EOP projects via their self-evaluation and the instructor's evaluation, students showed resistance to the EOP projects. More supporting materials, such as videos/lectures, for EOP techniques, are needed to support students' learning. In addition, the projects should incorporate more process control techniques, such as Laplace transform modeling or PID controller design of renewable energy processes, which would motivate students more to participate in the EOP project.

The lessons and supporting materials designed in this project have the potential to be used in other courses, such as Process Design or Material Balance, as the lessons mainly focus on the introduction of the EOP concepts. However, students' projects may be changed for other courses. For example, the feedback loop was in line well with systems thinking, so that projects related to control system design fit well with the scope of Chemical Process Control. As for Process Design, the life cycle analysis should be emphasized more in the students' project.

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