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Using Student Generated Senior Design Project Ideas to Achieve ABET Student Outcomes in a Chemical Engineering Process Design and Economics Course

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Abstract

Offering modern and engaging senior design projects is a challenging and time consuming task for chemical plant design instructors. Further, an offering of a chemical plant design project course may not include projects that align with student interests within the cohort. At the University of California Davis, a course in Process Design and Economics is a required senior-level course prior to the Plant Design Project course. In addition to the challenge of offering modern and engaging design projects, assessing students' ability to achieve the Accreditation Board for Engineering and Technology (ABET) student outcomes in these design courses using standard quiz and exam-type assessments can be difficult. In an effort to improve the assessment of ABET student outcomes in the Process Design and Economics course, as well as to offer modern and engaging senior design projects, students were tasked with proposing their own senior design project idea in the Process Design and Economics course for potential use in the Plant Design Project course. This design project proposal assignment required students to describe a potential design project idea and assess its potential merits using input/output (I/O) economics, safety, and societal assessments. The best proposals were considered for implementation as senior design projects in the Plant Design Project course.

After the completion of the assignment, students were voluntarily surveyed to gauge their perception of the effectiveness of the assignment as a measurement of their ability to develop a preliminary design idea. They were also surveyed to measure their perception of how strongly the ABET outcomes for the course mapped to this assignment. Student performance on the assignment was assessed on the basis of the students ability to 1) communicate in writing effectively, 2) design a preliminary process to meet a societal need within realistic constraints, 3) understand ethical responsibilities and potential safety issues, 4) understand the impact of the proposed design project in a global, environmental, and societal context, 5) gain a knowledge of contemporary issues, as well as 6) gain an ability to engage in life-long learning by immersing themselves in the literature. The survey results indicated that a majority of the students felt they achieved the ABET outcomes targeted by this assessment and gained an appreciation for how a plant design project idea is developed. Further, specific outcomes of this assessment appear to be especially beneficial to both female and under-represented minority (URM) students. Three new senior design projects have been adopted for the Plant Design Project course, initiated by the student ideas proposed though this assignment.

Introduction

At the University of California Davis (UC Davis), for many years the chemical engineering senior design sequence has consisted of three, four-unit courses offered over the period of one academic year. In the first course, entitled Process Design and Economics, students learn how a design idea is brought to concept, including how to assess design projects at various stages using rigorous profitability analyses, process safety considerations, and environmental/social considerations and constraints. In the second course, entitled Unit Operations and Separations, students learn heuristic and rigorous design of chemical process equipment, including design of pumps, pipes, compressors, reactors, heat exchangers, columns, and other separations equipment. Discussion and assignments related to use of Aspen Plus© are integrated throughout both courses. The final course, entitled Plant Design Project, is focused around the conceptual design of a chemical process, with emphasis on the flowsheeting, costing, and techno-economic evaluation of a complete industrial plant. Teams of up to four students address real-world plant design problems and report to their instructor roughly every two weeks in the form of memoranda, written design reports, and oral presentations.

Offering modern and engaging senior design projects is a challenging and time consuming task for chemical plant design instructors[1]. Further, an offering of a chemical plant design project course may not include projects that align well with common interests within the cohort. In the past, the chemical engineering faculty at UC Davis has collaborated with a colleague from industry to develop new and modern senior design projects. In addition to these industry-driven projects, the growth of the undergraduate student population has necessitated the development of an even greater number of new senior design projects. Informally, students have indicated that they would enjoy more control over their senior design project topic so that they can explore their interests in greater depth. While using student-initiated topics for senior design projects is inherently risky, there is great potential for students to develop and practice creativity and entrepreneurial skills[2, 3, 4]. In fact, involving students in project idea generation was the goal of a recent effort at the University of Michigan to revitalize the chemical engineering senior design experience[3].

Beyond the challenge of offering modern and engaging senior design projects, assessing students' ability to achieve the Accreditation Board for Engineering and Technology (ABET) student outcomes[5] for design courses can be difficult[6]. In the Process Design and Economics course, the first course in the senior design sequence at UC Davis, quiz and exam-type assessments have traditionally been used to assess course-level outcomes. In the current iteration of the course, in lieu of a mid-term examination, a project-based approach to assessment of the course material was implemented in an effort to both improve and better capture achievement of course-level student outcomes[7, 8]. The chemical plant design project proposal assignment was designed to better require use of and assess key skills taught in the course including the ability to carry out a literature survey, develop a chemical process idea, and carry out an input/output (I/O) analysis.

The Problem

Students were tasked with proposing their own senior design project idea in the Process Design and Economics course for potential use in the Plant Design Project course. This design project proposal assignment required students to describe a potential design project idea, clearly stating how the idea was significant and unique. They were required to present a survey of the relevant literature, establish the theoretical basis on which the proposed process was built, identify potential safety concerns, identify current competitive technologies, and prove that a market for the proposed product exists. They had to describe important process alternatives, including potential raw materials and reaction pathways as examples. Finally, a preliminary assessment of the design alternatives were made using I/O level economics, environmental, and social assessment. An evaluation of the results was made by the student, and they concluded by recommending that the project should or should not be considered in more detail as a senior design project. The best proposals were considered for implementation as senior design projects in the Plant Design Project course.

Student performance on the assignment was assessed on the basis of the students ability to 1) communicate in writing effectively (ABET Outcome G), 2) describe a preliminary process design concept that met a societal need within realistic constraints (ABET Outcome C), 3) understand ethical responsibilities and potential safety issues (ABET Outcome F), 4) understand the impact of the proposed design project in a global, environmental, and societal context (ABET Outcome H), 5) gain a knowledge of contemporary issues (ABET Outcome J), and 6) gain an ability to engage in life-long learning by immersing themselves in the literature (ABET Outcome I). The outcomes were integrated into six criteria for which students were judged to have met, exceeded, or been deficient (see rubric attached in Appendix 1). The criteria and related outcome (from the list above) included:

a) The problem statement and significance of the project were clearly explained. Related theory and works in the literature were presented and cited (Outcomes 2, 4, 5, and 6).

b) Potential environmental impacts, societal impacts, and safety hazards were detailed (Outcomes 2, 3, and 4).

c) Potential process schemes were evaluated, including different combinations of raw materials, different reaction pathways, and configurations of unit operations. Criteria that would be used to assess these alternatives were also discussed (Outcomes 2 and 6).

d) Potential profitability of the process was assessed based on raw material selection and I/O analysis. The market for the product(s) and other revenue generating streams was discussed (Outcomes 2 and 6).

e) A clear recommendation as to whether the project should be considered in more detail was made. This recommendation was based on the I/O economic assessment, as well as on environmental and social measures. It was also made clear which process alternative(s) were viable, if any (Outcomes 1 and 4).

f) The proposal was written in a logical format. There were minimal typos and formatting errors, the figures were clear and readable, and the references were cited correctly (Outcome 1).

Students were assigned the prompt on the first day of class and were allowed eight weeks to complete the assignment. Submissions were limited to a maximum of ten pages. During the eight weeks of preparation, the students had access to regular office hours with the two course instructors, special project-focused office hours sessions with one of the instructors, and weekly consultation sessions with an industrial consultant. The project topics proposed by the students were taken into consideration as potential senior design projects for the Plant Design Project course.

Data Collection and Analysis

After the completion of the assignment, students were voluntarily surveyed to assess their perception of the effectiveness of the assignment as a measurement of their ability to develop a preliminary design idea. They were also surveyed to measure their perception of how strongly the ABET outcomes for the course mapped to this assignment. On the survey, the students were asked to respond to a series of statements using a Likert-type scale to specify their level of agreement or disagreement with each statement. The statements included on the survey can be found in Table 1. Although achievement of select ABET outcomes were specifically targeted by this assignment, as outlined in the previous section, the students were asked to specify their level of agreement or disagreement regarding achievement of all of the course-level ABET outcomes using this assignment so that comparisons could be made.

The students were also given the opportunity to provide freeform comments on the survey in response to the following questions:

1) What do you feel was the most useful aspect of this assignment?
2) What about this assignment do you feel needs the most improvement?
3) What other feedback do you have regarding the design project proposal assignment?

The students were asked on the survey to optionally provide their demographic information including gender and ethnicity. For the students electing to respond to these questions, the survey responses were segregated by gender and URM status in order to compare the responses to the survey questions between these groups. Average responses were calculated for the survey statements requiring a Likert-type scale response by equating the response “strongly disagree” to 1, “disagree” to 2, “neutral” to 3, “agree” to 4, and “strongly agree” to 5. In order to make comparisons between the Likert-type scale responses to the survey questions, the average responses were compared as well as the number and percentage of responders who selected each Likert-item for a given question.

Results and Discussion

The mean and median responses to each statement in the survey are listed in Table 1. Sixty-eight of the one hundred and forty-four students enrolled in the course responded to the survey.

Table 1. Post-Assignment Survey Results (n=68)

Survey Statement	*Mean Response*	*Median Response*	*Standard Deviation*
This assignment gave me a better appreciation for how a chemical engineering plant project idea is developed.	3.85	4	0.83
This assignment has enhanced my ability to apply my knowledge of mathematics, science, and engineering.	3.34	3	0.96
This assignment has enhanced my ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.	3.53	4	0.87
This assignment has enhanced my ability to identify, formulate, and solve engineering problems.	3.41	3	0.85
This assignment has enhanced my understanding of professional and ethical responsibility.	3.68	4	1.01
This assignment has enhanced my ability to communicate (in writing) effectively.	3.57	4	1.01
This assignment has enhanced my understanding of the impact of engineering solutions in a global, economic, environmental, and societal context.	4.03	4	0.91
This assignment has helped me recognize the need for, and enhance my ability to engage in life-long learning.	3.76	4	1.09
This assignment has enhanced my knowledge of contemporary issues.	3.82	4	0.91
This assignment has enhanced my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	3.43	4	1.00
I feel that this assignment is a good assessment tool for the material learned in this course.	3.38	3.5	1.15

Fifty-three of the sixty-eight responders (78%) either agreed or strongly agreed that the assignment gave them a better appreciation for how a chemical engineering plant project idea was developed. Only four responders (6%) did not feel that they achieved this outcome. Thirty-four of the responders (50 %) either agreed or strongly agreed that the assignment was a good assessment tool for the material learned in the course while only 23.5% of responders disagreed with this statement. These responses are illustrated in Figure 1A.

As a cohort, the students felt most strongly that they achieved ABET Outcomes H (understanding the impact of engineering solutions), J (knowledge of contemportary issues), and I (recognition of the need for life long learning). However, when the responses were segregated by gender and URM status, it was found that there were distinct variations in the average responses to some of the survey statements based on gender and/or URM status, as shown on Table 2. Both female and URM students on average responded more positiviely to the first survey statement (better appeciation), and the statements relating to ABET Outcomes E (formulate and solve engineering problems), F (ethical responsibility), and H (understanding the impact of engineering solutions. The difference in the mean responses between gender groups and URM status was not statistically significant for any of the four survey statements cited.

Table 2: Comparison of Average Responses to Selected Survey Questions Between Demographic Groups

Survey Statement	*Female n = 26 (Av + SD)*	*Male n = 39 (Av + SD)*	*URM n = 9 (Av + SD)*	*Non-URM n = 52 (Av + SD)*
This assignment gave me a better appreciation for how a chemical engineering plant project idea is developed.	4.00 ± 0.69	3.74 ± 0.94	4.22 ± 0.44	3.85 ± 0.75
This assignment has enhanced my ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.	3.65 ± 0.75	3.51 ± 0.88	3.22 ± 0.97	3.62 ± 0.80
This assignment has enhanced my ability to identify, formulate, and solve engineering problems.	3.54 ± 0.76	3.41 ± 0.85	3.44 ± 0.88	3.42 ± 0.80
This assignment has enhanced my understanding of professional and ethical responsibility.	3.76 ± 0.82	3.67 ±1.08	4.11 ± 0.60	3.60 ± 1.01
This assignment has enhanced my ability to communicate (in writing) effectively.	3.88 ± 0.86	3.41 ± 1.02	3.44 ± 0.88	3.59 ± 0.98
This assignment has enhanced my understanding of the impact of engineering solutions in a global, economic, environmental, and societal context.	4.12 ± 0.65	4.03 ± 0.96	4.44 ± 0.53	3.96 ± 0.88
This assignment has helped me recognize the need for, and enhance my ability to engage in life-long learning.	3.77 ± 0.95	3.79 ± 1.13	3.89 ± 1.05	3.77 ± 1.04

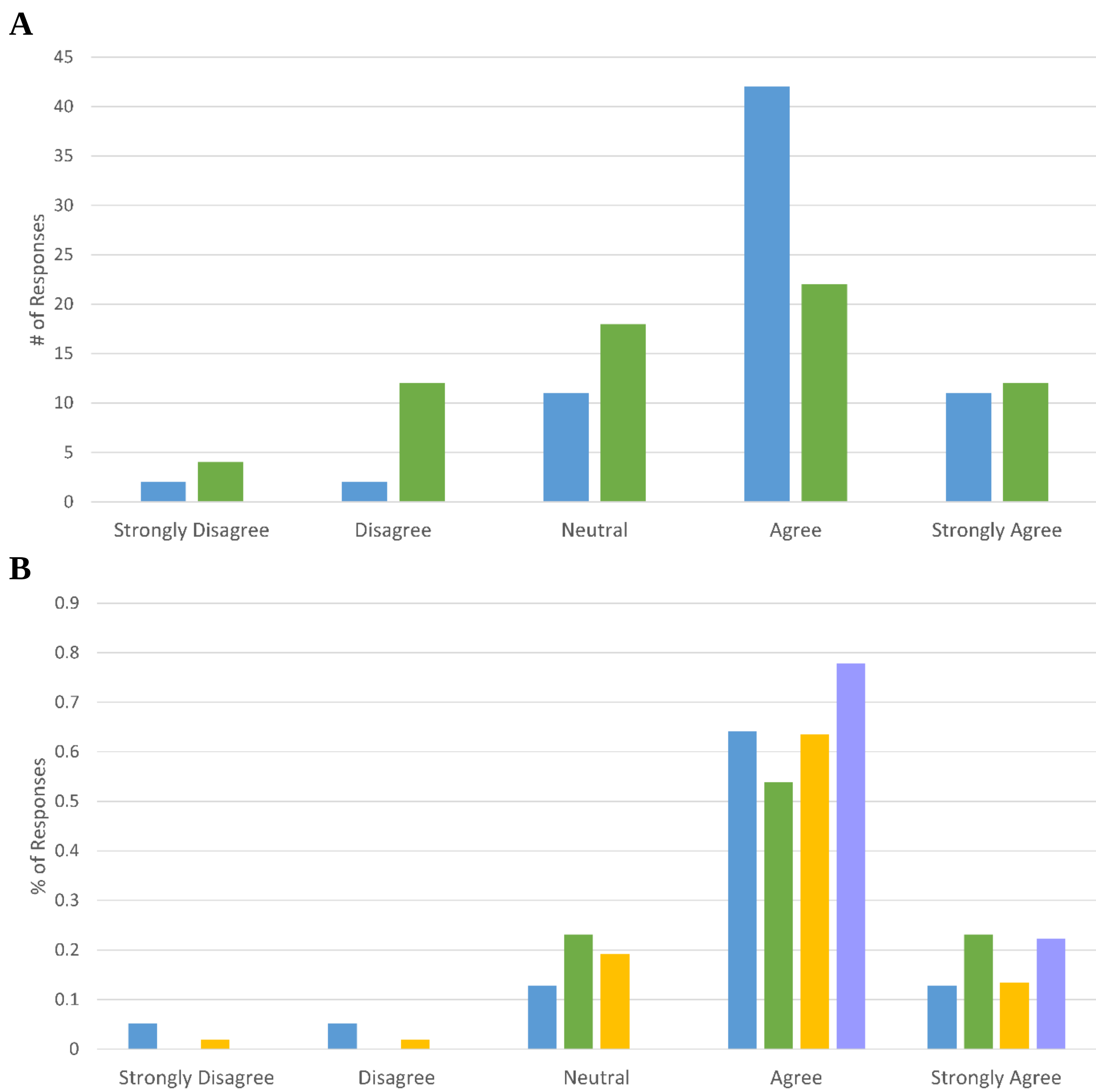

Figure 1. Overall student rating of the plant design project proposal assignment. (A) Students provided responses on a Likert-type scale to the statements *"This assignment gave me a better appreciation for how a chemical engineering plant project idea is developed"* (blue) and *"I feel that this assignment is a good assessment tool for the material learned in this course"* (green). 78% of the 68 responders agreed or strongly agreed with the first statement (*better appreciation*) and 50% of responders agreed or strongly agreed with the second statement (*good assessment*). (B) Responses to the "*better appreciation*" statement were segregated by gender and URM status. Female (green) and URM students (purple) were the most likely to strongly agree with this statement as compared to male (blue) and non-URM students (gold). All URM responders either agreed or strongly agreed with the statement.

The percentage of responses to the first survey statement (better appreciation), segregated by gender and URM status is shown on Figure 1B. The percentage of female and URM responders who strongly agreed that the assignment gave them a better appreciation for how a chemical plant project idea was developed was about 10% higher than that of male and non-URM responders. Further, all URM responders either agreed or strongly agreed with this first survey statement (better appreciation).

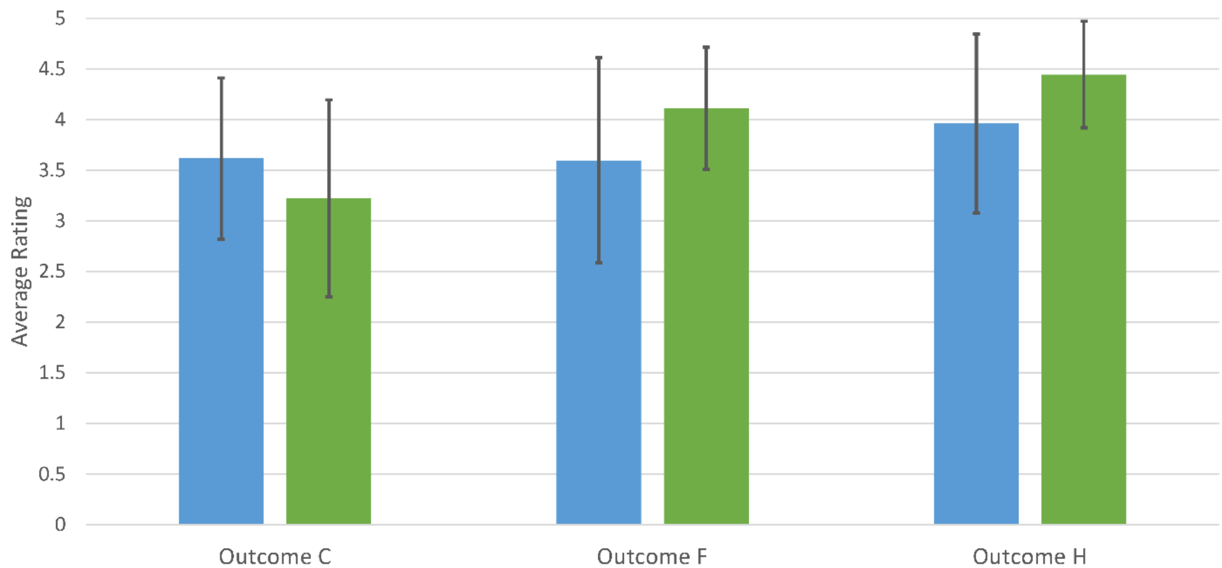

Figure 2. Differences in responses to select ABET outcome questions based on URM status. The average Likert-type scale rating to survey statements correlating to select ABET student outcomes were calculated based on URM status. Non-URM responders (blue) agreed to a greater extent that they had achieved ABET outcome C, the ability to design a process to meet desired needs within realistic constraints, on this assignment than the URM responders (green). URM responders agreed to a greater extent than non-URM responders that they had achieved ABET outcomes F, an understanding of professional and ethical responsibility, and H, understanding the impact of engineering solutions in a global, economic, environmental, and societal context, on this assignment. This differences in the average responses to each of these questions was not statistically significant.

Differences in responses to the survey statements were also observed to be most significant (although not statistically significant) between responders identifying as a URM vs. a non-URM for the survey statements relating to ABET Outcomes C (design a process to meet desired needs within realistic constraints), F (ethical responsibility), and H (understanding the impact of engineering solutions). These differences in average response are shown on Figure 2. URM responders on average felt that they achieved ABET Outcomes F and H to a greater extent through this assignment than did non-URM responders. Conversely, URM responders on average did not feel that they achieved ABET Outcome C through this assignment to the extent that non-URM responders did.

In response to the freeform survey questions, the students indicated in general that they enjoyed the freedom of choosing their own topic so that they could be creative and find out what aspect of chemical engineering they are truly interested in. Sample comments included:

> *Having the freedom to choose any topic was extremely useful because it allowed me to really analyze what I actually care about and can potentially use my major to affect change.*
>
> *I feel like this project helped everyone figure out what field they're interested in and learn more about that field. I liked this project because it gave us real life situations to work with. It was a lot more useful than only researching topics. I thought it was going to be impossible to fill up 10 pages but when I finishing I had a hard time cutting it down to 10 pages.*

Many students also indicated that the open-ended nature of the assignment made it difficult to know what was expected in their submission. Sample comments included:

> *I understand the idea of having the assignment open ended was to spur creative response from the class; however, in this case some more structure and instructions would have been helpful.*
>
> *The quality of the report was very dependent on the complexity of the idea. Thus, it was hard to write a design proposal with a well thought out design. It felt more of a writing exercise as opposed to an engineering & writing exercise. The idea of the assignment was promising, but it was difficult to formulate a well thought out and unique proposal based on engineering practices.*

Three new senior design projects were developed for the Plant Design course using the student project proposals. The topics of the projects were 1) Hydrogen production by gasification of biomass and waste feedstocks, 2) Acrylic acid production from glycerol by-product, and 3) Optimization of a water desalination plant. These topics were selected in part due to the quality of the project proposal(s) relating to the topic and in part due to the instructors' perceptions on the feasibility of these projects. In addition to these factors, the gasification of biomass, water desalination, and use of waste glycerol as a feedstock were observed to be common themes among the student's project proposals. Therefore, the final topics were defined in a way that incorporated ideas found across a number of the students' proposals. A sample student design project proposal is included in Appendix 2.

Conclusions

The plant design project proposal assignment was effective in both enhancing the students appreciation for how a chemical plant design project idea is developed and allowing the students to achieve the desired ABET student outcomes. There were indications that aspects of the assignment were especially beneficial to female and URM students. The students proposed a variety of interesting plant design project topics, and three new senior design projects were developed for the Plant Design Project course that were initiated by the student project proposals.

It is anticipated that this assignment will be carried out with additional cohorts. In future implementations of this assignment, in response to student feedback, aspects of the assignment will be clarified while maintaining the open-ended nature of the assignment. Specifically, additional clarification will be given as to why comparing design alternatives is important, and how one would assess which alternative is potentially more desirable. In addition, the expectations for the I/O economic analysis will be discussed in more detail, including where to find economic information and how one can determine how robust the proposed process concept is to fluctuations in key economic parameters.

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Appendix 1: Project Proposal Instructions and Rubric

Description: The design project proposal is a major midterm written report and your opportunity to pitch an idea that may become one of this year's senior design projects. In your report, you must describe your project idea, clearly stating how your idea is significant and unique. You must present a survey of the relevant literature, identifying current competitive technologies, establishing the theoretical basis on which your proposed process is built, and proving that there is a market for your proposed product. You must describe important process alternatives including potential raw materials, reaction pathways, etc., and a preliminary assessment of these alternatives using economic (I/O analysis), environmental, and social measures must be made. You must determine if your proposed project is potentially viable based on these measures and you must recommend whether or not you believe the project should be considered in more detail.

Specific Instructions:

Max Length: 10 pages, including references

Submission: pdf file emailed to instructors

Rubric:

Exceeded Criteria (A range)	**Meets Criteria Stated Below (B range)**	**Areas Needing Work (C range)**	**Did Not Address Criteria (D-F range)**
	Intro/Background (20 pts): Problem statement and significance of the project is clearly explained. Related theory and works in the literature are presented and cited.		
	Design Considerations (20 pts): Potential environmental impacts, social impacts, and safety hazards are detailed.		
	Design Alternatives (20 pts): Potential process schemes are discussed, including different combinations of raw materials, different reaction pathways, and configurations of major unit operations. Criteria that would be used to assess these alternatives is also discussed.		
	Economic Analysis (20 pts): Potential profitability of process is assessed based on raw materials selection and I/O analysis. The market for your product(s) and other revenue generating streams is discussed.		
	Conclusions and Recommendations (10 pts): A clear recommendation as to whether the project should be considered in more detail is made. This recommendation should be based on your I/O economic assessment, as well as on environmental and social measures. It is also clear which process alternative(s) are viable, if any.		
	Neatness & Organization (10 pts): The proposal is written in a logical format. There are minimal typos and formatting errors, figures are clear and readable, and references are cited correctly.		

Appendix 2: Sample Submission

Design Proposal:

Conversion of Glycerol to Acrylic Acid via an Allyl Alcohol Intermediate

Introduction

Glycerol is a main byproduct of biodiesel production. As the biodiesel industry has grown, so has the supply of glycerol, which is currently oversupplied in the market [1]. One valuable chemical product that can be produced from glycerol is acrylic acid. Acrylic acid is used in the manufacturing of plastics, coatings, paints, textiles, and more. The global market for acrylic acid is projected to reach $22.55 billion by 2022 [2, 3]. Previous methods of producing acrylic acid have been abandoned for environmental and economic reasons. Many mechanisms for the conversion of glycerol to acrylic acid have been studied but not commercialized due to rapid deactivation of the catalyst [1, 4].

This proposed method of acrylic acid production uses a reaction sequence that avoids such a problem. This process converts glycerol to acrylic aid via an allyl alcohol intermediate. The reactions involved, and their yields and catalyst properties, have been characterized by Li and Zhang [1]. A high acrylic acid yield is expected, and the problem of catalyst deprivation is circumvented by using a deoxydehydration reaction in place of an acid catalyzed reaction. In this report, the environmental, safety, and economic aspects of such a process are investigated for two designs possibilities. The two designs differ in the carrier gas employed during the gas phase catalytic portion of the process.

Background

Glycerol has typically been obtained from plants and animals, since it was not cost effective to produce synthetic glycerol. However in recent years, glycerol production has increased as it is the major byproduct of biodiesel production [1, 5].This has led to an oversupply in the market and lower prices, which presents an opportunity to commission a profitable chemical process with a glycerol input.

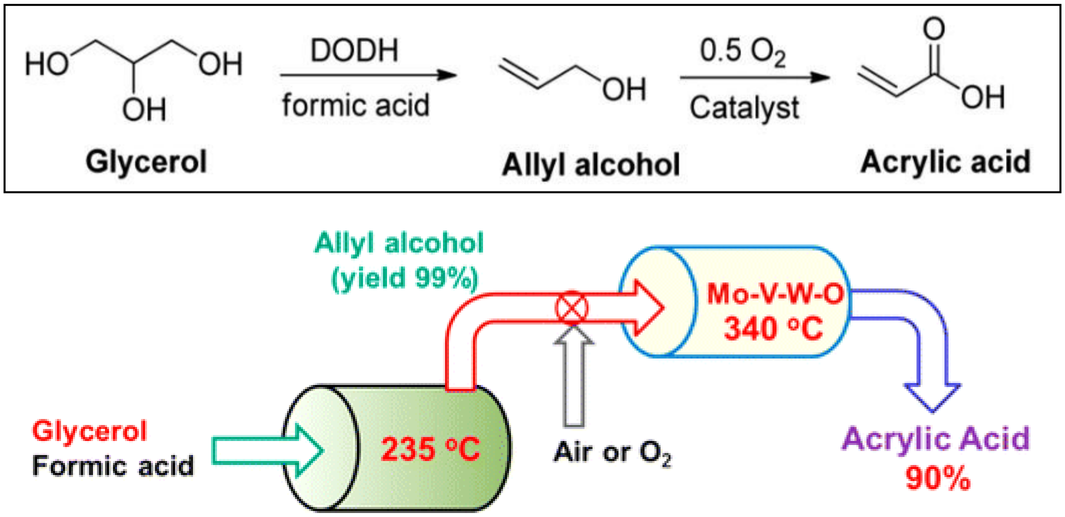

Figure 1: *Proposed process for converting glycerol to acrylic acid and the respective reaction mechanism, from Li and Zhang [1].*

Acrylic acid is a commodity chemical that can be produced from glycerol. It polymerizes to form polymers that are used in plastics, coatings, paints, and more. It can also be used an intermediate in acrylate production. A former process to produce acrylic acid involved ammoxidation and hydrolysis of a propene reactant. This process was environmentally unfavorable, as it created ammonium derivatives [4]. Other proposed acrylic acid manufacturing processes are dependent on insecurely priced starting materials, such as propane or propylene [6]. Multiple processes that produce acrylic acid from a glycerol starting material have been studied and patented [7, 8]; these processes involve an acrolein intermediate. These conversion processes involve the use of an acid catalyst to dehydrate glycerol and form the acrolein intermediate. The acrolein is then converted to acrylic acid with the assistance of an oxidation catalyst. Despite high product yields, this reaction mechanism has not been scaled up and commercialized due to heavy coke deposition, which leads to rapid catalyst deactivation. The coking is the result of the acidity of the catalyst and the high temperatures of the reaction [1].

By not using an acid catalyst, the issue of coking and catalyst deactivation can be circumvented. Thus, the mechanism shown in Figure 1 is attractive. Glycerol is deoxydehydrated to allyl alcohol via a well-studied formic acid-mediated reaction. This reaction does not involve any catalyst, instead using formic acid, an easily attainable green chemical. The resulting allyl alcohol intermediate is then catalytically oxidized to form the final product of acrylic acid. This mechanism avoids the use an acid catalyst, and thus avoids the issue of coking [1].

This process would involve two reactors, one for each step of the overall reaction mechanism. Step one exhibits complete conversion of glycerol to allyl alcohol, with no unwanted byproducts. Any unreacted formic acid (about 34%) is collected and recycled. Li and Zhang showed that high acrylic acid yields (up to 87%) are obtained after the allyl alcohol is sent through a gas phase catalytic reactor. The Mo-V-W-O catalyst used shows high stability over time under optimized reactor conditions (temperature of 340 °C). Catalyst stability and high product yields suggest this is could be a viable industrial process. The second reaction does result in additional side products, notably acetic acid and carbon dioxide, which are further discussed below [1].

Design Considerations

During the initial investigation of this process, many key design considerations were identified that relate to the viability and scalability of this process. Environmental, safety, and economic considerations are taken into account below for each key material.

Glycerol

Glycerol has a low toxicity and a low environmental impact. The main motivation for processing glycerol is economic benefits, due to it being a readily available chemical [9].

Formic Acid

Formic acid is a fairly safe green chemical that can potentially be produced from carbon dioxide or biom acrylic ass. Recently, BASF, a dominant formic acid producer, has increased its formic acid prices. Looking to the future, it may be to our benefit to produce out own formic acid. For now, formic acid is also a readily available input [1, 10].

Allyl Alcohol

Allyl alcohol is extremely toxic and is classified as an extremely hazardous substance by the government [11]. Thus, large amounts of the allyl alcohol intermediate should not to be stored during the process. Theoretically, allyl alcohol can be completely converted (either to acrylic acid or some other side product) by passing it through a fixed bed reactor [1]. This high conversion is extremely desirable, since allyl alcohol represents the most hazardous material involved in this process.

Acrylic Acid

Acrylic acid is known to be moderately toxic. It biodegrades quickly in water, with the possible effect of decreasing the pH of aquatic systems. Acrylic acid is highly flammable, thus temperature control would be necessary to ensure acrylic acid does not reach 438 °C (the reaction temperature is 340 °C). Furthermore, acrylic acid is known to polymerize, so would need to be stored and transported in a cool container with inhibitors to prevent polymerization [6, 12].

Side Products

The main side products from the conversion of allyl alcohol to acrylic acid are acetic acid, acetaldehyde, and acrolein, carbon monoxide, and carbon dioxide. The selectivity for the carbon oxides over the other components depends on the carrier gas's oxygen composition [1]. A lower selectivity for the carbon oxides is preferable, as this reduces the production of unwanted greenhouse gases. Thus the environmental and economic cost of carbon dioxide production must be weighed against the benefit of using a cheaper, oxygen rich gas.

Design Alternatives

The decision of the carrier gas used in the fixed-bed reactor for the gas phase catalytic oxidation of allyl alcohol to acrylic acid impacts economics and final product flows of the process. Choosing to use air instead of the optimal gas used in the literature provides economic benefits but also process efficiency costs. The optimal reaction conditions, those which lead to both the highest yield of acrylic acid (87%) and to proven long term catalyst stability, have been determined on the lab scale. This involves the use of 10% O_2/He as the carrier gas that flows through the bed reactor. An alternative design is to use air (21% O_2/ 71% N_2) as the flowing gas. The economic advantage of using air must be evaluated against the economic cost of a lower yield (81% selectivity for acrylic acid). Furthermore, the use of air leads to different oxidation levels, and thus different selectivity for the side products. Specifically, more carbon dioxide and monoxide is produced [1]s. This is undesired, especially if greater gas separation and treatment becomes necessary. The cost differences associated with different units needed to sufficiently process the side products would need to be evaluated at a later stage of the design process. At this stage, the savings from the use of air is evaluated against the loss in profit due to lower acrylic acid output flow.

Economic Analysis

The worldwide production of acrylic acid was 5750 kilo tons in 2014 [2]. A preliminary economic analysis of the process was done on the basis of producing 115 million lb/yr acrylic acid, which represents 1% of the market. Figure 2 shows the inputs and outputs of this process. Tables 1 and 2 provide a stream and profit summary for each of the two design possibilities.

Notes on assumptions made for these calculations:

- 100% of unreacted formic acid is assumed to be collected and recycled.
- The cost of the catalyst is not included.
- Acrylic acid is treated to be the only output stream that has an economic impact. This assumes the output gas does not require significant treatment, but cannot be recycled. Side products also do not contribute to profit calculations, which ignores possibility of selling acetic acid, as well as the negative impacts of greenhouse gas production/treatment.
- Glycerol price used from 2013 [13], formic acid price used from 2010 [14], acrylic acid used from January 2016 [15], and helium gas price from 2013 [16].

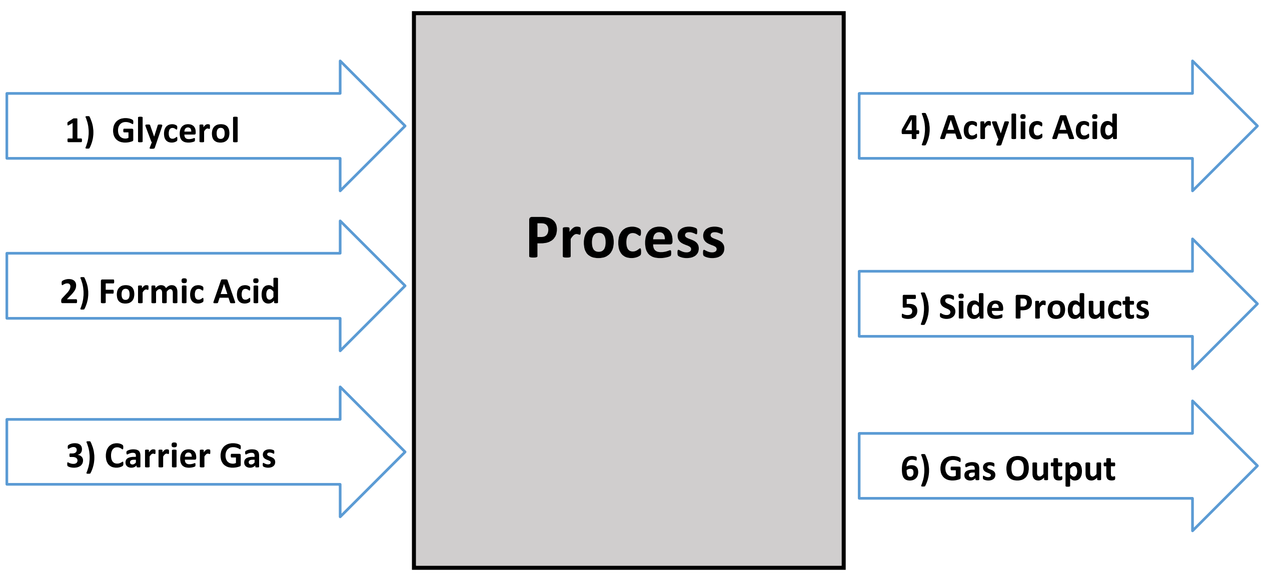

Figure 2: *Input/Output diagram for this process.*

Stream	Component	Mass Flow Rate (10^6 lb/yr)	Economic Impact ($/lb)	Total Profit (10^6 $)
1	Glycerol	86	-.04	-3.43
2	Formic Acid	51	-.57	-28.96
3	10% O_2/He	516	-.052	-26.81
4	Acrylic Acid	115	+.78	+89.70
5	Side Products	25	0	0
6	Purge Gas	513	0	0
				Total Profit: $30.5 Million

Table 1: *I/O Stream Summary and Economics for Design 1*

Gas: 10% O_2/He Gas; Selectivity for allyl alcohol to acrylic acid: 87.2%; Side Products: 57% Acetic Acid, 7% Carbon Oxides, 36% Other.

Stream	Component	Mass Flow Rate (10^6 lb/yr)	Economic Impact ($/lb)	Total Profit (10^6 $)
1	Glycerol	92	-.04	-3.66
2	Formic Acid	54	-.57	-30.91
3	Air	551	0	0
4	Acrylic Acid	115	+.78	+89.70
5	Side Products	64	0	0
6	Purge Gas	518	0	0
				Total Profit: $55.1 Million

Table 2: *I/O Stream summary and Economics for Design 2*

Gas: Air; Selectivity for allyl alcohol to acrylic acid: 81.7%; Side Products: 36% Acetic Acid, 47% Carbon Oxides, 17% Other.

Recommendation

A process to produce valuable acrylic acid from widely available glycerol was considered. Through the use of easily available inputs and not using an acid catalyst, this process evades the pitfalls of other acrylic acid manufacturing. After a preliminary economic analysis and consideration of environmental and safety impact, both of the two considered design alternatives for this process show healthy estimated profits. Both design options, which differ in the gas that flows through the gas phase fixed bed reactor, are viable and worth further pursual. Profit estimates increase by 80% when air is used instead of the oxygen/helium mixture which is known to lead to optimal yields in the literature. If resources only allow for one design to be investigated at this time, I would recommend the latter design which uses air as the input gas. It is important to note that this version of the process produces more carbon oxide side products, which ensures that the true profit will be significantly lower that the estimate. Additionally, further investigation into the Mo-V-W-O catalysts' availability and properties, which are not included in this report, will be necessary.

In summary, as the availability of glycerol in the market place continues to rise due to continued biomass processing, the conversion of glycerol to a valuable product such as acrylic acid is appealing. The high economic profit, reaction selectivity, and catalyst stability make the proposed process an attractive option worth further resources to research and design.

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