Using a Techno-Economic Model to Promote Consideration of Uncertainty in Bioengineering Design

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Introduction

Decision-making is an integral aspect of the engineering design process. Engineers solve complex open-ended design problems with a variety of technical and non-technical constraints. In many engineering courses, this kind of decision-making can lack realistic context (Jonassen et al., 2006; Jensen, 2015) and may often be reduced to the elimination of all or most of the real-world constraints. Research on the decision making process of engineering students is important because it can help guide curriculum and course development toward more authentic engineering practices.

In this paper, the factors bioengineering students considered in integrating complex objectives, concerns and data in decision-making were identified and characterized. The project was delivered in the first term of a three quarter, revitalized senior design sequence in a the Oregon State University Bioengineering program that includes instruction in both biomedical and bioprocessing engineering. The course is required for the Bioengineering Bachelor of Science degree. This first term is the bioprocessing course, which is followed by a bioproduct design course, and then a hands-on prototyping course.

We believe the authenticity and open-ended nature of the assignment gives students an opportunity to integrate material they have learned from a variety of technical and professional skills courses that will reinforce and deepen learning. However, as instructors using a new pedagogical tool, we have assumptions regarding student interaction with the tool that may be misinformed. Understanding how the students interact with the tool and their decision-making strategies will enable improved design of the project.

Students were tasked with considering a variety of technological, economic, ethical, regulatory, and environmental concerns about a process and the product. They were asked to make a qualitative recommendation on future investments. Options include proceeding with a detailed plant design, optimizing the design, pursuing further process development, allocating funds for specific research, abandoning the project, or other options.

A comprehensive techno-economic model (developed in MatLab) was provided to the students to assist in their decision regarding theoretical investments. The model is of an algae cultivation and downstream process to produce the nutraceutical glucosamine and a lipid co-product. Students were able to vary an assortment of input parameters (technical, economic and variability) and obtain the product selling price from the model. Example inputs include growth rates, chitin content, recycle fraction, internal rate of return, equipment costs, raw material and utility costs, etc.

We propose that the key features of the assignment include that the students:

- were tasked to make qualitative recommendations for an open-ended range of possible investments,

- worked in teams,
- had access to a techno-economic model with a broad array of variable inputs, and
- were provided with research indicating legitimate questions regarding efficacy of the product.

The project objectives were to:

a. provide students an opportunity to practice and become comfortable with decision making with multiple concerns and types of evidence,
b. promote student understanding of how a process design (techno-economic model) can be used, and
c. enable students' ability to navigate uncertainty, which is critical for practicing engineers (Nachtmann and Lehrman, 2002).

The student work (one-page recommendation memos) and post-project surveys were analyzed to answer the following research questions.

Research question 1. Did the project:

- provide students an opportunity to practice decision making with multiple concerns, and types of evidence,
- promote student understanding of how a process design (techno-economic model) can be used, and
- facilitate students' ability to navigate uncertainty.

Research question 2. Did the project promote the students':

- comfort with multiple concerns and types of evidence,
- confidence in understanding process design, and
- acceptance of uncertainty?

Methodology

The project and IRB consent were described to the students the week before the project was given. The project was delivered in two 2-hour class periods where students engaged (a) the written project objective and deliverables (Figure 1), (b) a short article critical of the effectiveness of glucosamine, (c) a process description, and (d) a techno-economic model built in MATLAB with a convenient user interface for input and output. About 30 minutes of a third class period was used for the post-project survey. The only project deliverable was a team-produced one-page memo. The assignment was a relatively low-stakes assignment, constituting 3.4% of the course grade, with little expectation of outside of class-time effort.

Project Objective:

Assume you are a team of four consulting engineers employed to give your recommendations for investment at a company. Your technical expertise is bioprocessing, but you are encouraged to consider all factors that may impact the company's decision on where to make investments.

Project Deliverables:

The company currently operates aquaculture feed algae facilities and is considering expanding into nutraceuticals. A techno-economic model was developed by the company on glucosamine and lipid production from marine diatom *Cyclotella sp* in tubular photobioreactor (PBR) cultivation systems. The techno-economic model predicts the required selling price given a number of user defined inputs. You are tasked to consider technological, economic, ethical, regulatory, and environmental constraints and concerns about the process and the product.

You are asked to provide a 1-page memo describing your recommendations for further investment (you do not have to consider the magnitude of investments). Options for investment include proceeding with a detailed plant design, optimizing some aspects of the design (be specific), pursuing further process development, allocating funds for specific research, abandoning the project, or other options that you consider reasonable. In your memo be specific about investment for further research and development – which areas to focus on and why you chose these areas.

Consider the following in your discussions and in the memo:

- Objective of the company
- Market price for glucosamine and lipid for fuel
- Glucosamine as a product and nutraceutical, market projections and concerns (see attached handout on the efficacy of glucosamine)
- Potential impacts to the objective from a safety, ethical, environmental, social, economic and political perspective
- Potential risks and pitfalls

The memo should explain your team's decision and include what type of data, concerns, and factors influenced your decision. The data used from the model, and other information/data obtained should be included in an appendix.

Figure 1*. Project objectives and deliverables*

Techno-economic analysis (TEA) is a well-established method to evaluate the economic viability of a chemical process by combining process design and economic evaluations. In this study, TEA was conducted to predict the selling price of glucosamine derived from algae cultivation given a specific internal rate of return. The model was developed using a combination of data generated from experimental studies and data from algal biofuel technologies reported in the literature. An economic analysis included capital and manufacturing costs, deprecation, tax, and internal rate of return.

The algae grow through the inputs of nutrients, CO_2 and water in a tubular photobioreactor system. Algae harvesting, glucosamine hydrolysis, lipid extraction, and anaerobic digestion follow cultivation. Chitin and lipid separation processes require high concentrations of algae cells. Thus, dewatering processes are utilized to harvest algae. Sedimentation, dissolved air floatation and centrifugation have been selected for algae harvesting. Chitin is separated by centrifugation, and is then subjected to hydrolysis reaction to obtain glucosamine. The soluble glucosamine is then precipitated by crystallization, filtration, and drying. Lipid is extracted from the remaining harvested algae and lipid-free algae debris is treated with anaerobic digestion to produce biogas and recycle to algae cultivation.

Cultivation, downstream operating parameters, and the major capital costs (e.g. photobioreactor and airlift column), raw material costs, and major economics parameters (e.g. tax rate and internal rate of return) were for modification by students. However, some of the capital and manufacturing costs, including the details for labor, power and maintenance were not adjustable due to their complexity. The input parameter categories are indicated in Figure 2.

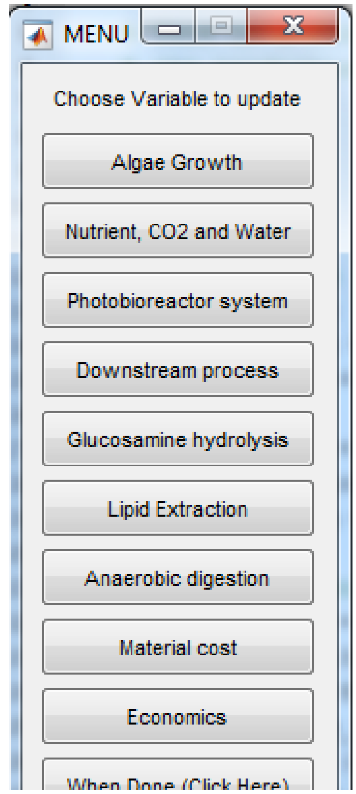

***Figure 2**. TEA Matlab model user interface for input parameters*

Thirty-seven students, whom all provided IRB consent, completed the project (eight teams of four students, and one team of five students) in a required senior bioprocessing design course during fall term in 2016. The student teams completed memos and individual student post-project surveys constitute the data used for this study. The survey included eleven Likert-response questions and three open ended questions (Tables 1 and 2).

Table 1. *Likert part of the survey (11 questions) completed by students after the project. The students were asked to rate the statements on a four-point Likert scale (strongly disagree, disagree, agree, and strongly agree). In the table they are ordered by the objective, but this was not the order of questions on the student survey.*

<table>
<tr><th colspan="20">Objective a. Provide students an opportunity to practice and become comfortable with decision making with multiple concerns and types of evidence</th></tr>
<tr><td colspan="4">I enjoyed the complexity of this project</td><td colspan="4">This project forced me to think more broadly about engineering solutions and their context</td><td colspan="4">I was uncomfortable being the person to decide how important different factors should be</td><td colspan="4">One of my team members surprised me with their ideas (in a good way)</td><td colspan="4">There were some concerns that we talked about, but did not include explicitly in our decision</td></tr>
<tr><th colspan="20">Objective b: Promote student understanding of how a process design (techno-economic model) can be used</th></tr>
<tr><td colspan="10">This project helped improve my understanding of my preliminary plant design project</td><td colspan="10">I understand the big-picture of the TEA model and how the output (sales price) was determined</td></tr>
<tr><th colspan="20">Objective c: Facilitate students' ability to navigate uncertainty</th></tr>
<tr><td colspan="5">This project seemed vague – I was not sure how to approach the problem</td><td colspan="5">We did not have enough good information to make a valid decision</td><td colspan="5">I did not know how to assign levels of importance to different concerns or objectives</td><td colspan="5">The project was not meaningful because any answer could be given</td></tr>
</table>

Table 2. *Open ended questions in the survey completed by the students after the project.*

What was the most uncomfortable or challenging aspect of this assignment?
Would you have come to the same decisions had you done this project alone? Explain why or why not? Do you think doing this project as a team made you consider more factors? If so, could you give an example?
What did you learn from this assignment?

Both the open-ended survey and the student-produced memos were analyzed by placing responses into categories to understand how the project met the objectives and to give insight on the research questions.

Results

Figure 3 illustrates the Likert question student responses (n=32 or 33, not all students answered all questions, not all student handed in a survey) arranged by the objective they may inform. The greatest agreement (88%) was in response to "This project forced me to think more broadly about engineering solutions and their context", while least agreement (12%) was in response to

“The project was not meaningful because any answer could be given”. A summary of the responses to the Likert questions is included in the Appendix.

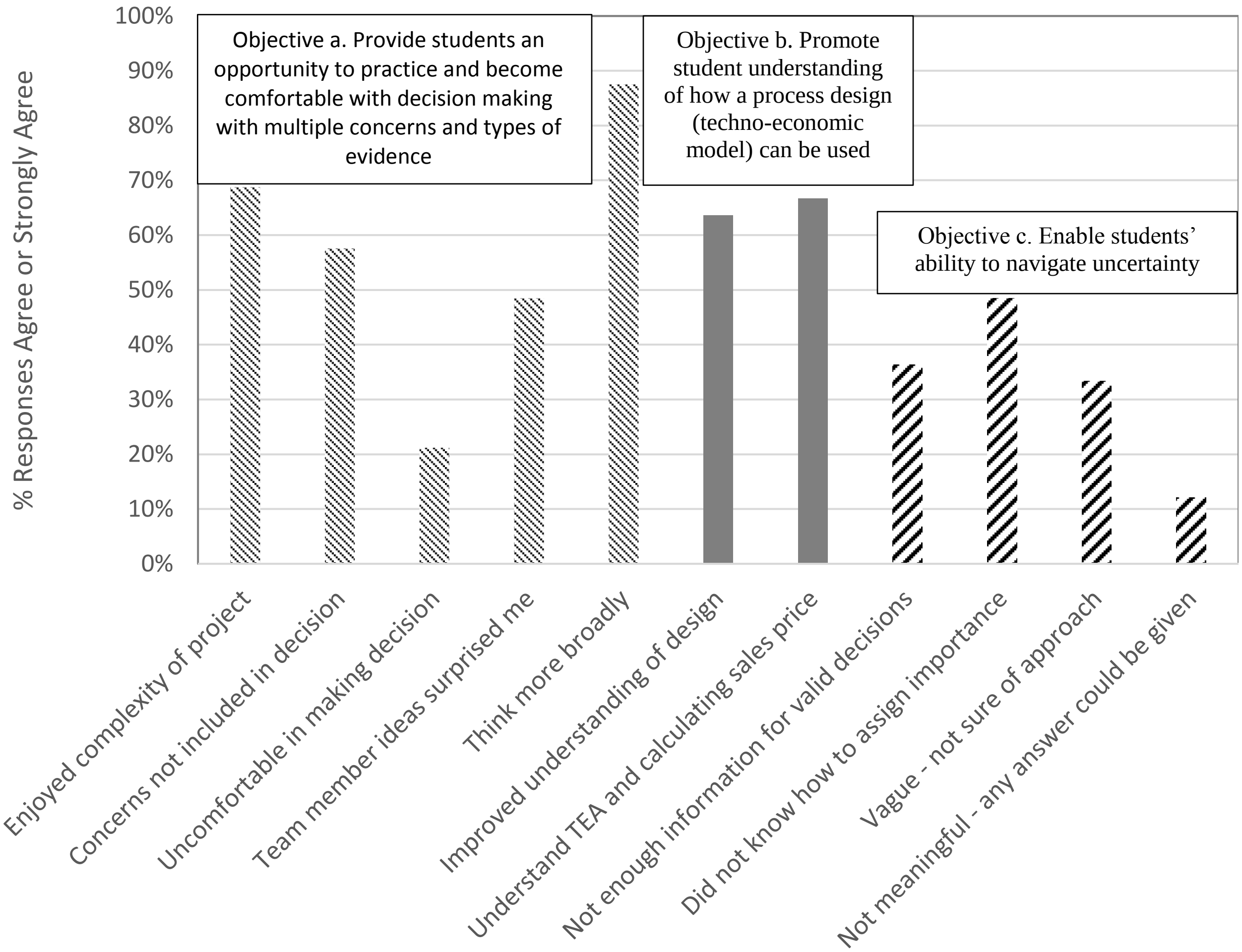

Figure 3. *% Respondents that Agree or Strongly Agree to each of the eleven post-project four-point Likert scale survey questions.*

The open-ended survey questions (Table 3) were analyzed for common themes. Themes that contained three or more responses are indicated in Table 3. In addition to the open-ended questions, the students were asked “Would you have come to the same decisions had you done this project alone?” There were 15 ‘no’ responses and 13 ‘yes’ responses.

Table 3. *Thematic analysis of three open-ended survey questions. Categories with three or more responses included. The number in parentheses is the number of responses in the category.*

What was the most uncomfortable or challenging aspect of this assignment?	Do you think doing this project as a team made you consider more factors?	What did you learn from this assignment?
Not knowing which factors have the most significant impact (6)	Having a team results in more ideas (15)	It is a complicated process to calculate the selling price, and is based on large number of parameters (more than expected) (10)
Model is too complicated, challenging, or vague to use (6)	Having a team saves time (6)	To have an open mind to make recommendations and decisions (3)
New concept (process and model) that needs more explanation before use (6)	Having more people yields more insightful ideas (3)	Team work (3)
It is not clear how the parameter affects the final result (6)		
Too many parameters (6)		

The deliverable description for the recommendation memo asked to explicitly include the following points:

1. Specific recommendations for further investment,
2. technological, economic, ethical, regulatory, and environmental concerns about the process and the product,
3. explanation of the team's decision, and
4. types of data, concerns, and factors that influenced the decision.

In addition, the students were asked to consider the following in their decision making process:

1. Objective of the company,
2. market price for glucosamine and lipid for fuel,
3. glucosamine as a product and nutraceutical, market projections and concerns (see attached handout on the efficacy of glucosamine),
4. potential impacts to the objective from a safety, ethical, environmental, social, economic and political perspective, and
5. potential risks and pitfalls.

The nine student-produced memos were analyzed for responsiveness to the deliverable specifications, which are indicated in Table 4.

Table 4. *Analysis of nine memos produced by teams describing responses to deliverable prompts.*

Deliverable response category	Summary of the nine teams' responses
Recommendation	All teams provided recommendations with regard to economics, technology, and risks
Technological	All teams made decisions for technological development, such as achieving target algal productivity or exploring for alternative diatom species
Economic	All teams considered the selling price of glucosamine and compared with commercial glucosamine product
Ethical	Four teams explicitly mentioned ethical considerations including expanding non-shellfish glucosamine availability, GMO and efficacy concerns
Regulatory	Two teams explicitly considered regulatory concerns
Environmental	No team mentioned environmental impacts
Market	Six team considered the preferential market of vegan glucosamine for Kosher, vegan, or shellfish allergic customers; Two teams considered the increasing market of an aging population
Safety	One team mentioned that the safety related to the glucosamine as nutraceutical is unclear
Risks	Seven teams considered the inconclusive efficacy of glucosamine for joint pain relief

Most of the teams (8 out of 9) recommended that the strain be optimized to increase chitin content. The teams' other investment recommendations are summarized in Table 5.

Table 5. *Summary of teams' recommendation for investment.*

Recommendation for investment	# of teams
Increase chitin content (through genetic engineering or strain selection)	8
Increase algal/chitin productivity	3
Research bioreactor design or materials to reduce costs	3
Research glucosamine efficacy for joint pain relief	3
Modify algae strain to grow under lower light environments	2
Increase harvest concentration	1

Discussion

According to Dym et al. (2005), good engineering design is characterized by six skills that include the ability to tolerate ambiguity, consider the big picture, deal with uncertainty, make decisions, work in a team, and communicate in design languages. This project engenders the practice of at least the first five of these design skills.

The teams suggested six different recommendations (Table 5) for further investment. The number of recommendations each team suggested ranged from one to three with an average of 2.2. That a variety of legitimate recommendations could be, and were, made by the student teams indicate that the project did provide students an opportunity to practice decision making with multiple concerns and types of evidence. All of the teams examined the effect of multiple input parameters on the calculated selling price of glucosamine required to achieve a given rate of return. All of the teams considered technological and economic factors, six teams considered potential market changes, four teams explicitly considered ethical concerns, and one team mentioned regulatory issues in describing investment decisions (Table 4), which indicates they were able to practice decision making with multiple types of evidence.

As all of the teams appropriately investigated the effect of multiple input parameters on the calculated selling-price of glucosamine, and selected parameters for which the selling price was most sensitive, the project promoted student understanding of how a process design (techno-economic model) can be used.

The student teams were presented with uncertainty in efficacy of glucosamine, model based projections, and a verbal discussion of a potential changing regulatory and business environment. Uncertainties are common in engineering work (Du, 2016), and these are authentic uncertainties for this process-product system. Students navigated these uncertainties by acknowledging them, recommending further research, and making preliminary evaluations of their impact (Table 4). Because students incorporated uncertainty into their decision making the project facilitated students' ability to navigate uncertainty. Consider how one team phrased incorporating uncertainty into their recommendation regarding efficacy of glucosamine: "Since the current efficacy of selling glucosamine for osteoarthritis is under scrutiny in the scientific community, the market stability of supplemental glucosamine should be carefully considered before proceeding with further investment."

The post project survey provides evidence for the students' response to the project. Most students enjoyed the complexity of the project (69% agreed or strongly agreed), and felt the project forced them to think more broadly about engineering solutions and their context (88% agreed or strongly agreed), while most were not uncomfortable deciding how important different factors should be (21% agreed or strongly agreed). These results indicate that the project promoted, or at least illustrated, a comfort with multiple concerns and types of evidence

Most students (but fewer than above) indicated that the project improved understanding of preliminary plant design (64% agreed or strongly agreed), and that they understood the TEA model and how sales price was determined (67% agreed or strongly agreed). These results indicate that the project somewhat promoted confidence in further understanding of process design.

To successfully navigate uncertainty students must recognize the presence of uncertainty, its role in deterministic problem solving, and that its magnitude is important. Therefore, if students were completely comfortable with any amount of uncertainty, it would imply that they do not recognize that uncertainty will influence their confidence in their decisions. Less than half, between 33 and 48%, of the students agreed or strongly agreed that the project seemed vague and they were unsure how to approach the problem, they did not have enough good information to make a valid decision, and they did not know how to assign importance to different factors. These results indicate that the students were certainly recognizing uncertainty, and were uncomfortable with and considering the importance of its role. We believe the project design was at an appropriate level between deterministic and open-endedness because despite students' concerns with uncertainty as indicated above, only 12% of the student agreed, and none strongly agreed, that the project was not meaningful because any answer could be given.

Interestingly, although the objective was provided directly on the project hand out ("Assume you are a team of four consulting engineers employed to give your recommendations for investment at a company"), only two teams re-stated this objective in their memo. The other nine teams stated something similar to the following statement by one of the teams: "Our process analysis objective was to lower the sales price of glucosamine by analyzing a computational model of the process". The students operationalized the stated objective into a narrower objective. During the in-class work, the instructors noticed that the students focused on model use over discussion of other non-technical or non-modeled factors and concerns. This is understandable, as the model was the only concrete information provided to the students.

Techno-economic analysis of glucosamine and lipid production from diatoms is a well-designed model, which involves process design, equipment and resource utilization, and capital and operating cost estimation. All students participating examined the economic effects and the risk due to the high selling price of vegan glucosamine from algae. With 70 input parameters available, all teams found the key factors related to the total costs. This model represents the actual predictions of costs for this process, for which the bioreactor cost completely dominates. Therefore, it is not surprising that the teams were able to quickly narrow in on the key parameters that effect bioreactor costs.

Conclusion

This project supports a number of the ABET expectations in design for engineering, and more specifically bioengineering, students. ABET defines engineering design as a "decision-making process" and anticipates design curricula to include a broad suite of features. This project includes many of the elements of good engineering design practice, in particular the use of open-ended problems, and the consideration of alternative solutions, economic and regulatory factors, safety, and ethics.

To overcome limited teaching regarding uncertainty in design (Du, 2016), materials (model, contextual assignment) were developed to provide more authentic engineering practice for students. Results from the student work (recommendation memo) and post-project surveys support that the project objectives provide students an opportunity to practice and become comfortable with decision making with multiple concerns and types of evidence, promoting student understanding of how a process design (techno-economic model) can be used, and enable students' ability to navigate uncertainty.

This project, with its emphasis on exposing students to and guiding them towards increased comfort and skill in tackling design problems with inherent uncertainty, should be of interest to engineering educators with similar interests in curricular and course development focused on incorporation of more authentic and realistic engineering practices.

Appendix

Table A. *Summary of post project survey Likert-scale questions*

Question	Question (shortened)	Strong Disagree	Disagree	Agree	Strongly Agree	# of responses
# 1	Project was vague - I was not sure of approach	1	21	11	0	33
# 2	Enjoyed complexity of project	1	9	19	3	32
# 3	Project improved my understanding of plant design	1	11	17	4	33
# 4	Project was not meaningful - any answer could be given	9	20	4	0	33
# 5	Project forced me to think more broadly about context	0	4	23	5	32
# 6	Team member ideas surprised me	3	14	14	2	33
# 7	Concerns were discussed that were not included explicitly in decision	2	12	17	2	33
# 8	Uncomfortable being the person to decide importance of factors	4	22	6	1	33
# 9	Not enough information for valid decisions	2	19	11	1	33
# 10	I did not know how to assign levels of importance	0	17	15	1	33
# 11	I understand TEA and calculating sales price	2	9	15	7	33

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