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PROJECT-ENHANCED LEARNING IN THE MASS AND ENERGY BALANCES (MEB) COURSE

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INTRODUCTION

Mass and Energy Balances (MEB) is in general the first core course in the chemical engineering undergraduate curriculum. The undergraduates typically take this course at the end of their freshman year or the beginning of their sophomore year. The course primarily prepares the students to formulate and solve material and energy balances on engineering systems and provides the foundation for advanced core and elective courses.^[1] This course is also a great avenue for developing various soft skills like critical thinking, communication, teamwork, and ethical perspective, as well as increasing awareness about professional responsibilities.^[2] As these skills are highly valued by prospective employers in both academia and industry, it is imperative that the students get the opportunity to develop them from early on in their education. Project-enhanced learning,^[3] where students collaborate on a project integrated within a traditional lecture-based course and solve a realistic and meaningful problem, can fulfill this goal. Additionally, the implementation of this active learning strategy can contribute to enhancing student learning and engagement, and increasing student retention in the program.^[4]

In this paper an example of project-enhanced learning is provided that can be used in the MEB course. The project is focused on solving a material balance problem related to the production of an Active Pharmaceutical Ingredient (API) for the non-steroidal anti-inflammatory drug, ibuprofen. The API is the central ingredient in the drug, responsible for the health benefits, while the remainder of the drug is composed of excipients.^[5] The project also includes open-ended problems, providing students the choice to propose their own solutions. As the project gets introduced to the students early

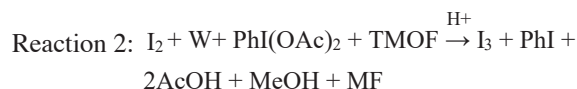
in the course when the material balance topics are discussed, the project is focused on the material balance problem. The students get the opportunity to work and reflect on the problem over an extended period of time while they learn the relevant concepts in the lectures. This paper includes a description of the project problem, instructions for the students, and a discussion of the expected project results along with the learning objectives for the students.

PROJECT DESCRIPTION

The student groups, consisting of three to four students, are provided with a hypothetical scenario for this project. The groups are formed with students from various cultural backgrounds to facilitate cross-cultural communication. The group works as part of the design team in a pharmaceutical company that produces the API for ibuprofen using Continuous Pharmaceutical Manufacturing (CPM).^[5] The colleagues from the pilot plant note that the current production process is not reaching the target production of 10 g of API per hour for some unknown reason. They request that the design team analyze and review the process to figure out the issue.

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The student groups receive information about the reaction stoichiometries and detailed production steps that are adapted from Jolliffe and Gerogorgis, 2015.^[5]



During production, isobutylbenzene (IBB) is first mixed with propanoic acid (PA), which is then mixed with an acid catalyst, triflic acid (TfOH). This mixture enters the first reactor, operating at 150 °C. IBB goes through Friedel-Crafts acylation to produce 1-(4-isobutylphenyl)propan-1-one or Intermediate 2 (I₂) in the first reactor, where the reactor outlet stream is cooled to 0 °C. The products from the first reactor are mixed with a cooled stream (0 °C) containing diacetoxyiodobenzene (PhI(OAc)₂) dissolved with trimethyl orthoformate (TMOF) in methanol (MeOH). The combined stream is the feed for the second reactor, operating at 50 °C. I₂ goes through PhI(OAc)₂-mediated 1,2-aryl migration to produce methyl 2-(4-isobutylphenyl)propanoate or Intermediate 3 (I₃) in the second reactor, with TfOH again acting as the acid catalyst. The by-products in this reaction are iodobenzene (PhI), acetic acid (AcOH), methanol (MeOH), and methyl formate (MF). The products from the second reactor are then mixed with potassium hydroxide (KOH) dissolved in a MeOH and water (W) mixture. The resulting stream is fed to the third reactor, operating at 65 °C. I₃ is saponified (base hydrolyzed) to produce the API in salt form. Isothermal operation is ensured in all the reactors through suitable heating media and thermostats. Finally, the API is purified using liquid-liquid extraction and recovered in the aqueous phase. The problem statement recommends that students assume that the API salt is acidified before purification, as the API in salt form is unsuitable for pharmaceutical formulation. The input flow rates and fractional conversions relevant to each reactor are provided in Table 1.

The student groups are also asked to propose an efficient waste disposal method, as the company intends to be more eco-friendly. Then they are notified that the upper management of their company is considering an increase in the API selling price due to a recent loss in profit. This could eventually lead to an increase in the final cost of the medicine that would be economically disadvantageous for the consumers. Lower-income individuals and people of color are usually the most affected by the rising drug cost, leading to systematic racism in healthcare.^[6]

The students submit a final report at the end of the semester. They receive feedback from the professor and the teaching assistants while working on the project, with a possible

Reactor	Component	Flow Rate (mmol/h)	Fractional Conversion
1	IBB	40	$f_{C,IBB} = 0.91$
	PA	40	
	TfOH	200	
2	PhI(OAc) ₂	45	$f_{C,I_2} = 0.98$
	TMOF	170	
	MeOH	1000	
3	W	1500	$f_{C,I_3} = 0.99$
	KOH	800	
	MeOH	4000	

project timeline between six to eight weeks. For their final report, the students are instructed to include the following information in addition to information on the background of API and its importance in drug formulation:

- Calculation of fractional atom economy (FAE) and its implications
- Block flow diagram for API production, showing the primary reactants and products
- Performance of component material balance and determination of output flow rates from three reactors, solved computationally using Microsoft Excel® or Python®
- Assessment of the design issue related to target API production and proposal of a solution
- Evaluation of the environmental impacts of the process and proposal of strategies for waste disposal
- Reflection on the social impacts related to an increase in API cost and proposal of strategies for mitigation
- Summary of the overall assessment in concluding remarks

Additionally, the students perform self and peer evaluations using a teamwork survey to assess their individual contributions to the project as well as the group's performance. Inclusion of this type of assessment is advantageous for training responsible, critical, and reflective professionals.^[7] The criteria for evaluating team members are included in Table 2. Based on the self evaluation and the team members' evaluations, an average teamwork score (out of 4) is calculated for each student. The technical report is worth 96% of the total project score, while teamwork is worth 4% of the total score. The entire project is worth 15% of the total course grade.

TABLE 2				
Criteria for Evaluating Team Members				
Criteria	Did Not Meet Expectations	Somewhat Met Expectations	Mostly Met Expectations	Met Expectations
Points	0.1	0.4	0.7	1
Contribution to teamwork	Rarely contributed or cooperated, had to be coerced	Cooperated most of the time, worked toward group goals with occasional prompting, or overall okay but not very willing to share duties	Participated and contributed most of the time, but did not initiate planning or discussions	Worked readily with others, worked hard on assigned tasks independently and cooperatively
Attitude towards group members	Always wanted to have things their way, needed constant reminders to be sensitive to the feelings of others, or very minimal interaction with group	Usually wanted to have things their way, needed to be reminded to be sensitive to the feelings of others, or only engaged when asked	Usually considered all views without siding too much with friends, showed sensitivity to the feelings of others, mostly engaged with the group	Valued the knowledge, opinion, and skills of all the group members, helped the team reach a fair decision
Independent problem solving	Tasks were unsatisfactory, could not finish any assignment without help	Worked towards goals, accomplished most of the assignments with occasional reminders, and occasionally needed help	Worked towards goals, accomplished most of the assignments	Excellent problem solver, finished all the assigned tasks on time without any help
Display of respect towards group members	Never	Sometimes	Often	Always

RESULTS AND DISCUSSION

Through a fractional atom economy (FAE) calculation for API production, the students analyze the efficiency of the provided reaction pathway in converting reactants to products.^[8] The FAE value of 0.35 would suggest that the reaction pathway is not highly efficient and would produce significant waste products. By drawing the block flow diagram (Figure 1) and formulating the component material balance equations for each process unit, the students apply the concepts learned in the course.

The open-ended problems included in this project require the students to perform a significant amount of research and brainstorming, facilitating student-centered learning. The design issue that is causing reduced target production of API can be addressed in multiple ways. One possible answer is increasing the input flow rates of IBB and PA to reactor 1 to 46.4 mmol/h, which would increase the target API production to 10 g/h. This exact answer is determined by solving the system of equations for the component material balances in each process unit. The system of equations, consisting of 34 equations, is solved either in Excel or Python. All the material balance equations and the computational solution

of the system of equations can be obtained from the author by emailing nzerin1@jhu.edu.

To evaluate the environmental impacts associated with API production, the students review the Safety Data Sheet (SDS) of the unused reactants and the byproducts and figure out their potential hazards. The students explore the pros and cons of various waste disposal methods and propose a suitable method. They could also propose an alternative reaction pathway with a higher FAE value, leading to reduced waste production and a greener process. The potential rise in the API cost provides the students the opportunity to reflect on the social impacts associated with high drug prices and the impact of their decision-making on peoples' lives. The possible solutions for reducing the API selling price could vary from using an alternative reaction pathway with cheaper raw materials to using a catalyst or recycling to increase API production. All proposed solutions should be logical and supported by appropriate evidence.

The learning objectives for this project meet several of the student outcomes specified by ABET for engineering programs:^[9] developing critical thinking and problem-solving skills by formulating and solving an advanced material balance problem, increasing awareness of their professional

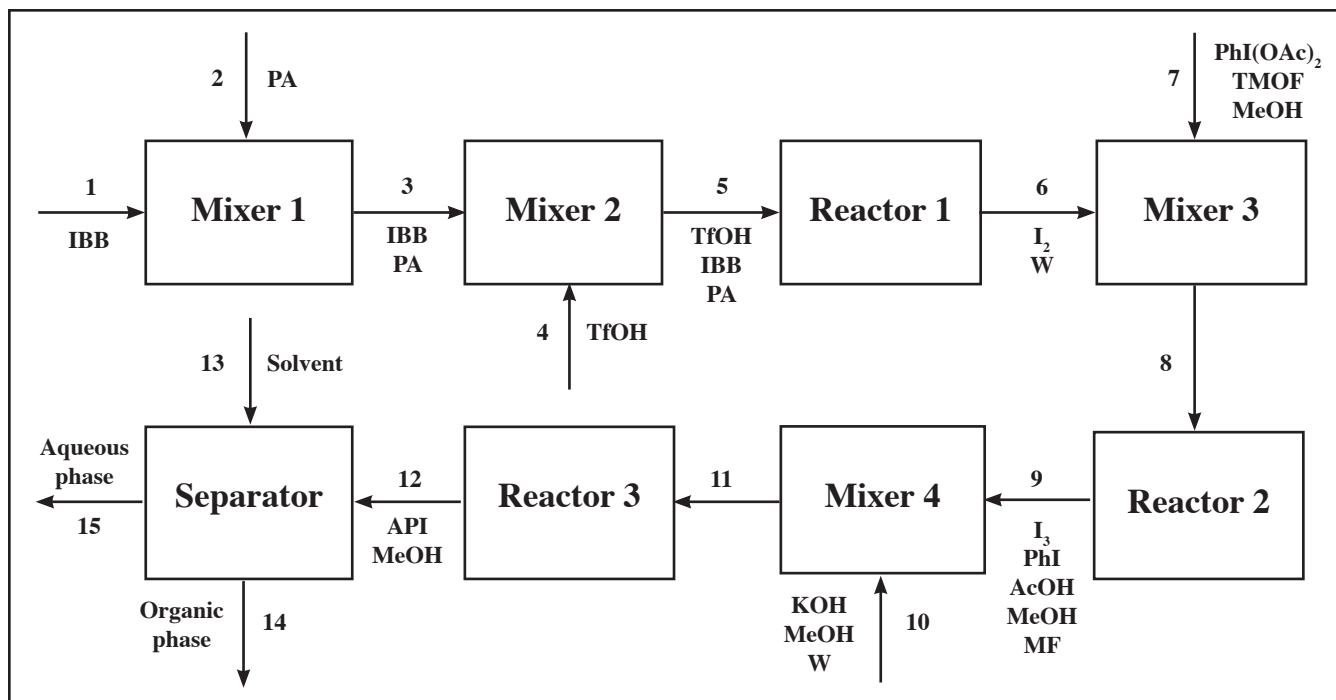


Figure 1. Block flow diagram for API production.

responsibilities by considering the impact of engineering solutions from environmental and social contexts, developing written communication skills by writing technical reports, and learning to meet specific project goals as part of a team.

CONCLUDING REMARKS

The API production problem is an example of project-enhanced learning, where students get the opportunity to solve a realistic and meaningful material balance problem as part of a group. It includes the environmental and social aspects of engineering problems that are not always reflected in traditional lecture-based problems. Therefore, in addition to meeting several of the ABET requirements, it serves as an initiative to promote diversity, equity, and inclusion in chemical engineering. This type of project also aids in improving student-student interactions as well as faculty-student interactions, which are highly beneficial for student learning.

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