INTEGRATING ELEMENTS OF TEAM-BASED LEARNING AND INCREASING INDEPENDENCE IN A 4TH-YEAR LAB COURSE TO PROMOTE THE DEVELOPMENT OF CRITICAL THINKING, PROBLEM-SOLVING AND TROUBLESHOOTING SKILLS

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Abstract Although conventional labs provide good opportunities to develop technical communication and analytical skills, they offer few avenues to develop creative problem-solving or experimental design skills. Even when an open-ended Problem-Based Lab (PBL) format is followed, many students remain reliant on TAs or instructors and when problems arise are reluctant to attempt a solution themselves. This paper describes a new design for a 4th-year chemical engineering PBL-based lab course that incorporates elements of Team-Based Learning (TBL), flexibility, and greatly reduces formal supervision to promote independence, problem-solving, troubleshooting, and critical thinking skills. The course structure and deliverables are described. Student feedback, collected from surveys, indicates that they preferred this approach compared to regular labs and felt it was quite successful in developing the aforementioned skills and in increasing their confidence in their engineering judgement. It will therefore be expanded in the future.

Keywords: Problem-Based Learning (PBL), Team-Based Learning (TBL), Critical Thinking, Problem-Solving, Independence

1. INTRODUCTION

Upper-year engineering students are generally quite adept at collecting and organizing experimental data as part of prescribed laboratory exercises, having had many opportunities to practice these skills over the course of their studies. Although these conventional labs provide good opportunities to develop communication and analytical skills, they are very structured, and generally offer few avenues for students to develop abilities in creative problem-solving or experimental design, both of which are hallmarks of the engineer's skillset. In response

to this, some institutions have shifted to more open-ended, Problem-Based Labs (PBL) in which students are granted more flexibility regarding their assigned tasks, which has been shown to be a very effective teaching method [4]. Faced with open-ended problems, however, many students remain reliant on TAs or instructors for direction, and when difficulties arise, are reluctant or unsure how to proceed, usually deferring to someone else to resolve the issue instead of working through a solution themselves. These situations represent missed opportunities for deeper learning or understanding. Every lab instructor has, at one point or another, asked a student why he or she decided to perform a particular experiment or set a parameter to a certain value, only to receive an answer along the lines of "because the TA told me to" while demonstrating no further insight into or understanding of the underlying reasons, or have had a student complain that a piece of equipment "doesn't work", after having made no attempt to understand or troubleshoot the problem. These behaviours have troublesome implications regarding the development of lifelong learning skills by students. As a consequence of these student habits, or perhaps as a symptom of an underlying lacuna in our instructional approach, employers often comment that graduates from engineering programs are technically quite competent, but lack independence and initiative, and critical thinking, troubleshooting, and creative problem-solving skills, or so-called transferrable skills, which are crucial for engineers [1-3].

This paper describes a design for a 4th-year chemical engineering PBL-based laboratory course that seeks to provide greater opportunities for students to develop these critical thinking, problem-solving and troubleshooting skills, while also focusing on their teamwork and self-reliance. This is achieved by providing open-ended experiments with flexible expectations of final deliverables, incorporating elements of Team-Based Learning (TBL) in the course organization and structure,

and greatly reducing formal supervision and TA support. This course was previously PBL-based, but the course organization and novel approaches that are the subject of this paper were only implemented in its most recent iteration. The structure and deliverables of this course are described in the context of each of these approaches, and the performance of students is assessed. Student feedback on their perception of the usefulness and relevance of this course design and pedagogical approach, and its impact on their learning and skill development are also presented, alongside recommendations for future iterations of the course.

2. COURSE STRUCTURE AND DELIVERABLES

In this course, each team of 4-5 students performs one of five available PBLs over nine weeks. Each session is scheduled for 6 hours, but students are free to use that time as they see fit, based on their experimental objectives. Manuals and/or operating protocols for relevant equipment are provided, but these do not contain any suggested experimental design or instructions for data collection. Rather, the students are responsible to decide what needs to be done, and how it should be done, in order to accomplish their experimental objectives. Open-ended industrially-relevant problem statements, consisting of design, optimization or investigative objectives, are provided to teams as context for the experiments, but teams are not bound by these statements and can choose alternative problems based on their own interests.

Each PBL lasts nine weeks, with deliverables due during different sessions. Although the schedule was flexible and varied to accommodate students' particular experiments, a typical schedule and its timeline of deliverables is presented in Table 1. The introductory session, used for students to familiarize themselves with the equipment in the presence of the TA/instructors, and the experimental sessions take place in the lab. 'Dry Labs' are open sessions in classrooms scheduled during the regular lab period that provide the opportunity for teams to meet and work on data analysis and their reports as a group.

2.1. Project Proposal

The first lab provides students with the opportunity to get their hands on the experimental equipment, and see what options are available to them prior to developing their experimental design. Although students are not allowed to begin their experimental work at this stage, they usually perform a few practice runs during this session or take standard readings to familiarize themselves with the operation of the equipment, all under supervision.

Preliminary experiments related to the use of the equipment, such as the drawing of calibration curves or the determination of the allowable operating ranges, are permitted. The TA for that lab is present for the first three hours of the six hour session, and is there primarily to ensure that the equipment is operated safely and that students arrive prepared.

Table 1. Standard PBL schedule and deliverables timeline

Time	Use of Session	Deliverable Due
Week 1	Introductory Session	---
Week 2	Proposal Oral Presentation	Final Written Proposal*
Week 3	Experimental Session 1	Weekly Work Plan
Week 4	Experimental Session 2	Weekly Work Plan
Week 5	Experimental Session 3	Weekly Work Plan
Week 6	Experimental Session 4	Weekly Work Plan
Week 7	Dry Lab	---
Week 8	Oral Presentation of Project	Oral Presentation
Week 9	Dry Lab	Final Written Report

*Due 4 days after the oral presentation, includes suggested revisions, to be approved before beginning experiments in Week 3

Before being allowed to begin their experimental work, each team prepares a project proposal, which includes a comprehensive review of background theory and literature, experimental objectives, a detailed proposed experimental design, an overview of experimental methodology, a work schedule with a detailed allocation of tasks to different group members, a safety/HAZOP analysis, and an environmental impact assessment of their work. Because the problems are open-ended and each proposed experiment is therefore different, each team is allocated a budget for supplies, and they must submit a list of required reagents and equipment, including supplier and product numbers, within one week of the introductory session, so that the order may be placed in time for the work to commence during the first experimental session.

During the 'Week 2' session, teams orally present their proposal to the course instructor(s) and TA for their lab, and feedback is provided, with particular focus on the experimental design, work schedule, and safety analysis. Teams must incorporate any suggestions or changes required by their evaluators in their final written proposal, due four days after the oral presentation, and are explicitly evaluated on these revisions as part of the rubric for the written report. This final proposal is then reviewed and marked. If approved, meaning that it contains all of the required components and incorporates the provided feedback, and that all safety issues have been identified, understood and addressed; students can begin their experimental work in Week 3.

2.2. Weekly Work Plans

At the beginning of each experimental session, teams must provide a work plan outlining the work performed to date, the work to be performed during that lab session, including a description of how the work will be distributed among team members, as well as any changes made to the original proposal along with a justification for those changes. The latter component is useful not only to ensure the continued safety of the experiment, but also to introduce the concept of change management within the larger scope of the students' project management training. Each work plan is evaluated by the TA, present only for the first hour of the 6-hour experimental sessions, and/or the course instructor. If the work plan is reasonable, complete, makes good use of the available time, and presents an equitable and efficient distribution of work, it is approved and the students can proceed with their experiments. If any issues are raised, or students arrive unprepared for that day's work, they are asked to leave the lab to go prepare or modify the work plan, and resubmit it for approval before being allowed to perform experiments. Students must therefore arrive to the lab prepared, as any experimental time lost cannot be recouped. All work plans are included as an appendix in the final report and evaluated as a whole. It should be noted that while the work plans are being reviewed, the students are asked questions about their work for that day, and must be able to satisfactorily answer them. Any student can be required to answer questions, which provides an incentive for the groups to work together and a sense of accountability for each individual student, as further discussed in section 3.3.

2.3. Oral Presentation and Final Written Report

In 'Week 8', each team presents their work in an oral presentation, and again receives feedback from the TA and instructor. They then have a week to complete a final formal written report, due at the end of the 'Week 9' session. In terms of allocation of marks, the proposal is worth 30% and the final report is worth 70% of the final grade, with the oral presentation and written report components worth 25% and 75% of each deliverable respectively.

3. PEDAGOGICAL APPROACH

As corroborated by the student feedback presented in Section 4, the three approaches at the core of this course design made the course particularly useful in improving students' critical thinking, problem-solving and troubleshooting skills. Each of these elements is discussed below. Although each of these changes has a limited

impact on its own, the combination of these elements created an environment in which student teams had to work independently while involving all team members, and in which students did not have to worry about "getting the right answer", instead having to focus on the critical analysis of the results and their own judgements, which was the main objective of adopting this approach.

3.1 Focus on Analysis, Not on Data

At the beginning of the course, it was made very clear that students would not be evaluated directly on the accuracy of their data (i.e. on whether they obtained the expected values or trends), but rather on their analysis of any data obtained. This approach diverges somewhat from earlier lab courses taken by the students, in which a part of the evaluation was based on obtaining 'correct' results. This did not mean that careless work was accepted, but rather that students had flexibility to pursue alternate experiments to explore or characterize unexpected trends, troubleshoot equipment, or revise their protocols as necessary, leading to more interesting work and removing the temptation of "adjusting" their results. As long as students could document their work, that they used their time effectively, and that they could justify the choices they made, their results, whatever they were, would be accepted and the reports would be evaluated on their merits.

This approach meant, among other things, that the results and experimental direction of each team performing an experiment were different. A good example of this variety can be found in the reports of the teams working on the production of hydrogen peroxide by electrosynthesis, using equipment that was only providing very low yields. Although each team initially approached the problem using similar optimization methods, the end results diverged substantially. One team took the 'standard' approach of performing experiments, fitting a model to the data and validating it, and suggesting possible reasons for the low yields. Another team, in response to the low yields and discrepancies in their mass balance calculations, redesigned their experimental plan to investigate these phenomena instead, identified the causes for these low yields, and produced a new design for the lab equipment that would solve the problems and be more efficient. Yet another group performed some preliminary experiments, performed a detailed economic analysis on the electrosynthesis process, determining it to not be cost-effective, and then designed a peroxide production system using an alternate technology. Each of these approaches produced a completely different data set, which included some unexpected results, required hands-on experimental lab work and engineering judgement, and made use of critical-thinking, troubleshooting, and problem-solving skills. Each approach and analysis was evaluated on its

merits, and not on the nature of the outcome. This flexibility emerged as one of the strengths of the course in student feedback.

3.2 Significantly Reduced TA Involvement

To increase the independence and self-reliance of the teams, the course was designed to minimize the involvement of TAs and instructors in the students' work. In previous iterations of the course, as is common for lab courses, TAs familiar with the experiment and equipment were present for the duration of lab sessions. In such courses, a good, motivated TA can be a valuable guide for the students and provide useful training and direction. In practice, however, it was found that often the TA set up the experiment, showed students how to use the equipment, and then had very little to do as students performed their work. When a difficulty arose, the TA, being familiar with the operation of the equipment, would step-in and quickly solve the problem for the students or dictate changes to the experimental protocols. Although TAs shouldn't, in theory, answer students questions outright and instead help them reason through problems or decision-making, in practice many students deferred to TAs or instructors as soon as something wasn't clear or deviated from expectations. This approach therefore led to missed opportunities for students to develop self-reliance and problem-solving skills.

In this PBL course, TAs were only present in the lab for the first hour of each experimental session to review and approve the work plan, ensure the students were prepared, and that they were able to perform their experiments safely. TAs were also instructed not to directly answer student questions, particularly about analysis methods or choosing appropriate models, and were there primarily as observers. This was made very clear to students at the beginning of the term. The instructors were present throughout the lab session, to ensure the safety of students and oversee the logistics of the course, but likewise did not answer technical questions directly, encouraging students to make and test hypotheses, or to rely on their engineering judgement instead. They did step in, however, in cases of complete equipment breakdown, or when necessary to ensure the lab proceeded as planned. It should be noted that TAs and instructors were of course available to answer any questions or concerns related to safety.

This approach forced students to make their own decisions and rely on their own judgements, to troubleshoot any faulty equipment or unexpected results, and experiment with the process themselves, all of which emerged as strengths of this approach in student feedback. It also forced them to get over their reticence to experiment with equipment and to deviate from the operating manuals when necessary. In chemical

engineering, where most of the conceptualization and design work is computer-based and focused on large-scale processes, the opportunity for open-ended hands-on operation of equipment was a valuable experience.

3.3 Focus on Team-Based Rather than Instructor-led Learning

The removal of formal supervision and open-ended nature of the assigned tasks forced groups to develop a good measure of independence and work as a team to successfully produce all of the elements required in the course. This added responsibility provided the opportunity to include elements of team-based learning in the course, which has shown to be quite effective as a learning tool [5]. Although not a full implementation of the classic TBL framework, elements of work allocation, accountability to other team members, work revision structures, and peer evaluation provided strong incentives to work effectively as a team and to ensure that all team members achieve the same learning outcomes.

In terms of the allocation of responsibility, the initial and weekly work plans had to clearly show an equitable and reasonable distribution of the work. This provided some measure of assurance to the instructors that all students were actively and equally participating in the preparation of deliverables. When the distribution was judged to be lopsided, the plans were re-drawn to ensure equity.

Although it was expected that team members would be responsible for individual sections of the report, it was also expected that each team member would be able to answer questions about any aspect of the work during the work plan review and oral presentations. If a student was unable to reasonably answer a question, it affected the mark for the whole group, creating a sense of accountability that drives participation and learning processes in groups. This ensured that team members would brief each other on the sections they prepared, and that each student would therefore understand the project as a whole. This approach is particularly useful for components like the discussion and analysis section of the reports, which benefit greatly from the input of multiple members, as opposed to being assigned to an individual. The 'dry lab' sessions provided a scheduled opportunity for all group members to meet and to work together on the project deliverables, facilitating this exchange. To further increase the accountability of individual team members, each student had to evaluate their peers at the end of the term, and the score they received, the only individual component of the evaluation rubric, had a significant impact on their final marks.

Finally, each team presented all of the components of their project proposal and final results. Although these

presentations were evaluated for marks, they provided an opportunity to discuss with, and receive feedback from, TAs and instructors, with a subsequent opportunity to incorporate that feedback and discussion into the written products. This allowed the team to help the students responsible for the ‘weaker’ components of the lab report to revise and improve those sections, to everyone’s benefit. This was also seen as strength of the course.

4. STUDENT FEEDBACK

When initially presented with this course structure, many students were apprehensive, with some voicing their displeasure at having traditional supports and direction removed. A few stated outright that they just wanted to know what to submit so they could get their mark and move on. At the conclusion of the course however, student feedback, collected through a survey, was overwhelmingly positive, and the majority of students indicated that they had benefitted from this approach, as opposed to traditional labs. The survey consisted of one multiple choice, four Likert-scale questions, and one (fittingly) open-ended question allowing them to provide any feedback about the course they had. 96 out of the 101 students enrolled in the course answered the Likert-scale questions, and 76 students provided answers to the open-ended question. The results are summarized here.

As shown in Fig. 1, when students were asked whether they preferred this PBL approach to conventional labs, the majority (70%) indicated that they preferred the PBL, with only 9% indicating they preferred the conventional approach. The balance had no preference. This was further supported by comments in the open-ended question. Out of 76 responses, 61 (80.2%) were entirely positive, 10 (13.2%) were mixed (contained both positive and negative comments), and 5 (6.6%) were entirely negative. Most of the positive comments explicitly identified the benefits of this approach, in statements such as:

“I liked that there is more freedom in this PBL lab than other lab sessions. We had a lot of flexibility over how we wanted to conduct this lab [...]. It was a refreshing change to design a lab ourselves and overcome challenges, and gave a better understanding of how research is conducted. It is also nice to be responsible for our own decisions”.

“I like the independence of this course. I also like the fact that we are encouraged to not make stuff up if our data doesn’t make sense. We are just encouraged to say exactly what the data shows [when we explain the results].”

Fig.1. Student responses to the question “Do you prefer Problem-Based Labs (PBLs) or Regular Labs (RL)?”

To assess students’ perception of how useful this course design was in terms of skill development, they were asked how this approach affected their troubleshooting and critical thinking abilities, with results presented in Fig. 2 and Fig. 3 respectively. More than two thirds of students indicated that this approach helped them develop these skill considerably (scores of 4 or 5) with only four students indicating that the lab had no effect on their troubleshooting skills, and two students indicating it had no effect on their critical thinking skills. These results are encouraging, suggesting that most students were challenged by this approach and benefitted from the opportunity to develop skills that are at the core of the engineering profession. This was further supported by comments such as:

“I agree with this approach. It forces us to think critically and figure things out on our own, which are important qualities of engineers.”

“Fantastic, I like having a wide mile to problem-solve and think it is a much needed lesson to students before we enter the workforce!”

Fig.2. Student responses to the Likert-scale question “To what extent did the PBL help you develop troubleshooting skills?”

Fig.3. Student responses to the Likert-scale question "To what extent did the PBL help you develop critical thinking skills?"

One of the major changes implemented in this course design was the removal of formal supervision, notably through the reduction of TA involvement and the explicit expectation that students would work on their own and not receive answers or definitive instructions from the instructors. Since this could have an important effect on students' experience in the course, they were asked to what extent this approach had an impact on their learning, and the results are shown in Fig. 4. A small majority of students (54.2%) indicated that the reduction of TA involvement in the lab had a positive effect on their learning (scores of 4 or 5), and 39.6% indicated it had no impact, on their learning. Only 6.2% indicated it had a detrimental impact on their experience.

Fig.4. Student responses to the Likert-scale question "TA involvement was considerably reduced in these labs, forcing you to work and problem-solve largely by yourself. This:" 5 – Had a positive impact on my learning; 3 – Neutral, had no impact on my learning; 1 – Had a negative impact on my learning.

These results are quite interesting as they show that an overwhelming majority either benefitted from this intervention, or was not impacted by this change. Some of those having provided the latter answer indicated they were able to perform the lab with no additional support,

suggesting a good measure of independence and self-reliance, which is expected of 4th-year students. Those benefitting from the change, indicated in the open-ended question that they appreciated the added responsibility, the opportunity to make their own decisions, and the feeling of accomplishment that resulted from designing and achieving goals themselves, as opposed to having been led through an exercise, through comments such as:

"Really enjoyed having more responsibility and less involvement by the TA's. Made it feel like we were trusted to operate the equipment safely and correctly, and gave us the opportunity to troubleshoot."

Some students also stated that this imposed independence helped develop their team-working skills, which supports the rationale for incorporating TBL elements in the course, in comments such as:

"It encourages teamwork and overcoming obstacles amongst our teams as opposed to checking in with TAs"

Finally, students were asked how this particular lab, given the independence it provided, affected their confidence in their engineering skills, with the results shown in Fig. 5. The majority again validated the usefulness of this approach.

Fig.5. Student responses to the Likert-scale question "How did these labs affect your confidence in your engineering skills and judgement (e.g. abilities to problem-solve unfamiliar problems)" 5 – I am now more confident in my engineering skills; 3 – Neutral, no effect; 1 – I am now less confident in my engineering skills.

It is important to acknowledge that not all of the feedback was positive, and that some students felt the PBL approach was not useful or not relevant, either as a learning exercise or as preparation for entering the workforce. The majority of the negative comments related to TAs (mostly about marking reports or their refusal to directly answer questions) or equipment that wasn't working properly or that were not yielding expected

results. A few also stated that the work load was too high. Some comments, such as the following, indicated a lack of buy-in for this approach altogether and a belief that it demanded a lot of extra work without adding any real value.

"I find that when I work for a company, the things I learned in school are not always used in the workplace. So, this approach is probably useful to improve our critical thinking skills, but not necessarily useful in the workplace"

"This approach for lab is useful for the problem solving, but it is very hard at the beginning of the lab because we sometimes do not have enough background knowledge for the lab."

These comments further suggest that some students do not realize the importance of soft or transferrable skills, including the abilities to think critically, to take-on and solve unfamiliar problems, and to communicate effectively as part of a team, to them securing a position after graduation and progressing through their career path. Although this is not a new phenomenon, with engineering students often valuing technical skills over soft skills [1,2], additional efforts must be made to persuade reticent students of the value of this approach to improve buy-in. Despite the reservations voiced by this small minority of students, however, given the overall apparent benefit of this course design, it will be continued and built-upon in the future.

5. CONCLUSIONS

This paper describes the design for a PBL-based 4th-year chemical engineering lab course that removed formal TA and instructor supervision, and provided increased flexibility in terms of reports and deliverables. These approaches were taken with the objectives of improving the independence and self-reliance of students, and their critical thinking and problem-solving skills. Based on student feedback, this course design was successful, and will be expanded to a full-year course (a PBL during each of two terms) in the future. Several students also stated that open-ended problems like the ones assigned in this course should be introduced in the lab courses in earlier years, which will be considered going forward.

Because the work required by PBLs is greater than for conventional labs, buy-in to this approach is necessary for students to really benefit from it. Although the majority of students, after some measure of apprehension, did take the opportunities presented to them, and those that did produced outstanding work in the process, some pushback

was received, which suggests the need for additional efforts in explaining the potential benefits of this model. Although a more comprehensive analysis of student performance is warranted in future work, this design seems effective, and its objectives were successfully accomplished. One student comment in particular summarizes these benefits and the usefulness of this course design:

"I honestly believe that the PBL benefitted me more as an engineer (I'm not exaggerating this) than all of the other labs I have ever taken combined. Traditional labs are cookie-cutter, "how much time did you spend reading the pre-lab" and "how well can you follow written instructions". Neither of these are conducive to the development of a critical-thinking, problem-solving leader that is an engineer. In a PBL you are told "here is a problem, fix it". THAT is what an engineer does."

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