Using the Delphi Method to Understand Convergent and Divergent Perspectives of PBL Experts and Engineering Faculty in Aerospace Engineering

Abstract

Problem based learning (PBL), though recognized as beneficial to student development, still faces challenges to adoption in engineering education. We conducted a Delphi study with PBL and (aerospace) engineering domain experts to understand areas of consensus and disagreement in consideration of learning outcomes, problem design, facilitation, and assessment. The context for the study was an introductory aerospace engineering course, transitioning from a traditional lecture to a PBL format. We found consensus among both expert groups as it relates to ideas about learning outcomes and assessment. However, with respect to problem design and facilitation, we observed a slower and more contentious convergence, with some ideas failing to reach consensus. From this, four salient issues emerged as critical barriers to PBL implementation that can support a diverse student population in their professional development: problem framing, making relevant connections to society, a deficit view of students, and discomfort with facilitation.

Introduction

Finding a way to authentically prepare and train students for engineering careers has been an important area of research over the last two decades (Direito et al., 2012; Mills & Treagust, 2003; Passow & Passow, 2017; Terenzini et al., 2001). While many have argued that traditional pedagogies – i.e., lecture followed by well-structured problem sets (Jonassen, 2014) – are inadequate in preparing students for the profession (Direito et al., 2012), alternative pedagogies are often met with resistance from both students and faculty (Felder et al., 2011; Perrenet et al., 2000; Terenzini et al., 2001; Tharayil et al., 2018). Problem-based learning (PBL) is one such approach that faces resistance, owing to a variety of challenges (Chen et al., 2021). Even when pedagogical training is provided, educators can find it difficult to adjust and effectively implement PBL (Tik, 2014).

PBL, as considered in this study, is a student-centered pedagogy in which students learn by working through realistic problems under the guidance of an instructor (Servant-Miklos et al., 2019). Toward understanding how to overcome reported resistance, and expand adoption of PBL in engineering education, this study considers the perspectives of both engineering domain faculty and PBL experts. At the heart of this paper is the use of a Delphi method – a method for reaching consensus among experts (Gordon, 1994; Green, 2014) – to consider elements of learning objectives, problem design, implementation/facilitation, and assessment of PBL in an undergraduate aerospace engineering course. Experts on PBL and aerospace engineering domain content were recruited to participate in the study. While the typical aim of the Delphi method is to find consensus among experts, we found that it was not always possible to meet this objective, at least not completely. This study explores this reality and its implications for pedagogical innovation through PBL, as reflected in two research questions:

1. What areas of consensus exist among PBL and domain-specific experts?
2. What areas of disagreement exist among PBL and domain-specific experts?

In the next section, critical elements in the development and implementation of learning experiences are discussed through the lens of PBL literature. These elements informed our Delphi study design and engagement with the respective expert groups. That discussion is followed by a brief overview of the Delphi method.

PBL Pedagogical Considerations

To inform the structure of our Delphi study, we considered the Understanding by Design (UbD) framework of (Wiggins & McTighe, 2005) to identify the key structural elements that govern good pedagogical design. In the context of UbD's backward design process (Wiggins & McTighe, 2005), successful PBL deployment requires consideration of: learning objectives ("identify desired results"), problem design and facilitation ("planning learning experiences and instruction"), and assessment ("determining acceptable evidence"). Through the Delphi study, understanding expert perspectives in this manner was toward informing a transition to PBL that avoids what Wiggins and McTighe call the "twin sins" of traditional pedagogical design: learning activities that are engaging but not always intellectually appropriate, and coverage of content for the sake of coverage. Here, we recognize these as specific challenges that faculty must contend with in transitioning to PBL from more traditional pedagogical approaches.

Problem Design

Once objectives have been considered, the type of problem used to meet that objective can be selected. (Pasandín & Pérez, 2021) identified four types of engineering problems for use with PBL, including (1) simple problems that reflect specific concepts, (2) complex yet structured problems with sufficient information for students to resolve, (3) complete but ill-structured problems with insufficient information given (requiring students to search for information in order to solve the problem), and (4) complex, ill-structured problems that also require analysis to determine a solution. These problems reflect a progression/range of difficulty and complexity levels that students could be asked to solve.

Jonassen and Hung have written significantly on the topic of problem design. Their work considers the types of problems engaged by engineers, and others (Jonassen, 2000, 2010, 2014), as well as dimensions and characteristics of problems, like structuredness and complexity (Hung, 2016; Jonassen, 2000). Though there are approaches describing how problem design might be achieved in the literature (Garcia-Barriocanal et al., 2011; Holgaard et al., 2017; Hung, 2006; Riis et al., 2017) operationalizing that literature is difficult, owing to a lack of granularity in research studies (Author, 2023). This compounds other challenges of PBL related to lack of instructor training and scalable assessment strategies (Chen et al., 2021).

Implementation and Facilitation

While the potential benefits of PBL are hard to refute (Galand et al., 2012; Kolmos & de Graaff, 2014; Strobel & van Barneveld, 2009; Terenzini et al., 2001; Warnock & Mohammadi-Aragh, 2016), successful execution can be a struggle for both faculty and students (McCracken & Waters, 1999; Mills & Treagust, 2003). The infrequency with which PBL experiences are encountered in engineering means that both faculty and students face significant discomfort in adapting to those experiences (Chen et al., 2021). Allowing students time to ramp into PBL work and increase their familiarity with the process over time has been recommended as a way to counteract the uneasiness some students feel with this often-new style of learning (Blair et al., 2002; Mills & Treagust, 2003).

Additionally, a mixed-methods approach that balances traditional lecture-based coursework with PBL projects has been shown to be a successful way to approach PBL in an engineering curriculum (Blair et al., 2002; Perrenet et al., 2000) as it addresses this uneasiness on both the part of the student and teacher (Mills & Treagust, 2003). Perrenet et al (2000) noted the value of this gradual phase-in for PBL in engineering specifically, noting “In engineering some topics are characterized by an hierarchic knowledge structure and complex problem solving. These topics cannot be approached without risk in a PBL-setting. Therefore, direct instruction and supervised practice are needed: direct instruction of outlines, demonstration of expert problem solving, teacher-guided discussions, and problem solving tutorials with specially structured group work."

Finding this balance, however, is non-trivial. The addition of structure may make students (and faculty) more comfortable but may undermine some of the learning outcomes PBL seeks to promote: "...students wanted more structure, and these lectures were added in response. But once the students learned that the lectures would be coming, they knew that with lectures would come answers, so this had the effect of undermining some of the goals of PBL…" (Hmelo-Silver, 2012).

The Delphi method

With these and other challenges of PBL (Author, 2023; Chen et al., 2021) in mind we sought expert opinions to inform our PBL transition. The Delphi method is a research tool that fosters "controlled indirect interaction among experts" (Fink-Hafner et al., 2019) in an effort to answer a given research question (Skulmoski et al., 2007). In this process, expert feedback is gathered, analyzed, and then reshared iteratively until a conclusion or consensus is reached or until the research goals have been achieved (Skulmoski et al., 2007). This approach has been successfully utilized in a broad range of research fields and applications (Adler & Ziglio, 1996; Clayton, 1997; Donohoe & Needham, 2009; Magana, 2017; Streveler et al., 2003; Woodcock et al., 2020) including, as it relates to our study, program planning in education (Delbecq et al., 1975; Green, 2014).

While the classical Delphi method utilizes one-on-one interviews to get individual participant responses for these iterative rounds of data collection (Fink-Hafner et al., 2019), modifications are often made to this structure to best fit the individual study being performed

(Skulmoski et al., 2007). For example, the e-Delphi refers to a variation of the Delphi method where data is collected through computer-based interactions (Donohoe et al., 2012). The Modified Delphi is another variation of this process that reduces the researcher’s heavy burden of successive one-on-one interviews by having individuals respond in parallel for structured discussions (Woodcock et al., 2020) or questionnaires. For this study, a modified e-Delphi method was used in which expert panelists responded to a series of electronically delivered surveys/questionnaires, which were developed after an initial round of focus group discussions.

Methods

This multi-case modified e-Delphi study considered two distinct systems of experts: (1) PBL in engineering experts and (2) aerospace engineering faculty experts. PBL experts were researchers who had published multiple papers on PBL in engineering. The second group consisted of practicing aerospace engineering faculty. Because there is limited research on the use of PBL in aerospace engineering and because many aerospace engineering faculty do not have significant experience implementing PBL, both groups were critical for the Delphi study to capture the expert know-how that intersected both pedagogy and engineering domain knowledge. Consistent with the definition of case study research, multiple data sources were used (through two distinct focus groups and three rounds of continued data collection via Delphi survey responses) to deeply understand the ideology of each system (Creswell & Poth, 2016).

The Modified e-Delphi Method

Concept formulation and research team. For this study, the goal of using the modified e-Delphi method was to gather expert perspectives on the learning objectives, problem design, facilitation, and assessment of PBL for an introductory, 1-credit, second year undergraduate aerospace engineering course. The research team was led by two engineering faculty, one who teaches an introductory aerospace engineering course and one whose research is focused on improving teaching strategies in engineering education. The team also had two Ph.D. candidates whose research is focused on STEM education. Both worked in the K-12 STEM education space. Of note is that while everyone on the team is rooted in engineering education, the team is heterogeneous in terms of gender and work/professional experiences within engineering. In addition, an extensive literature review of PBL, specifically as it relates to college-level engineering courses, was conducted in parallel to the Delphi study (Author, 2023) to ensure all participants of the research team had a thorough understanding of the current state of PBL in engineering prior to making decisions about how best to elicit expert opinions related to it (Fink-Hafner et al., 2019).

Recruitment of experts. Explicit criteria for who would be considered an expert in both the aerospace and PBL fields were set in order to begin identifying candidates for the Delphi study (see subsequent sections for details related to each group of experts). Once these criteria were identified and applied, personal recruitment emails were sent to individuals who met these initial guidelines to explain the Delphi study, request participation, and ask for their recommendations for other experts in the field (Belton et al., 2019). The target recruitment was 15-20 participants in total with an even distribution of aerospace and PBL experts (Streveler et al., 2003), understanding that it is likely that some may not actively participate all the way through the process (Belton et al., 2019; Fink-Hafner et al., 2019). A total of 12 participants were ultimately secured for this study.

Engineering PBL experts. A Google scholar search of “PBL” and “engineering” was initially utilized to compile a list of potential experts. Authors of these papers were then searched independently to explore their body of work. Experts with multiple papers about both PBL and engineering (n = 12) were contacted by email and asked (1) to participate in the study, and (2) to recommend any other experts they think would add value to the study. Of the initial list of twelve, four did not get a response and three people declined, though two of these people did offer referrals for other participants. The remaining six participants agreed to participate in the study, with several offering additional referrals. Two additional experts were secured through the recommendation process. Information regarding these experts is summarized in Table 2. Of these eight experts, seven were able to attend the synchronous survey kick-off meeting and therefore made up the panel of PBL in engineering experts included in this study (see Table 2 for details of these experts).

Aerospace engineering faculty experts. The planned transition to a PBL environment being investigated and implemented in this study occurred within an introductory aerospace engineering course. Instructors of a similar class at ABET-accredited universities were identified from class offerings listed online. Aerospace faculty within the authors' networks who had demonstrated interest in pedagogical practice in aerospace engineering were also identified. Like the PBL experts, these faculty were contacted by email and asked (1) to participate in the study, and (2) to recommend any other faculty they think would add value to the study. Six experts agreed to participate in the study, but one participant was unable to attend the dates. Information regarding these experts is summarized in Table 3.

Table 2 *PBL in Engineering Expert Panelists*

	Institution Type/Location	**Experience**
Expert #1 (he/him)	Research Institution/Southeastern US	Retired research scientist and PBL researcher
Expert #2 (he/him)	Research Institution/UK	Professor of communications systems engineering and PBL researcher
Expert #3 (she/her)	Research Institution/Southeastern US	Director of learning sciences research in the college of engineering, PBL researcher
Expert #4 (she/her)	Research Institution/Europe	Professor of engineering education and PBL, researcher
Expert #5 (he/him)	Research Institution/Southeastern US	Engineering department chair, PBL researcher

Expert #6 (he/him)	Research Institution/Europe	Teaching faculty and PBL researcher
Expert #7 (he/him)	Research Institution/Australia	Teaching faculty and PBL researcher

Table 3 *Aerospace Engineering Faculty Expert Panelists*

	Institution/Location	**Experience**
Expert #1 (he/him)	Research Institution/North Midwest US	Retired aerospace engineering teaching faculty
Expert #2 (he/him)	Research Institution/Southwestern US	Aerospace engineering faculty, industry experience
Expert #3 (she/her)	Research Institution/Southeastern US	Aerospace engineering faculty
Expert #4 (he/him)	Research Institution/Southeastern US	Retired teaching faculty
Expert #5 (he/him)	Undergraduate Institution/Northeastern US	Teaching faculty, consultant

Table 4 *Modified e-Delphi Protocol*

	Round 0	Round 1	Round 2	Round 3	Notes
Methodology[1] *(including question type, etc.)*	Focus groups with a semi-structured, open-ended questioning script	Survey w/ Likert scale and open-ended qualitative questions	Survey w/ Likert scale and open-ended qualitative questions (shared with quantitative results from Round 1)	Survey w/ Likert scale and open-ended qualitative questions (shared with quantitative results from Round 2)	
Delivery medium	Face-to-face Zoom meetings	Emailed links to Google forms-based questionnaires	Emailed links to Google forms-based questionnaires	Emailed links to Google forms-based questionnaires	*To maximize convenience, participants were given a 1-week window in which to complete and return the questionnaire.*
Pilot/test strategy			n/a	n/a	
Estimated time to complete the activity[2]	60 minutes	30 minutes	30 minutes	30 minutes	*Total expected time obligation for participants to complete the study was 2 ½ hours*[3].
Target time to complete post-analysis by research team	3 weeks	2 weeks	2 weeks	2 weeks	*Total time required to complete the Delphi data collection and analysis is 9 weeks, with participant involvement for 7 weeks.*[4,5]

[1] Skulmoski et al. (2007)

[2] Belton et al. (2019)

[3] Participants were informed that this could change based on how quickly a consensus is formed during the modified e-Delphi process.

[4] This aligns with related research that indicates 2-3 months is an optimal time span in which to complete the surveys to keep participants engaged (Belton et al., 2019; Donohoe & Needham, 2009).

[5] As the Delphi method has been shown to be time-consuming not only for participants but for researchers as well (Fink-Hafner et al., 2019), the span of time utilized for this study should be selected such that it optimizes the time resources of both groups.

Delphi Protocol/Framework. The overall framework for this modified e-Delphi method is summarized in Table 4, and the details related to this framework will be explained in the subsequent sections.

Data Collection

The data collection strategy for each round of the modified e-Delphi study is explained in this section, starting with Round 0, the focus groups.

Round 0. As research recommends, a Delphi process should begin by generating issues for consideration in the Delphi survey (Schmidt, 1997) through open-ended questioning or exploratory interviews (Belton et al., 2019). This was achieved using focus groups with semi-structured open-ended question scripts. Specifically, this study conducted two distinct focus groups - one for each group of experts - for this introductory, idea-generating phase. These focus groups were approximately one hour in length and asked each group of experts questions about the design, facilitation, and assessment of PBL in engineering courses. Additionally, the focus group containing faculty experts was asked questions specific to what learning objectives should be addressed. The focus groups were facilitated by a member of the research team with both qualitative research experience and content-area expertise. Each focus group consisted of the groups of expert panelists previously identified for the Delphi survey and were conducted "face-to-face" over Zoom. This face-to-face interaction served several purposes. First, it allowed the research team to introduce themselves, the project, and the benefit of the project to the prospective participants to encourage their motivation to participate in the full study. Second, it showed which participants were motivated to engage in this study through their attendance.

Focus groups were recorded so that transcript coding and analysis could be completed after the session ended.

Round 1. The Round 1 survey consisted of two sections, both presented using Google Forms. The first section gathered basic information and identifiers about the panelists (such as occupation, years in that role, academic background, experience using PBL, and their overall familiarity with PBL). The second section of the survey consisted of both Likert-scale and qualitative, open-ended questions and asked participants to consider the questions generated through the Round 0 focus groups. Participants were given a series of statements related to problem design, facilitation, assessment, and learning objectives and were asked to rate their agreement with each statement on a 7-point Likert scale (with 1 equating to strongly disagree and 7 equating to strongly agree). Participants were also asked to include open-ended, qualitative rationale for their answers (Belton et al., 2019) and were informed that they did not have to answer any questions in which they felt they lacked the expertise to answer appropriately. The survey also included open-response questions at the end of each section to give participants the opportunity to share other information they thought might be relevant to the study. For the convenience of the participants, a 1-week window in which to complete and submit/return the survey was given. Of the 12 participants who were invited to participate in the study, 11 completed the Round 1 survey. The breakdown of these experts was evenly distributed, with 6 participants being part of the aerospace engineering faculty expert panel and the remaining 5 participants being PBL-in-engineering researchers.

Round 2. Data for round two were collected in much the same way as in Round 1. Based on the analysis of the Round 1 responses (which will be discussed in detail in the data analysis and findings sections), a new Google form was generated that contained an updated series of statements that asked participants to reconsider any unconverged statements from the previous round, again related to the four main categories of design, facilitation, assessment, and learning objectives. Participants were again instructed to rate each statement, this time in terms of the importance they placed on each and offer open-ended explanations for their evaluations. Unlike the previous round, participants were now supplied with additional information related to the results of the first round. The mean score and standard deviation for each Round 1 statement were supplied along with a short summary of the overall sentiment of the open-ended data. In addition, the full, de-identified data set (including numerical responses and open-ended responses) was linked in the survey and available to participants as they worked through the second round form. As in Round 1, 11 responses were gathered for this round of the study. The goal of this round, as was the goal of the entire process, was to offer data from the group to the participants as a way to broaden each person's understanding of other perspectives in an effort to move toward a consensus for each statement.

Round 3. The third and final round of this study included a much smaller data set, as only feedback regarding the four most divergent Round 2 statements was elicited from the participants. Again, statements and response ideology (along with full open-ended responses) from the previous round were presented to the participants along with a final revision of the divergent statements. Instead of giving a Likert-scale rating, however, participants were simply asked to discuss their agreement or disagreement with the statement through open-ended responses. Like the previous rounds, eleven responses were collected in this concluding round of the study.

Data Analysis

The data analysis for each round of the survey is explained in this section. Of note is that while the Round 1 survey was analyzed largely quantitatively, the data analysis to determine statement convergence shifted from predominantly quantitative to predominantly qualitative as the rounds progressed through the third and final round.

Round 0. The transcripts of the audio recordings of the Zoom-based focus groups were compared against the actual recordings for accuracy in the final transcripts. These final transcripts were reviewed and deductively coded to understand the content and key ideas expressed by the experts. The transcript was structurally coded to help code and categorize the transcripts using the key areas for PBL implementation defined in this study: learning objectives, problem design, facilitation, and assessment. The result of this analysis was a list of statements regarding utilizing PBL for an introductory aerospace application that acted as the starting point for the research group to formulate Round 1 of the modified Delphi study. If the ideas expressed in the focus groups were multi-faceted, they were split into separate statements. Similarly, if the same view was expressed in both focus groups, the statement was combined. A detailed exploration/discussion of these results can be found in (Author, 2023).

Round 1. The results of the Round 1 survey were investigated both quantitatively and qualitatively, starting with a quantitative analysis of the Likert-scale rating statements. Survey data was exported into a spreadsheet for analysis, and data for each statement were analyzed to calculate an overall average score and an average score for each group of experts (Aerospace and PBL in engineering). The difference between the average scores for each group of experts was also calculated as a way of capturing the level of agreement between the groups. Finally, the standard deviation of the overall average was calculated so it could be added/subtracted from the average score to calculate the statistical upper and lower limits of the data. Items were initially considered converged if the delta between groups of experts was less than 0.5 points for the mean and if the overall standard deviation of the score was less than or equal to 1.

The data were then qualitatively considered, investigating the open-ended responses justifying each Likert-scale rating. Using the given rationale from each expert, the research team met to perform a second, qualitative convergence check which identified any additional statements that could be considered converged based on similar ideology and logic throughout the experts. The research team also discussed and considered the open-ended feedback from the experts to modify the divergent statements in a way that better reflected the experts' input. These modified statements were used to conduct the Round 2 data collection.

Round 2. Like in Round 1, the data collected in Round 2 was exported into a spreadsheet and was first considered through quantitative strategies. The overall average score and standard deviation were calculated for each Likert-scale statement, however instead of this being the primary source of convergence used in this round, it was used mostly to identify trends for the researchers to use as they discussed the open-ended content for each statement. The team met and examined the experts' suggestions and ideas related to each Round 2 statement to determine what level of convergence was met for each. This will be examined in more detail in the Findings section. Statements that still were clearly divergent, as defined by a standard deviation of greater than 2, were used as the starting point for the third and final round of the study.

Round 3. Data from the third round was again exported into a Google spreadsheet for analysis. This time, however, no ratings or qualitative data were collected. The research team met to compare the open-ended responses from each expert against the latest statement (given in the third round survey) and categorized each response as having either "agreement," "partial agreement," or "disagreement" with that statement. The results of this rating were used to determine whether convergence was achieved for this final round of statements.

Delphi Study Progression

In this section, the outcomes from the modified e-Delphi survey are presented round-by-round, starting with the focus group round (Round 0). The convergence process for each topic area is presented in Tables 6-9, as described below.

Focus Group Results (Round 0) and Initial Survey Development

The baseline statements used for Round 1 of the Delphi survey were developed as an outcome of the Round 0 focus group data analysis, as explained in the previous section. There were 14 statements related to problem design, 16 statements related to facilitation, 9 statements related to assessment, and 9 statements related to learning objectives for an introductory aerospace engineering course.

It should be noted that the focus group itself was structured differently for the two different groups. Learning objectives were only specifically prompted for discussion with the aerospace faculty experts, and problem design was specifically prompted for discussion with the PBL experts. Facilitation and assessment were discussed in both groups. In both groups, however, discussions related to all four of these categories arose. Full details about the Round 0 focus groups are described in (Authors, 2023).

Tables 5 and 6 show the round-by-round progression of the Delphi survey for problem design and facilitation. In consideration of manuscript length, we only consider these areas because the statements related to learning outcomes and assessment quickly converged among the experts and therefore, proved less insightful and interesting. Each table is constructed to show the quantitative results of the survey and how statements evolved (in some instances, two or more statements were merged – e.g., statements 1.5 and 1.6 merge as 2.4 in Table 5) based on feedback from the experts. Quantitative results are broken out by domain expertise for the first round because this was the first-time input from both groups was considered simultaneously, so seeing initial convergence/divergence by domain is presented. Though the convergence process is shown for all statements, we focus on the statements that appeared most tenuous and thus required additional rounds and/or combination with other statements to reach convergence, if they did.

Delphi Study Progression: Problem Design

Table 6 *Problem Design Statement Convergence*

Round 1 Statements Group mean(SD); PBL mean; Aero mean *Convergence Categorization*	**Round 2 Statements** Group mean (SD) *Convergence Categorization*	**Round 3 Statements** *Convergence Categorization*
1.1 Students should be given the opportunity to design their own problems. All: 4.09(2.07); PBL: 4.80; Aero: 3.50 *Not converged*	2.1 We should have students identify and frame their own problem within a given problem context. All: 4.27(2.20) *Not converged*	3.1 Given a general problem topic that students will be given 2 weeks to solve, we should have students participate in framing their own problems by generating appropriate lists of requirements and constraints that will guide their problem solving. *Qualitative*
1.2 Problems should be designed with a clear understanding of the learning objectives and how the project/problem will meet those objectives. All: 5.64(1.63); PBL: 6.20; Aero: 5.17 *Not converged*	2.2 We should design problems such that they address specific learning outcomes for the course. All: 5.91(1.14) *Quantitative*	
1.3 Problems should be designed such that students work within constraints and requirements that simulate engineering practice. All: 6.18(1.17); PBL: 6.0; Aero: 6.33 *Qualitative*		

1.4 Students should be tasked with identifying the constraints and/or requirements for their problems. All: 5.78(1.30); PBL: 6.50; Aero: 5.20 *Not Converged*	2.3 We should task students with identifying the constraints and/or requirements for specific problems and, as introductory level underclassmen, ensure they are supported as they build their proficiency in this area. All: 5.82(1.89) *Quantitative*	
1.5 A single, large/system-level problem that is broken into smaller subproblems should be utilized to offer depth of understanding within the aerospace engineering field. All: 4.64(2.01); PBL: 4.20; Aero: 5.00 *Not converged*	2.4 We should utilize a series of different problems to cover a range of topics and solution strategies students might encounter in the aerospace engineering field as opposed to focusing on a single, larger problem context that offers more depth. All: 5.82(1.54) *Quantitative*	
1.6 A series of different problem types should be utilized to cover a wide range of topics and solution strategies within the aerospace engineering field. All: 5.82(1.47); PBL: 6.00; Aero: 5.67 *Not converged*		
1.7 Projects should be designed such that each team's work is interdependent on other team's work. All: 3.70(2.16); PBL: 2.75; Aero: 4.33 *Not converged*	2.5 We should design problems such that students are required to collaborate with other students in their team, but not require collaboration outside of the team for an introductory course. All: 6.00(1.34) *Quantitative*	
1.8 Projects should be designed such that they require collaboration among students (i.e., students are not able to simply divide the work, do it in isolation, and compile their findings at the end). All: 6.18(0.87); PBL: 6.00; Aero: 6.33 *Quantitative*		
1.9 Projects should be designed such that they help students develop an understanding of society.	2.6 We should design problems/projects such that they help students understand how the aerospace engineering field integrates with society.	

All: 4.36(1.63); PBL: 4.80; Aero: 4.00 *Not converged*	All: 5.36(1.69) *Quantitative*	
1.10 Problems should be designed to be exciting for students in order to engage them and keep them motivated. All: 6.45(0.82); PBL: 6.60; Aero: 6.33 *Quantitative*		
1.11 Problems should be designed such that students feel their projects have a purpose for the greater good. All: 4.27(1.62); PBL: 4.00; Aero: 4.50 *Not converged*	2.7 We should design projects so that they show students how the aerospace field connects to the greater good to help engage a diverse group of students. All: 4.55(2.07)	3.2 We should design problems that allow students to see how the aerospace engineering field impacts society. *Qualitative*
1.12 A variety of different problem types should be utilized to reflect authentic engineering practice. All: 6.09(1.51); PBL: 6.60; Aero: 5.67 *Not Converged*	2.8 We should utilize a variety of different problem types (selection, case analysis, design, etc.) to broaden students' exposure to the range of problems they will face in engineering practice. All: 5.64(1.12) *Quantitative*	
1.13 Projects should be designed such that they help students develop problem-solving skills. All: 6.91(0.30); PBL: 6.80; Aero: 7.00 *Quantitative Convergence*		
1.14 Problems should be authentic to the practice of engineering. All: 5.55(1.69); PBL: 5.60; Aero: 5.50 *Not Converged*	2.9 We should design problems to be authentic to the practice of engineering; meaning that student engineers should experience some of the messiness of practice through simplified scenarios. All: 6.27(0.90) *Quantitative*	

While specific metrics were put in place to help the research team determine convergence throughout the three rounds of the Delphi study, convergence was fundamentally a function of whether or not the general ideology expressed by the experts was the same as the statement (converged) or suggested conflicting/divergent views (not converged). For problem design (Table 5), several of the initially proposed statements were found to be uncontroversial within the panel of experts, and converged in the first round of the study (1.3, 1.8, 1.10 and 1.14). The majority of statements, however, required further revisions to move toward consensus within the group as a whole.

Some statements simply required revisions to clarify meaning or to include wording to address a specific area of concern exposed by the experts (1.2, 1.7), however there was an underlying theme that recurred as a concern for many of the statements that were presented. Experts expressed concern about whether or not the ideology for a given statement was appropriate for a single-credit, second-year aerospace engineering course, where students are still relatively inexperienced in terms of their engineering coursework and general engineering practice. This was specifically seen in statements (1.4, 1.9, 1.12, and 1.13), and therefore updates to the wording to address these concerns were added as needed for the statement revisions for the subsequent round. A final convergence strategy that emerged in the analysis of the problem design statements was combining questions. Specifically, if two statements conflicted (such as statements 1.5 and 1.6), the expert feedback from both of these responses was used to generate an updated version of the statement that addressed the topic with one statement only (such as with statement 2.4).

There were two statements within problem design that the panelists had distinctly opposing views on, however, and these statements did not converge based on the aforementioned convergence strategies. The first, statement 1.1, yielded a full range of Likert-scale responses from the experts, with their ideology ranging from agreement supported with the logic that "when students are given autonomy they form agency and are more motivated to learn" to disagreement related to the opinion that “the students, in general, do not have the knowledge they need to design meaningful problems.” Much of the other feedback either loosely supported those two divergent views or was based on the previously discussed concerns related to having young engineers with little experience attempt a task like this. To offer a more centralized statement that reflected both sides of the argument, the research team modified this statement for the second round to create statement 2.1. While experts acknowledged the change in the statement, feedback was still split in the second round for the many of the same reasons previously discussed. No improvement in convergence was achieved with this updated statement, as the standard deviation actually increased between the first and second rounds. This statement was again updated to address the specific concerns expressed by the experts (such as clarifying the scale of the problem itself and the recognizing the need for second-year students to have guidance in framing a problem) to form statement 3.1. The responses from this final revision indicated clear agreement and therefore the statement was judged to be converged. Through this progression, however, the resulting statement ideology merged with another existing statement (1.4 evolving to 2.3) and ultimately contextualized framing the problem as a function of requirement and constraint setting only.

The second statement that required additional convergence was statement 1.11. Expert feedback seemed nearly convergent after the first round with the exception of one expert who simply needed more clarity in the question, however after reformulating the statement to improve clarity, convergence was still not achieved. In this case, the revised second-round statement did not offer clarity to the experts effectively and instead introduced more disagreement and confusion among the experts (per their feedback). Statement 3.2 was provided as a final revision that eliminated the points of contention the experts shared throughout the study and this final statement converged in the third round. Like the previously discussed statement, however, the resulting statement that the experts were able to find consensus with had shifted to reflect less the idea of helping society introduced by the "greater good" term in Round 1 and more of a how-it-connects-to-society ideology that was already captured in an existing statement (1.9/2.6).

Delphi Study Progression: Facilitation

Table 6 *Facilitation Statement Convergence*

Round 1 Statements	**Round 2 Statements**	**Round 3 Statements**
Group Mean (SD); PBL mean; Aero mean *Convergence Categorization*	Group mean (SD) *Convergence Categorization*	*Convergence Categorization*
1.1 Failure should be both valued and accepted as a part of the learning process. All: 6.36 (.81); PBL: 6.40 ; Aero: 6.33 *Quantitative*		
1.2 PBL is best utilized if/when students are fully immersed in the PBL experience throughout the course. All: 6.00 (1.18); PBL: 5.60; Aero: 6.33 *Qualitative*		
1.3 As teams work through their problems/project, facilitators should ask probing questions that promote an increased depth of understanding of the project and related content. All: 6.55 (.52); PBL: 4.60 ; Aero: 4.83 *Quantitative*		
1.4 Facilitators should introduce chaos into problems if and when they feel it can be managed. All: 4.18 (1.40); PBL: 4.60; Aero: 3.83	2.1 We should introduce chaos (such as new or additional challenges) into problems if and when they feel it can be managed, keeping a close watch on morale to ensure this does not have a negative impact on students having an introductory experience with aerospace engineering. All: 4.27 (2.41) *Not converged*	3.1 We (as faculty) should introduce new or additional challenges into problems if/when we feel it can be managed, keeping a close watch on morale to ensure it does not have a negative impact on the student's introduction to aerospace engineering. *Not converged*

Not converged		
1.5 There should be multiple facilitators for a course taught with PBL so that different facilitators can take on a different role (such as "Teacher" and/or "Client") within the PBL framework. All: 4.73 (.65); PBL: 4.60; Aero: 4.83 *Quantitative*		
1.6 Student/team progress should be monitored using milestone checkpoints to ensure students are "on track" before they advance to the next phase of the project. All: 6.64 (.67); PBL: 6.20 ; Aero: 7.00 *Qualitative*		
1.7 Careful consideration should be paid to ensure students have the background skills (such as fabrication skills, software-specific skills, etc.) needed to complete the project. All: 5.00 (1.95); PBL: 4.80 ; Aero: 5.17 *Not converged*	2.2 We should teach the background skills needed to complete a given project (such as fabrication skills, software-specific skills, etc.) in class along with the content. All: 4.91 (1.76) *Quantitative*	
1.8 Students should be treated as junior colleagues (as opposed to the traditional teacher-student relationship) to help build a mindset that more closely reflects a practicing engineer. All: 5.18 (1.33); PBL: 5.40; Aero: 5.00 *Note Converged*	2.3 We should treat students as junior colleagues (as opposed to having a traditional teacher-student relationship that focuses on one-directional knowledge transfer from the teacher) to help build a mindset that more closely reflects a practicing engineer. All: 5.45 (1.75) *Quantitative*	
1.9 A variety of different team sizes and groupings should be utilized to reflect authentic engineering practice. All: 3.82 (1.83); PBL: 4.20; Aero: 3.50 *Not Converged*	2.4 We should keep team sizes consistent between groups for logistical purposes. All: 5.82 (1.54) *Qualitative*	
1.10 Facilitators should take care to not have preconceived ideas about what the "correct" solution is to problems that are posed.	2.5 Facilitators should have a general idea of the expected outcome for given problems but should take care to be open to new solutions posed by students.	

All: 5.27 (1.68); PBL: 5.80; Aero: 4.83 *Not Converged*	All: 6.09 (1.38) *Quantitative*	
1.11 Facilitators should build a class culture where the process is more important than the outcome. All: 5.55 (1.57); PBL: 5.20; Aero: 5.83 *Not Converged*	2.6 Facilitators should build a class culture where both the process and outcome are highly valued. All: 6.00 (1.00) *Qualitative*	
1.12 Traditional lecturing should not be utilized in a PBL curriculum. All: 3.27 (2.24); PBL: 4.40; Aero: 2.33 *Not Converged*	2.7 We should utilize traditional lecturing on an as-needed basis in a PBL curriculum. All: 5.36 (2.25) *Not Converged*	3.2 We should use different teaching practices (discussion, lecturing, etc.) as needed to best help students progress forward in their problem-solving work. *Qualitatively*
1.13 Faculty should be enthusiastic about the content area and problems that are posed. All: 6.36 (1.03); PBL: 6.00 ; Aero: 6.67 *Quantitative*		
1.14 Facilitators should understand the mindset and level of a young undergraduate and ensure their communication and expectations match this level (as opposed to speaking at a high-level researcher or industry professional level). All: 6.00 (1.00); PBL: 5.60; Aero: 6.33 *Quantitative*		
1.15 Upperclassmen who have previously taken the course should be utilized as teaching assistants to improve facilitation (and additionally offer growth opportunities for the upperclassmen) All: 6.36 (.81); PBL: 6.20; Aero: 6.55 *Quantitative*		
1.16 Class time should be spent in two-way discussion as opposed to one-way communication solely from the instructor. All: 5.73 (1.42); PBL: 6.00; Aero: 5.50 *Redundant*		

For facilitation (Table 6), several initial statements converged without iteration (1.1, 1.2, 1.3, 1.5, 1.6, 1.13, 1.14, 1.15) and one statement (1.16) was deemed redundant. A few statements (1.7/2.2, 1.8/2.3, 1.9/2.4, 1.10/2.5, 1.11/2.6) required minor revisions and clarification to reach consensus but revealed some deeper beliefs or attitudes about the nature of the faculty-student relationship and responsibility for learning and knowledge acquisition. This is particularly true of 1.7/2.2 and 1.8/2.3, where we concluded that convergence was contentious owing to a deficit view of students among some experts.

Statements 1.7/2.2 focus on relevant, adjacent prior knowledge that might be valuable to students engaged in PBL scenarios. For example, students engaged in an analysis problem might bring to bear software like Excel or MATLAB as part of the problem solving tasks. Experts indicated a concern that a lack of such prior knowledge would put more onus on the class to teach those skills. Sentiment among experts was that "surface level" introduction to software is okay, but a need to teach too much would lead to a class being "over-stuffed" with content. This type of feedback seemed more concerned with the logistics of the course and how much content could be covered. Other experts were more concerned that worrying about students having all necessary knowledge or directly teaching certain skills would actually undermine the classroom: "…if you expect to give them all the skills in advance then you're not really doing problem based learning…"

Statements (1.8/2.3) related to students as "junior colleagues" was viewed as an ideal aim for a PBL environment, but some experts bristled, especially aerospace experts. The most extensive comment, that seemed to summarize the group as a whole stated: "In theory, this would be great, in practice you'd probably lose 50%+ of the class. Actual engineering requires people to do self-learning to find solutions, given that they have the basic fundamentals down.

For intro students, they don't know the fundamentals yet, and the US primary school system does not really teach self-learning that much. So you'd get a lot of students flailing around and being lost. There will be a handful who thrive and do a lot of their own searching and learning, but we should teach to the whole class, not just the really good students." Ultimately, experts saw treating students as junior colleagues as desirable, but potentially something that might be difficult to achieve given variability among students.

A series of statements related to the amount of lecture (1.12/2.7/3.2) that should be used in PBL were contentious. Though a qualitative convergence was found, the final statement (3.2) is sufficiently vague as to hide some of the deeply held beliefs and attitudes of experts toward lecture. For some experts, lecture is vital to teaching: "Traditional lectures are the best way of transmitting factual information which may be required for projects" or important to reinforcing student independent learning: "Lecturing should always follow student research to deepen and broaden what they have already discovered." On the other end of the spectrum, lecture has no place is a PBL setting, and the final statement is moving in the wrong direction: "The revised statement is meaningless – 'we should have variety' is not the same concept as 'we need to move away from traditional lectures.' The goal here is to ensure that the move to a new pedagogy doesn't get weighed down by faculty bringing their dependence on lectures with them."

One series of statements (1.4/2.1/3.1) related to challenging students through the introduction of "chaos" did not converge. While a few experts agreed with the final statement or offered minor changes, many did not agree. The divergence of opinion among experts included a deficit view of students ("…should be presented as an option for excellent students…more suitable for later year group"), concerns over the student experience ("…introducing mid course changes in expectations, no matter how realistic, will detract from the student experience";

"introducing new challenges will only confuse the students"), and a view that disrupting the process is important to student professional preparation ("the chaos isn't about the experience at the time, it's about building resilience for everything that follows"). The lack of convergence appears to be rooted in divergent perspectives on how education should prepare students.

Discussion

Two research questions were considered in this study: 1) What areas of consensus exist among PBL and domain-specific experts? and 2) What areas of disagreement exist among PBL and domain-specific experts? Our study generally found consensus (i.e., quick convergence) among the experts as it relates to learning outcomes and assessment. Within categories of problem design and facilitation, we identified specific issues that appear to be at the root of the lack of consensus (or contentious convergence): problem framing, the social impact of (aerospace) engineering, a deficit view of students, and the fraught nature of facilitating student engagement with more open-ended, less well-structured problems. As these issues are intertwined and transcend the categories of the study, we address them directly.

Framing of Problems

Involving students in the framing of problems was ultimately reduced to having students identify constraints and requirements. In converging to this, the element of design and framing is slowly excluded from the original idea through progressive rounds of the Delphi study. The experts' feedback suggests either they were unfamiliar with what framing entails ("Faculty should not just let students do whatever they want") or a discomfort with students taking ownership for designing and framing problems ("asking students to 'create a problem' then 'solve the problem' muddles the process of defining objectives and constraints and how a design should adhere to them") and perhaps losing the design intent.

Framing a problem is more than a just understanding requirements and constraints (Svihla & Reeve, 2016), and involves consideration of impacted stakeholders, understanding the root cause of the problem, and considering multiple approaches to solving that problem, which is beneficial for students in their problem solving abilities. This ideology was distinctly opposed by some of the experts, however, who believed either that students were too young and inexperienced to tackle problem framing or that it was not the right place to implement an activity like this ("While it is important to establish a definition of (to 'frame') a problem and to agree upon the problem definition with the client and design partners, this is not the place to establish ownership"). In so much as engineering acts in the service of design (Dym et al., 2005) and framing is an essential element of design problems (Dorst, 2019), students should be provided with multiple opportunities to develop and practice this skill throughout the curriculum. Middle years PBL environments seem like an ideal place for that development, but the middle years are often focused on engaging core theory (Lord & Chen, 2014) with little attention on non-technical facets of problem solving, like framing. Arguably, problem framing is an increasingly important skill for humans to develop as a complement to the ever-improving problem solving capability of artificial intelligence (Cukier et al., 2022). Our findings indicate that work is needed to advance faculty knowledge of and comfort with involving students in the framing of problems.

Broader Connection to Society

Another area where convergence did not come easily was in the category of problem design that integrates and connects aerospace engineering to society. Dissenting feedback on the original statement seemed rooted in the use of the words "greater good" with expert sentiment stating "[Greater good] is a very subjective concept. The greater good has many, many dimensions, many not quantifiable" and "I do not understand what this statement means in the context of the subject of this survey." These concerns were still voiced in the second round, with experts suggesting explicitly that the statement could be modified to say "something like 'the ways in which the aerospace field connects to...'. Not everything aerospace is for the greater good."

Through these modifications, however, the idea of aerospace engineering having a *positive* impact on society was lost, and simply the impact of the field on society was captured. Research suggests that engineering students, particularly underrepresented groups like women and persons of color, often lean towards fields where they can clearly see the positive impact their work can make on humanity (Capobianco & Yu, 2014) and their respective communities (McGee & Bentley, 2017). Our experts specifically noted that they were unfamiliar with this research, which may explain a convergence away from the initial sentiment of connecting with a "greater good." While generally we agree that not everything in aerospace engineering can or should be cast in terms of a greater good, developing PBL environments that do some of this work has potential to broaden participation in aerospace engineering (and other engineering disciplines), which generally lacks diversity (Roy, 2019).

Deficit view of Students

Among some experts, a deficit view of students seemed to undermine or constrain ideas about what facilitation strategies could work. Deficit thinking holds to assumptions about what students cannot do owing to individual traits, prior experiences, and/or cultural and community deficits (Davis & Museus, 2019). Deficit thinking has long been observed as applying to individual students from historically oppressed and marginalized groups (Valencia, 2010) but has, over time, also come to consider educational systems (e.g., schools) as reinforcing deficits in students' abilities (Davis & Meuses, 2019). This limits opportunities for students' participation and important forms of learning in engineering and is particularly harmful to students from underrepresented populations (Long III & Mejia, 2016; Mejia et al., 2018; Minichiello, 2018).

In the introductory PBL context explored in this study, in addition to students' lack of fundamental knowledge, perceptions that half of students cannot be self-led learners is cited as a limiting factor in how students might be expected to work in a more independent fashion. The implication is that facilitation strategies that require students to direct their learning should be deferred to a later time in the curriculum. However, further delaying students' engagement with self-led learning experiences does not resolve the issue. Being a self-led learner matters to the profession and is expected of good problem solvers (Passow & Passow, 2017). There is a need to disrupt forms of educational engagement that fail to develop this skill and reinforce deficit perspectives in the first place. PBL environments are ideal spaces to develop and refine that skill.

PBL Facilitation is Uncomfortable

We identify meaningful overlap between a statement from problem design and a statement from facilitation that required all three rounds. In problem design, there was a difference of opinion between PBL and aerospace faculty around the extent to which students should be allowed to formulate their own problems. The modification of this statement over each round saw additional guardrails placed on the framing of the problem. Aerospace engineering faculty expressed a desire to know about, and have some control over, the progression and end point of the problem. There was also a difference of opinion around the idea of introducing (controlled) chaos into the PBL environment. Unexpected challenges and required changes in direction are a meaningful, and common, part of authentic engineering problems. However, implementing this in a classroom setting where the learning objectives are still met, and student morale does not suffer is an area of concern and there is a need for further research to support faculty in this role.

Facilitation in a PBL environment is a fragile and fraught balancing act. Our experience with PBL environments is that students are often concerned (perhaps even afraid) about working in teams and engaging with problems that are not completely defined. Yet, the statements from faculty in our study suggest that educators may be as afraid (if not more) than students about the open-ended nature of PBL problems. The introduction of even "controlled chaos" further moves the problem into an open-ended space where the outcomes of the student work will likely possess increased variability and there are greater chances for failure. Such open-ended and chaotic environments are often found in capstone design courses. These courses are often taught by professional-track teaching faculty or those engaged in educational research. The degree to which tenure-track faculty are willing to cede control of the classroom environment, given the additional time and mentoring requirements that come with it, continues to challenge PBL adoption.

Conclusion

Overall, this study shows the value of multiple, related groups of experts to inform the transition of an engineering course to a PBL pedagogy. Specifically, it showcased the value of considering the opinions of PBL and aerospace engineering experts, highlighting areas of consensus while exposing contentious issues that threaten to undermine that transition. While there is consensus among these experts as it relates to learning outcomes and assessment, the contentious issues related to problem design and facilitation practices are such that realizing those learning outcomes will be difficult, if not impossible. Though we followed best practices, we note three important limitations of this study. First, the findings of this work are limited by the number of expert participants. Though we believe the perspectives and derived findings are representative of the broader engineering education community, it may not fully capture the variability of that community. Second, the asynchronous and anonymous nature of the modified e-Delphi study may have impacted convergence, as it naturally limits the nature of interaction among the experts. Third, the consideration of four categories – learning outcomes, assessment, problem design, and facilitation – may have limited the level of feedback given constraints on individual experts' time.

Considering the study's findings and limitations, we conclude with two broad implications of this work. First, contentious issues that impact problem design and facilitation signal specific ways in which faculty perceive PBL as a risky endeavor. Lack of formal pedagogical training alongside pressures related to research output and teaching evaluations might make this a risk not worth taking. As we have argued elsewhere (Authors, 2023) design based research at the granularity of individual problems is needed to further inform design and facilitation practices in PBL. In consideration of this study, that research should bring together PBL and domain experts to capture and analyze deep forms of data that contend with these issues to inform pedagogical training. Such research should capture problem design intent, faculty intent and reflection on facilitation strategies, faculty-student interaction, and the extent to which individual student learning aligns with design intent.

Second, replicating the general study protocol employed here, but expanding to include additional PBL and domain (including other engineering disciplines), alongside synchronous conversations that consider more focused topics could yield more robust understanding of the issues. Doing so would further inform the classroom-based research envisioned. It may also set stronger foundations for a still somewhat disparate PBL community of practice that can collaborate on problem design and facilitation strategies, as well as assessment methods that align learning outcomes with problem design and facilitation strategies. Furthering the development of this community is critical to a synergistic research to practice cycle that enables broader adoption of PBL.

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