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

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Abstract

Problem based learning (PBL), though recognized as beneficial to student development, faces implementation challenges in engineering education. We conducted a Delphi study with PBL and (aerospace) engineering domain experts to understand challenges around 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. 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 potential barriers to PBL implementation that supports students in important aspects of their professional development: problem framing, making relevant connections to society, a deficit view of students, and discomfort with

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facilitation. Implications related to these issues are discussed, with consideration given to complications stemming from the isolated, individual-course implementations of PBL commonly found in practice.

Keywords: aerospace engineering; Delphi method; facilitation; problem-based learning; problem design

Introduction

Finding ways 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). Traditional pedagogies – i.e., lecture followed by well-structured problem sets (Jonassen, 2014) – are increasingly viewed as inadequate in preparing students for the profession (Direito et al., 2012). Problem-based learning (PBL), the focus of 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). However, non-traditional pedagogies like PBL are often met with resistance from both students and faculty (Du et al., 2022; Felder et al., 2011; Henry et al., 2012; Perrenet et al., 2000; Terenzini et al., 2001; Tharayil et al., 2018). Resistance to PBL can be attributed to a variety of challenges (Chen et al., 2021; Du et al., 2022; Mabley et al., 2020; Mora et al., 2017), and educators can find it difficult to adjust and effectively implement PBL in engineering environments even after receiving pedagogical training (Tik, 2014).

This study was motivated by the research team transitioning a traditional lecture-style introductory aerospace engineering course into one where problem-based learning (PBL) was the central instructional mechanism. In undertaking this transition, we sought to better understand how experts in PBL conceptualize the approach (e.g., what they view as essential to its theory and practice) and how aerospace engineering instructors perceive what can realistically be accomplished through PBL in an introductory course. These differing perspectives raised questions about how the course should be structured, what kinds of problems are most effective for fostering learning, and how facilitation and assessment practices might be aligned with both PBL principles and disciplinary expectations.

This study considers the most common form of PBL in engineering – an individual course implementation taken up at the discretion of an individual faculty member (Chen et al., 2021; Kolmos & de Graaff, 2014). The position of the authors of this paper is that of individuals who want to leverage the benefits of student-centered pedagogies, like PBL, but also operate within institutions where curriculum-coordination is minimal. Though we recognize and agree that an integrated-curricula would be more desirable from the perspective of the student experience (Kolmos & de Graaff, 2014) and programmatic coherence (Moesby, 2005), challenges associated with curriculum-level implementation and concerns stemming from isolated course implementations are beyond the scope of this study. However, limitations stemming from isolated-PBL implementations (representative of the context explored here) and their relevance to the findings and implications of this study are taken up in the Discussion and Conclusion sections.

This study explores this reality and its implications for PBL implementation, particularly in an introductory engineering course. By considering the perspectives of PBL experts and aerospace engineering faculty as domain-specific experts, two research questions are explored:

1. Where do PBL and domain-specific experts' ideas about PBL implementation converge?
2. Where do PBL and domain-specific experts' ideas about PBL implementation diverge?

We used the 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. While the typical aim of the Delphi method is to find consensus among experts, we leveraged it as a systematic approach to understand both consensus and lack thereof. Through this study we found consensus is more easily reached on the topics of learning objectives and assessment, while there are important areas of disagreement around problem design and facilitation. These areas of disagreement provide an avenue for fostering communication and collaboration between PBL and domain-specific experts so that adaptable and scalable PBL models can be created that overcome the implementation challenges often faced by engineering faculty.

In the next section, critical elements in the development and implementation of learning experiences are discussed through the lens of PBL literature with specific focus on problem design and facilitation, as these were areas of greatest disagreement. 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.

Pedagogical challenges of PBL

The structure of our study was framed around consistent challenges in PBL implementation that fall into categories of problem design, facilitation, and assessment (Chen et al, 2021; Olewnik et al., 2023a). PBL is an active learning pedagogy in which "students are confronted with an open-ended, ill-structured, authentic (real-world) problem and work in teams to identify learning needs and develop viable solutions, with instructors acting as facilitators rather than as primary sources of information" (Prince & Felder, 2006). PBL, as envisioned in this study, has been classified as a case-based learning style in which students have high autonomy (Lavi & Bertel, 2024). Students work in self-directed teams that require significant learning of new course material (Borrego et al., 2013). The problem, not the instructor, is the primary vehicle for students' self-directed learning and knowledge construction (Hmelo-Silver, 2004; Kolmos & de Graaff, 2014). Here, we highlight specific aspects of these categorical challenges of PBL described in the literature, limiting that treatment to problem design and facilitation given that these aspects were the most contentious among experts.

Problem design

Designing good problems for PBL is a hallmark challenge, which must contend with the types of problems and characteristics like structuredness and complexity (Hung, 2016; Jonassen, 2000, 2010, 2014). Though there are approaches describing how problem design might be achieved (Garcia-Barriocanal et al., 2011; Holgaard et al., 2017; Hung, 2006; Pasandín & Pérez, 2021; Riis et al., 2017) operationalizing that literature is difficult because reporting on the operationalize context is often not sufficiently granular to inform translation into similar contexts (Olewnik et al., 2023a). This compounds other challenges of PBL related to lack of instructor training and scalable assessment strategies (Chen et al., 2021).

In engineering contexts, a contemporary focus on theory and math (Grayson, 1980) and meeting accreditation criteria (e.g., ABET in the United States) has fostered curricula rooted in well-structured problems (Jonassen, 2014; Lord & Chen, 2014) at the expense of more professionally relevant competences (Dym et al., 2005; Passow & Passow, 2017). Well-structured problems often take form in abstractions of real systems constrained such that students engage a "plug-and-chug" problem (Bucciarelli, 1994; Jonassen, 2014). Students rarely participate in even the development of objectives, requirements, and constraints that might be associated with activities of identifying and formulating problems (ABET, 2025); and even that is not fully representative of the activities that engineers might expect to engage to frame problems (Svihla

& Reeve, 2016). Thus, making students part of the problem design process is arguably an important need in PBL environments (Holgaard et al., 2017).

Implementation and facilitation

While the potential benefits of PBL are hard to refute (Beagon et al., 2019; Boelt et al., 2022; Galand et al., 2012; Kolmos & de Graaff, 2014; Kolmos et al., 2021; Strobel & van Barneveld, 2009; Terenzini et al., 2001; Warnock & Mohammadi-Aragh, 2016), successful execution can be a struggle for both faculty and students (Du et al., 2022; Henry et al., 2012; Mabley et al., 2020; McCracken & Waters, 1999; Mills & Treagust, 2003). The level of exposure to PBL environments can vary significantly from country to country and institution to institution. For example, Aalborg University uses PBL across their engineering curriculum. On the other hand, the use of PBL within engineering at the three U.S. institutions represented by this paper's authors is limited and at the discretion of individual course instructors. This is consistent with findings from Chen et al. (2021), which suggest that PBL implementations are more likely to be at course- rather than curriculum-level. Thus, PBL experiences encountered in engineering remain relatively rare and 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 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), especially in engineering contexts (Perrenet et al., 2000). 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 (Henry et al., 2012; Hmelo-Silver, 2012).

The Delphi method and expert opinion

While there exist PBL experts, implementation of PBL is often done by instructors who lack sufficient training and that implementation takes place primarily at a course level (Chen et al., 2021; Tik, 2014). The introductory aerospace engineering course considered in this paper is taken by second-year engineering students and was added to the curriculum in 2014. The class meets once per week for 75 minutes. This course was added to the four-year curriculum by the Aerospace Engineering Course and Curriculum Committee, who then tasked a faculty member with designing and structuring the content. For the first 7 years, this course was a topics-based survey class. After receiving funding to restructure the course, the research team viewed this as an opportunity to incorporate PBL into the curriculum by making it the focus of the course. Because this course is not a prerequisite to other classes in the department, the research team had unprecedented freedom; the faculty member teaching it is the sole instructor of record and learning objectives and outcomes could be redefined.

Collaboration between PBL experts and non-experts seems like a pathway to overcome implementation challenges associated with PBL implementation, but such collaboration is limited in undergraduate engineering education. Considering this reality, we sought expert opinion in terms of how it might impact PBL implementation, which necessitated an understanding of convergent and divergent perspectives.

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, 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 domain experts. PBL experts were researchers who had published multiple papers on PBL in engineering. Domain experts 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 systematic literature review of PBL, specifically as it relates to college-level engineering courses, was conducted in parallel to the Delphi study (Olewnik et al., 2023a) 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
After identifying potential experts in both PBL and aerospace engineering, recruitment emails were sent to potential candidates requesting their participation and ask for their recommendations for other experts in the field (Belton et al., 2019). The target recruitment was 15-20 total participants and 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 at least three publications related to PBL and engineering, and explicit or implicit experience implementing PBL as presented through those publications (n=12) were contacted by email. Of the initial list of twelve experts, four did not respond and three declined, but 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. Of these eight experts, seven were able to attend the synchronous focus group meeting and therefore made up the panel of PBL in engineering experts included in this study. There were five men and two women representing institutions from the U.S. (3), U.K. (1), Northern Europe (2), and Australia (1). Information related to their experience and institutional context is shown in Table 1.

	Institution Type/Location	Role (Years of Instructional Experience)
Expert #1	Research University/Southeast US	Retired research scientist and PBL researcher (20+ years)
Expert #2	Research University/UK	Professor of communications systems engineering and PBL researcher (20+ years)
Expert #3	Research Uni./Southeast US	Director of learning sciences research in the college of engineering, PBL researcher (20+ years)
Expert #4	Research Uni./Northern Europe	Professor of engineering education and PBL researcher (20+ years)
Expert #5	Research University/Southeast US	Engineering department chair, PBL researcher (20+ years)
Expert #6	Research University/Northern Europe	Professor and PBL researcher (18 years)
Expert #7	Research University/Australia	Teaching faculty and PBL researcher (40+ years)

Table 1. Engineering PBL Expert Profiles.

Aerospace engineering faculty experts

The planned transition to a PBL environment motivating this study occurred within an introductory aerospace engineering course in the U.S. Instructors of a similar class at ABET-accredited U.S. universities were identified from class offerings listed online. A total of 12 experts were contacted, but only five participated in the study. Of these five experts, there were four men and one woman, representing institutions across the U.S. Information related to their experience and institutional context is shown in Table 2.

	Institution/Location	**Role (Years of Instructional Experience)**
Expert #1	Research University/North Midwest US	Retired aerospace engineering teaching faculty (20+ years)
Expert #2	Research University /Southwestern US	Aerospace engineering faculty, industry experience (10 years)
Expert #3	Research University /Southeastern US	Aerospace engineering faculty (10 years)
Expert #4	Research University /Southeastern US	Retired teaching faculty (30+ years)
Expert #5	Undergraduate Institution /Northeastern US	Teaching faculty, consultant (3 years)

Table 2. Aerospace Engineering Faculty Expert Profiles.

Data collection

The overall framework for the modified e-Delphi method is summarized in Table 3. The data collection strategy for each round of the study is detailed in this section.

	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.

Table 3. Modified e-Delphi Protocol.

Round 0: Focus Groups

Following best practices, we used focus groups with semi-structured open-ended questions to generate issues for consideration in the survey rounds (Belton et al., 2019; Shmidt, 1997). Two distinct focus groups – one for each group of experts – were conducted virtually and were one hour in duration. Semi-structured questions related to design, facilitation, and assessment of PBL in engineering courses were used to guide discussion. The focus group with aerospace domain experts additionally considered learning objectives. Each session was facilitated by two members of the research team, one with qualitative research experience and one with content-area expertise. Discussions were recorded and subsequently transcribed for analysis.

Survey Round 1

The Round 1 survey consisted of both Likert-scale and qualitative, open-ended questions derived from the focus group discussions. 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 bipolar scale (strongly disagree to strongly agree). Participants were also asked to provide rationale for their ratings (Belton et al., 2019) and were informed that they did not have to answer any questions in which they felt they lacked necessary expertise. The survey also included open-response questions to allow participants to share other relevant thoughts. Eleven of the 12 experts (5 aerospace, 6 PBL) completed the Round 1 survey.

Survey Round 2

Based on the analysis of the Round 1 responses a new survey was created with a revised series of statements that asked participants to reconsider any nonconverged statements from the previous round. 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. Participants were also provided with information related to the results of the first round. This included the mean rating score and standard deviation for each Round 1 statement and a short summary of the overall sentiment of the open-ended data. The full, de-identified data set (including numerical responses and open-ended responses) was made available to participants as they worked through the Round 2 survey. In line with the Delphi method, providing group data to study participants is a way to broaden each person's understanding of other perspectives in an effort to move toward consensus. As in Round 1, 11 responses were gathered for this round of the study.

Survey Round 3

The final round comprised a much shorter survey, as only feedback regarding the four most divergent Round 2 statements was elicited from 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. Rather than Likert-scale ratings, 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

Analysis for each round of the survey is explained in this section. While the Round 1 survey was analyzed largely quantitatively, the data analysis to determine statement convergence shifted from predominantly quantitative to predominantly qualitative as each survey round progressed.

Round 0: Focus Group Analysis Overview

Transcripts of the focus groups were reviewed and deductively coded to understand the content and key ideas expressed by the experts as part of a complementary study (Olewnik et al., 2023b). The transcript was structurally coded to help identify and categorize according to the key areas for PBL implementation considered in this study: learning objectives, problem design, facilitation, and assessment. The result of this analysis was a list of statements related to integrating PBL in an introductory aerospace engineering course, representing a specific application context application for study participants.

Survey Round 1 Analysis

The results of the Round 1 survey were investigated both quantitatively and qualitatively, starting with a quantitative analysis of the Likert-scale rating statements (Clayton, 1997). First, Likert-scale responses for each statement were analyzed to calculate an overall average score and an average score for each group of experts (Aerospace and PBL). 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. The standard deviation of the overall group was also calculated. As noted previously, this quantitative analysis was performed so that the relative convergence of the Round 1 questions could be shared with the experts during Round 2, thus informing participants of the group perspective (Clayton, 1997). To maintain participation in subsequent rounds – a noted problem for Delphi studies (Donahoe & Needham, 2009; Fink-Hafner et al., 2019) – the time obligation for subsequent rounds was minimized by considering statements with close statistical agreement as converged (Belton et al., 2019; Clayton, 1997). The research team identified statements with a delta between groups of experts of less than 0.5 points for the mean and an overall standard deviation of less than or equal to 1 as converged.

Data were then qualitatively considered, investigating the open-ended responses justifying each Likert-scale rating. The research team summarized the experts' sentiment from Round 1 and shared that, along with a link to the complete, open-ended qualitative data set with participants in Round 2 (Belton et al., 2019). Using the given rationale from each expert, the research team also performed a second convergence check to validate the quantitatively converged statements and to identify any additional statements that did not meet quantitative convergence criteria but that could be considered converged based on similar ideology and logic throughout the experts' statements (Belton et al., 2019). Finally, the research team 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.

Survey Round 2 Analysis
Like Round 1, the data collected in Round 2 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. Statements that still were clearly divergent, as defined by a standard deviation greater than two, were used as the starting point for the final round of the study.

Survey Round 3 Analysis

The research team met to compare the open-ended responses from each expert against the latest statement provided 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.

Findings: Delphi study progression

In this section, the outcomes from the modified e-Delphi survey are presented round-by-round. We limit presentation of findings to topics of problem design and facilitation because the statements related to learning outcomes and assessment quickly converged among the experts and proved less insightful and interesting. Design and facilitation, on the other hand, had a more contentious convergence process and for some ideas there was no convergence. The convergence process for each topic area is presented in Tables 2 and 3. Each table presents 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 2) 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

For problem design (Table 4), we eventually found consensus among experts for all 14 of the initial statements. Four 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). Most statements, however, required revision to move toward consensus within the group.

Some revisions were just 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 a recurring concern for many of the statements that were presented. Experts expressed concern about whether 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 revision strategy that emerged in the analysis of the problem design statements was combining survey statements. Specifically, if two statements conflicted (such as statements 1.5 and 1.6), the expert feedback for both statements was used to generate an updated version of the statement that addressed the topic with one statement only (e.g., statement 2.4).

There were two statements related to problem design that experts had distinctly opposing views on, however, and these statements did not converge based on the revision strategies. The first, statement 1.1, yielded a full range of Likert-scale responses from the experts, with their ideology ranging from agreement supported by 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 many of the same reasons in the previous round. No improvement in convergence was achieved with this updated statement, as the standard deviation increased between the first and second rounds. The statement was again updated to address the specific expert concerns (such as clarifying the scale of the problem itself and 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 other statement that required additional convergence was statement 1.11. Expert feedback seemed nearly convergent after the first round except for 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 (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).

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.	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: 5.78(1.30); PBL: 6.50; Aero: 5.20 *Not Converged*	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.	
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*	All: 5.82(1.54) *Quantitative*	
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.	
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*	All: 6.00(1.34) *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) *Not converged*	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*	

Table 4. Problem Design Statement Convergence.

Delphi study progression: facilitation

For facilitation (Table 5), several initial statements converged without revision (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 sentiment 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 in 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.

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 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 problem 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 *Not Converged*	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*
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.	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: 5.00 (1.95); PBL: 4.80; Aero: 5.17 *Not Converged*	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. All: 5.27 (1.68); PBL: 5.80; Aero: 4.83 *Not Converged*	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: 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*	

Table 5. Facilitation Statement Convergence.

Discussion

Two research questions were considered in this study: 1) Where do PBL and domain-specific experts' ideas about PBL implementation converge? and 2) Where do PBL and domain-specific experts' ideas about PBL implementation diverge? Our interaction with PBL and aerospace domain experts considered four general areas – learning outcomes, assessment, problem design, and facilitation – but design and facilitation proved to be the most contentious topics, so we focused our reporting on those. Specific points of convergence, contention, and divergence for design and facilitation are shown in Table 6.

	Well implemented PBL experiences…
Convergent	… include students in the identification of problem constraints and requirements
	…address specific course learning outcomes through a series of problems (breadth) rather than a single semester-long problem (depth)
	…simulate engineering practice, exposing students to different types of problems and the messiness of those problems
	…establish student teams of consistent size and limit collaboration to within those teams
	...excite and motivate students' engagement through interesting problems and facilitators who are enthusiastic about the problem topics
	…recognize failure as a valuable part of the learning process
	…are full PBL-immersion throughout the course (i.e., student-centered problem-engagement is the primary pedagogical approach)
	…use probing questions to promote deeper understanding and engagement
	…include multiple facilitators who can assume different roles as needed and who adapt their mindset to the experience level of students; integrate PBL-experienced upperclassmen as facilitators
	…teach background skills for tools (e.g., software, fabrication tools) if necessary for producing problem deliverables
	…monitor student progress using milestone checkpoints
	…have some sense of the boundary for the expected solution outcomes but are open to new solution paths
	…create a culture where both solution process and product are valued
	…position students more like junior colleagues/engineers who co-construct knowledge with facilitator/expert guidance rather than relying on one-directional transfer of knowledge from expert (teacher) to novice (student)
Contentious	…allows for different teaching practices (e.g., discussion, lecture) as needed to help students
	…engage students in framing of problems
	…help students understand how aerospace engineering integrates w/ society
Divergent	…introduce new or additional challenges to a problem after engagement begins to simulate the emergent or changing nature of problems in practice

Table 6. Summary of convergent, contentious, and divergent ideas among experts.

We eventually found consensus among experts as it relates to problem design, though for two issues – problem framing and the connection of aerospace engineering society – this proved contentious. For facilitation, we generally found consensus, but one issue related to facilitation strategies (i.e., lecture or not) was contentious, and one issue (i.e., introducing emergent issues) did not reach consensus. Through the Delphi process we identified four specific issues that reflect potential points of contention between PBL and domain experts: 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. Additionally, we consider potential complications stemming from isolated-PBL implementation as described in the Introduction.

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 just understanding requirements and constraints (Holgaard et al., 2017; 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. 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).

Given this, middle years PBL environments seem like an ideal place for that development, especially since 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. In isolated-PBL implementations, limiting students' framing work to requirements and constraint identification may be more realistic. More substantive framing work by students would be more appropriate in systemic-PBL models -- i.e., programs in which problem- and project-based learning are coordinated across the curriculum (Kolmos & de Graaff, 2014), where students have multiple problem-based experiences that can support progressive engagement with framing. 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." Overall, experts struggled with PBL and broader societal conceptions in ways similar to students (Servant-Milkos & Kolmos, 2022).

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 divergence 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 were 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. However, isolated-PBL is likely to amplify the deficit-view of faculty and impede the ways in which students are allowed to become self-led learners.

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 isolated-PBL environment. Unexpected challenges and required changes in direction are a meaningful, and common, part of authentic engineering problems (Jonassen, 2014; Passow & Passow, 2017). 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 isolated-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, in line with existing literature (Chen et al., 2021; Henry et al., 2012; Hmelo-Silver, 2012). 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. Thus, pedagogical training, facilitator characteristics, and scaffolding strategies are vital considerations for successful implementation of PBL (Ertmer & Glazewski, 2019; Hmelo-Silver et al., 2019).

Conclusion and implications for practice

This study demonstrates the value of engaging multiple groups of experts to inform the implementation of new pedagogies. Specifically, it showcased the value of considering the opinions of PBL and aerospace engineering experts when implementing an isolated-PBL experience in a single course within a 4-year curriculum. Our findings highlight areas of consensus while exposing contentious issues that threaten to undermine the transition of a course from a lecture format to PBL. 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 associated with the implementation of our Delphi 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. Of note, our study lacks perspective of experts from institutions in regions like Asia and Latin America. 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 as it relates to isolated-PBL implementations. First, as it relates to the key findings, 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 (Olewnik et al., 2023a) 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. This is necessary to give more confidence to faculty who may consider PBL but want to see more specific evidence of successful application. Formalizing an engineering PBL community of practice, with regular, research-informed training opportunities would be a valuable outcome. Complementing the formation of such a community, institutions should do more to incentivize and support the adoption of student-centered pedagogies, like PBL. This idea is not new but continues to be reinforced by technological advances (e.g., devices, online demonstrations) that make access to problem relevant knowledge increasingly ubiquitous.

Second, as it relates to overcoming the current study's limitations, replicating the general study protocol employed here, but expanding to include additional PBL and domain (including other engineering disciplines) experts, alongside synchronous conversations that consider more focused topics could yield more robust understanding of the issues. This includes a need to expand the pool of experts to a range of institutions and regions/cultures. Additionally, conducting such a study synchronously and in-person over several days with a more focused set of issues may yield more nuanced understanding within the community. This would further inform the classroom-based research envisioned above. 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 more effective implementation of PBL.

Future work should contend with the transition from isolated- to systemic-PBL implementations. Such work is necessary to overcome inherent challenges of isolated-PBL tied to the student experience (Kolmos & de Graaff, 2014) and a need for curricular coherence (Moebly, 2005). It poses important questions related to the design, facilitation, and assessment of PBL scaled across the curriculum beyond the scope of this study.

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