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A Systematic Review of PBL Literature: In Search of Implementation Guidelines for Engineering Situated Problem Design, Facilitation, and Assessment*

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Problem-based learning (PBL) is recognized as a pedagogical approach that is well-suited to preparing engineering students for the realities of the profession, but there are persistent implementation challenges that serve as barriers to broad adoption. This systematic literature review focuses on three facets of PBL – design, facilitation, and assessment – in search of operational guidelines for engineering faculty considering a transition to PBL. Findings led to two broad conclusions. First, there is a need for research on methods to support engineering faculty in problem design. Second, while current research provides thorough support for PBL facilitation and suggestions for assessment, there is a need for additional research to evaluate the efficacy of the various models of facilitation and assessment suggested by the literature.

Keywords: assessment; facilitation; problem-based learning; problem design

1. Introduction

Engineering professors have many options when it comes to the teaching methods they can use in the classroom. Lecture-tutorial methods have traditionally been popular but research suggests that lecture-based teaching methods have limited effectiveness in engineering courses [1, 2]. Calls for pedagogical reform at the course and curriculum level within engineering education has led to faculty being increasingly encouraged to adopt pedagogies like active learning and flipped classrooms [3–6]. This has resulted in a shift in higher education away from traditional teacher-centered methods to learner-centered approaches [7].

One such approach, problem-based learning (PBL), supports students' learning through real-world problem-solving [8]. With origins in medical education, educators have also used PBL in nursing, architecture, business, the general sciences, and engineering [9–14]. Definitions for PBL in the literature can vary but often point to learning experiences characterized by real-world problems, engaged by small groups, with facilitation by a faculty/instructor [8, 15, 16]. Based on social constructivism, PBL enables learning through student-led interactions and requires students to take responsibility for their learning process, encouraging active engagement to build skills and competencies that translate to practice [17]. Whereas in traditional teacher-centered teaching methods an instructor acts as the primary source of knowledge, PBL installs the instructor as a facilitator that guides students as they acquire and construct knowledge.

PBL offers students an opportunity to participate in active learning, because it engages their learning process, improving their problem-solving capabilities, instead of learning knowledge for purposes of regurgitation [18, 19]. Overall, PBL has been found to have a generally positive impact on student learning of core knowledge and complementary skills (e.g., problem-solving) aligned with the profession, and supporting student learning in ways that lay "the foundations for a lifetime of continuing education" [19–24].

The design and implementation of PBL environments for engineering education is challenging for a number of reasons; problem design, facilitation, and assessment represent specific facets of PBL that are particularly challenging and deter adoption [25–28]. In the face of these challenges to broader PBL adoption, we conducted a literature review with a goal of distilling specific guidance that might support engineering faculty in design, facilitation, and assessment. This literature review considers the

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application of PBL within university level engineering courses with these three implementation challenges in mind. Particular interest was a unit of analysis at the individual problem level. Two research questions guided a systematic approach: (1) What operational lessons are captured in the literature to support engineering faculty in PBL implementation? (2) What opportunities for the engineering PBL community are revealed?

2. Reference Frame

We approached this literature review as a research team supporting the transition of an introductory engineering course from a traditional lecture to a PBL approach. Thus, we are interested in PBL research as a course level instance [25]. While all authors of this manuscript have integrated various forms of active learning in classrooms and other learning environments, we have not attempted to integrate a "pure" form of PBL (if such a thing even exists) [4, 5]. We have integrated elements of PBL but readily admit that our prior implementation might be best described as ad hoc. Toward a more intentional implementation, we consulted the PBL literature to devise an evidence-based approach.

Our initial literature search considered three questions aligned with recognized PBL challenges [25]: (1) how should a problem for PBL be designed? (2) how should problem engagement be facilitated? and (3) how should problem engagement be assessed? An initial review of the literature led us to conclude that while there is a significant body of research on PBL from a variety of domains, operationalizing that knowledge is non-obvious. Thus, the purpose of this literature review is to answer these questions but with a mind toward operationalizing those answers and exposing current gaps in our understanding.

Our reference frame imagines the transition from a traditional to a PBL approach as something like that in Fig. 1. The traditional approach is instructor-centered, with class rooted in instructor-led lectures and students' problem engagement primarily in the form of "story problems" [29]. A reductionist view of student-faculty interaction in the traditional approach is shown in the left panel of Fig. 1. The interaction follows a sequential 1-2-3-1 loop that includes: (1) instructor transmitting knowledge to students; (2) students producing problem-solving artifacts demonstrating application of acquired knowledge; (3) review of artifacts by faculty; and (1) faculty providing feedback and assessment to students. This loop could continue indefinitely but is typically terminated after a single iteration because problems have a single correct solution. Central to this interaction is a well-structured problem that has been sufficiently defined for students to solve in a single iteration.

Relative to traditional learning environments and in consideration of existing definitions, we imagine PBL environments as enabling interactions between faculty and students that follow less predictable paths. Arguably, one of the benefits of a PBL environment is to disrupt the traditional pathways. A representative model of faculty-student interaction in PBL environments is shown in the right panel of Fig. 1. The interaction reflects the idea that faculty play a facilitation role and the pathways for faculty-student interaction do not follow a predefined loop. This model of the PBL environment considers a multitude of pathways between the primary actors (faculty and students), many of which are mediated by problem related artifacts. The pathways have been labeled and we define them as follows.

Paths (1) and (2) represent the relationship between faculty and students as mediated by the problem. Path (1) flows from faculty to problem and is focused on issues related to problem design. Creating realistic problems requires that problems will be more ill-defined and open to interpretation, and the design of a problem is recognized as an important challenge in PBL [25, 27, 30–32]. Path (2) is related but is focused on the relationship between students and the problem. Once students are given a

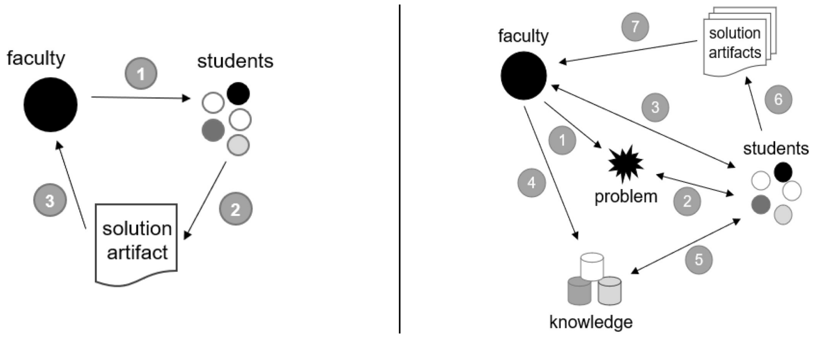

Fig. 1. Left panel: Traditional faculty-student interaction in engineering problem-solving environments. Right panel: Faculty-student interaction in PBL environments.

problem, we imagine that they might play a role in informing updates to framing and scoping of the problem. Specific questions we sought to understand through a review of the literature included: *Q1: How should faculty design problems that build upon students' varied prior knowledge? Q2: What format, type, and level of information should be provided in the problem statement? Q3: How much should students be involved in framing and scoping of the problem?*

Path (3) is the direct relationship between faculty and student (i.e., no mediating artifact). Along this pathway, we imagine that concepts related to faculty in the role of facilitator to be particularly important but complex [33]. As a facilitator, the faculty should be guiding without providing direct answers on what to do, or perhaps more importantly, how to do it. This can be a difficult change for faculty who may be used to demonstrating or directing students on what/how to do things through well-structured problems. The lack of structure in PBL can be a shock for both students and faculty, which can lead to more familiar structured practices (e.g., lecture) that undermine learning [25, 34]. However, we also note that facilitating still requires some level of teaching engagement. As noted by [35] (in a makerspace context), there is sometimes a sense that students should figure things out on their own – "activities will themselves serve as the teacher" – and this is potentially harmful. Finding a balance between facilitator and teacher may be particularly difficult to achieve. Thus, the question we seek to understand through the literature is: *Q4: How do you structure and scaffold learning to balance the dual facilitator/teacher role?*

Paths (4) and (5) reflect a relationship between student and faculty around the identification and production of knowledge. Here, we consider explicit forms of knowledge that might be curated. Examples of such explicit knowledge might take form in theorems and equations (a form of knowledge common to engineering classrooms), experimental procedures, codes, and regulations (e.g., ASME Pressure Vessel codes), and data/analysis reported in journals or technical reports. In a PBL environment, we expect that students will have some responsibility for discovering relevant knowledge that already exists and for producing other knowledge necessary to frame and solve the problem. Thus, the question to be answered through the literature review here is: *Q5: How much knowledge should students be expected to produce/acquire as they go?*

Paths (6) and (7) represent the relationship between faculty and students mediated through solution artifacts. Path (6) considers the production of relevant artifacts that demonstrate student progress toward a solution. Path (7) concerns faculty assessment and feedback on that progress. The question of interest here is: *Q6: How (what artifacts) and when should students be assessed?*

With this reference frame in mind, this literature review explores PBL in terms of design (Q1, Q2, Q3), facilitation (Q4, Q5), and assessment (Q6) for engineering. It is important to note that while design, facilitation, and assessment will be discussed separately, a successful PBL curriculum will ensure that these elements align with one another.

3. Methodology

3.1 Identification and Filtering of Papers

To identify and evaluate relevant publications we used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) model [36]. We implemented a four-step process to identify sources, and filter and analyze papers. We considered publications from the past 25 years (1997–2022).

Step one was identification of appropriate databases and compilation of articles. The criteria for identifying papers were that they (1) were PBL, (2) engineering focused, and (3) situated in higher education environments. We included the European Journal of Engineering Education, Interdisciplinary Journal of Problem Based Learning, International Journal of Engineering Education, Journal of Engineering Education, and the Journal of Problem Based Learning in Higher Education. We also included conference proceedings from the American Society of Engineering Education. Additionally, we utilized the EBSCO Host search to identify related papers outside of our original database list. The full list of sources resulting from step one is in Appendix A and the total number of articles from these sources that resulted from searches using the prescribed criteria was 196 (Appendix A).

In step two, one researcher reviewed the paper abstracts to ensure that all three criteria were met (e.g., some papers addressed PBL for engineering but were situated in a primary or secondary education setting). Based on this filter, the number of papers was reduced to 87 (Appendix A).

In step three, one researcher performed a cursory review of the remaining manuscripts to ensure that at least one of the challenge issues – problem design, facilitation, or assessment – were addressed in the manuscript (i.e., some papers provided a reflection on an engineering PBL implementation in higher education or were more focused on student perceptions without providing a level of detail on design, facilitation, or assessment that addressed the questions from our reference frame). This filter reduced the number of papers to 59.

The fourth step was an iterative and collaborative analysis process of reading and coding toward finding papers that substantively addressed problem design, facilitation, and/or assessment. This phase of the process resulted in a final set of 31 manuscripts and is detailed in the next section. A heat map is shown to demonstrate how those manuscripts map to our six operational questions (Table 1). The paper number indexed at the top of the table corresponds to the list of references.

3.2 Analysis

To analyze the (final) 31 manuscripts and ensure trustworthiness in our analysis, two researchers were assigned to review each paper. This was toward ensuring a consensus that each manuscript addressed part or all of the operational questions (Q1-Q6). We followed four guidelines for our deep dive analysis and to support internal discussions toward consensus: (1) review papers in the context of specific questions and identify specific claim(s) related to the operational question, (2) note any specific evidence offered to support claim(s), (3) consider the extent to which the work answers the question, and (4) note potential gaps that remain. Where disagreements occurred among the two reviewers, the four authors discussed each case and came to a final decision whether to include or exclude.

This analysis is intended to distill from published

Table 1. Distribution of papers across operational questions for design (D), facilitation (F), and assessment (A); Q1: How should faculty design problems to build upon students' varied prior knowledge?; Q2: What format and type and level of information should be provided in the problem statement?; Q3: How much should students be involved in framing and scoping of the problem?; Q4: How do you structure and scaffold learning to balance the dual facilitator/teacher role?; Q5: How much knowledge should students be expected to produce/acquire as they go?; Q6: How (what artifacts) and when should students be assessed?

		Design			**Facilitation**		**Assessment**
		Q1	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*
	17				■		
Reference Number	40	■					
	41	■					
	42	■					
	43		■				
	44		■				
	45		■				■
	46			■	■		
	47				■		■
	48						■
	49				■		
	50				■		
	51				■	■	
	52				■		
	53				■	■	
	54				■	■	
	55				■		
	56				■		
	57				■		
	58				■		
	59				■		
	61						■
	62					■	
	66						■
	67						■
	68						■
	69						■
	70						■
	71						■
	72						■
	73						■

papers operational lessons regarding PBL for engineering in higher education. While we acknowledge that some papers may have been unintentionally filtered or that there may be papers outside our sources, we do not anticipate a significant impact on our findings, discussion, or conclusions.

4. Findings

Findings from our analysis are presented within the context of the six operational questions organized by the overarching themes: design, facilitation, and assessment. The key findings are summarized in Table 2 and detailed in each subsection.

4.1 Problem Design

Problem design is critical to successful PBL [27]. There are generalized frameworks intended to support problem design – e.g., the 3C3R model – and guidelines intended to support problem design through consideration of problem type, characteristics (e.g., structuredness), and representation [37, 38, 31, 39]. We sought to understand if and how these or other frameworks may have been leveraged in engineering higher education settings but found limited evidence as it relates to our three problem design related questions.

4.1.1 Q1: How should faculty design problems to build upon students' varied prior knowledge?

Three papers were found that relate to this question. Two papers highlighted the value of designing problems such that the topics explored are familiar to students. The rationale being that when students are more comfortable with the topics covered, they will be more likely to engage in the problem. Riis et al. claim that idea generation and "intuitive evaluation" of proposed solutions is improved ("more fruitful") when concepts that are readily comprehensible and easily understood by the students are used [40]. However, it is unclear what is meant by "intuitive" and how prior knowledge that fits that definition is explicitly accommodated in problem design. Similarly, McLoone et al. describe learning modules with content related to a PBL course being taught in the prior semester as important to student success [41]. However, there is no specific guidance on how prior knowledge is assessed or integrated within problems designed for the PBL experience.

Garcia-Barriocanal et al. describe an approach rooted in novice/expert comparison to systematically identify gaps in prior knowledge to support the development of additional related (sub-) problems that can be used to build student knowledge [42]. The intent of this approach is to (re-) develop problems and subproblems that better scaffold learning to develop students' capacity for increasingly ill-structured problems. The method sounds promising but there were no specific examples demonstrating how existing problems were evolved or how new problems were created based on the approach.

4.1.2 Q2: What format and type and level of information should be provided in the problem statement?

Three papers addressed this question, though not at the granularity that might best support operationalization by others. Khalaf et al. summarize efforts to create three different problems "from an iterative process of prototyping, running, analyzing, and redesigning" to create problem "cores" that can be covered with different "skins" [43]. The core of each problem is aligned with specific skills or competencies deemed important to a biomedical engineering setting – probability/statistics in health screening and decision making, experimental design, and mathematical modeling/computer

Table 2. Summary of key findings for the six operational questions

Design	
Q1: How should faculty design problems to build upon students' varied prior knowledge?	(3) papers address this question, but the level of detail is insufficiently granular to extract operational guidelines
Q2: What format and type and level of information should be provided in the problem statement?	(3) papers address this question but tend to describe general approaches or philosophies; specific examples that demonstrate approaches and philosophies are missing
Q3: How much should students be involved in framing and scoping of the problem?	(1) paper describes a methodology to support students in the framing process; the approach is a conceptual model derived from experience
Facilitation	
Q4: How do you structure and scaffold learning to balance the dual facilitator/teacher role?	(14) papers discuss issues of structuring/scaffolding; lack of comprehensive guidelines and need for evidence regarding efficacy
Q5: How much knowledge should students be expected to produce/acquire as they go?	(4) papers discuss this issue but there is conflicting opinion (students should acquire and apply vs. knowledge should precede application) that aligns with implementation challenges described in the literature
Assessment	
Q6: How (what artifacts) and when should students be assessed?	(12) papers discuss a variety of artifacts that should be assessed but there a need for evidence regarding value/efficacy of artifacts alone or in combination

simulation – and serve to introduce students to that world. The paper informs some thinking about the philosophy behind a problem (or set of problems) at the center of a PBL environment and provides an example problem statement. However, it stops short of providing specific guidelines on how to develop problems and how iteration and analysis support problem evolution.

Similarly, Mitchell et al. describe the philosophy and shift to a PBL curriculum [44]. A brief discussion about how problems ("trigger material") were formulated through a top-down structure that starts with selecting appropriate topics and skills. Consideration of specific technical knowledge (content knowledge) and engineering specific skills (transferable skills) are described but evidence regarding the effectiveness of the approach to designing problems is not presented. An example problem statement is provided as representative of the underlying philosophy, but nothing is explicitly mapped in terms of knowledge and skills to aspects of the problem statement.

Lantada et al. describe a systematic analysis that considers 40 factors to find and formulate the nine biggest challenges in problem- and project-based learning [45]. The approach is based on a survey of eight faculty as representative of the 40 faculty in the program. Through cause-effect analysis they map factors to areas of methodology, resources, teachers, and students. Thus, the evidence is conceptual and derived from their experience as a group with PBL. As it relates to developing problems at an appropriate level of detail, they propose the use of limited topics, curating references (e.g., classic books) related to the topic, use of patent databases, and visit and support seminars. However, there are no specific examples of problem statements that result from these guidelines.

4.1.3 Q3: How much should students be involved in framing and scoping of the problem?

One paper was related to supporting students as part of problem framing and scoping activities. Holgaard et al. present a 5-step model to support students in defining the problem: (1) relating to a theme, (2) mapping the problem field, (3) narrowing down the problems, (4) problem analysis and contextualization, problem formulation [46]. It recognizes the need for research regarding problem design and argues for students to serve as problem designers lest they "develop a blind spot" with respect to the challenges involved with the process of understanding problems. This is a conceptual model inspired by findings from interviews with PBL staff and students from two programs at Aalborg university but there is no evidence as it relates to the effectiveness of this approach to involve students in framing and scoping of problems. Additionally, the approach may be more appropriate in project-based learning environments, where engagement with a problem occurs over a longer period.

4.2 Facilitation

The open nature of PBL allows for a variety of structures and instructional approaches and seems to be effective in generating student interest and motivation [47, 48]. There are many factors to consider as a PBL facilitator, including a need to balance providing students with information/knowledge versus expecting students to acquire it themselves, the type and amount of support to provide during the process, and the role of the facilitator in the classroom.

4.2.1 Q4: How do you structure and scaffold learning to balance the dual facilitator/teacher role?

While 14 papers provide insights and perspectives about how learning should be structured and scaffolded, none offered comprehensive strategies and had limited forms of evidence to support implementation. When all papers are considered, four themes emerged: (1) PBL implementations involved hybrid environments and/or hands-on problems, (2) students must own the problem-solving process while milestones are developed by the facilitator, (3) multi-step processes that explained how instructors guided and facilitated problem-solving, and (4) the revealing of problem aspects throughout the semester.

Four papers described how PBL changed the educational environment by requiring facilitation that occurred throughout the semester and sometimes required hands-on activities. Hunsu et al. describe how students perceive PBL as being more hands-on while in Mora et al. the importance of allocating time for teamwork is noted [49, 50]. Four lecturers participated as facilitators as students engaged in problems throughout the semester [50]. An active learning environment was achieved through PBL and conventional courses with short problems that supported PBL. In Stewart, course concepts were taught in the first six weeks of a 13-week semester [51]. While students found PBL interesting and expressed high desires for learning, their self-reported scores for self-management were low. Linking with questions about problem design, Tan & Shen note that project scope differs between hybrid PBL and conventional lecture environments [52]. They describe how PBL problems allow students to pursue multiple pathways and acknowledge this as a structural difference from traditional problem-solving. However, the discussion about how such differences are managed (or created) and the impact on facilitation is minimally addressed.

Three papers discussed how milestones for the PBL experience were developed by the instructor. Using semi-structured interviews of PBL faculty, Mitchel & Rogers discuss that a significant challenge is identifying when an instructor should let the student lead the problem-solving process [53]. In these interviews, faculty described how activity was more important than the solution, and that students leading the problem-solving process required the faculty to make carefully timed interventions. Successful interventions were viewed as those that guided the students back onto the path toward the correct solution, rather than simply giving them the solution. Further, they note that successful interventions also require faculty to know something about student prior knowledge [53].

A similar argument for student ownership is found in Jaeger and Adair, where students were expected to take ownership and responsibility for solving the problem [54]. Students were expected to do work and advance the solution before receiving helpful hints from the faculty. Helmi et al. provide a cooperative PBL structure and its potential impact on students' "deep thinking and problem-solving assets" [55] but the structure of the study is not such that observed improvement is necessarily linked to the cooperative model. Additionally, there is a lack of detail on what the interaction among students and faculty within that framework. This interplay between student ownership, their existing knowledge, and careful interventions is also highlighted by Tik, where it is noted that instructors in PBL environments need to be "ready" for the instructional form and have the "right skill sets" for facilitation [28].

Three papers describe facilitation around structures and scaffolds that involve multi-step processes [56, 57, 46]. A fourth explores the integration of concept maps as a potential PBL scaffold but found no impact on student progression in engaging the problem as intended [17].

Mabley et al. [56] offer one of the most complete descriptions of their facilitation process. Teams were responsible for analyzing the case, identifying the problem, and then generating hypotheses and their associated knowledge gaps, supported by a problem-solving process from the instructors. This allowed students to identify learning objectives by the end of the first class. One hour of in-class time was allotted, and then students were expected to engage in individual research outside the classroom. Another hour was allocated the next week where students would get together with their group and share the information that they collected. The keywords from this process were found to drive initial discussion during the first hour, but the learning objectives turned into a checklist that the students focused on checking off without giving them much thought.

The facilitation process described in Stamou et al. starts with a lecture to convey important theoretical knowledge [57]; this model appears similar to more traditional pedagogical models. This lecture transitions to a simple example that is solved as a class and is followed by an authentic or real-world problem. It was also acknowledged that instructors may have to fill-in missing knowledge or refresh students on knowledge that they have forgotten.

Holgaard et al. describe how students become active members in problem refinement (as previously described in Q3) by using a 5-step approach that spans problem identification, analysis, and formulation [46]. This process was viewed as providing a scaffold for defining tasks that relate to learning outcomes.

Finally, three papers discuss how problem elements were revealed during PBL experiences. Macho-Stadler and Elejada-Garcia describe how a macro problem is decomposed into smaller, consecutively faced problems [47]. Each smaller problem required students to conduct research, generate hypotheses, identify the unknown aspects of knowledge, and manage the tasks needed for completing the problem. They then integrated these sub-problems when solving the original macro problem. Masek and Yamin use a similar strategy as a subject-centric problem was decomposed into five sub-problems over a two-week period [58]. In the first week groups received the problem, and ten-minute mini-lectures were used to provide necessary information.

Vidic offers a comparison approach, where the instructor facilitated and established the milestones for the PBL-section, while students in the non-PBL section saw the complicated problems only at the end of the semester [59]. Pre- and post-tests were used to compare population groups, presenting one of the few investigations into the effect of facilitation strategy in PBL environments.

4.2.2 Q5: How much knowledge should students be expected to produce/acquire?

The literature describes PBL as supporting a range of knowledge acquisition. This includes acquiring professional (e.g., communication) and higher-order problem-solving skills as well as uptake of specific domain knowledge (e.g., statistics) [60, 24, 58, 57, 61]. In many cases it is unclear whether this acquisition was as an inherent byproduct of the experience or accommodated through more direct instruction.

Four papers did offer some (indirect) insight specific to this operational question. Mitchell and Rogers argue that students should acquire all knowledge necessary for PBL [53]. To promote this knowledge acquisition, "staff must move from a practice of giving information to posing probing questions" [53]. This requires students to independently acquire the knowledge, as well as determine when additional knowledge is needed to solve their problem. Specific information regarding the size of the knowledge gap that students might be expected to bridge is not described.

Jaeger and Adair take up this issue, in part and indirectly, by modeling student perceptions of a PBL environment as it relates to factors of personal situation, engineering interest, and ability to succeed [54]. Among their findings is that if the problem is situated within a knowledge gap that students can bridge, their beliefs about success are not impacted by facilitator support. However, Ribeiro and Mizukami contradict that quantitative finding, at least among some students [62]. Through a qualitative study that considered student feedback at the end of a PBL experience, they found that some students viewed "the problem preceding the theory" as a limitation of PBL. At least one student indicated feeling "insecure" in such a learning environment. Thus, while Jaeger and Adair imply that it is a matter of finding the right size knowledge gap [54] the implication from Ribeiro and Mizukami is that any knowledge gap is too big [62].

However, Ribeiro and Mizukami point out that putting students in scenarios where they must span the knowledge gap is a feature of PBL environments [62]. They note that student insecurity in this scenario is a function of their prior learning experiences occurring "in more directive learning environments, with logical, sequential methods of knowledge acquisition." This may suggest that students who are more capable self-directed learners will be more comfortable in bridging knowledge gaps inherent to the PBL approach. Stewart explored this issue with international engineering graduate students who participated in a PBL engineering management course [51]. Using a self-directed learning readiness survey, he found that students with a higher level of self management (planning and time management ability) gain more from a PBL environment. He suggested that the use of a self-directed learning readiness diagnostic tool may be necessary when implementing PBL curriculum to ensure that learning outcomes are met within a PBL structure that makes students responsible for knowledge acquisition [51].

Going back to our question – *how much* knowledge should students acquire – we found a lack of specificity regarding the amount of knowledge students are expected to acquire in the reviewed literature. The types of knowledge and artifacts reflecting that knowledge might be described but how much students are acquiring in a self-directed manner and details about how specific activities (e.g., research, analytical modeling, prototyping) support that acquisition are lacking.

4.3 Assessment

Assessing ill-structured student problems or projects is a notorious struggle for engineering faculty and can be even more challenging when implementing PBL in engineering courses [63]. Because of the inherent goals and learning objectives of PBL (i.e., creating professionally situated, student-directed independent and group work aimed at solving ill-structured problems that can sometimes have distinctly different outcomes), paper-and-pencil style unit tests generally do not accurately capture student performance [63]. In other words, the problem-solving and professional skills students use during PBL are not captured with a traditional testing approach [64]. Identifying what should be assessed and understanding what strategies have been successfully utilized to assess students in those areas is critical to implementing PBL. Since PBL is meant to help engineering students grow in both technical competencies and professional skills (including teamwork, communication, and problem-solving skills), it is important that PBL assesses students in all these areas and not just a subset of these skills [65]. A widely-accepted benchmark for quality assessment for PBL in engineering has yet to be developed, despite several attempts discussed in the literature [45, 48, 61, 64, 66–70]. It is therefore important to understand research related to what assessment strategies have been investigated so future progress can be made in this area.

4.3.1 Q6: How (what artifacts) and when should students be assessed?

Twelve papers were found that relate to the assessment-specific question. While little evidence was included to support claims of why different assessment tools should be used, papers do suggest several artifacts, including self-reflection, an engineering journal, self- and peer assessment, written and oral reports, content-specific tests, solution debates, and portfolios [44, 45, 48, 61, 67, 68, 70]. Hersam et al. extends the assessment ideologies listed above even further, suggesting not only additional artifacts students can produce, but the use of an evaluation committee to assess students' work and final presentations [69].

Exemplifying the nature of the reviewed literature, an assessment approach specific to software engineering education (PBL-SEE) is extensively described by dos Santos [71]. The approach is situated at the intersection of four theoretical frames: a process for managing PBL implementation, a revised Bloom's taxonomy to support derivation of learning outcomes, a PBL implementation model specific to software engineering (xPBL), and consideration of an "authentic assessment" model. Through this approach assessment can occur multiple times and case studies demonstrate how that can be used to visualize the evolution of student learning. This work presents a viable assessment model grounded in technical (i.e., content knowledge) and professional (e.g., client satisfaction) competency development. However, it does not provide any comparative evidence to demonstrate how or why it is effective.

Of these papers, reflection was highlighted as the most commonly suggested artifact for assessment. Though evidence to support the voracity of claims was sparse, papers mentioned the value of having students assess and consider what they learned in a given project before moving on to the next project so they can consider that new knowledge moving forward. The same trend was seen in terms of *when* students should be assessed, with papers commenting on when to assess students yet not validating those ideas [47, 48, 66, 67, 70]. Related to this, the value of continuous feedback and assessment throughout the problem-solving activity was noted by multiple sources [47, 69, 72].

While several publications offered insight related to assessment in PBL-based engineering programs, most papers were largely focused on assessing the *value* of PBL practices as opposed to evaluating the assessment strategies proposed. While recommendations for assessment strategies (such as incorporating reflective practices) were offered, evidence-backed suggestions for assessment strategies for engineering PBL were limited and generally recognized as challenging.

Perhaps best encapsulating this sentiment is work from Howard et al. who argue that qualitative assessment methods are better suited than quantitative ones to assess PBL in terms of professional skills central to the pedagogy [73]. Based on a qualitative study that included analysis of project artifacts and interviews with academic staff at multiple institutions, the authors developed a "strategic assessment framework" and guiding principles. Their study concluded that PBL assessment should primarily be done through consideration of a "folio of evidence" at the end of the term [73]. However, from piloting the strategy in multiple courses, they found that instructors had difficulty articulating what learning outcomes should be and how they might best be demonstrated. Further, instructors were still focused on content and not outcomes. This underscores the need for continued, structured research to define and evaluate the effectiveness of these proposed strategies.

5. Discussion

We entered the process of our literature review with an assumption that design and implementation issues associated with PBL problem design, facilitation, and assessment would be described across the papers we identified. To take the findings from the literature, in the context of noted operational challenges, would require the unit of analysis to be at the problem-level. However, we found that analysis is often focused on the course or curriculum level. While few papers offered specific strategies for addressing these core challenges at the problem-level, we synthesize our findings across all papers in the context of the operational lessons and opportunities, toward answering our guiding research questions: (1) What operational lessons are captured in the literature to support engineering faculty in PBL implementation? (2) What opportunities for the engineering PBL community are revealed?

This review of the literature has exposed gaps in our understanding of PBL in engineering higher education curriculum, particularly along the pathways highlighted in Fig. 2. This includes a need to advance our understanding of and develop guidelines to support problem design (paths 1 and 2), the knowledge gap that students can reasonably be expected to span (path 5), and assessment practices that integrate a range of learning outcomes related to technical and professional skills (path 7).

5.1 Problem Design Operational Synthesis

Problem design is a critical and challenging element of the PBL pedagogy [27]. Yet, we find that nearly all papers included in our literature review present, assess, and discuss their PBL efforts at a course and/or curriculum level. Because the unit of analysis is at the course level (or higher), there is limited discussion how problems were (re-)designed to accom-

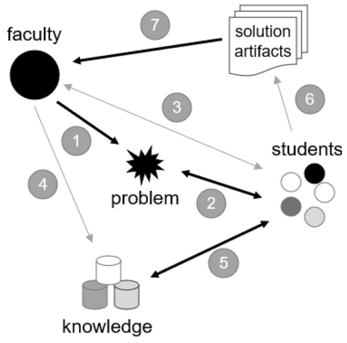

Fig. 2. Conceptual model of PBL environment and pathways requiring focused research.

modate students' prior knowledge or how that knowledge was even accommodated and mapped to the problem in the first place.

The result is that the effect of problem-specific characteristics, like structuredness and complexity, or problem types are not specifically considered or studied within an engineering context [9, 31, 39, 74]. Formalizations of these concepts are described in the problem design literature but often are not acknowledged or referenced in the PBL papers that we studied. Given that our questions around problem design are situated at the problem-level there are no obvious guidelines that can be extracted from explorations at the course and curriculum level of analysis.

We have found that papers outside the scope of our review do discuss problem-specific characteristics [9, 31, 39, 74]. For example, Pasandin and Perez [74] describe four types of PBL problems that derive from manipulation of complexity and structuredness. They chose a "complex structured problem" for PBL "because it better reflects the real tasks that civil engineers face at a professional level." However, neither a problem statement nor mapping to characteristics of complexity and structuredness are shared. Rather, the focus is on the organization and assessing if the learning resources and computational tools introduced to help navigate the problem-solving experience are effective.

Even though [9, 31, 39, 74] do not provide nuanced details of their problem design, their description could be used by faculty unfamiliar with PBL when considering the type and complexity of the problem they are aiming to produce. Yet, standards for operationalizing principles of PBL problem design require a documentation of the logic and thinking used by problem designers within a framework like structuredness and complexity. Such considerations will also be important to facilitation practices.

5.2 Facilitation Operational Synthesis

Facilitation in PBL is challenging because adopted strategies directly impact the faculty and the student. Many faculty are unfamiliar with PBL environments, and they must prepare to become effective facilitators while managing increased workloads [75, 45, 52]. Further, some students struggle with working in PBL environments because it is a new style of learning. Our review again found that much of the literature occurs at the course and/or curriculum level, which makes distilling operational guidelines challenging.

As it relates to structuring and scaffolding of learning and supporting students with problem engagement, we did find a variety of possible frameworks and processes to consider. However, these facilitation strategies are often not evaluated for their effectiveness nor how students engage with them at a granular (i.e., problem) level. Studies that compare various process models would help to inform implementation decisions under varying educational conditions. Additionally, understanding how practitioners might best integrate process models such that they are not uncritically adopted by students is important. For instance, rather than providing a process for students to follow, there may be value in co-constructing the process model with students. Incorporating students into process construction aligns with the "devise process" competency of professional practice that engineering undergraduates must learn to develop [76].

We also identified a tension between strategies associated with structuring and scaffolding and the learning process as reflected in expectations of student knowledge acquisition in order to engage the problem. At one end, students are taught the entirety of the "core content", often in a lecture-style format, before engaging with the problem. On the other end, students may be responsible for all knowledge acquisition, perhaps with facilitators curating information/knowledge for students to leverage in a self-directed manner. In between, some models prescribe a "just-in-time" delivery of necessary knowledge to support students.

There is no apparent agreement on exactly how much knowledge students should be expected to acquire while engaging with a problem. Further, how factors like prior learning experiences, knowledge gap, motivation, self-directed learning ability, and available time (a critical resource constraint) might interact are not well understood. There are three implications that stem from our analysis: (1) faculty need to have a good understanding of prior and concurrent learning experiences of students when facilitating problem engagement, (2) the more students are responsible for acquiring and applying knowledge, the longer it may take them to move the problem toward meaningful ends, and (3) PBL is likely to be more successful as a cross-curricular philosophy rather than as a "one off" experience among mostly lecture-based courses.

Finally, facilitation impacts assessment but as much of the literature works at the course/curriculum level, there is limited evidence as it relates to problem-specific outcomes. Often, the focus is on student perceptions of the PBL experience instead. How facilitation and assessment co-exist is important to overall implementation.

5.3 Assessment Operational Synthesis

Assessment in PBL is challenging and requires a different approach that can capture individual student performance in an effective way [63]. PBL provides opportunities for students to build technical competencies and professional skills necessary in practice. However, professional skills are not only challenging to teach but also difficult to assess [77].

Some methods of assessment, including portfolios and self, peer, and/or instructor-based assessments have been suggested [28, 44, 45, 47, 61, 67, 70, 78]. But individual students' work is challenging to assess in PBL when students are working collaboratively with others. To combat this, reflective activities and feedback during each phase of the problem have shown promise as a successful evaluative technique [64, 68, 72]. This reflection and feedback mechanism can help capture complex learning outcomes and fits with perspectives of a more holistic educational experience that better align with realities of practice. However, while some proposed assessment strategies describe a focus on process instead of the product (citation needed), care must be taken to ensure both are captured through assessment, since engineering practice clearly relies not only on process, but on generating successful final products as well.

The types of assessments for PBL are varied and each has its own strengths and weaknesses. While these assessments do answer our question regarding the type of evidence students might create, further research should compare different types of assessments within PBL. Does one assessment method capture a student's performance more accurately than another? Are some assessments tied more closely to a specific problem? Ideally, this continued research would also provide more supporting evidence in regard to how faculty frame, develop, and evaluate the effectiveness of proposed assessments, since a general issue found in existing literature is limited empirical evidence to support claims about assessment methods.

6. Conclusion

This literature review explored the higher education engineering PBL literature to answer two research questions: (1) What operational lessons are captured in the literature to support engineering faculty in PBL implementation? (2) What opportunities for the engineering PBL community are revealed? To accomplish this, we reframed these higher-level questions in terms of six operational questions across areas of PBL design, facilitation, and assessment, derived from a conceptual model of the PBL environment (Fig. 1). One thing that stands out in the literature is a belief that PBL is valuable and that it is possible to integrate this pedagogical format within engineering curricula. Continuing research is important because it can offer support to faculty who hold this belief and are interested in implementing PBL in their own classroom but are stymied by significant challenges that still exist.

A variety of ideas, factors, and methods to consider in PBL implementation are described in the literature, however there is need for more detail and supporting evidence regarding their effectiveness as operationalized. This review contributes to the argument that more research is necessary, particularly at a more granular, individual problem-level. Faculty new to PBL require support not only in adjusting their teaching style, but in designing appropriate problems, facilitating problem engagement, and assessing learning. We conclude that there is an opportunity for the engineering PBL community to develop that evidence and see two related needs.

First, across design, facilitation, and assessment areas, the community would benefit from documenting PBL implementation in ways that support replication. We recognize that the literature considered here was not necessarily written to support direct replication. However, we see an opportunity for the community to consider that endeavor. To practically enable that development and adoption of reporting standards, similar to standard operating procedures, represents a specific opportunity for PBL community collaboration.

Second, and building on the first opportunity, collaborative research to test specific ideas, factors, and methods that support PBL design, facilitation, and assessment in engineering contexts represents an important opportunity for the community. Collaborative research could span these areas and operational Questions 1–6 are representative starting points.

Based on our work, we believe these opportunities should be pursued collaboratively by groups at multiple institutions, leading to the development of standard research protocols and building evidence from the level of individual problems.

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Appendix

Research Journals with publications regarding PBL in engineering higher education from the past 25 years

Research Journal	Evidence of PBL in Abstract (196)	Papers Meeting Additional Criteria of Engineering Higher Education (88)
Advances in Engineering Education (Vol. 1 – 2007)	7 publications	2 publications
American Journal of Engineering Education (Vol. 1 – 2010)	3 publications	0 publications
Engineering Studies	1 publication	0 publications
European Journal of Engineering Education	54 publications	24 publications
IEEE Transactions on Education (Vol. 1 – 2000)	31 publications	10 publications
International Journal of Engineering Education (Vol. 1 – 2005)	60 publications	33 publications
The Interdisciplinary Journal of Problem Based Learning (Vol. 1 – 2006)	12 publications	7 publications
International Journal of STEM Education (Vol. 1 – 2013)	1 publications	0 publications
Journal of Engineering Education (Vol. 1 – 1993)	11 publications	3 publications
Journal of Problem Based Learning (Vol. 1 – 2014)	3 publications	3 publications
Journal of Problem Based Learning in Higher Education (Vol. 1 – 2013)	12 publications	5 publications
Journal of Science Education and Technology	1 publication	1 publication

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