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Principles of Problem-Based Learning (PBL) in STEM Education: Using Expert Wisdom and Research to Frame Educational Practice

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Abstract: Developing teacher knowledge, skills, and confidence in Science, Technology, Engineering, and Mathematics (STEM) education is critical to supporting a culture of innovation and productivity across the population. Such capacity building is also necessary for the development of STEM literacies involving the ability to identify, apply, and integrate concepts from STEM domains toward understanding complex problems, and innovating to solve them. However, a lack of visible models of STEM integration has been highlighted by teachers as a challenge to successfully implementing integrated STEM education in schools. Problem Based Learning (PBL) has been well-established in higher education contexts as an approach to learning in the STEM disciplines and may present an effective way to integrate knowledge and skills across STEM disciplines in school-based STEM education and support the development of students as capable, self-directed learners. However, if PBL is to effectively contribute to STEM education in schools and build teacher capacity to teach STEM, then this approach needs to be better understood. This paper aims to generate a set of principles for supporting a PBL model of STEM education in schools based on insights from the literature and expert focus groups of PBL professionals. Four principles of PBL emerged from the data analysis: (a) flexible knowledge, skills, and capabilities; (b) active and strategic metacognitive reasoning; (c) collaboration based on intrinsic motivation; and (d) problems embedded in real and rich contexts. The study outcomes provide evidence-informed support for teachers who may be considering the value of adopting a PBL approach in school-based STEM education.

Keywords: problem-based learning; PBL; STEM; teacher development; professional development

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1. Introduction

Building teacher knowledge, skills, and confidence in Science, Technology, Engineering, and Mathematics (STEM) education are critical to supporting a culture of innovation and productivity across the population [1–4]. Such capacity building is also essential to developing STEM literacies involving the ability to identify, apply, and integrate concepts from STEM areas toward understanding complex problems and innovating to solve them. Employers agree such education is essential for future economic development and growth [5–7]. Yet, set against this demand for a strong STEM future, "there is evidence that our education systems are not up to the challenge" [8] (p. 1). A lack of suitable resources, teacher education (both pre-service and continuing in-service), and visible models of STEM integration are some aspects that have been highlighted as challenges to implementing integrated STEM education [9].

Teachers are the critical link in addressing this challenge in two distinct ways:

1. Building teacher knowledge, skills, and confidence in STEM teaching and learning, and
2. Implementing useful and useable models of STEM education that focus on the pedagogical practices that underpin STEM as an integrated, cohesive, and meaningful approach to learning is something that is missing in the current educational landscape.

Problem Based Learning (PBL) has been proposed as one approach to support the authentic integration of the STEM domains [10,11]. A PBL approach can assist students in developing their thinking skills, problem-solving capabilities, and knowledge integration. Situating a problem at the core of students' STEM learning can support a more integrated and engaging learning experience [10] and help students understand the relationship between their learning and real-world applications at the same time [12,13].

The general characteristics underpinning PBL have been well-researched, particularly in the tertiary education sector [14–16]. However, if PBL is to effectively contribute to STEM education in schools and build teacher capacity, then this approach needs to be better understood within teachers' contexts. This paper focuses on defining the fundamental nature and intention of a PBL model of STEM education for schools. In particular, this paper analyses data from PBL expert focus groups and relevant literature to generate a set of principles of practice for a PBL model of STEM education in schools.

Thus, the research questions guiding this study are as follows:

(1) What principles of practice characterise a PBL model of school-based STEM Education?
(2) How can PBL effectively contribute to school-based STEM Education?

2. Literature Review

2.1. STEM Education

STEM and STEM education have become global phenomena, but for very different reasons. STEM is seen as an economic imperative to provide future workers in an increasingly globalised and technology-driven world [17]. On the other hand, STEM education focuses on the moral imperative of education to prepare learners to live effectively and contribute to society. For this reason, STEM education embraces a vision of contributing to a better global society and its citizenry by preparing students who can effectively respond to multifaceted economic, social and environmental challenges, such as those foregrounded by COVID-19 and climate change [11]. STEM Education is the focus of this paper.

STEM Education has a focus on connecting learning across disciplines. It is not intended to replace learning in each of the STEM disciplines but rather recognises that learning in each of these disciplines is not enough when done separately. As Vasquez and others [18] suggest:

> STEM education is an interdisciplinary approach to learning which removes the traditional barriers separating the four disciplines of science, technology, engineering and mathematics and integrates them into real-world, rigorous, relevant learning experiences for students. (p. 4)

This definition of STEM education highlights three important points: (1) the removal of traditional barriers between disciplines, (2) the integration of these disciplines, and (3) situating the learning experiences in relevant real-world contexts. STEM education is therefore well aligned with PBL with its focus on problems that are meaningful to the learner, embedded in real-world contexts and in building capabilities to utilise skills, knowledge and resources in the practice of solving problems [12,19].

STEM education is important in developing a scientifically and technologically literate population, an important purpose of 21st-century education [20,21]. Bybee [22] elaborated on this need for a scientifically and technologically literate population, calling for STEM literacy that requires individuals to develop the knowledge, attitudes and skills to identify real-world problems; understand the characteristics of STEM subjects; develop an awareness of, and ability to explain, the natural and designed world with this knowledge, and gain a willingness to engage and reflect upon STEM-related issues as global citizens. In our continually evolving and increasingly global society, real-world problems are often complex and multifaceted [17], requiring the integration of multiple STEM concepts [17,23] and collaborative teams of STEM professionals to solve them [24].

In preparing students for solving complex real-world problems and for them to make sense of their experiences in and out of school, they need to be given opportunities to engage with different STEM disciplines and to engage with STEM disciplines differently. Bringing an integrated approach to STEM education can provide students with more relevant and stimulating experiences [25,26] that focus on establishing connections between STEM disciplines and real-world problems [27]. Hence, integration in STEM education should include the opportunity to develop problem-solving skills and inquiry-based instruction, as well as disciplinary content knowledge [11,17]. This requires teachers to rethink the types of experiences provided to students in STEM education.

To understand how PBL may effectively contribute to STEM education, it is necessary to understand the origins of PBL and the defining characteristics of this approach.

2.2. Origins of Problem-Based Learning (PBL)

Originating in higher education contexts in the late 1960′s, PBL was described as "the learning that results from the process of working toward the understanding or resolution of a problem" [28] (p. 1). In this original conception, the skills associated with PBL were deemed essential to the ongoing work of physicians, who, throughout their careers, needed to continually self-evaluate their own capabilities and develop the skills, knowledge and resources they required to meet their patient's needs [28] effectively. PBL was therefore seen as an effective approach for training future medical practitioners in patient diagnosis and treatment [16,28]. Engineering educators later adopted PBL because of the suitability of this learning approach to engineering practice [29]. Specifically, PBL addressed the need to develop future engineers with problem-solving skills transferable to a range of different contexts [30]. PBL has since been applied in a diversity of fields, including law, physiotherapy, psychology, and computer science [31].

The use of PBL appears well suited to the development of practice within STEM professions as it helps to develop characteristics in students that enable them to respond to the needs and demands of their profession, namely to:

- construct an extensive and flexible knowledge base,
- develop effective problem-solving skills,
- develop self-directed lifelong learning skills,
- become effective collaborators, and
- become intrinsically motivated to learn [12].

While PBL seeks to develop particular learner characteristics, it should be noted that there is no single agreed approach to its implementation [15]. Neither is there agreement about whether there is, or should be, one type of PBL or many variants [29]. For example, de Graaf & Kolmos [32] describe five different models of PBL, based on five different views of the purposes of PBL, including "the attainment of knowledge, PBL for professional work, PBL for interdisciplinary comprehension, PBL for cross-discipline learning and PBL for critical competence" (p. 657). While there may be different models of PBL, below we highlight some commonly described key characteristics of PBL:

(i) The nature of the problem

Central to PBL is the nature of the problem(s) and the context in which such problem(s) exist. One of the most complex aspects of PBL is the framing of appropriate problems, as the quality of the chosen problem has a major influence on the quality of the learning process and outcomes of PBL [33]. When determining what might make an appropriate problem, different characteristics of the problem need to be considered, including how the problem is structured, the problem-solving processes to be used, how meaningful the context is, the complexity of the problem, the types of reasoning patterns required, and the abstractness of the problem [34].

The amount of structure inherent in the problem is an important consideration. The most suitable problems for a PBL context are ill-structured problems [12,35,36]. Ill-structured problems are characterised by multiple unknown problem elements, ambiguity regarding the concepts needed to solve them, multiple possible solutions, and no obvious path to finding a solution [36–40]. Examples include diagnosis problems, strategic performance problems, situated cases/policy problems and design problems [35,40]. The aim of using such messy, ill-structured problems is to help students develop their ability to responsively and flexibly apply their knowledge to work within complex problem situations and develop systems thinking skills that are typically experienced in real-world settings [37,40–42]. The nature of an ill-structured problem also lends itself to allowing interactions and collaboration between the students [43], enabling opportunities for developing student self-directedness [37,40,44].

(ii) The context in which the problem is embedded

The context in which problems are set is fundamentally important if students are to develop the desirable characteristics detailed above. Problems embedded in relevant and rich learning contexts require deep thinking in order to identify and evaluate multiple possible solutions and to select and apply appropriate and meaningful strategic thinking [45]. The use of relevant and rich learning contexts also serves to intrinsically motivate students to address such problems by engaging in opportunities for collaboration [46]. When students are challenged to collaboratively engage with relatable problems that are meaningful to the local, national, or global contexts in which they live, intrinsic motivation is also likely to be enhanced as such challenges may appeal more broadly to their values and beliefs.

(iii) The integration of different subject areas

Problems set in relevant and rich contexts inevitably require different kinds of knowledge, skills, and abilities to understand and resolve them. A problem-based approach to learning is interdisciplinary in nature, and learners should be encouraged to access information and resources from a wide range of disciplines or subjects that replicates how "people in the real world must recall and apply information integrated from diverse sources in their work" [19] (pp. 85–86). Careful consideration of diverse perspectives leads to a more thorough understanding of the issues under consideration and the development of more robust solutions [19].

(iv) A learner-centred approach

Aligned with the teacher's role as a guide, students must be willing and able to take responsibility for their own learning. When responsibility for the learning and the learning process rests with the learner, then learner motivation and ownership of the problem increases [14,15,47–50]. Furthermore, learners should be able to explain "what they know and about what they need to learn more". This includes learners accepting responsibility for their role in seeking "relevant information and bringing that back to the group to help inform the development of a viable solution" [19] (p. 86).

(v) Teacher as guide or facilitator of the learning process

Importantly, to create rich learning contexts with a focus on active and self-directed learning, a teacher's role becomes one of a guide or facilitator, supporting, modelling, monitoring, and evaluating learner progress through the PBL process [44]. Hence, the teacher is not a provider of content per se [28] but instead is expected to model expert thinking ("metacognitive modeling" [50]) while students work in largely self-directed, small groups. The teacher's role shifts from one of providing information or solutions to "guide, probe, and support students' initiatives" [19] (p. 87).

2.3. Summary—Linking PBL and STEM Education

While PBL originated in higher education settings, this approach may have much to offer STEM education in schools. Utilizing a PBL approach may help students integrate knowledge from various STEM disciplines, enabling the development of problem-solving and critical thinking skills through small-group collaboration in meaningful and authentic learning contexts. A PBL approach in STEM education may also enable students to understand the relationship between what they are learning, how they are learning, and potential real-world applications. While PBL has been introduced into schools internationally, this has tended to occur in ad hoc ways and across different subject domains. In other words, there is no common framework for PBL in school STEM Education that can be used by researchers, practitioners and curriculum developers. Hence, our motivation for this research is to draw upon existing PBL literature along with interviews from experts in PBL practice to propose a set of principles for guiding PBL in school STEM Education.

3. Methodology

The study used a qualitative research methodology involving an exploratory design framework, using focus groups as the main data collection tool. Focus groups can provide in-depth data by exploring different perspectives, attitudes, behaviours and experiences [51] and highlighting agreement and inconsistencies within groups [52]. Focus groups are considered appropriate when collecting information about a topic from a group of people with common characteristics [52]. In this study, the focus group participants shared a common profile as PBL experts across different international contexts. Expertise was defined in terms of reputation in the field through (a) research, i.e., highly cited in PBL (using google scholar) and/or working in a world-leading centre for PBL and/or (b) teaching, i.e., they are well-known within the PBL community as highly regarded PBL practitioners.

Focus group questions were developed and validated through the following process: (1) A set of preliminary questions was developed by a sub-group of authors based on the focus of the study to investigate the nature and characteristics of PBL and the potential contribution of PBL to school-based STEM Education. (2) These questions were circulated to the rest of the author team for feedback and potential modification. (3) Questions were revised based on team feedback. (4) Questions were trialled with a small sample (n = 2) of PBL researchers at the authors' institution to check the wording and appropriateness of the questions and that the questions were sufficiently open-ended that a variety of responses was possible. (5) A final version of the questions was prepared based on feedback from the sample group.

3.1. Participant Recruitment and Selection

The recruitment of focus group participants began with a personalised email to nine PBL experts inviting them to participate in the study. The group included PBL experts from four different countries who were currently working in research and/or practice in PBL in a STEM-related area in higher education or in a school context. All of the nine experts contacted agreed to participate. The participant group included a mix of STEM disciplinary backgrounds, including science, engineering, medicine, and general education. The mixed group composition was intended to promote discussion from different PBL perspectives and contexts, as well as provide a range of ideas about implications for the use of PBL in school-based STEM Education. Two focus groups were conducted: Focus Group 1 (n = 5) and Focus Group 2 (n = 4). The organisation of the groups was determined by convenience according to different time zones and participant availabilities. Ethics permission for the study was sought and obtained by the University of the research team, and the participants provided consent.

3.2. Approach

Consistent with a focus group approach, a set of questions was circulated to participants prior to the focus group session (see below) to familiarise them with the expectations of the discussion [52]. The questions were designed to prompt discussion, draw from participants the key characteristics, issues, and values associated with PBL and elicit participants' views about implementing PBL in school-based STEM education. While the questions were basically the same for each group, the order of questions and the amount of time spent on each question varied according to the extent of discussion triggered by a particular question. A constant for both groups was the question of exploring implications for implementing PBL in school-based STEM Education.

Focus group questions:

1. Why use PBL? (Why is it important? What does it have to offer?)
2. What makes a good problem for PBL?
3. When planning a PBL experience, what needs to be considered? (Is a team-teaching approach necessary? How should groups be formed? How do you anticipate resources that will be needed?)
4. What are the important roles for the teacher and the student when engaging in PBL?
5. What are some of the challenges in implementing PBL?
6. As educators, we often talk about engagement from a cognitive, affective and behavioural perspective. What does PBL have to offer in terms of student and teacher engagement?
7. What outcomes could be expected from engaging in a PBL process?
8. What would be the success indicators for a successful PBL experience?
9. We are developing a pedagogical framework for PBL in STEM education for years 6–10 (ages 11–15 years). The siloed nature of the school curriculum can present many barriers to implementing PBL. How might such barriers be overcome? What else should we consider in developing a pedagogical framework for PBL in school-based STEM education?

Focus groups were conducted online via Zoom, a video conferencing platform, and were audio/video recorded using the platform's internal recording feature. Field notes were recorded for supplementary information. Each focus group lasted for approximately 1.5 h. The focus group interviews were transcribed and de-identified (pseudonyms used throughout). A reflexive thematic analysis was conducted within a constructionism paradigm, using a six-phase approach: familiarisation; coding; initial themes generation; theme development and review; theme refining, defining and naming; and writing [53]. The transcripts were analysed independently by four members of the research team, looking for "core insights, common phrases and words, a specific mood or tone to group interaction" [54] (p. 7). The analytical focus centred on the co-production of perspectives in the group context rather than on the perceptions of specific individuals [55]. An inductive thematic analytical process [56] was applied to the data, constantly moving back and forth between the data set, the coded extracts, and the analysis of the generated data [57]. The researchers then met to compare and negotiate emerging themes. This collaborative analysis brought a diversity of perspectives to the data analysis. Themes were accepted if repeatedly emerging across transcripts and agreed upon by the majority of researchers. Subthemes were further identified by the repeated use of language and alignment of particular examples. An example of moving from codes to themes is presented in Table 1: Thematic Map.

Table 1. Thematic map, showing some of the codes and categories to develop one of the themes.

Code	Category	Theme
Learning that really matters	Relevant & authentic context	*PBL requires a rich problem*
Dynamic, real changes		
Big context, rich meaning		
Authentic, contextual picture		
Connected across disciplines		
Amount of open-endness	Open ended, complex problems	
Onion layers		
Digging deeper		
Scaffolded process		
Convergent/divergent		
Feedback	Collaboration	
Sharing ideas		
Process assessment		
Community of learners		

4. Results

Three overarching themes emerged from the thematic analysis of focus group data: (1) The nature of learning in PBL, (2) the characteristics of a rich problem, and (3) pedagogical implications. As the findings from the analysis of the expert focus groups are intended to capture the co-production of perspectives in the group context, the findings are illustrated by presenting quotes from focus group discussions which are representative of agreed positions.

4.1. Theme 1: The Nature of Learning in PBL

Participants in both focus groups discussed PBL in ways which conveyed insight into the nature of the learning associated with this approach. Learning was generally discussed as a process leading to change in thinking, knowledge and skills due to experience. The learner was intended to play a very active role, and their interests and abilities were sometimes used to determine the suitability of experiences in PBL. The problem itself formed part of a continual loop of learning. Discussions across both groups emphasised that nurturing such learning requires the learner to be immersed in what was often described as the "messiness" associated with making meaning.

4.1.1. Learning as a Process

Within both focus groups, a general agreement was reached that PBL involves learners in a continuous process of questioning, reflection and re-clarifying information. This shifted the focus of learning beyond simply undertaking a project or focusing only on tangible outcomes.

> "It's (PBL) more about the process of how they approach the learning, and not the product. So, understanding that problems are not something that you can solve step by step, but rather it's something that you can try to understand first, and then when you understand it you start trying different things to approach the problem. And that reflection on what you're doing and the result and what you need to do next, and where to find information, and what questions to ask... that's what helps with this as a learning strategy." (Focus Group 1)

Focus Group 2 explained PBL as a process of learning by exploring the differences between PBL and Project-Based Learning (PjBL). PBL was discussed as being more focused and conducted over a relatively short time frame, whereas PjBL often involved a longer time frame and a broader scope and was often more outcome driven. These differences are illustrated in the following quotes from Focus Group 2, which draw on PBL origins in medicine and then consider the transfer of PBL to engineering.

> "...a scenario (in medicine) . . . is the trigger for learning . . . they go to the doctor and they have a sore throat and various other symptoms. And what you are trying to figure out is not only what is wrong with them but . . . also learn about the throat and airways or something and maybe viruses and bacteria at the same time . . . trying to see this as a whole system. And the whole intent is that students would go to the library, seek out information, come back, have another meeting and try to resolve this issue. It may take three or four meetings before they get to the point when they go Ah ha! we've got this! And in the process, they have taught each other a whole lot about the scenario." (Focus Group 2)

> "The problem-based (approach) was more about a problem that you could deal with in a short space of time . . . the reality of engineering was a much larger project that took time and needed that time in order to be able to solve the problem . . . moving towards a project." (Focus Group 2)

However, discussions across both focus groups also acknowledged that the associated time needed for PBL differed according to the problem's complexity and the needs of learners. Two representative samples of such considerations are provided below.

> "And sometimes the problem would take two class periods . . . So, it was a much smaller, much more defined problem, but it would use the same process of looking at the problem, trying to work out what it was that they were trying to do as a team. Breaking up, going away, doing a bit of research. Which might only have been 15 min, and coming back and sharing that with the rest of the team, looking at how that helped them solve the problem that they had." (Focus Group 2)

> "It takes a long time to get the students to understand what this is. They need to understand the process of working with PBL and that takes time. So, I think patience is very important. It's not necessarily going to be what you expect it to be the first time. . . . that takes a long time to make it really work, make it like a good program . . . be patient with the results, the outcome, what you actually expect to see." (Focus Group 1)

4.1.2. Active Learning

Focus Group 1 emphasised that PBL involves the learner actively in constructing knowledge. This active learning process relies on learners being positioned as key decision-makers who draw from their experiences to develop meaningful learning.

> "I think PBL works because it helps students connect to all the things that they know and that they're familiar with. And when you're able to bring previous experiences, developing learning is easier." (Focus Group 1)

The role of metacognition was also emphasised as part of the learning process. "Students can understand, they become better at metacognition, and they can understand the self-directedness in learning" (Focus Group 1). Attending to these considerations enhanced the nature and intention of PBL, providing the potential to empower learner agency and innovation.

> "PBL is also a way of empowering kids and students into thinking about how can I have agency in terms of these new complex problems that arise? And we do not know all the answers, for sure. And in many ways, young people have more innovative approaches to some of these problems." (Focus Group 1)

Learners actively construct knowledge and ultimately become agentic learners. The problem always remains central to the learning process.

4.1.3. Learning as 'Looped'

Focus group discussions emphasised that PBL requires learners to continually return to the problem to seek clarity and further develop their understanding. By doing so, the problem becomes a touchstone for recurring "loops" of learning in the PBL process.

> "You've got, first of all, a loop of 'Do I really understand that problem?' You've actually then got another loop, which is 'How do I design a solution to this problem?' Quite apart from 'What do I need to know that I haven't learned in classes or that I've forgotten in classes?'" (Focus Group 2)

Positioning the problem at the centre of the learning experience means that PBL relies on providing learners with time to establish an understanding of the problem itself. This was discussed as different from other approaches, which often move the learner to seek a solution to a problem immediately. There was agreement across the two focus groups that not only was time exploring the problem valued, but it was also essential in terms of knowledge production.

> "And that's a very different dichotomy, and the one that you've described really clearly, that two loop thing. ... the focus [usually] is too much on the second loop. And they miss the first loop, which is the learning, that inherent knowledge base, going through that thought process." (Focus Group 2)

Focus group discussions described the need for learners to spend time clarifying the problem under investigation. This requires balancing play and uncertainty with purpose and focus and this was seen as difficult but valuable. "The messiness is important. The fact that they need to find information that is not clear, that they might need to talk to others, that they cannot solve it by themselves" (Focus Group 1).

4.2. Theme 2: PBL Requires a Rich Problem

Features of a rich problem include issues drawn from relevant and authentic contexts, problem complexity, the open-ended nature of a problem, and the dependence on collaboration to enhance learning. All features increased the likelihood that a problem would provide deep and challenging learning opportunities.

4.2.1. Relevant and Authentic Contexts

Both focus groups highlighted the importance of context as a critical consideration for PBL. It was agreed that problems arising from authentic, meaningful, and socially significant situations represented problems drawn from rich contexts. Such problems require learners to draw on their prior knowledge and experiences, and these types of problems are more likely to be of interest to the learner and be rich enough to sustain investigation. According to participants, this was important because "being able to relate to the problem is important ... It shouldn't be that removed that they don't have a clue of what's going on" (Focus Group 1).

Problems which were situated in relevant and authentic contexts were also seen to enhance learner motivation and a desire to take ownership of their learning.

> "We work with what we call 'real problems' when we work with PBL, which I think is both relevant for the students no matter what age ... .it makes them more motivated. They choose maybe the problem themselves, they know what they want to do. It's student-centred, which gives them a lot of opportunities." (Focus Group 1)

Relevant contexts also enabled learners to understand how the knowledge they were developing related to the world in which they lived. This was seen as important for continued learner engagement with key ideas and sustained investigation.

> "I suppose, it's about maintaining engagement with what students are learning in STEM . . . . I think success criteria would be that it helps students contextualise why they learn the things they learn and they can see how it actually helps build that picture of the world around them." (Focus Group 2)

4.2.2. Open-Ended, Complex Problems

Both focus groups valued complex, open-ended problems which require a breadth of knowledge. Open-ended problems were seen to provide greater opportunities for all learners to be involved in PBL and promoted a diversity of ideas and perspectives in the learning process. These types of problems also contribute to learner engagement because a range of possible outcomes is considered and valued in the process.

> "A certain amount of open-endedness, so that every group can engage differently with it and come up with a different solution. As long as it's well argued and well thought through. Whereas, if it's so convergent that everybody is hunting for the same answer, ... students lose interest, because they just go, 'Ah, well, that groups already found the answer. So, why are we bothering?' But, if everybody's contributing something unique to the topic . . . then it's really rich and then you discover that the whole class has got a much richer view of the story than any single group within the class." (Focus Group 2)

As the previous quote indicates, open-ended problems also invite learners to reconsider the importance of persistence and embrace various alternative solutions. This was seen as valuable for promoting critical thinking, as outlined above, and also creative thinking.

> "And there's not one right or one wrong, and we may have three or four different designs that all turn out to be really valuable, and we may have one design that ended up to be a flop, but it had such great ideas as part of it that this group got an idea from that group." (Focus Group 1)

Open-ended problems also present complexity which group members consider to be important. The open-endedness and complexity of some problems may be initially challenging, so learners need to be reassured that 'not knowing' is a valuable part of learning, "it's okay to not know and find ways to know" (Focus Group 1). Complex problems were described as similar to "layers of onion" (Focus Group 2) that allowed learners to "dig into, deeper and deeper and deeper" (Focus Group 2). However, these types of problems also demanded learners to ask questions and seek clarity, and this often meant that students faced new expectations about their habitual learning behaviours. This was not always an easy transition for learners.

> "Students got really grumpy, because they didn't understand that they had to ask questions. They thought that they were given an assignment, the assignment would be self-contained. They would just go away and do it and bring back the answer... they really needed to ask clarifying questions, and they didn't realise they needed to ask clarifying questions. They just felt stuck. So, learning the process is really important." (Focus Group 2)

Therefore, determining how open-ended or complex a problem should be was discussed in terms of ensuring the problem was framed by a clear learning focus and aligned with student ability levels. These considerations provided opportunities for learners to engage with problems in ways which enhance a sense of personal ownership.

> "How tightly scoped does it need to be, how open-ended does it need to be? . . . there is a sweet spot for ensuring that it's open enough, but still keeps them on the task that you want them to actually achieve." (Focus Group 2)

> "But if we can design curriculum where they actually can take small action steps that do empower them to feel like they can be part of a solution, even on whatever

> level they are . . . if that can be part of a curriculum to some actionable steps that they can take as individuals, then that just makes their learning and their ownership that much better." (Focus Group 1)

4.2.3. Requires Collaboration

Problems drawing on relevant and authentic contexts were understood as often demanding a variety of expertise to enable the problem to be fully understood. Therefore, a rich problem also generated a need for collaboration.

> "...collaboration . . . would be a huge part of any work related to good problems that can take a team of people trying to figure things out...the sharing of the ideas of design, whatever we're designing, to say, 'Oh, here's what we're thinking, and here's a picture, here's materials. We're trying to build this.' Or, 'These are ideas right now.' And every group is thinking about it differently and they're sharing and they're giving each other feedback and they're saying, 'Oh, what about that? Is that going to be a problem?' Or, 'Oh, here's an idea for you.'" (Focus Group 1)

Focus groups discussed the essential role of sharing ideas and giving feedback and the cyclic nature of this process.

> "Something that is really central . . . what I have found really valuable for students on many levels is the sharing of the ideas of design . . . whatever we design . . . to say 'here is what we're thinking' . . . every group is thinking about it differently and their sharing, and their giving each other feedback." (Focus Group 2)

Collaboration was seen to create a community of learners rather than putting learners in competition with each other. Focus group discussion highlighted that while such problems might become difficult, persisting is valuable as these types of problems potentially provide rich opportunities for learning.

> "To create this community of learners, we have a problem we're working on, we have different ideas, we're going to try to pursue it differently, but we're really collaborating and we're not competing, we're really collaborating to see which design is going to be most effective for what we're trying to learn. And there's not one right or one wrong, and we may have three or four different designs that all turn out to be really valuable, and we may have one design that ended up to be a flop, but it had such great ideas as part of it that this group got an idea from that group. . . . . they can be a valuable part of other people's learning, not just the teacher as the valuable part of people's learning." (Focus Group 1)

Focus groups generally agreed that problems which offer rich opportunities for learning are drawn from relevant and authentic contexts, are open ended, complex and encourage collaboration. These types of problems enhance learner motivation, interest and engagement to collectively achieve a range of intended learning outcomes.

4.3. Theme 3: Pedagogical Implications

Supporting rich learning in a PBL approach requires attention to particular areas of practice. These include scaffolding learning, enhancing an integrated approach to learning which may require a reconsideration of siloed curriculum, and facilitating effective learner collaboration. Discussions also revealed that PBL requires a willingness to reconsider what is traditionally assessed as learning. However, these conditions also raise some challenges and further considerations for PBL practice.

4.3.1. Effective Scaffolding

The discussions in focus groups identified the importance of ensuring PBL is supported by a carefully structured and scaffolded program of instruction.

> "It sounds quite boring, but it's more about the structure than it is about the problem, in a sense. As long as that problem is something of interest to them

> and engages them [the students], their enthusiasm and their creativity and they can find a niche within it that they want to explore, you're still going to have a very scaffolded and structured program sitting behind it. And I think that's some of the downfalls of some of the projects we've seen that didn't do that." (Focus Group 2)

Discussions acknowledged there is no one correct way of providing such support. Effective scaffolding was dependent upon learner needs and ability levels. This requires educators to establish a knowledge of their learners and a willingness to provide a variety of responses to support learning.

> "Because students at different levels of development will have different capacity to cope with open-ended questions to a different degree. So, I think that question is really one of scaffolding. I think you have to think of the learners in the age group that you're dealing with and their prior experience and where you're wanting them to go. So, it's a continuum rather than a single juncture in learning. So, it has to be a scaffolded experience." (Focus Group 2)

4.3.2. Integrating Learning

It was agreed that generally PBL aims for a problem to connect ideas across disciplines. Focus Group 1 recognised that a problem may need to reside within a single discipline if confidence in PBL is to be developed. Generally, however, pedagogical approaches were required that promote deep learning in a discipline, as well as an ability to facilitate learning across disciplines.

> "You've got to have those three levels of learning, like that surface level, the knowledge stuff, the in-between stuff which is being able to do the sort of deep level thinking where you link synoptically different things from different subject areas. And then the transfer level, which is the ability to extrapolate beyond the scenario kind of stuff. And I think you have to build that within a good project. You need the knowledge, you need the application across disciplines and you need the transferability. And you have to build a project, I think, that has those three elements." (Focus Group 2)

Integrating learning across discipline areas requires a move away from the curriculum as siloed areas of learning. Rich problems invite deep learning, which promotes links across learning areas. As stated in Focus Group 2, this requires "problems that give scope to not pretend that the world is siloed, that make those connections with other areas, that show that scientific problems have a social significance" (Focus Group 2). Curriculum coherence was also discussed, emphasising a need for teachers to understand the big picture for learning:

> "Curriculum coherence is really important for teachers. I think the curriculum needs to be coherent and I think teachers need to have this understanding of coherent. So, this idea of reading the curriculum before to get the big picture and understand that with that, with PBL that the act of construction of ideas, and that this idea of learning over time and building understanding takes time. And so, if you have a coherent curriculum that you can connect back and forth with, that it's not something as a teacher that, 'Oh, this week they need to understand this and this and this,' but that it takes time. So, the idea of curriculum coherence and tying that with pedagogy." (Focus Group 1)

Whilst each PBL activity is grounded in the curriculum, Focus Group 2 emphasised the importance of not frontloading learners with information. Allowing a learner to realise which content and skills are needed to solve a problem is important, and this requires strategic approaches to support student learning.

> "Get a clear problem statement. And that might be the first one or two weeks where students are just learning about the problem and getting successively

> better statements of what the problem is to be solved . . . . what's the problem to be solved here? Interesting question that might take us several weeks. Then to say, 'Oh, but then we can start to dig into what do the solutions look like to that problem.' And that can take several weeks . . . So, you can do it in a very structured way, where in a sense you've got a cascade of problems of different layers." (Focus Group 2)

Creating a community of learners among teachers was one suggestion as a way to break the existing discipline-based and siloed approach to teaching.

4.3.3. Reconsidering Assessment

As PBL demanded a reconsideration of curriculum and a shift towards focusing on conceptual ideas and on the process (not the product), the approach was viewed as valuable for learning. However, Focus Group 1 raised concerns regarding how to accurately assess learning progress and debated the common use of 'learning objectives', a term often associated with behavioural objectives that do not fit a PBL approach. The shift from 'learning objectives' towards 'intentions of learning' was discussed as a potential change.

> "I think this is where we go wrong with PBL. I think we're very focused on learning objectives . . . we should not be talking about behavioural learning. We should be talking about intentions of learning . . . otherwise you're locking us into a curriculum which is not creative, which is not collaborative. And that's what the problem with objectives is—that they are too behavioural . . . you're closing the learning down." (Focus Group 1)

PBL presented many considerations for assessment intentions and practices along with the importance of redefining 'failure' as a valuable part of the learning process. The focus groups emphasised a need to shift pedagogical focus away from the negative notion of failure towards a more positive view, where failure is seen as a necessary part of the learning process. The focus groups also considered that PBL necessitated a move away from the intention of coming up with the 'correct' solution to the problem or devising a workable final product. Instead, focus groups agreed more suitable indicators of learning in PBL included an ability to identify the problem, articulate the intended processes of exploration along with sharing the successes and failures experienced when attempting to solve the problem.

The importance of joy as an indicator of success was also discussed as being demonstrated in persistence, and a willingness to embrace challenges and remain engaged in learning was also discussed.

> "I can see students in terms of the joy of learning, the persistence because of the challenge and the joy of the challenge, and also that there's a true interest in solving this problem or whatever we're doing, so that to me is the engagement part. And then this idea of an indicator is that they want to continue, they want to do more, they want to go on in science or in STEM because of what has taken place in their experiences." (Focus Group 1)

Supporting students to articulate their learning was also highly valued, although there was no consensus regarding how to do that effectively. "I think that reflection is super important and about how being able to articulate what you've learnt, but how do you motivate students to actually engage with that meaningfully?" (Focus Group 2). The assessment of learning through PBL was seen as a challenge, requiring further clarification.

5. Discussion

The purpose of this study was twofold: (i) to develop a set of principles that characterise a PBL model of school-based STEM Education, and (ii) to consider how PBL can effectively contribute to school-based STEM Education. We noted earlier in this article that while PBL seems to be gaining in popularity in schools, particularly as an instructional approach to support STEM Education, there is no commonly shared set of principles for guiding PBL in school STEM Education.

5.1. Principles of a PBL Model of School Based STEM Education

In terms of our first purpose, the perspectives expressed in the focus groups and from the literature revealed alignment of ideas about effective PBL in a number of areas, including (i) the features which define a rich problem, (ii) a focus on student-centred learning, (iii) the nature of the knowledge, skills and capabilities developed in a PBL approach and, (iv) the inherent requirement for, and value of, collaboration. Insights from the literature were used to frame some key assertions about PBL, and the focus group discussions provided further detail and nuances from a practice perspective. From this information, four key principles emerged that we describe below.

Effective PBL requires:

- Problems embedded in rich and relevant learning contexts.
- Flexible knowledge, skills, and capabilities.
- Active and strategic metacognitive reasoning.
- Collaboration based on intrinsic motivation.

5.1.1. Problems Embedded in Rich and Relevant Learning Contexts

Critical to the success of a PBL approach is that problems are embedded in relevant and rich contexts that enable learners to develop their capabilities to utilise skills, knowledge and resources within and across different disciplinary areas. Providing real and rich learning contexts for engaging with PBL can be achieved by providing students with problems that connect to real-world contexts and learning relevant and authentic situations [45]. The problem should be sufficiently recognisable (i.e., relevant to the students) and located in reality (i.e., the real world) [58]. As highlighted by the focus groups and in the literature review, providing real and rich contexts helps to promote student engagement and motivation in their learning and offers sufficient complexity (i.e., richness) to encourage deep thinking and make the problem worthwhile to solve. However, both the literature and focus groups confirmed that setting up such contexts requires considerable skill on the part of the teacher that allows for student engagement at different levels of ability and remains manageable within the scope of the curriculum.

5.1.2. Flexible Knowledge, Skills and Capabilities

Learning in PBL develops flexible thinking, which, as highlighted in the literature and focus groups, is evident when knowledge, skills and capabilities are fluently retrieved, transferred and applied across various circumstances. PBL aims to use rich problems which integrate information from a range of traditionally siloed learning areas to promote fluent and deep learning within and across disciplines. Focus groups highlighted that teachers need to reconsider the curriculum to understand the big picture for learning and achieve curriculum coherence. Research indicates flexible thinking is important in developing self-directed, autonomous learners and independent enquirers [8,59] and the associated learning behaviours and skills are important for lifelong learning [12]. The focus groups identified that such emphases might challenge what is presently valued and assessed as learning in schools, raising new considerations for assessment, including identifying more relevant indicators of learning.

5.1.3. Active and Strategic Metacognitive Reasoning

Due to the learner-centred nature of PBL, metacognitive reasoning is seen as a critical aspect of the PBL process [60]. Metacognition is an intellectually active process whereby students critically examine and monitor their own thinking and learning [58]. As highlighted by both focus groups, PBL involves a strong emphasis on the process rather than the products of learning so that, in order to make sense of and solve a problem, students need to identify what they already know, any gaps in their knowledge, gaps in the information they are presented with, and their own goals for their learning. As students learn to engage with these metacognitive processes, they develop an understanding of their particular strengths and weaknesses. They can become more deliberate in their actions and strategic in how they apply their thinking to various tasks. Tasks which provide opportunities for the learner to identify gaps in their knowledge are therefore highly valued, as these types of experiences support the development of metacognitive reasoning skills such as critical evaluation, reflection and problem-solving [45].

5.1.4. Collaboration Based on Intrinsic Motivation

Collaboration based on intrinsic motivation is essential to PBL. This involves a series of discussions and negotiations through focused and purposeful group interactions. Motivation becomes an important driver and is enhanced when learners value what they are exploring and when they believe the outcome is under their control. The focus group discussions indicated the problem-solving process necessitates that learners collectively decide how to clarify a problem, generate further questions, and undertake purposeful research and this process initiates a demand for learning. Collaboration requires learners to share ideas, listen actively, value diversity of ideas, offer and accept feedback, and engage in metacognitive reasoning and decision-making [14,58]. Learners strategically position themselves and their ideas to build on their prior knowledge, construct new knowledge and ultimately direct their own learning [14]. Therefore, collaboration in PBL demands active involvement and conditions that encourage learners to engage with trial and error to collaboratively reassess alternate approaches to select the most effective solution to a given problem.

5.1.5. Interconnectedness of PBL Principles

Importantly, while we have described the characteristics of each PBL principle separately in the above section, they are inevitably interconnected. For example, the focus groups discussed the real and rich contexts for learning, emphasised in the PBL literature in relation to the student experience and the importance of aligning problems with areas of student interest. Personal relevance was central to considerations of context as a potential motivation for ownership and autonomous learning. Rich and relevant contexts encompassed all aspects of PBL learning. Further, while the literature highlighted that ill-defined problems characterise PBL, the focus group discussions identified the use of open-ended problems to demand higher-order learning where learners are required to ask questions and sit comfortably with the messiness of exploring options. Such problems often incorporate big ideas, inviting the exploration of knowledge across disciplines requiring flexible knowledge, skills and capabilities to clarify and respond to the focus issues and dilemmas. Collaboration assists this process, potentially providing multiple perspectives and ways of working to collectively achieve a valued and purposeful outcome. Hence, we emphasise that these principles are not intended to stand alone but are interconnected, supporting and enhancing the overall aims of PBL. The potential interconnectedness between each of the four principles of PBL practice and the positioning of all within rich and relevant learning contexts has not yet been addressed in research to date and thus represents a contribution of our study to the PBL literature. A schematic representation of the four PBL principles and their interconnections is illustrated in Figure 1.

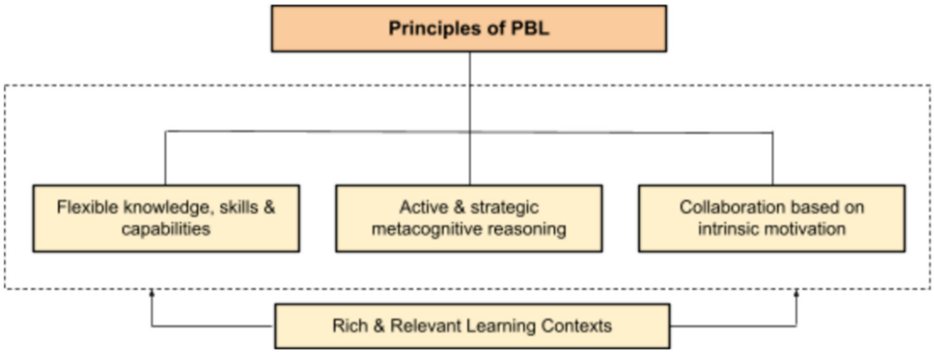

Figure 1. Principles of PBL and their interconnections.

5.2. PBL in School-Based STEM Education

In terms of our second purpose, to consider how PBL can effectively contribute to school-based STEM Education, the research literature and focus group data indicate that PBL may provide an approach that offers an effective way to integrate knowledge and skills across STEM disciplines and support the development of particular learning capabilities which enable students to become capable, self-directed learners. While research shows that students of different gender, ethnicity, and socio-economic status are impacted differently by different kinds of classroom inquiry approaches [61,62], there is reasonable evidence to support the value of a real-world inquiry or PBL approach to STEM education for all students [21].

However, in order to fulfill this purpose, PBL requires teachers to move away from traditional teaching approaches towards more contemporary understandings of learning and teaching. As noted by Thibaut et al. [63] in their systematic review of instructional practices in integrated STEM, one of the major challenges of implementing integrated STEM is the shift required from segregated disciplinary instruction to creating meaningful connections between STEM disciplines. Making this shift can be difficult for teachers and students for several reasons, including redefining the nature of learning; redefining the role of the student and the teacher in the learning experience, and identifying suitable teacher support. PBL in school-based STEM education will also require teachers to reframe embedded understandings of and approaches to assessment. As identified by focus group data, assessment in PBL must provide more suitable indicators of learning with attention to critical thinking and associated decision-making. Failure must be repositioned as a valuable and necessary experience in the process of learning. Although PBL and STEM education share common learning intentions, developing reliable and valid assessments in interdisciplinary STEM education has remained a consistent challenge for teachers [64], and assessment in PBL has also been problematic [65]. When assessment in PBL is not effectively addressed, this can be a source of possible confusion where inappropriate assessment methods lead to misapplications and misconceptions of PBL [65].

While our research supports the position that PBL can provide a promising approach which contributes to enhancing school-based STEM education, dilemmas exist for systematic and effective translation into practice. Clarifying the principles that characterise PBL is essential to informing an alignment between STEM education and intended learning, providing evidence-informed support for teachers considering the value of adopting a PBL approach in school-based STEM education. Opportunities for teachers to engage with, explore and understand these principles will be essential. Research exploring how teachers identify and address the emerging interrelated teaching and learning issues will be critical to developing suitable and systematic approaches to PBL in school-based STEM education.

6. Conclusions and Implications

The fundamental principles of PBL that have emerged from this research offer a framework that may be useful for refining learning in school-based STEM education.

School-based teachers who wish to effectively implement PBL in STEM education could use this framework to address four key practical considerations to frame their educational practice. (i) The PBL principles could potentially be used to focus professional dialogue on establishing a shared understanding of PBL among teaching colleagues. (ii) Using the principles, teachers could work together to determine alignment between existing STEM planning and teaching approaches and the pedagogical intentions of PBL. They could identify areas needing consolidation and opportunities for change. (iii) Individual teachers could use the principles to focus critical reflection on personal STEM teaching practice. (iv) Finally, this framework could be used to guide many future pedagogical decisions in STEM education, for example selecting appropriate student learning experiences and determining effective ways to facilitate learning interactions. The insights gained when teachers work collectively and individually to attend to such practical considerations could potentially benefit overall school-based change. However, we acknowledge that achieving such changes may present challenges, particularly in contexts where traditional approaches to teaching and learning are strongly embedded. While the findings from this research help to illuminate the role of the student and subsequent implications for the role of the teacher, further research is still needed to understand the influence of context and the role of teacher decision-making in the effective translation of PBL in school-based STEM education.

There are obvious limitations in the scope of the focus groups in terms of the number of participants involved in this research. However, we believe that the careful selection of international participants represented a broad range of expertise and perspectives. Future research could continue to test these ideas with PBL experts in different contexts and with teachers in schools.

This paper aimed to generate principles of practice and to define the fundamental nature and intention of a PBL model of STEM education in schools. By analysing data from relevant literature and testing these ideas with expert focus groups, four principles of PBL have been developed and presented. Most of our findings reinforce characteristics and practices found in the literature on PBL; however, we extend this prior work by exploring in detail, through focus groups, the nuances of practice that shape what PBL looks like in context. The insights derived from this research provide evidence-informed support for teachers who may be considering the value of adopting a PBL approach for STEM education in schools.

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Abbreviations

PBL	Problem-based learning
PjBL	Project-Based Learning
STEM	Science, Technology, Engineering and Mathematics

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