Teaching Problem Solving to Undergraduate STEM Students: A Systematic Literature Review

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Abstract. This systematic literature review aims to explore the field of undergraduate teaching using the Problem Based Learning (PBL) methodology and to discover the ways that researchers have used the PBL methodology as a means to teach problem solving. This is a review of 20 primary studies on teaching problem solving by means of PBL to undergraduate Science, Technology, Engineering and Mathematics (STEM) students. Through a thematic analysis of the 20 papers, four central themes emerged as being significant to PBL regardless of the subject discipline. These themes are: the role of prior knowledge; teamwork and team composition; the role of the instructor; and contextual learning methods. In terms of prior knowledge, it was found that students need to have sufficiently mastered the subject's domain knowledge at an individual level before they can benefit from PBL. The teamwork theme emphasized the importance of teams in problem solving. Small heterogeneous teams appear to be conducive to effective teaching by means of PBL. In terms of the role of the instructor, it was found that teams significantly benefit in their learning experience, from an instructor or tutor who facilitates and motivates the team as opposed to telling them what to do. Lastly, most of the PBL studies employ learning methods that are specific to their domain but will help the students better solve the problem. Based on the insights gained from the literature, the review suggests good practices that can be used by other researchers when trying to implement the PBL methodology in their undergraduate STEM classes.

Keywords: Problem solving · Problem based learning · STEM · Undergraduate students · Systematic literature review

1 Introduction

The skill of practical problem solving is integral to the work environment and is considered to be indispensable [1]. The 1993 National Adult Literacy Survey (NALS) found that basic problem solving skills are in short supply in the workplace, with more than half of employed adults having difficulty solving even simple assigned tasks [2]. Employers have noted that they actively seek graduates

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who have shown to engage in problem solving [3]. The ability to solve complex real-world problems is particularly important in the STEM disciplines [4]. Unfortunately, problem solving is not taught explicitly at most universities, with subjects being mainly taught at a theoretical level with little focus spent on teaching the subject's practical value [1]. Students need to be provided with opportunities to build the skills and abilities that are necessary to solve the various types of problems that can occur in the field that they work in.

Problem-based learning (PBL) is a teaching method that requires students to solve problems relevant to their discipline in an active learning environment [5]. It was originally developed in the medical domain but subsequently proved to be a valuable means to teach problem solving in the STEM disciplines [4,5].

This systematic literature review seeks to collect research evidence on the use of PBL in undergraduate STEM fields in order to identify how PBL is used to teach problem solving. Using the systematic approach to evaluate existing literature helps us to more dependably find patterns that exist in the studies, or even review any conflicts in the existing body of work.

This paper is organised as follows. The next section provides literature background, in particular about problem solving and PBL in undergraduate teaching. Following this, the research method is presented. An analysis of the structured literature review's key findings is subsequently presented, starting with descriptive statistics before proceeding with a thematic analysis. The paper ends with a reflection of findings in the Conclusion.

2 Literature Background

This section first considers the notion of problem solving before proceeding to PBL as a learning strategy that is centered on problem solving.

2.1 Problem Solving

Problem solving is the process of finding a solution when the path to the solution is uncertain, according to Martinez [6]. Martinez further states that "problem solving involves an interaction of a person's experience and demands of the task" [6], p. 606. Universities can teach problem solving through the use of problem solving methods and strategies in order to help develop students' cognitive abilities. The generic problem solving process as defined by Kimbell, Green and Stables [7] is shown in Fig. 1:

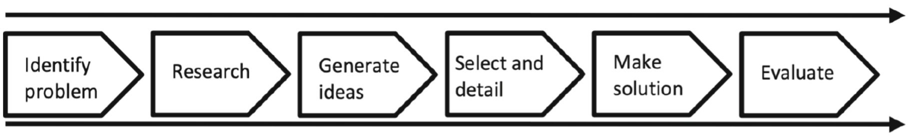

Fig. 1. The problem solving process, adapted by [7].

Davidson and Sternberg [8] states that the types of problems that can be classified for solving can either be well defined or ill-defined. Well defined problems are those with clear goals, obstacles and path to the solution, while ill-defined problems have an unclear path to the solution. This then makes it more difficult to solve ill-defined problems as they do not have an unambiguous problem statement which makes problem representation more difficult. Davidson and Sternberg [8] gives a meta-level problem solving process consisting of eight steps that largely correlates with and partially extends the process presented in Fig. 1. The steps are: recognizing that a problem exists; defining the nature of the problem; allocating appropriate resources to solve the problem; deciding how to represent information pertaining to the problem; deciding on appropriate problem solving steps; combining the steps into a problem solving strategy; monitoring the execution of the strategy; and finally, evaluating the problem's solution.

2.2 Problem Based Learning

PBL is "an active pedagogical strategy commonly used in some disciplines to develop general and specific competences" [9], p. 105. It is a teaching model that encourages learning by applying knowledge of content and the use of problem solving skills to solve problems relevant to a specific discipline [10]. The introduction of PBL in universities has been used to develop professionals who are better at actively seeking solutions.

PBL was first used in the medical studies at McMaster University by Barrows and Tamblyn [11] who hypothesized that learning through solving problems would be more valuable than memorizing a large amount of content knowledge and that problem solving skills are more important for medical practitioners than having competent memory skills. PBL places the responsibility for determining the requirements of the problem in order to best define and then solve it on the student instead of the teacher. This may also include finding needed learning material in order to solve the problem [12].

The six core features of PBL, as defined by Barrows [13], are what differentiates the classroom pedagogy from other collaborative learning pedagogies. The features are: student-centered learning; learning in small groups; teachers who only act as facilitators in the learning process; problems being the main focus when learning; the use of problems to spur the development of the students' critical thinking and problem solving skills; and the discovery of information through self-driven learning.

Janpla and Piriyasurawong [14] developed a PBL model, with the following steps: define the problem; understand the problem; continue the research; synthesize the knowledge; conclude and evaluate the answer; and present and evaluate the students' work. It can be seen that these steps resemble the problem solving processes described in the previous section.

PBL enables students to be better prepared for the real world [5]. Skills are developed that can be learned through solving problems and to help store, retrieve and use information. PBL assists with achieving the following [4]:

1. The ability to connect content knowledge to real world application;
2. Creating deeper understanding by requiring the use of content knowledge in new ways through collaboration with others;
3. Encouraging students to reflect on their use of thinking structures by helping them evaluate their thinking process;
4. Employing the use of technology to help students independently find the most apt tools to solve their problems with;
5. Using students to create, verify and evaluate their own contributions and the contributions of others;
6. Providing opportunities for students to solve complex problems that may result in new perspectives and solutions to problems;
7. Encouraging collaborative efforts in the gathering of information, the solving of complex problems, the brainstorming and sharing new of ideas;
8. Providing opportunities for students to take responsibility for their learning and working well with others; and
9. Helping students connect between subjects, ideas and other people.

3 Research Method

The research methodology carried out in this systematic literature review follows the guidelines by Okoli and Schabram [15], as shown in Fig. 2:

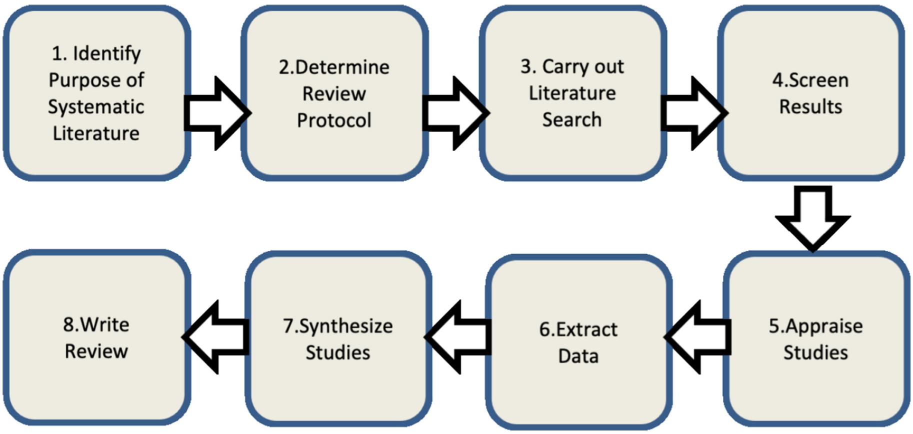

Fig. 2. The SLR process (Okoli and Schabram, 2010)

The research question guiding this study is: *How is PBL used to teach problem solving to undergraduate STEM students?*

The research question is limited in scope by focusing on PBL and how STEM undergraduate students - students who are in the Science, Technology, Engineering and Mathematical fields are taught. The following search term was used:

(("problem based learn*" OR "teaching problem solving") AND "undergraduate" AND ("engineer*" OR "math*" OR "comput* (NEAR/2)"))

A Google Scholar search returned 2500 results, which were too many even before applying selection filters. The same search term was subsequently used in a different database search, namely EBSCOhost while restricting the database to only return results from MasterFILE Premier and Academic Search Complete. These databases included full text search results. After applying the source selection and inclusion and exclusion criteria presented below, this search returned 127 potentially relevant sources.

3.1 Source Selection

- The databases chosen included journals and articles that gave detailed information on problem solving and problem based learning for undergraduate students in STEM.
- The databases chosen included comprehensive information on the topics presented and each database was not subject specific.
- The databases allowed for advanced Boolean searches with keywords.
- Through the University of Pretoria library, full text documents were accessible from the database search.
- Two other relevant sources, namely the Journal of Information Systems Education (JISE) and the African Journal of Research in Mathematics Science and Technology Education (AJRMSTE) were included. These were not available through the data-bases and were searched separately.

3.2 Inclusion Criteria

- Texts that directly answer the research question.
- Focus on teaching using PBL to undergraduate computing/computer science, information system, engineering and mathematics students.
- Studies that were published in the years 1980–2018.
- Empirical studies on problem solving in computing/computer science, information system, engineering and mathematics.

3.3 Exclusion Criteria

- Texts that focus on teaching problem solving for STEM subjects to non-STEM students.
- Studies that rely purely on expert opinion or are purely anecdotal.
- Studies that are not related to any of the research questions.
- Studies that are not of undergraduate STEM university students - including high school students and post-graduate students.
- Studies whose findings are unclear.
- Studies that are not in English.

The PRISMA flowchart summarizing the search process is presented in Fig. 3.

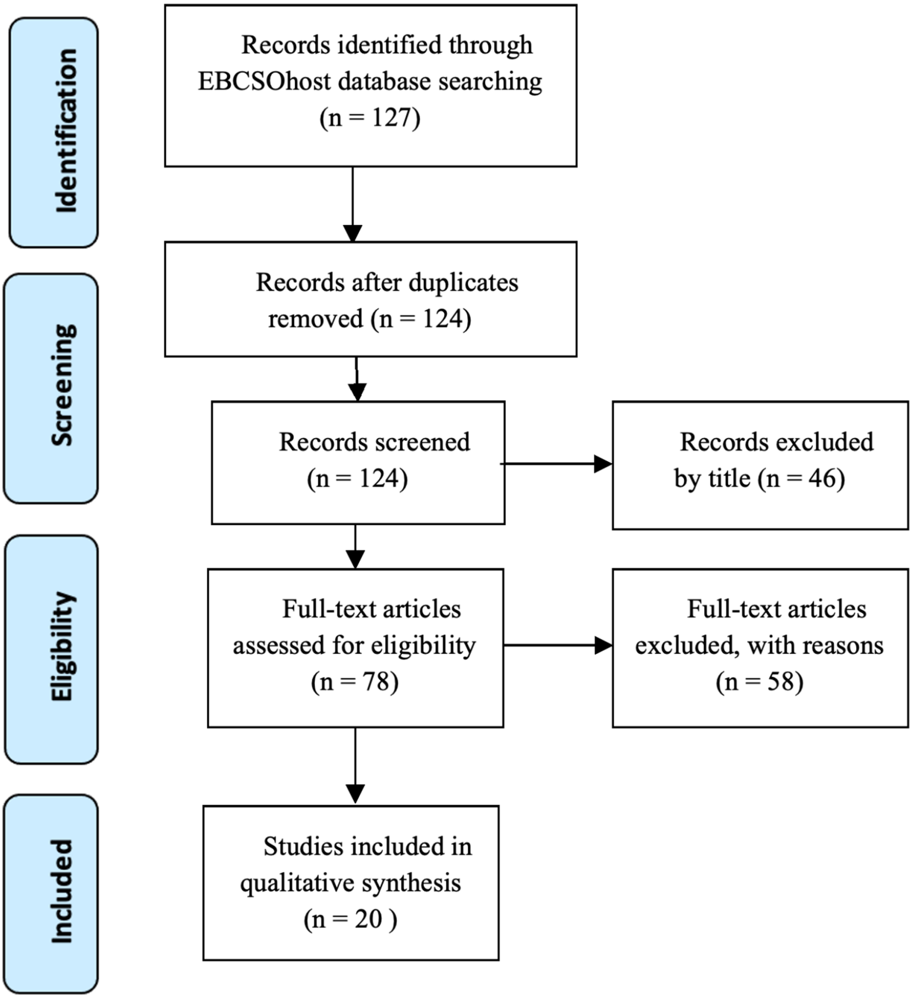

Fig. 3. PRISMA flowchart

4 Analysis of Findings

This section reports on the findings arising from the 20 articles analysed. The analysis will commence with a summary of the data in the form of descriptive statistics. Thereafter a thematic analysis will be presented.

4.1 Descriptive Statistics

Countries in Which Studies were Performed. Figure 4 indicates that the United States dominates as the country with the highest number of studies of

PBL in undergraduate STEM students. Seven of the 20 studies were performed in the USA, more than double the number performed in any of the other countries. Overall, most of the studies occurred in the US, UK and Europe.

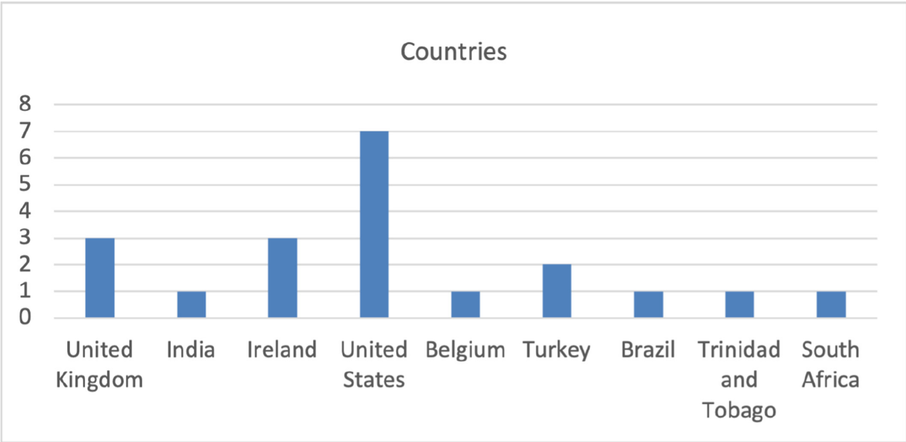

Fig. 4. Countries in which the studies were performed

Journals in Which Studies were Published. The journals that included the largest number of studies were engineering education journals, with the European Journal of Engineering Education containing the most studies, namely five of the 20 (see Fig. 5).

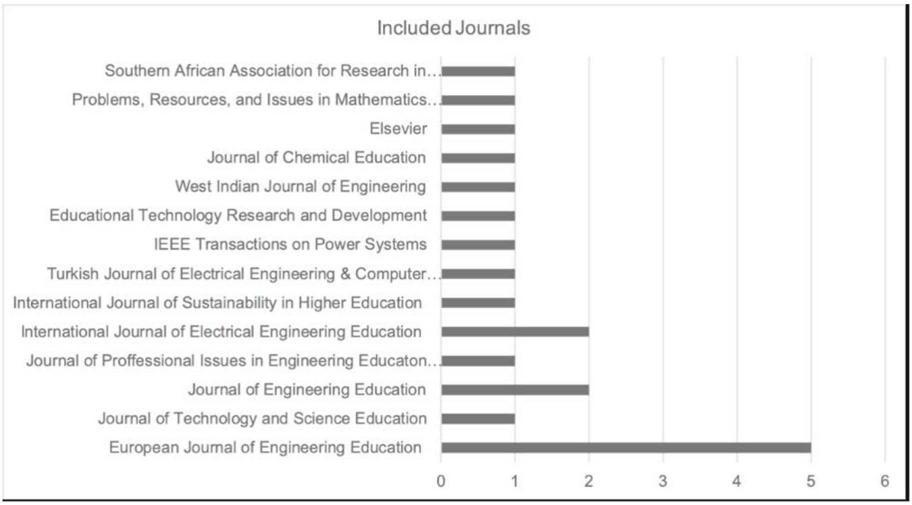

Fig. 5. Journals in which studies were published

Domains. The overwhelming majority (15 of the 20) studies were performed in engineering education, as can be seen in Fig. 6. However, there were also 3 studies in computing education, which will be further discussed in the thematic analysis that follows.

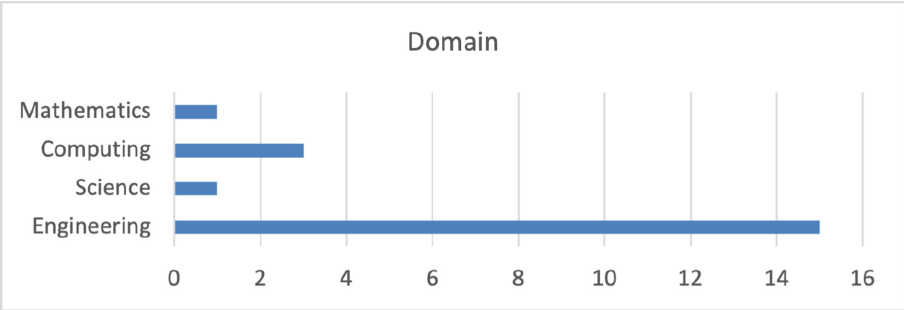

Fig. 6. Domains in which studies were performed

Study Year During Which PBL was Introduced. From Fig. 7 it is evident that there is a preference to introduce PBL at the earlier years of study. This makes sense, as problem solving is a basic capability required by STEM students, and in particular engineers (since most of the studies were in the engineering domain).

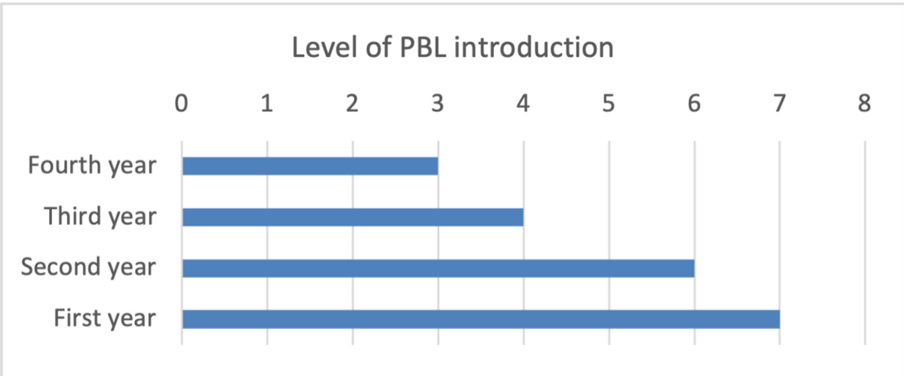

Fig. 7. Study year or level of introducing PBL to students

From the descriptive statistics, we learn that in the 20 articles included in the SLR, engineering education dominated as the domain where most studies were performed. There was a preference to introduce PBL in the earlier years of undergraduate study. Further, the USA, UK and Europe dominate as the locations where most studies were performed.

4.2 Thematic Analysis

A thematic analysis of the 20 papers resulted in the identification of four emergent themes. The analysis was done with the assistance of a data table, where the articles appeared as rows and the issues they addressed were noted in columns. The four common themes that emerged are: The role of prior knowledge, teamwork and team composition, the role of the instructor, and contextual learning methods.

The Role of Prior Knowledge. Prior knowledge is the amount of content knowledge imparted to students prior to the introduction of the PBL methodology. The amount of prior knowledge that has been imparted to students seems to have a favourable effect on the students and their perception of the PBL methodology, as will be seen in the discussion that follows.

In McCrum's [5] interdisciplinary study involving structural engineering students, he observed that students need to have a strong base on their content knowledge that they should be able to draw from in order to better engage with the PBL tasks. This will allow them to use, examine, and integrate problems more effectively [5]. The students will then be encouraged to connect prior learned ideas, experiences and knowledge and use those ideas in identifying patterns and principles that may exist, examining evidence against the initial assumptions made, and critically checking the logic and arguments [5]. "Based on the principle of using problems as a starting point for the acquisition and integration of new knowledge, the method is designed to create learning through prior learning experience and to reinforce existing knowledge" [16]. Ensuring that the students have reinforced their content knowledge would provide them with the skills and confidence to engage more fully in the PBL interaction which will address Gavin's [17] concern namely that missing concepts may cause a failure to learn in the PBL approach.

Research has shown that students rely heavily on their prior knowledge when solving problems in the PBL approach, which has created the assumption that a stronger knowledge base results in better problem solving [18]. This has been illustrated by Bledsoe and Flick [18] in Fig. 8.

Prior knowledge can be reinforced in multiple ways, with the most popular approach being to follow the didactic (traditional learning) approach for one or two years of undergraduate study [19]. In Mitchell and Smith's [20] study involving electrical engineering students, the students followed the didactic learning approach in order to be taught foundational knowledge as preparation for introducing PBL in their curriculum. However, other learning approaches such as didactic, Socratic and inquiry-based should be viewed as complementary to the learning process to ensure that the students receive the best possible outcome from PBL [19].

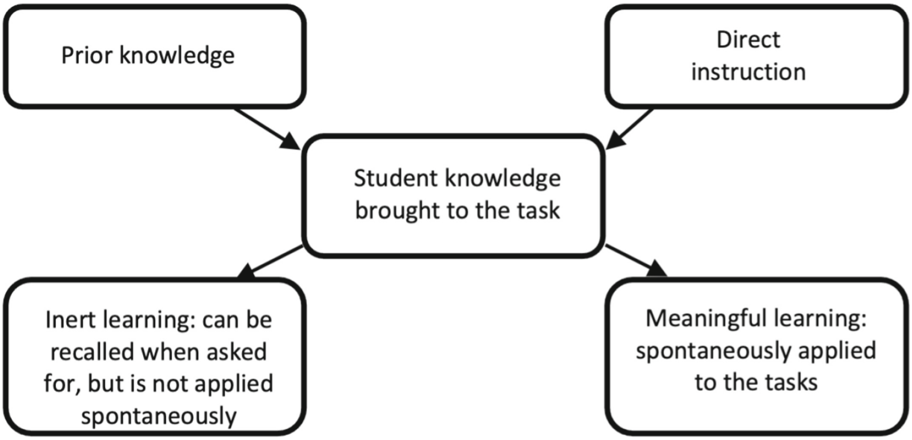

Fig. 8. A model of learning as adapted from Bledsoe and Flick [18].

The use of PBL in computer science education is also viewed as a way to engage with prior knowledge while moving away from the didactic learning approach to a more problem centred pedagogy. Dunlap [21] used the software development life cycle (SDLC) approach to solving problems that students would be more familiar with and mirrored it to the PBL approach as it is more closely aligned when restructured to accommodate prior knowledge. This helps both the instructors and students as they don't have to introduce new concepts while partaking in the problem centred pedagogy [21].

If prior learning is not carefully reinforced, it may have adverse effects on the progress of introducing PBL to students. In a study by Dyer, Grey and Kinnane [22], the majority of civil engineering students were unable to create simple sketches at the beginning of the design-led introduction of problem based learning, even though they were expected to have skills such as being able to sketch and draw when practicing professionally. This needed to be addressed by the instructors where formal lectures and design studios had to be held in order to first show the students how to do those tasks properly and then engage in the PBL approach [22].

Adverse effects may occur where the solution to the ill-defined problem that is given in a PBL environment cannot be found through the following of a set of classroom notes or the use of an example given in a textbook [23]. When traditional tools used to understand and solve problems are no longer sufficient in the PBL approach, students have found that they have to use external sources of information such as the internet or library in order to gain more insight on the important concepts and how to approach and solve the problem presented [23].

Teamwork and Team Composition. Studies across engineering as well as computer science have noted the importance of teamwork during use of the PBL approach [5]. This section discusses the number and types of students in the teams that the researchers have decided to form as part of their studies related to PBL.

A study by Yadav and colleagues [24] promotes heterogenous teams with numbers ranging from 3–5. Students work with an instructor who facilitates the students' learning journey. At least one electrical and one computer engineering student was placed in the same team [24]. In a study by Vemury, Heidrich, Thorpe and Crosbie [25] 8–12 civil engineering students of heterogenous academic abilities were placed in what they referred to as design groups to produce deliverables that reflected the objectives given in the design brief.

In Johnson and Hayes' study [26], students worked in groups to develop a number of competences in the collection, evaluation and duplication of data in order to solve complex problems that reflect those found in the real world.

Mitchell and Smith [20] struggled to find guidance from literature with regard to the selection of teams in a PBL approach, and opted for a solution that combined having tutors select groups based on their ability and having students select their own teams. Students were given the flexibility to choose two of their friends to be their partners while tutors randomly selected another group of students to form part of the group to form a larger group of six [20].

In a study with computer science students [21], the team was composed of what would most likely look like a software development team structure with three to four students working together to define the problem given by the client and the clients' needs, the written proposals, conduct analyses, plan solutions, implement and test those solutions [21].

In Şendağ and Odabaşi's [27] study, smaller groups termed sub-groups were randomly assigned. In this study individual reports on the problem solution are combined with group work to determine individual merit [27]. Martí, Gil and Juliá [28] opted to create groups of five to twelve students that could suggest either a problem or project that works towards the solution. Quinn and Albano [23] found having two to four students in a group with a faculty advisor playing a supportive role was an ideal arrangement for PBL. The students selected their own groups and used their interests to help them choose a faculty advisor based on their needs [23]. In her study of BSc Computer Science and Information Technology students, Havenga [29] followed a similar model with groups that comprised of only two members. However, because of the course demographics being mostly male, the teams were homogenous in skill set and gender [29]. Persad and Athre's [30] study of various engineering disciplines finds that students should not be given the choice to form their own teams and should be pre-screened by the instructor before being assigned. This is to ensure that students who are stronger academically are distributed evenly throughout all the groups while also having a student that is proficient with creating prototypes and models [30]. This creates heterogeneity and balance in the class. The number of students that made up a group was four, with each class having an even number of groups [30]. Denayer, Thaels, Sloten and Gobin [31] opted to have a randomized group of five to seven students without pre-screening students' academic abilities or skill sets. This strategy was mirrored in Cowden and

Santiago's [32] study where three to five students were selected based only on their pre-existing lab partnerships.

To conclude: while there is no consensus on the sizes of teams that perform PBL, the heterogeneity of teams in terms of skills, ability as well as demographics is emphasized.

The Role of the Instructor. The role that the instructor plays in the PBL approach is one that facilitates the students' learning. The amount of support offered to the students varies by study but the most common role of the instructor is to act as a guide and motivator to the students.

In a PBL study with structural engineering students [5], in the architectural design module, the tutor played a role that presented students with guidance with regards to design and not instructions. Students were assisted to improve their learning of foreign concepts through interactive engagement, to reflect on their content knowledge and to motivate them with their tasks [5].

In Quinn and Albano's [23] study involving structural engineering students, the instructors role was defined as one that would stimulate learning and research thinking by avoiding the traditional didactic role of being the expert source of knowledge. The instructor had to be approachable by listening and asking questions from the students, cultivating an environment where the students would be comfortable to share their ideas and discuss their understanding of the theories for solving the problem [23].

The PBL approach encourages instructors to facilitate the students' learning process [26]. With the instructor no longer taking the role of being the sole source of content or information, the responsibility is placed on the student to find external sources of information [26]. This was found to urge the groups to more extensively explore their options and only receive input from the instructors when asked or when the direction of the problem was obscure [20]. However, with traditional teaching methods engrained in the instructors, guiding the group towards the instructor's way of thinking was sometimes inevitable [20].

Motivating the students and creating the desire to learn has been shown as integral to the teacher's role in a study involving civil engineering students [33]. In this study, students were found to feel frustrated as facilitators only provide limited guidance on how to tackle the problems and could not provide them a concrete solution to the problem [33].

In a study with computer science students, the instructor did not provide direct instruction to the students on solving the problem but gave guidance to help the students with the process of brainstorming and prioritizing ideas [21].

In Şendağ and Odabaşi's [27] study of online computer science students participating in PBL, the instructor played a more active role in participating in discussion forums, responding to questions, encouraging students to think more deeply and conduct external research and use that information to make decisions on how to approach the problem. He challenged students through questions and encouraged questions from students but avoided responding directly to enquiries that would lead to him giving explicit information [27].

In the PBL approach, the role of the tutor changes to become that of an advisor in the quest to solve the problem and not only an evaluator [28]. This fosters a better working relationship between tutors and students that can make tutors more approachable [28]. The role of the tutor is given as [28]:

- "Clarifying the student's ideas. Tutors should not impose their points of view, but rather identify contradictions in the group's reasoning and request opinions from all members;
- Encourage critical evaluation of ideas and knowledge;
- Facilitate discussion, through student interaction and exchange of ideas and experiences; and
- Discuss strategies with the students".

In Denayer et al.'s [31] study, the instructor was more heavily involved in the team's progress and monitored it using a pre-designed manual throughout the project lifespan. The tutor monitored the teams and had various tasks which include but were not limited to: answering questions about the design problem; acting as the customer to assist the students during the early phase of the design process; steering the various groups through the process; managing the students and their time schedule; evaluating the efforts from the teams and give feedback; and attending the team meetings to ensure they apply the design methodology [31].

Contextual Learning Methods. With PBL, learning can be enhanced through the use of contextual learning methods. In McCrum's [5] study of engineering students in the architectural design module, students were encouraged to use sketches of complex engineering ideas to help them achieve higher order thinking and equip them with the tools to solve more complex problems. It was believed that the ability to solve complex problems that were en-countered in the study would enable the students to better engage in the creative engineering and architectural design problems and be less frightened of the unknown [5].

In a study involving electrical engineering students, [24] problems were presented in a realistic case study format. The problems encouraged students to make more complex engineering decisions in the context of tasks which helped the students better develop their final project with the use of their conceptual understanding by means of in-class problems [24]. This is in line with Johnson and Hayes' [26] use of the PBL approach where real-world scenarios are used to help students conceptualise solutions.

Quinn and Albano's [23] study was based on an undergraduate project known as the major qualifying project (MQP) that comprises part of the degree requirements for engineering students. MQP concentrates on the application of the learned material in the students' discipline by creating a solution for real-world problems while working with an external organisation or company [23].

In Alayont's [34] study of Mathematics students, she created pre-class activities that the students could complete beforehand in order to give them relevant knowledge on the lecture subject and also help students work more efficiently during in-class activities. Mota, Mota and Morelato [35] chose to use computer-mediated learning in order to enforce PBL, since the study was conducted in a web environment. In a study with computer science students, the systems design for a real-life client was used to further enforce learning by means of a PBL approach [21].

Overall, it can be seen that authentic, real-life problem scenarios were typically presented to students as part of their PBL.

5 Conclusion

This study presents a systematic literature review of 20 papers with empirical studies on using PBL as a means to teach problem solving to STEM students. It was found that the United States appears to be most active in conducting PBL research in STEM education, followed by the United Kingdom and Europe. The overwhelming majority of the studies were done in engineering education (15 of the 20) and also published in engineering education journals. This makes sense as the ability to solve real-world practical problems is at the essence of engineering. It was encouraging to see that the second most number of studies were in the computing field.

A thematic analysis of the 20 studies resulted in the emergence of four overarching themes. These themes were evident regardless of the subject disciplines. The first theme emphasized the importance of prior subject knowledge when attempting PBL. PBL requires the creative application of domain knowledge, and hence can only be successful if participating students' domain knowledge is at the appropriate level. The second theme was around the importance of teamwork during PBL activities. Team members learn from each other, hence heterogeneity in team composition was emphasized as important. Thirdly, it emerged that PBL initiatives benefited from instructors who acted as facilitators in the students' learning process without helping them too much. Lastly, the role of contextual learning methods were emphasized. The real-world decision-making environment of the STEM graduate needed to be emulated in order for them to benefit most from the experience.

Of the 20 studies, the one where all of the mentioned themes were explicitly acknowledged was McCrum's [5] study on developing creative problem solving abilities in engineering students. Interestingly, the four identified themes also align closely with the framework presented in [36] for developing the creative ability of under-graduate Information Systems (IS) students.

This study was limited to the studying of selected empirical studies on PBL for undergraduate STEM students. It contributes by synthesizing from the literature, a number of suggested practices for teaching problem solving to STEM students by means of PBL. Further research is suggested to expand these practices for IS and computing students, since there are very few studies focusing on the use of PBL in the IS and computing domains. In the light of the importance of problem solving skills in the workplace it is also suggested that the 1993 National Adult Literacy Survey be revisited to see whether and how workplace problem solving skills have improved in the decades since.

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