Combining Immersive Technologies and Problem-Based Learning in Engineering Education: Bibliometric Analysis and Literature Review

Mahgol Nowparvar[1], Xing Chen[2], Omar Ashour[3], Sabahattin G. Ozden[4], Ashkan Negahban[1]

[1]*School of Graduate Professional Studies, The Pennsylvania State University, Malvern, PA 10355*
[2]*Computer Science and Engineering, The Pennsylvania State University, University Park, PA 16802*
[3]*Department of Industrial Engineering, Penn State Behrend, Erie, PA 16563*
[4]*Information Sciences & Technology, Penn State Abington, Abington, PA 19001*

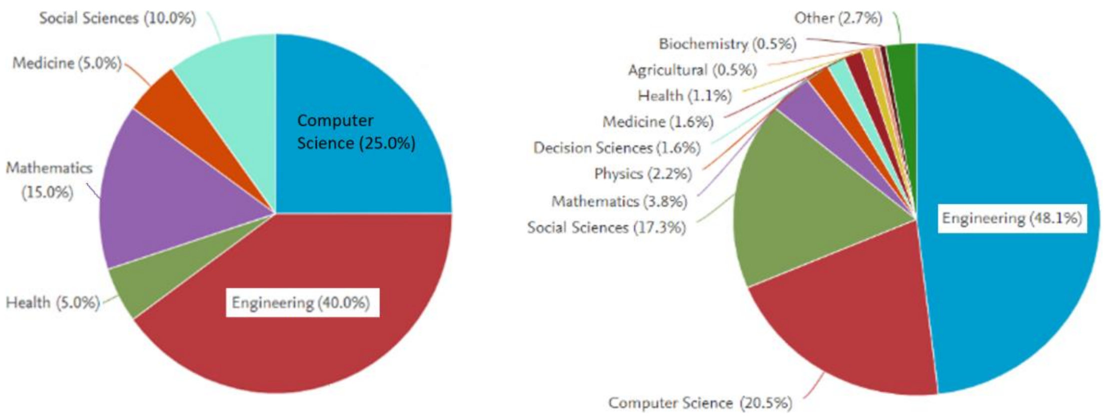
Abstract

There is a cohesive body of research on the effectiveness of problem-based learning (PBL) for a wide range of learner groups across different disciplines in engineering education. On the other hand, there is a growing interest in using immersive technologies such as virtual reality (VR) in engineering education. While there are many literature review articles on each of these subjects separately, there is a lack of review articles on the application of combined PBL-VR learning environments in engineering education. This paper provides an assessment of the applications and potential of implementing immersive technologies in a PBL setting to utilize the advantages of both paradigms. More specifically, this paper aims to provide insights related to two main questions: (1) where (in what disciplines/subjects) PBL and VR have been used together in engineering education? And, (2) how are VR and PBL integrated and used in engineering education? The first question is investigated by performing a bibliometric analysis of relevant papers published in the proceedings of previous ASEE annual conferences. The second question is explored by performing a literature review and classification of ASEE papers that discuss the use of VR in conjunction with PBL. Our findings reveal a gap between the application of integrated PBL and VR across different disciplines in engineering education. We also analyze the trends related to PBL and VR application in engineering education over time. Finally, we identify and propose future opportunities related to the combination of PBL and immersive technologies, including but not limited to immersive simulation-based learning (ISBL) and incorporating artificial intelligence (AI) into immersive virtual/simulated learning environments used in engineering education.

Introduction

Problem-/project-based learning (PBL) is a form of student-centered active-learning approach in which students learn by solving complex problems that resemble those encountered in the real world. After decades of evolution, PBL has grown into an extensive teaching and learning method in a wide range of disciplines, including engineering education. Current studies show that students find PBL more engaging and effective, as they actively apply the information learned in the classroom to tackle real-life problems [1].

Immersive technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), use computerized environments and objects to simulate a “real” user experience [2]. There is a wide range of research on the effectiveness of immersive technologies in education. For example, several papers suggest immersive technologies to enhance specific learning outcomes in engineering by enabling remote/online teaching and providing a flexible and safe virtual environment [3]. Furthermore, immersive technologies can facilitate teaching and learning of design concepts (e.g., 3-dimensional design for a new product) while enhancing students' interactions, creativity, and spatial skills [3].



(a) Discipline breakdown for PBL. (b) Discipline breakdown for VR.

Figure 1: Search results for PBL and VR in the Scopus bibliography database.

The use of immersive technologies in the context of PBL can potentially enable the advantages of both paradigms and further improve critical thinking and problem-solving skills, encourage effective communication, and enhance students' motivation and learning experience. Motivated by the above and the fact that engineering is one of the main application areas for both PBL and VR (Figure 1), the objectives of this paper are to:

1) Use bibliometric analysis to show *where* (in what engineering disciplines/subjects) PBL and VR have been applied.
2) Provide a literature review to assess and understand *how* VR has been used in a PBL setting in engineering education.

The remainder of the paper is organized as follows. We first provide a brief overview of the bibliometric analysis technique. We then present the main results of our bibliometric analysis along with the observed trends over time in the use of PBL and VR. We then narrow down our focus and provide a summary and qualitative assessment of only those papers that discuss the use of *VR in a PBL setting* (i.e., integrated use of both tools). Finally, we present the conclusions and potential future opportunities. Figure 2 summarizes the general process used in this paper.

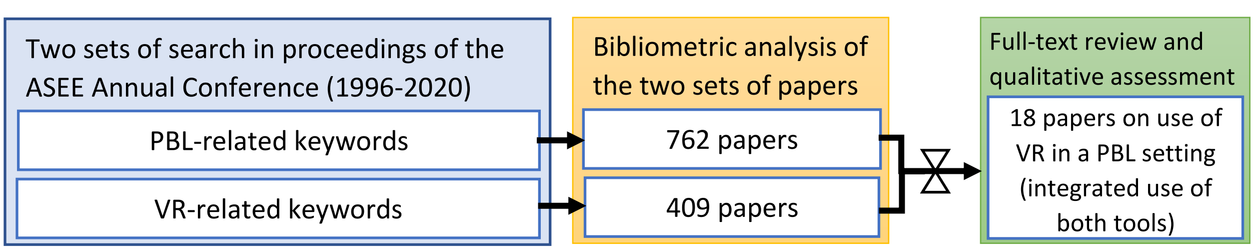


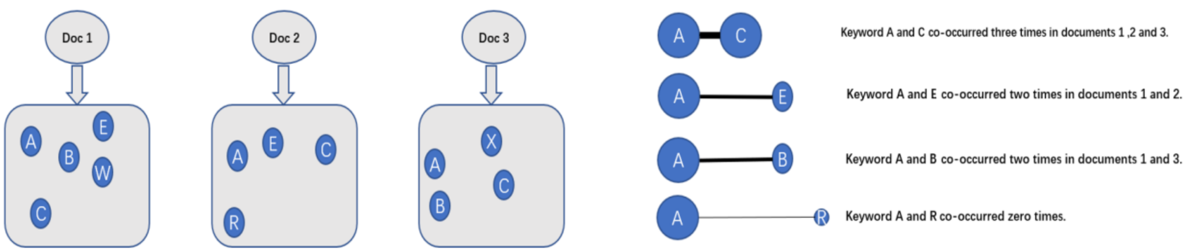
Figure 2: The general review process followed in this paper.

Bibliometric analysis: Where PBL and VR are used in engineering education

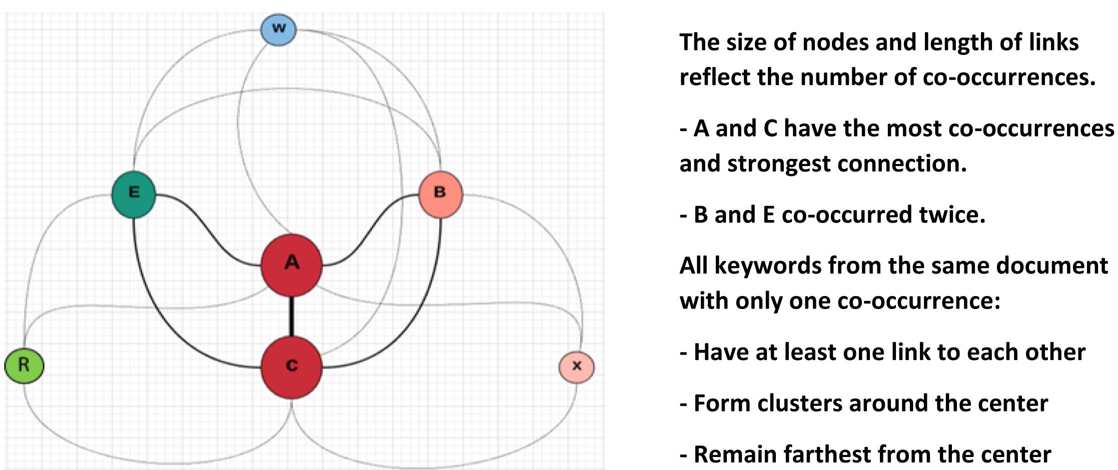
Bibliometric analysis involves statistical techniques that can be used to analyze a scientific field by its publications and their characteristics [4]. Here, we use the VOSviewer tool to perform a bibliometric analysis of the proceedings of the American Society for Engineering Education (ASEE) annual conferences over a 25-year period from 1996 to 2020 collected via Scopus searches in their *title*, *abstract*, and *keywords*, using various search phrases related to PBL and VR. Our bibliography search using the phrases "problem-based learning", "project-based learning", and “PBL” led to 762 papers. Similarly, 409 papers are identified using “virtual reality” and “VR” as search phrases. An example of the complete Scopus search expression is:

> TITLE-ABS-KEY ((*"Problem-based learning"* OR *"Project-Based Learning"* OR “*PBL*”)) AND (LIMIT-TO (EXACTSRCTITLE , *"ASEE Annual Conference And Exposition Conference Proceedings"*) OR LIMIT-TO (EXACTSRCTITLE , *"ASEE Annual Conference Proceedings"*))

Next, we perform co-occurrence analysis [5]–[7] to classify and map co-occurred words and phrases among the collected papers related to PBL and VR to describe research trends. Figure 3 presents an illustrative example of co-occurrence analysis with three hypothetical documents (Doc 1-3) and the resulting map/network of keywords/phrases (denoted by A, B, C, E, R, W, X).



(a) The three documents and their keywords used in the example of co-occurrence analysis.



(b) The co-occurrence map/network of keywords in the three documents in Figure 3(a).

Figure 3: An illustrative example of co-occurrence analysis.

Results of the co-occurrence analysis

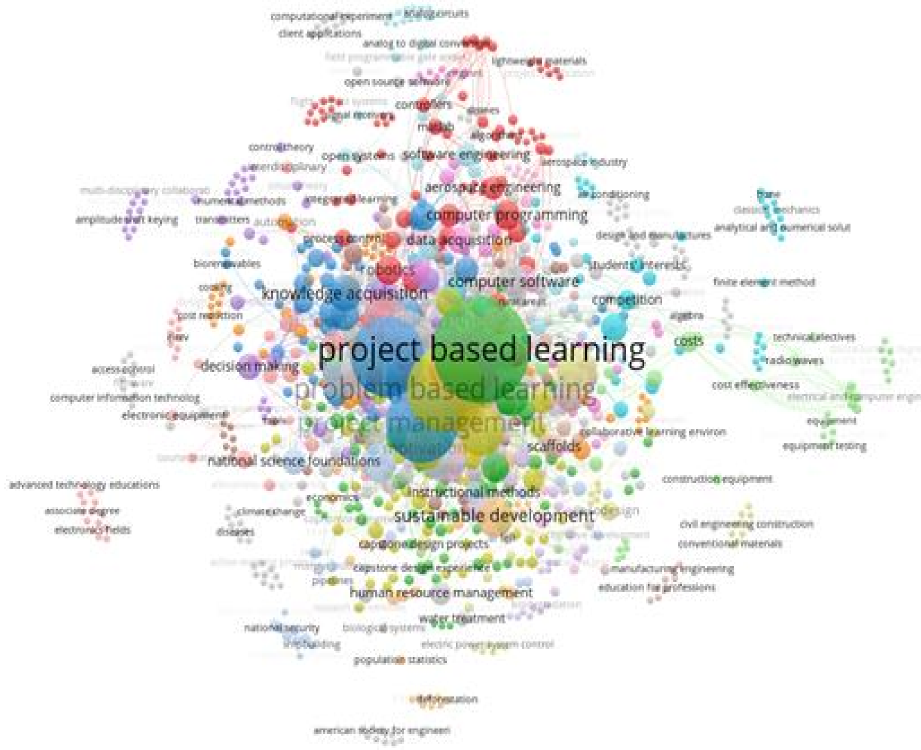
Figure 4 shows the co-occurrence map of keywords in the two sets of publications related to PBL and VR considered in this paper. The two maps help us identify clusters of keywords that co-occurred, which are then used to extract the related topic and engineering discipline as summarized in Table 1 for PBL and in Table 2 for VR along with a list of sample references.

Table 1. Engineering discipline and topics derived from the co-occurrence map for PBL.

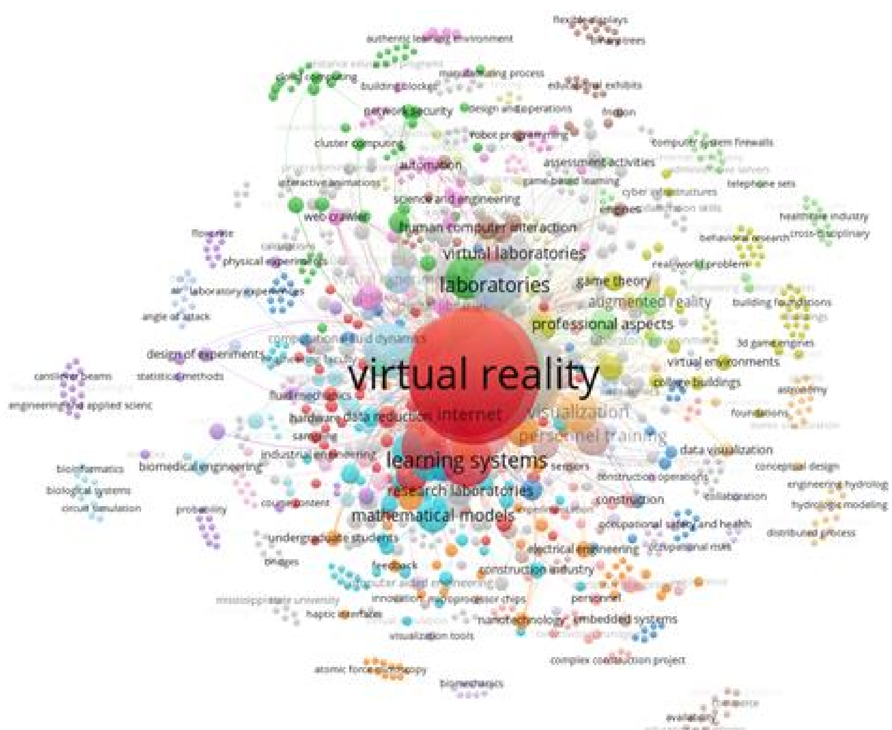
Discipline/Field	Keywords/Topics	Sample Papers
Electrical Engineering	Electrical equipment, Analog electronics and transistor, Electric system, frequency devices, Electronics technology program	[8], [9]–[13], [14], [15]
Mechanical Engineering	Machine concepts, Finite element analysis, HVAC, Fluid and Thermal design, Thermodynamics, Dynamic	[16], [17]–[19], [20], [21], [22]
Aerospace Engineering	Aerospace research materials	[23]
Computer Engineering	Concepts of CE (generic)	[24]
Biosystem Engineering	Biosystem engineering concepts (generic)	[25]

Table 2. Engineering discipline and topics derived from the co-occurrence map for VR.

Discipline/Field	Keywords/Topics	Sample Papers
General Engineering	Mathematical models, Probability and statistics, Engineering design education, Laboratory accident training, Medical care technology, Community health, Building environment, Web-based learning, Simulation, Visualization	[2], [26] – [33]
Computer Engineering	CE technology, VR Development, Computer game application, Mobile robot simulations, Game training environment, Engineering design	[34], [35], [36]
Mechanical Engineering	Wind tunnels, Prototype vehicles, Robot system, physical experiment, Virtual dynamic laboratory, Uncertainty analysis	[37], [38], [39]
Electrical Engineering	Nanotechnology, VR simulation	[40]
Biomedical Engineering	Simulations in biosystems	[41]

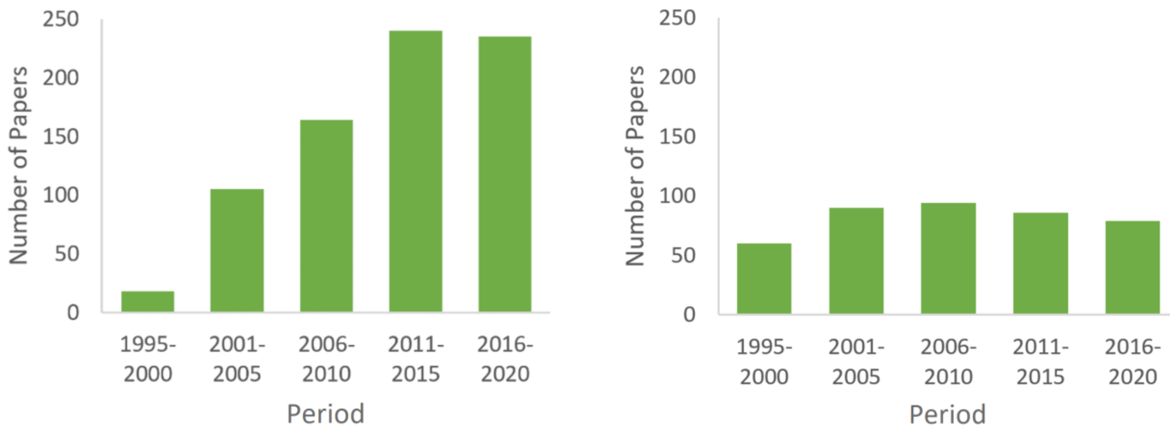


(a) Project-/problem-based learning.



(b) Virtual reality.

Figure 4. The co-occurrrence network for the two sets of papers related to PBL and VR.



(a) PBL (b) VR

Figure 5. Trend analysis for PB and VR.

Figure 5 presents the trends in the use of PBL and VR in engineering education measured by the number of papers published on the corresponding topic in the proceedings of ASEE annual conferences. We observe a clear increasing trend in the use of PBL over the years. However, we observe an initial uptick trend in the use of VR in the early 2000s after which the trend seems to have leveled out. By comparing Figures 5(a) and 5(b), we can see that PBL is used much more frequently than VR in engineering education. This is expected as PBL has been around for much longer and is well-established in educational settings with a more cohesive body of research, empirical evidence, and theoretical support in comparison to VR.

Literature review: How PBL and VR are integrated in engineering education

This section aims to provide a review of papers published in the proceedings of ASEE annual conferences to highlight how PBL and VR have been integrated and used together in engineering education. Through full-text review of the original 409 papers returned by our keyword search related to VR, 18 papers are selected that use a combination of PBL and VR, which are summarized in the following subsections. We divide the reviewed papers into the following groups based on the engineering discipline they belong to: Computer Engineering and Information Sciences, Mechanical Engineering, Electrical Engineering, Biomedical Engineering, Geotechnical Engineering and Environmental Engineering, and Industrial and Manufacturing Engineering. If a paper belongs to multiple disciplines or does not neatly fall under a single category, then it is included under “General Engineering”. At the end of this section, we discuss the main findings and insights derived from our literature review.

General engineering

In [26], the author employs a combination of formal and informal learning using immersive technologies and PBL for interdisciplinary teams consisting of engineering and nursing students.

The team project involves developing healthcare-related apps that patients can use on their smartphones, including apps that use immersive technologies (e.g., for cognition and memory health). The main goal of the study is to expose STEM and non-STEM students to various fields, such as health care, virtual reality, and social and community issues and understand how interdisciplinary instruction affects students' ability to identify, formulate, and solve problems, communicate effectively, appreciate the impact of planning and engineering solutions, and develop understanding of ethics-related factors. The effectiveness of integration of PBL and immersive technologies is measured with pre/post surveys related to the above outcomes and the results indicate increased technical and collaborative skills in students.

The authors in [42] work with graduate and undergraduate students to develop a web-based 3D visualization and cluster computing system for disaster data management, resource distribution and communication between local authorities and disadvantaged populations affected by a disaster. The developed tool can be used on Google Earth-enabled mobile and desktop devices as well as a Cave Automatic Virtual Environment (CAVE). More than 30 graduate and undergraduate students participated in the research and hands-on experiences involving PBL and VR in order to develop the web-based disaster management and communication system. The authors mention that three graduate students completed their master's thesis based on this project, and more than 10 undergraduate students completed their senior design project based on this research. However, they do not provide any additional assessment data related to the impact of PBL-VR integration on student learning or motivation.

The work in [43] develops a prototype of a multi-dimensional Desktop Virtual Reality (dVR) framework to help students organize, present, and visualize engineering and technological literature (as an alternative to reading textual information). The literature is represented as geometry objects embedded in a graphic interface where users can navigate within the 3D environment, view the literature from multiple perspectives, and interact with the virtual environment by sorting and re-structuring the visualized literature. The authors discuss the extension and application of the dVR prototype in PBL exercises, for example, an IT project involving generation of a taxonomy to classify operating systems or programming languages for a Computer Information Technology course. However, no assessment results are reported on the effectiveness of PBL-based exercises enabled by the proposed dVR environment.

Computer engineering and information sciences

In [44], the authors propose novel immersive simulation-based learning (ISBL) modules for teaching and learning database concepts. The proposed modules include a three-dimensional, VR-compatible simulated environment with PBL activities defined around the virtual environment to mimic a real-world situation where the student is hired as an intern to design a database for a hypothetical company/system. Students observe the simulation as it is running and are asked to create an entity-relationship (ER) diagram and relational schema by identifying relevant entity types, their relationships, and attributes. As part of the assessments, students are divided into two groups. The "intervention group" uses the ISBL module, while the "control group" is assigned to an equivalent PBL assignment without the accompanying immersive simulation. The authors collect data on demographics, motivation, usability, and students' grades in pre/post quizzes. The results confirm the effectiveness of the proposed modules with potential improvements in certain constructs related to motivation.

The work in [45] proposes a PBL-based approach wherein an interactive VR framework is used for delivering instructional materials to the students in an introductory computer animation course. The framework includes a VR laboratory capable of delivering conceptual and practical training and extensible VR modules designed to support immersion, navigation, and interaction. However, this is a work in progress paper and does not discuss any formal assessment results on the effectiveness the proposed PBL-VR integration.

The authors in [46] develop an advanced learning lab equipped with tablet PCs, wireless slates, and a SMART interactive whiteboard as an educational infrastructure to promote problem-based learning, collaborative learning, and assessment. A supplementary VR learning platform is also discussed for enhancing student learning outcomes by converting abstract concepts into vivid animations and providing game-like interactivities, and by making the learning experience fun while still retaining the underlying content. The authors report that the lab and support VR platform are at the initial implementation and testing phase, hence no quantitative assessment data are provided, but they lay out future assessment plans involving both formative and summative evaluations in a data structures course and an object-oriented design and analysis class.

Mechanical engineering

The authors in [47] develop, implement, and test two immersive prototype applications called AR-Skope and VR- Skope to support collaboration among Architecture, Construction, and Mechanical Engineering students. The prototype integrates AR and VR with Building Information Modeling (BIM), visual simulations, and interactive lessons. One course from each of the three participating disciplines is selected for implementation. Students are divided into four different groups to complete a project that involves physically visiting a campus building and a walk-through using VR and AR Skope (like having an interactive x-ray vision) to explore its various components such as the façade system, structure, mechanical systems, plumbing, etc. Pre/post attitude surveys, technical reports, videos and interviews are used to assess the effectiveness of the integration of VR and AR in interdisciplinary projects. The results suggest that the proposed method can effectively decrease students' negative attitudes toward collaborative learning and improve interdisciplinary team interactions.

In an effort to improve student learning and engagement, the authors in [48] develop and integrate an interactive virtual laboratory in a pneumatics and hydraulics systems course designed based on a PBL pedagogical model. The framework allows students to compare virtual experimentation using Automation Studio software with physical real-world experiments in a traditional lab setting. Preliminary assessment results from student skills in pre-lab preparation, lab report grades, and a survey indicate that incorporating virtual experiments in conjunction with physical experiments in a PBL setting is advantageous to student preparedness and understanding of the course material.

In an early paper [49], the authors develop an interactive virtual environment using the LabView software to support both inquiry-based and project-based learning in a Thermal Systems Laboratory course. Traditionally, the course involves equipment-intensive experiments where students are given detailed and rigid procedures to follow, creating a passive learning environment and suppressing students' motivation. The virtual environment aims to address these issues and overcome cost, safety, and other limitations of the physical lab. The PBL activities in the virtual environment involve designing instruments and data acquisition systems. However, the paper does not present any assessment results related to the effectiveness of the virtual lab.

Electrical engineering

The authors in [50] propose a set of interactive simulations and virtual experiments intended to facilitate "learning-by-doing" and PBL in fiber optics, photonics, and telecom courses and for onsite, online, and hybrid delivery methods. For example, in the simulation, learners can explore the procedure of switching or handing off a mobile phone from one cell to another as it moves across cell boundaries in a system of different sized cells. The student can also change the parameters (e.g., probability of blocking, traffic intensity, and number of users) and see their effect on the simulated system. However, no assessment data are reported on the effectiveness of the simulations and virtual experiments.

Biomedical engineering

In [51], besides traditional teaching and learning methods, and laboratory activities, the author presents case-based and problem-based learning using browser-readable interactive 2D and 3D objects, animation, videos, 3D objects of real components, and 3D internal and external human body virtual tours, that the students can study. According to our reviewers, learners and assessors, this an effective method for problem solving and assessment in biomedical engineering because it forces both the student as well as the tutor to focus, create new wealth, and encourage outcome-oriented educational practices. However, no formal assessment experiments are discussed.

Geotechnical and environmental engineering

The work in [52] studies the use of VR for teaching Concentrating Solar Power (CSP) technology. A scale model of an actual alternative energy research facility in Louisiana is developed in the CAD software and imported into a VR game engine with interactive educational activities placed throughout the VR environment and students complete them to virtually produce solar power. The VR environment is then used in conjunction with PBL, where students are presented with a problem, that is, to start up the (virtual) CSP plant in order to produce the needed solar power. Pre/post-tests and a questionnaire are administered for college and high school students. The assessment results show a substantial improvement on the post-tests as well as a positive feedback about the VR experience, exploration, collaboration, and interaction combined with PBL as an effective educational method.

The game-based module for geotechnical engineering students in [53] develops a mixed-reality and mobile game-based learning environment called "GeoExplorer" that supports PBL and experiential learning, and enables students to experience field testing to design and assess a particular site's flood-protection levee. Students are assigned to games related to cone penetration tests and levee design and assessment capabilities after attending lectures. As part of the assessments, pre/post surveys are administered, which contain the same technical questions as well as additional questions designed to assess the game quality and students' perception of its effectiveness. The results indicate students' positive attitude towards the VR-PBL integration with over 90% of participants perceiving this to be an effective way to implement class learning in practice. There was also a 20% improvement in students' understanding of the material measured by their scores on the technical questions.

The authors in [54] combine PBL and VR in wind/green energy education by assigning students to projects that involve designing and testing different components (such as wind turbine blades) using 3D modeling software, including SolidWorks and Unity. Preliminary assessments suggest students can effectively complete the design tasks in a virtual setting and the feedback received from the students was mainly positive, especially with regard to exposure to the green product topic surrounding materials, fabrication, testing, and measurements.

In another paper related to green energy [55], a VR learning environment and laboratory is developed using the VRLE platform and SolidWorks to support project-based learning and improve students' learning related to Proton Exchange Member (PEM) fuel cells. During VR simulation, students can vary the fluid parameters and explore the changes in current and voltage, perfectly mimicking the physical laboratory activity. Assessments are yet to be conducted to establish the effectiveness of these VR learning modules of PEM fuel cells.

The work in [56] deliver interactive GIS instructional material using an immersive CAVE-based technology named iSpace and a low-cost desktop VR (dVR). While the dVR lacks the high fidelity and immersion of CAVE, it addresses accessibility and affordability issues. A three-tiered framework is used including a concept model for GIS instruction, mapping component, and customization for mode-specific delivery of design materials. The framework enables PBL, experiential learning, and active learning in the context of VR. However, this is a work-in-progress paper and does not report any assessment data.

Industrial and manufacturing engineering

In [57], the authors introduce an interactive VR, PBL and case-based learning environment to support student collaboration and problem-solving related to Failure Risk Analysis. The goal is to for students to work on open-ended, interdisciplinary problems and interact with real-life challenges, where students can learn by doing in an interactive 3D multimedia environment. For example, students can disassemble and then re-assemble 360-degree panoramic and 3D VR interactive objects by virtually going to factories, R&D studios, and laboratories. In addition, spreadsheets and video are used as part of the integrated PBL-VR modules. This work has been ongoing for several years, and several universities and companies have adopted the technology, however, the paper does not provide any formal assessments on its effectiveness.

The authors in [58] develop a set of VR models, PBL, and case studies to be integrated with various courses in the industrial engineering curriculum and help address competency gaps in manufacturing workforce. Student teams are assigned to work on industry-based projects that require VR walk-through tours enabled by a discrete-event simulation model of an actual Boeing manufacturing line. A formal rubric is used for scoring the projects as recommended by the "Field-Tested Learning Assessment Guide", classifying the assessment based on the students' learning outcomes such as knowledge, skills, or attitude. The results indicate that integrating VR and PBL can address students' competency gaps by incorporating the knowledge and skills gained from various course lectures.

Discussion and qualitative assessment of the reviewed literature

This section discusses the main insights derived from our qualitative assessment of the papers included in our literature review.

- <u>*Increased attention to learning theories:*</u> While Figure 5(b) shows that the number of papers that discuss VR in engineering education seems to have plateaued in the last decade, the number of papers that integrate VR and PBL seems to be increasing according to Figure 6 with a clear uptick during the 2016-2020 period. This is an interesting an important finding as it can be an indication of a possible shift from *development* of computerized VR simulation environments to *designing meaningful immersive learning activities* that are supported by pedagogical and psychological theories enabled by PBL such as constructivism theory, self-determination theory, and information processing theory.

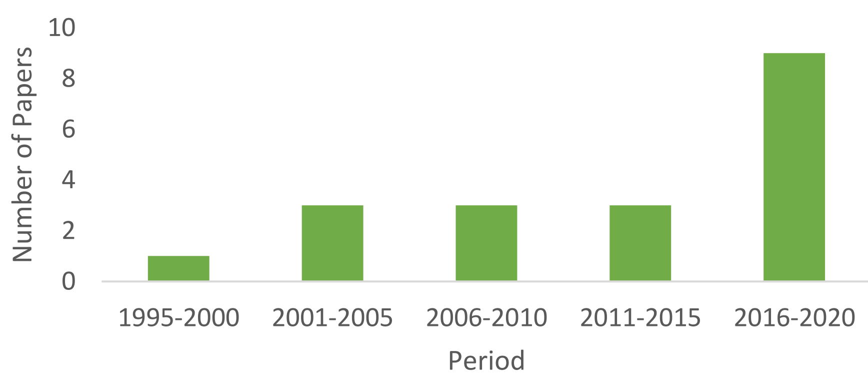


Figure 6. Trend analysis for the use of PBL in the context of or enabled by a VR environment.

- *Breadth of application domains:* The 18 articles included in our literature review cover seven engineering disciplines and several related subjects, indicating a broad interest in the integration of PBL and VR in engineering education. However, these applications are not uniformly distributed among engineering disciplines. For example, we see more examples of PBL-VR integration in geotechnical, environmental, and mechanical engineering.

- *Type of learning activity:* Our literature review reveals that VR has been integrated with both problem-based and project-based learning as the reviewed papers report different types of learning activities from small assignment-like modules to more complex, semester-long projects and case studies. We also see that PBL-VR integration is used for both individual activities and teamwork including interdisciplinary teams from different programs/courses. Therefore, it does not seem that integrating VR into PBL affects the team aspects and potential for collaborative and interdisciplinary learning.

- *Lack of formal assessments:* The most important gap in the reviewed papers is the lack of formal assessments of the effectiveness of PBL-VR integration. The majority of the reviewed papers discuss the technical details related to development of the VR environment and/or explore potential uses in a certain course or program, but do not perform assessments (e.g., controlled experiments) or report quantitative assessment data on the impact of their intervention on student learning, motivation, skill development, retention, and other important outcomes. However, the few studies that did perform assessments indicate improvements as a result of combining VR and PBL.

Conclusions, limitations, and future work

In this paper, we first perform a bibliometric analysis on the ASEE annual conference proceedings from 1996 to 2020 to identify the engineering disciplines and related topics where PBL and VR are used. Our trend analysis on the number of publications over the years shows an increase in the use of both PBL and VR and their integration in engineering education. The increased popularity of VR can be partly due to the increased availability and affordability of immersive technologies in recent years that have led to many engineering programs adopting VR technologies (e.g., in the form of virtual learning factories/laboratories) due to the flexible, cost-effective, and risk-free environment they offer (e.g., compared to physical laboratories that involve expensive and complex equipment).

We also perform a qualitative assessment of the studies that implement VR in conjunction with PBL across different engineering fields. Perhaps the most critical gap in the reviewed literature is related to lack of formal assessments as many papers report on developing a new and/or implementation of an existing immersive environment without providing rigorous evidence on the effectiveness and impact on student learning, motivation, and other outcomes. Far more attention needs to be given to assessments given the paucity of scientific evidence on the effectiveness of immersive technologies, and especially given the existence of mixed findings in some cases related to impact on students' motivation vs. learning and task performance (for example, see [59]).

Scalability (in terms of learners' access to VR equipment) and high development time/cost of VR learning environments are among the significant factors that affect the adoption and use of immersive technologies in education including engineering education. While there are several studies aim to reduce or eliminate such scalability barriers, we believe future research could focus more on these issues. For example, the immersive simulation-based learning (ISBL) method proposed in [44] supports both a "desktop mode" or "low-immersion mode" of use on a typical 2D display as well as a "VR mode" or "high-immersion mode" via a VR headset (if available) for an enhanced immersive experience. Moreover, by using a commercial discrete-event simulation software with 3D animation features and VR compatibility, the development time/cost of their ISBL modules is significantly less than the programming effort required to implement similar simulations in a VR platform such as Unity. Finally, we found a small number of studies that integrate artificial intelligence within immersive virtual environments. Design, development, and assessment of combined AI-VR learning environments is another rich area for future research.

We hope that this paper accelerates the discussions and ongoing research on PBL enabled by immersive virtual environments in engineering education. We plan to extend our literature analysis to encompass all STEM fields and other journals and conferences that publish educational research.

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