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PROBLEM-BASED LEARNING VIA IMMERSIVE SIMULATIONS: EFFECTIVENESS AND REPOSITORY OF SAMPLE MODULES

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ABSTRACT

Traditional teaching methods often place learners in a decontextualized space due to students' lack of access to real-world facilities to gain hands-on experiential learning. This paper discusses integrating problem-based learning with immersive simulated environments, where the simulation serves as the context by mimicking a real-world system. This allows students to perform virtual site visits of the simulated system instead of visiting and collecting data from a real facility. Supporting pedagogical theories for the proposed immersive simulation-based learning (ISBL) approach are discussed. A free online repository of ISBL modules is shared and a sample module is presented. The paper also provides a review of educational research studies on the effectiveness of ISBL in terms of students' learning outcomes. The paper is intended for simulation educators who are interested in adopting immersive simulation-based learning in their teaching by reusing/re-purposing the models developed as part of their simulation projects for educational purposes.

1 INTRODUCTION

Simulation has been used for decades as a tool for teaching and learning in various educational settings and disciplines as it can replace or augment real-world inquiry-based and experiential learning experiences by providing learners with a low-cost and risk-free platform to develop knowledge and skills in a simulated environment. Simulation offers several advantages as a teaching and learning tool, namely: (a) simulation experiments are less costly and risk-free, require less set up time, and enable learners to perform more experiments (under many different configurations) in a given time window; (b) simulation enables experiments that are infeasible in physical experiments such as performing what-if analysis on the impact of natural or man-made disasters on the power grid and other critical infrastructure; (c) adjusting the time scale in the simulation makes it possible for learners to perform experiments that would otherwise take months or years to complete a real-world setting; (d) simulation enables students to investigate unobservable phenomena such as atomic-level dynamics, chemical reactions, thermodynamics, or electricity currents; and, (e) computer simulation enables online and distance learning for students who do not have access to a physical lab or the real-world system under study. Due to these advantages, there is an ongoing transition from traditional teaching and learning methods to digital simulations and immersive simulated learning environments. Negahban (2024) provides an overview of such transition in engineering education, and highlights two major implementation and research gaps related to simulation-based learning methods, namely their lack of integration with learning theories and limited formal assessments of their effectiveness.

Over the past five years, our research team has been working on a federally-funded educational research project to address the above gaps by: (1) developing immersive simulation-based learning (ISBL) modules and integrating them with Problem-Based Learning (PBL), a well-established active-learning method; and, (2) conducting various controlled experiments with human subjects (i.e., students) to assess ISBL effectiveness both quantitatively and qualitatively. This paper presents the proposed ISBL framework and a review of our research findings on the effectiveness of ISBL. We also share a repository containing more than 25 ISBL modules with the simulation community. Ultimately, the discussions in this paper are intended to help simulationists who are interested in designing and/or utilizing simulation-based learning and immersive technologies in their teaching. As simulationists, we have many simulation models that were developed as part of our research and industry projects. Many of our simulation models can potentially be used as learning context for PBL activities through the ISBL framework presented in this paper. In addition, many commercial simulation software now offer enhanced animation features and VR compatibility. The ISBL framework enables utilizing existing simulation models and built-in features of commercial simulation software to significantly reduce the development effort compared to developing immersive learning environments from scratch using game engines such as Unity and Unreal. Considering these factors, and by publicly sharing the sample ISBL modules, this paper aims to facilitate the adoption of ISBL by simulationists.

The remainder of this paper is organized as follows. Section 2 describes the different components of ISBL, supporting pedagogical and psychological theories, and how it enables contextualized learning when access to a real-world system is infeasible. Section 3 describes the ISBL module repository and presents a sample ISBL module. Section 4 provides a review of research findings on the effectiveness of ISBL in enhancing learning outcomes. Lastly, Section 5 discusses the conclusions and future directions.

2 PROBLEM-BASED LEARNING VIA IMMERSIVE SIMULATIONS

Besides its use as a powerful analysis tool for modeling complex systems in various contexts such as manufacturing (Negahban and Smith 2014), healthcare (Mielczarek and Uzialko-Mydlikowska 2012), military (Naseer et al. 2009), supply chain (Oliveira et al. 2019), and marketing (Negahban and Yilmaz 2014), simulation can also be utilized as a tool for teaching and learning the underlying dynamics and the various decision-making scenarios that can arise in such systems. For these complex systems, site visits or physical experimentation with the real system are infeasible. In many other cases, access to real-world facilities is difficult or impossible due to geographical barriers or safety concerns. In distance and online education, site visits are infeasible due to geographically dispersed students. As a result, learners often find themselves in a *decontextualized* space, which prevents development of critical skills necessary to tackle real-world engineering problems once students join the workforce. The idea here is to represent the real-world system by an immersive simulation model to serve as the context in order to enable contextualized learning.

For example, real-world problems are often uncertain and ambiguous in terms of their scope, requiring careful *problem framing*. Furthermore, in real-world settings, engineers need to identify appropriate model design, input data, and performance measures, requiring proper *conceptual modeling*. Engineers also need to assess the feasibility and validity of their model and its results for the real system under study, requiring proper *model validation*. However, traditional teaching and learning methods often lead to learning gaps related to *problem framing*, *conceptual model development*, and *validation* techniques due to lack of contextualization and absence of interaction with the real-world system under study. The proposed ISBL approach utilizes a realistic simulation model as the learning context and an experimentation environment that are often missing in current engineering education to address development of critical skills as illustrated in Figure 1.

2.1 ISBL: Specification and Supporting Pedagogical Theories

An ISBL module is specified by: (1) A 3D animated, VR-compatible discrete-event simulation model that resembles the real system under study. The simulation serves as the context and enables technology-enhanced PBL. The simulation models used in the proposed ISBL modules can be explored in 2D on any typical display or via a VR headset for an enhanced immersive experience; and, (2) a problem-/project-based learning activity that is defined around the simulated system. The PBL activity is inspired by and resembles real-world situations that learners may face in future workplace or professional settings. PBL is a

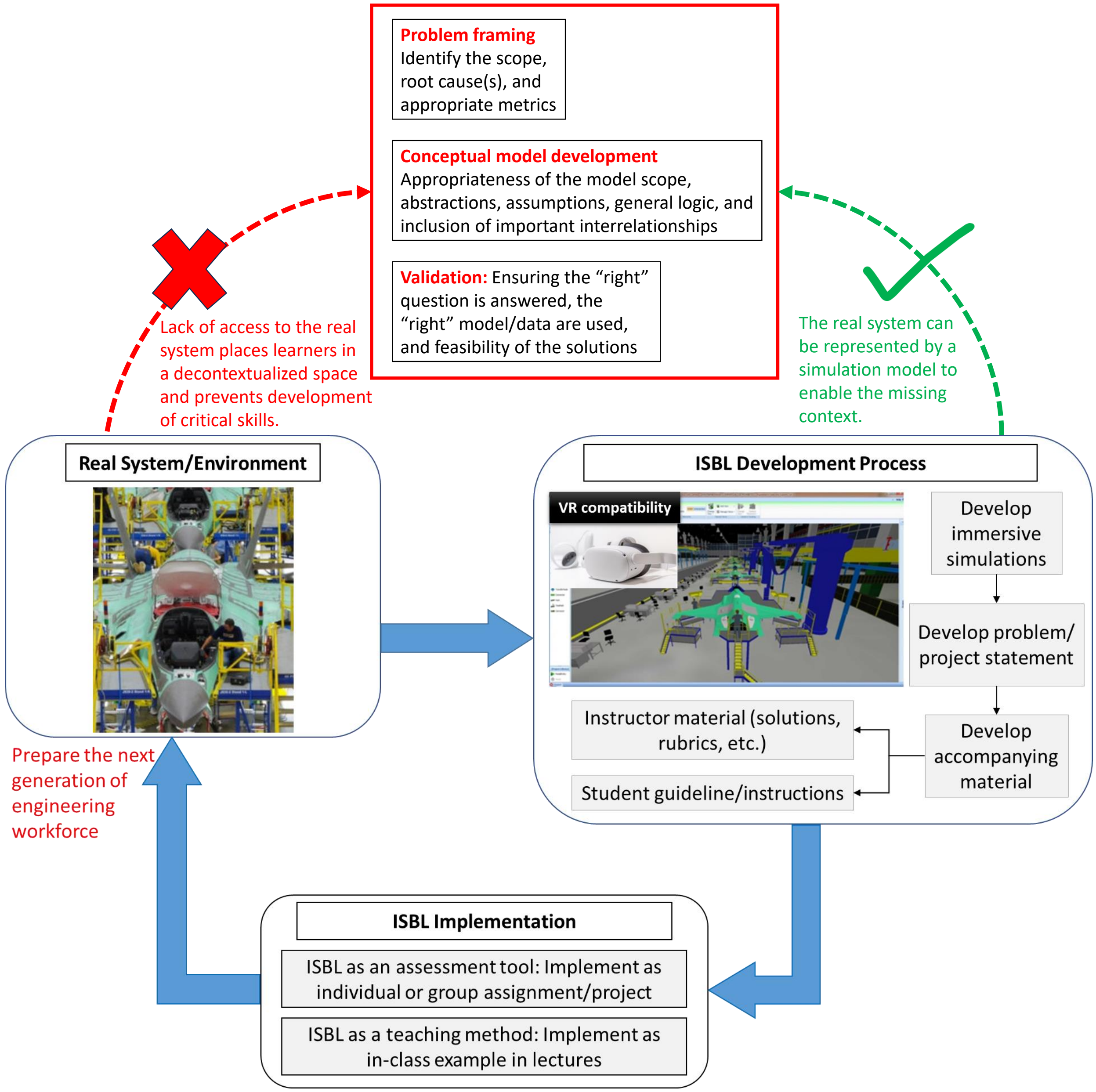

Figure 1: ISBL overview and how it enables contextualized learning when access to the real-world system is infeasible.

well-established active-learning method with a cohesive research evidence on its effectiveness for all learner groups, including K-12 (Wirkala and Kuhn 2011), undergraduate (Karantzas et al. 2013), graduate and professional (Fenwick 2002), and online students (Baturay and Bay 2010). PBL supports various theoretical educational and psychological foundations (Marra et al. 2014; Onyon 2012; Hmelo-Silver 2004). As a result of the integration of PBL with a virtual/simulated environment, ISBL supports and augments many of the pedagogical and psychological theories that apply to PBL, namely:

- *Constructivism* theory (Jonassen 1991): This theory suggests that learners construct their interpretations of the real-world world through cognitive and interpretive activities that help construct mental models by accommodating new ideas/phenomena with prior knowledge. The immersive simulation in ISBL serves as the context and provides an environment to interact with. This enables knowledge to be constructed through the interactions with the simulated environment and indexed by relevant contexts.

- *Information Processing Approach to Learning* theory (Anderson 1977): The three principles of this theory apply to ISBL and support long-lasting development of critical thinking and problem-solving skills. This is realized by: (a) activating prior knowledge related to the context under study as represented by the simulation model; (b) enabling contextually enriched learning through an immersive simulation that mimics a real-world system; and, (c) allowing learners to expand their prior knowledge to solve a realistic practical problem.
- *Self-determination* theory (Albanese 2000): ISBL supports this theory as it promotes autonomous motivators in contrast to traditional learning and teaching methods that are primarily based on controlled motivators such as rewards and punishments (e.g., passing or failing a test) that can lead to superficial learning and cause a sense of stress and anxiety in students. ISBL promotes autonomous motivators as it enables students to incorporate their views and take greater responsibility for their learning.
- *Adult Learning* theory (Merriam 2001): ISBL supports some of the main pillars of this theory by presenting problems/projects that resemble real-world situations and providing a self-directed and problem-centered learning experience that draws on previous work experiences and integrates into the professional learner's everyday life.

In addition, due to the use of an immersive simulation, ISBL also supports the Cognitive Affective Model of Immersive Learning (Makransky and Petersen 2021), which suggests learners' presence and agency are psychological constructs that arise from immersion and interactions with a simulated environment, and that presence and agency influence affective and cognitive factors that play a role in immersive learning, such as interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation.

3 SAMPLE MODULES AND MODULE REPOSITORY

The website for our NSF project associated with this paper provides 27 ISBL modules, which can be found at: https://sites.psu.edu/immersivesimulationpbl. The modules cover a wide range of topics primarily related to operations research, information science and technology, and computer science as summarized in the module matrix shown in Figure 2. Each ISBL module comes with a set of learning objectives, a simulation model that can be used in desktop and VR modes, and a document that includes the problem statement for the PBL activity and instructions for students. These material are openly available for anyone to download. The website also provides a mechanism for instructors to request instructor material including the solutions to the ISBL modules, recommended time allocation, assignment types, and other information for instructors. It is worth noting that many of the ISBL modules publicly shared on our project website, including the example discussed next, utilize pre-made simulation models that come with the Simio simulation software (Smith and Sturrock 2021), which also provides advanced animation features and VR-compatibility. This exemplifies how simulationists can reuse their existing simulation models for educational purposes. In the following subsection, we present a sample ISBL module that can be used in a simulation or statistics course.

3.1 An ISBL Module for Statistical Hypothesis Testing

The sample ISBL module presented here is related to hypothesis testing. The problem statement for the PBL activity can be summarized as follows. The construction of a new airport terminal in a small town was recently completed. The terminal has two areas with several self-service check-in kiosks, a check-in counter with agents, an ID/boarding pass checkpoint station, and two advanced imaging technology (AIT) units for scanning passengers and their luggage. There are two gates in the boarding area at the terminal

Discipline	Related ISBL Modules	Probability & Statistics	Stochastic Simulation	Engineering Economy	Workplace Design & Safety	Facilities & Inventory	Queueing Networks	Deterministic OR	Object Oriented Programming	SQL	Unified Modeling Language	GUI Development	Database Normalization	Entity Relationship Diagram	Relational Schema	DB Application Development	Data Collection & Time Study
Industrial and Systems Engineering, Operations Research (OR), Engineering Management	Point Estimation and Confidence Interval – A Small Airport Terminal	✓	✓														✓
	Statistical Hypothesis Testing – A Small Airport Terminal	✓	✓														✓
	Fault Tree and Cost-Benefit Analysis for a Warehouse			✓	✓												✓
	Break-even Analysis – Advertising Campaign for a Pizza Restaurant			✓													✓
	Rate of Return Analysis for an Airport Terminal			✓													✓
	Loan Payment Methods for a Pizza Store			✓													✓
	Replacement Analysis for a Warehouse			✓													✓
	Capital Budgeting Analysis in a Warehouse			✓				✓									✓
	EOQ Problem for a Pizza Restaurant					✓											✓
	Queueing Analysis of an Airport Terminal						✓										✓
	Optimization Analysis of an Airport Terminal							✓									✓
Information Science and Technology, Computer Science	Pseudocode and UML Diagram – Manufacturing Assembly								✓		✓						✓
	Pseudocode and UML Diagram – Hotdog Stand								✓		✓						✓
	Pseudocode and UML Diagram – Hospital Emergency Department								✓		✓						✓
	Pseudocode and UML Diagram – Airport Terminal								✓		✓						✓
	GUI Database Application Development Using Object Oriented Programming – Manufacturing Assembly								✓	✓		✓				✓	✓
	GUI Database Application Development Using Object Oriented Programming – Hotdog Stand								✓	✓		✓				✓	✓
	GUI Database Application Development Using Object Oriented Programming – Hospital Emergency Department								✓	✓		✓				✓	✓
	GUI Database Application Development Using Object Oriented Programming – Airport Terminal								✓	✓		✓				✓	✓
	Database Application Development Using Object Oriented Programming – Manufacturing Assembly								✓	✓						✓	✓
	Database Application Development Using Object Oriented Programming – Hotdog Stand								✓	✓						✓	✓
	Database Application Development Using Object Oriented Programming – Hospital Emergency Department								✓	✓						✓	✓
	Database Application Development Using Object Oriented Programming – Airport Terminal								✓	✓						✓	✓
	Spreadsheet Tables and Normalization – Hotdog Stand												✓				✓
	Entity Relationship Diagram and Relational Schema – Hotdog Stand													✓	✓		✓
	Creating and Querying Hotdog Stand Database – Hotdog Stand									✓							✓
	Developing Database Application – Hotdog Stand									✓						✓	✓

Figure 2: The module matrix for the ISBL module repository.

Figure 3: The immersive simulation of the airport terminal associated with the example ISBL module.

each having its own seating area where passengers wait before boarding their flight. Flights board and leave according to a stochastic process specified in the simulation model. A screenshot of the immersive simulation associated with the PBL activity is shown Figure 3. In the problem narrative, the student is "hired" as a consultant to perform hypothesis testing related to different aspects of the operation in this terminal. Students are asked to treat the simulation as the "real" system and use virtual site visits to collect the data that they need to perform the statistical analysis.

The ISBL activity has three parts. The problem statement for part 1 is as follows: "*Based on past time studies, the median time that passengers spend in the self-service check-in areas is thought to be 140 seconds. This is the elapsed time from arrival at the queue for the check-in kiosks to the time the passenger finishes checking in and leaves the kiosk. However, the airport management suspects that the true median time might be different. You are asked to perform a hypothesis test at a 5% level of significance. Assuming the distribution of the time that passengers spend in the self-service check-in area is symmetric, your task is to answer the following specific question: Is there enough evidence to conclude that the median time differs statistically from 140 seconds?*" Parts 2 and 3 of the ISBL module have similar structures but pertain to different processes at the airport and would require a different kind of hypothesis test due to the statistics being compared (such as comparing medians, means, or proportions). More specifically, in part 2, students need to investigate whether passengers who use the self-service check-in kiosks spend more time, on average, compared to those who check in at the counter with the help of an airline agent. In part 3, students investigate whether there is a significant statistical difference between the proportion of passengers that use the two self-service check-in areas.

To solve each part of the ISBL module, students need to determine the type of test to use depending on the statistics being compared (e.g., comparing means versus comparing medians). They will then need to perform virtual site visits (by observing the simulation) and perform time studies to collect the data that they need for the analysis. This is where students directly interact with the simulation and also practice data collection as if they are collecting data from a real airport, providing them with hands-on experiential learning opportunity. They can also adjust the speed factor to make the interactive run faster or slower based on their preference to facilitate observation and the data collection. Lastly, they will perform the hypothesis test both in Excel and using a statistical software. Therefore, as for the learning objectives, after successful completion of this ISBL module, the student will be able to:

1. Determine the appropriate type of hypothesis test to be used given the statistics that need to be compared/analyzed.
2. Set up the null and alternative hypotheses of the test based on the question being asked.
3. Collect data from the real-world system under study and obtain the sample statistics required to perform the hypothesis test.
4. Perform the hypothesis test manually or in Excel.
5. Perform the hypothesis test using a statistical software package.
6. Interpret the outcome of the test and draw correct conclusions based on both p-value and critical region for the test.

4 A REVIEW OF RESEARCH FINDINGS AND EFFECTIVENESS

The integration of immersive simulations with PBL enables utilizing the advantages of both paradigms (Nowparvar et al. 2021). A key research question is how this integration in ISBL impacts students' critical thinking and problem-solving skills, motivation, experiential learning, and overall learning experience. This section provides a review of a series of studies conducted by our team on ISBL's effectiveness across several course implementations over a period of five years.

In our first test run experiments (Ozden et al. 2020), ISBL modules were implemented in an undergraduate course for teaching and learning fundamental concepts related to database design. The study involved a controlled experiment with two groups of students: students in the control group complete a traditional PBL assignment (without an accompanying simulation model), while the test group uses the ISBL version of the same PBL assignment. The assessment data collected included demographics, prior preparation, motivation, usability tests, and pre/post quizzes to measure knowledge gain. Statistical analysis of the results showed that ISBL performs at least as well as PBL. The results also provided important insights into effective design and implementation of ISBL, that informed the future course implementations and research experiments discussed previously. It was found that, in ISBL, there has to be a clear purpose for the simulation and meaningful interactions with the simulated environment in order for learners to truly appreciate its value. Relevance to potential future career paths was found as another critical consideration when designing an ISBL module. This informed our subsequent investigations and was the motivation behind two follow-up studies on impact of context choice and learner interaction/navigation within the simulated environment as will be discussed next.

Providing simulated learning experiences is significantly less costly compared to physical, real-world environments. ISBL enables educators to offer learning experiences related to a variety of contexts, giving learners the option to choose the context of their interest, hence enhancing their motivation, engagement, and interest in the topic at hand. Ozden et al. (2023) investigate the effect of context choice for assignments in an object-oriented programming course that covers various topics from basic concepts to database design and implementation, graphical user interface design, and web application development. Students complete three ISBL modules as course assignments. Equivalent ISBL assignments in terms of workload, difficulty, and learning objectives are defined around three simulated systems/contexts: an airport, a manufacturing system, and a hospital emergency department. The research experiments involve four groups: (1) students with no choice who use the same assigned simulated system for all three ISBL assignments; (2) students with no choice who are given a different simulated system for each of the three ISBL assignment; (3) students who can choose their preferred simulated system at the beginning but cannot change their choice for future assignments; and, (4) students who can choose at the beginning and switch between the three simulated systems for subsequent assignments. Data are collected over multiple semesters and statistical analyses are conducted to compare the four groups in terms of motivation, experiential learning, and self-assessment of learning. The results indicated that context choice had a statistically significant effect on students' motivation. Qualitative assessments in the form of interviews were also performed and supported the statistical findings.

Nowparvar et al. (2024) study how learners' interactions and navigation in the virtual environment affect their learning and skill development, where navigation is characterized by the total time spent in the simulation and time allocations to different areas within the simulated environment. A set of ISBL modules are implemented in an undergraduate computer science course with eighteen students and their screen is recorded as they navigate in the simulation environment to perform the tasks needed to complete the ISBL assignments. The recorded videos are then processed using a video analytics tool proposed in Soriano et al. (2023), which is used to analyze the videos and collect statistics related to a set of navigation-related measures for each student. In addition, surveys are used to collect data on students' demographics, prior knowledge and experience, personality, experiential learning, and self-assessment of learning. A set of multivariable regression analyses are then performed to characterize and explain the relationship between navigation measures and constructs assessed via survey instruments to determine how/if users' navigation in the simulated environment can be a predictor of their learning outcomes. The results suggest that the total time spent in the simulation and the distribution of time allocations among different areas within the simulated environment are statistical predictors of experiential learning and students' self-assessment of learning.

ISBL is advantageous when access to real-world facilities is difficult or impossible due to geographical barriers or safety concerns as well as in distance and online education due to geographically dispersed students. Ashour et al. (2024) investigate the impact of class delivery mode (remote vs in-person) on students' learning experience when ISBL modules are used as course assignments. The study compares two groups of students who are taught by the same instructor and use the same course material, including the same ISBL modules. The only difference between the two groups is the course delivery mode, i.e., one group from a section of the course that involves synchronous online sessions, while the section/group is taught in person in a traditional classroom setting. Data are collected on demographics, prior preparation, motivation, experiential learning, usability scale, and self-assessment of learning. Statistical comparisons are performed to test the hypothesis that ISBL modules will help maintain remote students' motivation and learning outcomes compared to in-person students. The results show no statistically significant difference between the two groups on any measure, suggesting that ISBL is equally effective in the two delivery modes.

In another study, Nowparvar et al. (2022) assess the effectiveness of ISBL modules for teaching and learning engineering economy concepts. The research experiments involve two groups of students: a control group that completes a set of traditional assignments, while the intervention group uses ISBL modules. Data are collected on demographics, prior preparation, motivation, experiential learning, engineering identity, and self-assessment of learning objectives based on Bloom's taxonomy. Statistical analysis of the results shows that ISBL enhances certain dimensions related to motivation and experiential learning, namely relevance, confidence, and utility. Qualitative assessments of the proposed intervention are also provided based on detailed, one-on-one user testing and evaluation interviews.

While recent years have seen significant growth in the use of immersive technologies in education, there is a general lack of understanding of the effect and contribution of the additional immersion offered by VR (Negahban 2024). Given the high development and implementation cost of immersive simulation games due to coding and equipment costs (a VR headset currently costs hundreds of dollars), it is critical to assess immersion's added value to inform cost-benefit analysis and justification for the use of immersive technologies. To address this gap, Bandi et al. (2024) assess the impact of immersion level and mode of use on the effectiveness of a simulation game for teaching and learning optimization concepts. The simulation game is implemented in three modes: VR (played on a head-mounted display), Desktop (played on a desktop computer with a 2D display), and PowerPoint slides (played by clicking through a set of animated slides). Research experiments are then conducted with three groups of students who play the game in one of the above modes. A set of surveys and quiz questions are used to collect data on students' sense of presence, learning, and motivation under each mode of use. The performance of the three groups is then compared statistically, and the results suggest that the enhanced immersion in the VR mode enhanced students' sense of presence and learning.

In summary, our literature review of educational research studies on ISBL indicates that the combination of immersive simulations and PBL can enhance students' motivation and experiential learning as well as in online/remote learning. The immersive simulations in ISBL also improve students' cognitive presence and present an opportunity to perform enhanced learning analytics by providing rich navigation and usage data that can be extracted from screen recorded videos of students' navigation within the simulated environment.

5 CONCLUSIONS

This paper presented the case for ISBL as a way to integrate PBL with immersive simulated environments, where the simulation serves as the context by mimicking the real-world system under study. This allows students to perform virtual site visits of the simulated system instead of visiting and collecting data from a real facility. Supporting pedagogical theories for the proposed ISBL approach were discussed. A free online repository of ISBL modules was shared and a sample module was presented. The paper also reviewed a series of educational research studies on the effectiveness of ISBL in terms of students' learning outcomes in various settings.

Besides its potential to enhance teaching and learning, ISBL also presents several avenues for future educational research. Exploiting the rich usage/navigation data generated as a result of learner-simulation interactions can help guide and optimize the design of immersive simulated environments in terms of their interactivity and user engagement. Interaction types can vary from simply observing the simulation run and manipulating the input parameters to more sophisticated interactions with static and dynamic objects in the simulation, interactions with artificial intelligence (AI) and other interactive entities in the model (such as those found in computer games), and interactions with other learners and/or the instructor who are present in the simulation as avatars. Identifying the most effective interaction types can help develop more effective simulation-based learning experiences. Exploring the potential of machine learning methods for extracting and analyzing learner-simulation interaction data is an interesting area for future research in the field of learning analytics. While our ISBL discussions primarily focused on VR, other immersive technologies such as Augmented Reality (AR) can also be incorporated into the ISBL framework as as discussed in Estadt et al. (2024). The effectiveness of alternative forms of ISBL involving AR and mixed-reality presents another rich area for future educational research.

We hope that the discussions in this paper encourage simulation educators to reuse/re-purpose the models developed as part of their simulation projects for educational purposes through the proposed ISBL approach and other pedagogical frameworks.

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