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RITEL: The Development of Manufacturing Knowledge and Learning Skills through an Educational Simulation

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Abstract

This study investigates the impact of a simulation-based educational game on undergraduate engineering students' knowledge and metacognitive problem-solving skills. The game presents learners with a realistic manufacturing environment in which they must meet customer demand, balance production capacity, and maximize profit for a simulated water bottle-filling company. Participants completed pre- and post-assessments measuring content knowledge, self-regulated learning (SRL) skills, usability, situational interest, and in-game performance.

Results from this initial implementation highlight differences in knowledge outcomes, perceptions of usability, early-game performance, and player characteristics across situational interest levels. Findings also reveal limitations related to knowledge assessment difficulty and participant characteristics, which inform future design iterations. Overall, the results support the potential of simulation-based manufacturing games to provide engaging, authentic learning experiences while emphasizing the need for adaptive scaffolding and increasingly complex problem scenarios to better align motivation and learning outcomes for STEM students. This research is funded through NSF Research for Innovative Technologies for Enhanced Learning (RITEL).

Introduction

Rapid technological change has increased the demand for educational approaches that prepare learners to apply knowledge in complex, dynamic environments. Traditional instructional methods often struggle to support the transfer of conceptual knowledge to real-world problem-solving, particularly in engineering and manufacturing contexts. As a result, experiential and technology-based learning approaches, including simulation-based learning environments, have become increasingly prominent in higher education.

Simulation-based learning environments offer learners safe, cost-effective opportunities to engage with realistic systems that mimic real-world complexity. These environments are particularly well-suited for manufacturing education, where learners must reason about interconnected processes, system constraints, and trade-offs among competing objectives. Beyond content knowledge, effective performance in such environments requires metacognitive problem-solving skills, including planning, monitoring, and evaluating one's decisions.
The current study examines the initial implementation of a 3D manufacturing simulation designed to teach operations management concepts while supporting metacognitive self-regulated learning. Specifically, the study explores how learners' situational interest relates to knowledge outcomes, self-regulation, usability, and in-game performance.

Literature Review

Simulation-Based Learning in Engineering Education

Simulation-based learning environments allow learners to engage in iterative decision-making and "what-if" analyses without the financial, logistical, or safety constraints of physical systems. In engineering education, simulations and games have been shown to support systems thinking, decision-making, and problem-solving skills that are difficult to foster through traditional instruction alone. These environments also improve access to experiential learning for students who may be limited by distance, scheduling, or safety concerns [1], [2].

In manufacturing education, simulations provide learners with exposure to realistic system dynamics, including bottlenecks, resource constraints, and process variability. By allowing learners to practice decision-making in low-risk environments, simulations can reduce anxiety, improve confidence, and support safer behavior in real-world settings [3].

Self-Regulated Learning and Motivation

Self-regulated learning (SRL) refers to learners' ability to plan, monitor, and evaluate their learning processes as they work toward specific goals. SRL skills are strongly associated with achievement and effective problem-solving, particularly in complex, ill-structured tasks. Simulation-based learning environments are well-suited for supporting SRL because they provide immediate feedback, opportunities for reflection, and repeated practice [4].

Motivation also plays a critical role in learning outcomes. In this study, motivation is conceptualized as situational interest, which reflects learners' immediate engagement and enjoyment in an activity. Situational interest has been shown to influence persistence, effort, and learning outcomes and is often considered a precursor to longer-term interest development [5].

Current Study

This study represents an initial evaluation of a manufacturing simulation-based learning environment. The primary research question guiding the study is: *Do students differ in their self-regulation, knowledge, game performance, or usability scores based on their level of situational interest?*

Methods

3D Simulation-Based Educational Game

The simulation was developed using the 3D game engine Unity and represents a water bottle manufacturing system with multiple production stages, including bottle formation, cleaning, filling, capping, labeling, and packaging. Conveyor systems and forklifts transport materials between stations.

Players assume the role of a new employee responsible for releasing production orders while balancing customer demand, production capacity, and system constraints. Poor decisions, such as releasing too many/too few orders, result in congestion, increased inventory costs, and reduced profit. The goal is to maintain a balanced system while maximizing profit.

Figure 1. Snapshots of the water bottle manufacturing environment

Figure 1 shows snapshots of the game environment. The game consists of a tutorial level, a preparation level, three progressively complex production levels, and a final reflection activity. As complexity increases, additional production lines and forklifts are introduced. Embedded prompts guide learners through planning, monitoring, and reflection reminders aligned with SRL processes.

Participants

Participants included 17 undergraduate engineering students recruited from the School of Engineering at Penn State Behrend. Participants were predominantly male (70.6%) and primarily white (82.4% white, 11.7% Asian, 5.9% Hispanic/Latino), with an average age of 21.65 (SD = 1.80) years. Most participants were senior-level (76.5% seniors, 23.5% juniors) students majoring in Industrial (70.6%) or Mechanical (28.4%) Engineering.

Measures and Procedure

Participants completed a pre-survey assessing demographics, prior professional experience, self-efficacy [6], personality traits [7], Gamification User Types Hexad questionnaire [8], and pre-existing knowledge. The Hexad questionnaire identifies six user types based on participants' motivations, which helps explain why individuals may engage with tasks in different ways.

After completing the simulation, participants completed a post-survey measuring knowledge, situational interest [9], usability [10], and metacognitive SRL skills [11].

In-game performance data, including profit and interaction logs, were collected automatically by the simulation.

Results

Descriptive Findings

Pre-knowledge scores indicated a ceiling effect, suggesting the assessment was too easy for participants. No significant difference was found between pre- and post-knowledge scores overall. Usability score showed moderate variability, and participants generally reported moderate situational interest and SRL engagement.

Group Comparisons by Situational Interest Level

Participants were divided into high- and low-situational-interest groups using a median split. The groups differed significantly in several key areas.

Students with higher situational interest scored higher on the Hexad Player subtypes of the gamification user type scale, indicating a greater focus on rewards and in-game outcomes. The low-situational-interest group scored statistically significantly higher on the post-knowledge assessment and demonstrated a small positive change from pre- to post-assessment, whereas the high-interest group showed a decline in knowledge scores.

In terms of performance, the high-situational-interest group achieved higher in-game profits in the initial game level, though no significant differences were observed in later levels or total profit. Usability scores were significantly higher for the high-interest group, suggesting a relationship between interest and perceived ease of use. No significant differences were found between groups on self-regulated learning measures.

Discussion and Conclusions

This study examined how situational interest relates to learning outcomes and performance in a simulation-based manufacturing game. Several findings have important implications for the design of educational simulations.

First, the ceiling effect in the knowledge assessment limited the ability to detect learning gains, highlighting the importance of aligning assessment difficulty with participants' prior knowledge. The finding that students with lower situational interest demonstrated better post-knowledge performance suggests that highly interested players may have focused more on gameplay optimization than on underlying conceptual understanding. This interpretation is supported by the higher Hexad Player subtype scores observed among highly interested participants.

Second, the strong relationship between situational interest and usability suggests that ease of use may be critical in fostering engagement. Learners who perceive the system as intuitive and accessible may be more willing to invest effort in the activity.

Overall, the results indicate that situational interest is associated with meaningful differences in user experience and performance, though not always in expected directions. While engagement and usability are critical for adoption, they do not guarantee learning gains. These findings underscore the need for adaptive scaffolding that balances engagement with deliberate attention to learning objectives. Future iterations of the simulation will incorporate more challenging knowledge assessments, adaptive instructional supports, and increasingly complex problem scenarios to better align motivation, learning, and performance outcomes.

Limitations and Future Work

This study was limited by a small sample size and the use of upper-level engineering students who already possessed substantial prior knowledge. These factors reduced the sensitivity of the knowledge assessment and limited generalizability. Future work will involve larger, more diverse samples and revised assessment instruments better aligned with the simulation's learning objectives. Despite these limitations, this study provides valuable insights into the design and evaluation of simulation-based manufacturing games and highlights the complex relationship between interest, usability, and learning.

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