2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52238

# The Impact of an Educational Game on Manufacturing Knowledge and Metacognitive Problem-Solving Skill Development

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# The Impact of an Educational Game on Manufacturing Knowledge and Metacognitive Problem-Solving Skill Development

**Abstract**

This work explores the impact of a game-based manufacturing simulation on learners' knowledge and metacognitive problem-solving skills. The game is designed to teach students operations management concepts and to test their application in a simulated experience. Users begin the game as a new employee and complete an orientation to learn relevant manufacturing concepts. Users are then tasked with balancing customer demand and the manufacturing line's capacity while maximizing profit for a hypothetical water bottle-filling company. Participants' content knowledge and metacognitive problem-solving skills were assessed using pre- and post-assessments.

This study examines the instructional and simulation portions of the design. In addition to examining the impact of the game on users, comparisons were made between users' knowledge, metacognitive self-regulation skills, self-efficacy, and game-player types based on participants' situational interest. The results of these comparisons inform the development of scaffolding for future iterations of the game. Further, the results support the development of increasingly complex problem scenarios in the game. Broader implications include creating an engaging manufacturing game that can both aid learning and serve as a recruitment tool for potential STEM students.

## Introduction

Throughout society, individuals are required to adapt rapidly to environmental changes. They are constantly exposed to various challenges as technological advancements are made across the globe. Technology provides many resources for individuals in their education, careers, and day-to-day lives. As a result, educational systems have increasingly emphasized experiential and technology-based learning approaches that support learners' ability to apply knowledge in dynamic, real-world contexts [1], [2]. Recently, researchers have integrated simulation-based learning environments to support learning. Simulation-based learning environments provide learners with safe, cost-effective experiences that can mimic real-world experiences and problems. This type of preparation is increasingly important for properly preparing future workforces.

In manufacturing education, these environments offer particular promise for supporting learners as they engage with complex, interconnected systems that require both conceptual understanding and effective problem-solving strategies. However, additional research is needed to better understand how learners interact with such environments and how simulation-based experiences support both knowledge development and metacognitive problem-solving.

The current study examines the implementation and testing of a manufacturing simulation-based learning environment designed to support learning and problem-solving in an operations management context.

## Literature Review

### Benefits of Simulations for Education

Virtual learning simulations have been used across various disciplines to provide individuals with accessible and cost-effective resources [3]. Simulation-based learning environments allow learners to engage in "what-if" analyses and iterative decision-making without the financial, logistical, or safety constraints associated with physical systems [2], [4]. Additionally, these simulations provide individuals with the experience and training they may need to pursue a future career or advance in their current career. Prior work in engineering education has demonstrated that simulation and game-based environments support the development of systems thinking, problem-solving, and decision-making skills that are difficult to foster through traditional instruction alone [5]-[7].

Pursuing education beyond high school can pose various challenges. Some individuals may not have access to certain training within their field of interest to gain experience. Individuals may be limited by various disabilities, safety concerns, or distance from the work site [3]. These obstacles may prevent individuals from taking advantage of opportunities for growth within their field. Research has shown that learners often struggle to transfer classroom-based knowledge to authentic, ill-structured problems when access to real-world practice is limited [1]. Therefore, these individuals need alternative resources to aid in situations where they face one of these obstacles. Individuals may experience physical or cognitive disabilities that can interfere with their ability to learn in an unfamiliar environment [8]. Simulation-based learning environments offer alternative pathways for engagement by allowing learners to interact with realistic systems at their own pace and with appropriate scaffolding [9], [10].

Some learners may also have busy schedules that limit their ability to take advantage of opportunities to learn on a job site. In addition, individuals learning job skills on-site may be more likely to experience a safety threat if they perform a task incorrectly [3]. Simulation games have been shown to reduce these risks by enabling learners to practice decision-making and procedural skills in environments that realistically mimic system behavior while eliminating physical danger [2], [11]. Distance may also prevent individuals from pursuing job or training opportunities at a job site that could benefit them. If an individual is unable to access a job site within a certain radius, it may be considered impractical. Technology-mediated simulations help overcome geographic barriers and increase equity in access to experiential learning opportunities [5], [12]-[18].

From an instructional perspective, simulation-based learning has been identified as a cost-effective alternative for both educational institutions and industry partners, thus reducing the need for physical infrastructure [2], [4]. In this instance, simulations may also be cost-effective for industrial factories. Individuals who engage in simulation-based learning may be better equipped to behave safely in a factory [3]. Exposure to realistic system dynamics through simulation has been shown to improve learners' understanding of process interactions, constraints, and consequences, thus supporting safer, more informed behavior in real environments [6], [7]. There may also be a reduction in stress due to the absence of performance pressure on the individual being assessed, since they have previously engaged with a simulation that provided them with the skills needed for their role [19]. This reduction in pressure aligns with research on self-regulated learning, which suggests that opportunities for practice, feedback, and reflection can improve learners' confidence and efficacy before entering high-stakes environments [9], [20], [21]. Simulations are typically designed to be as representative of the given environment as possible, which provides a sense of realism for those who engage in these simulations [22]. High-fidelity simulation games, when carefully designed, preserve the essential characteristics of real systems while incorporating instructional feedback and performance metrics that guide learning [2], [23]. Thus, individuals may experience a sense of familiarity with the physical environment that simulation mimics.

Overall, when integrating simulation-based learning into more hands-on fields, individuals may experience a smoother transition from education to the workplace. Prior studies in engineering and manufacturing education have shown that simulation- and game-based learning environments support knowledge transfer by situating learning within realistic, contextualized problem scenarios [2], [5]. If students are unable to access experiences that help them learn job skills safely and effectively, they may be deprived of the knowledge necessary for their future occupation. Simulation games provide learners with repeated exposure to complex decision-making tasks, enabling them to develop both conceptual understanding and metacognitive problem-solving skills [10], [20]. Those who can engage in simulation-based learning may be exposed to realistic tasks and expectations of their desired work environment without concerns for safety risks. When this resource is available to students, they may experience a transition from education to the workplace that is lacking stress, anxiety, and perceived pressure [19]. As a result, simulation-based learning environments represent a promising instructional approach for preparing students to navigate complex, real-world manufacturing systems while supporting accessibility, safety, and learner confidence [2], [18].

**Development of SRL Skills and Motivation**

In addition to exposing learners to complex, real-world problem-solving scenarios in a safe, cost-effective manner, simulation-based learning environments also create opportunities to develop self-regulated learning (SRL) skills critical for effective problem-solving. SRL is defined as the effective control over one's learning while working to accomplish specific goals [20], and high-level SRL skills have been linked to higher achievement levels and more efficient learners. Transferring both content knowledge and SRL skills to novel problems is challenging. Still, it can be supported and assessed in simulation-based learning environments, providing learners with immediate feedback to adjust their problem-solving approach.

Learners need to be able to plan how to solve the problem, monitor their progress and make adjustments as necessary, and reflect on the effectiveness of their strategy at the end of a task to inform future attempts [9]. Simulations that present multifaceted, ill-structured problems are a useful instructional approach for training individuals to develop and apply the necessary SRL skills. As noted above, achievement, or successful problem-solving, is influenced by SRL skills, including metacognitive skills and learners' strategies, as well as motivation. The Social Cognitive model of Self-Regulation includes all three components: metacognition, motivation, and strategic knowledge [9]. For learners to solve real-world, ill-structured problems, they need to practice engaging with these problems. While cost, location, and safety concerns may limit learners' access to real-world experiences, simulations offer a great opportunity to expose learners and deliver feedback that supports improvement in a low-stakes scenario.

One problem many classrooms encounter with students is a lack of engagement with class content because it feels detached from their future careers. Simulations, on the other hand, can increase students' motivation by mimicking real-world environments and problems. In this study, motivation is operationalized as situational interest, an important precursor to sustained interest and motivation [2], [20]. By sparking situational interest in the simulation activity, learners will be more engaged and achieve better learning outcomes. Overall, simulation-based learning can motivate students by providing them with the opportunity to "learn by doing", increasing their transfer of knowledge and skills to real-world problems.

**Current Study**

The current study examines the implementation of a manufacturing simulation-based learning environment on participants' knowledge, metacognitive SRL skills, interest, and game outcomes. This is the initial evaluation of the first component of the game, focusing on individuals learning to balance a manufacturing line based on demand and production ability. The main research question guiding this study is: *Do students differ in their self-regulation, knowledge, game performance, or usability scores by level of situational interest?*

## Methods

### 3D Simulation-based Educational Game

The 3D simulation-based game was developed using Unity, a widely used 3D game engine that supports the creation of robust, versatile cross-platform applications [24]. Unity allows developers to build immersive three-dimensional (3D) and two-dimensional (2D) games and simulations, making it a popular platform for developing educational tools in engineering and related disciplines [24].


Figure 1. Snapshots of the water bottle manufacturing environment, including game user interfaces

The simulated environments represent a water bottle manufacturing system designed to mirror real-world production operations. The system is composed of multiple stations, each corresponding to a key stage in the manufacturing process:

- **Blow molding machine:** Produces plastic water bottles.
- **Cleaning station:** Prepares bottles before the filling process.
- **Filling station:** Dispenses water into the bottles.
- **Capping and sealing station:** Seals and secures the bottles.
- **Labeling station:** Applies product labels and branding information.
- **Wrapping and packaging station:** Bundles bottles into packages according to customer order specifications.

Conveyor belts and robotic arms facilitate material transfer between stations and the movement of packaged products to shipping pallets, respectively. Figure 1 shows snapshots of the game environment.

The game is designed to teach fundamental concepts of supply and demand within a simulated manufacturing environment. Players assume the role of operations manager responsible for releasing orders into the system by controlling forklift operations. Each order is defined by several parameters, including the quantity of pre-molded bottle material, the selected production line (up to three production lines), the number of release batches, and the timing of each release. These decisions are constrained by system limitations such as forklift speed, forklift capacity, and the funnel capacity at the start of each production line.

Throughout the gameplay, players must continuously monitor customer demand to avoid over-releasing orders into the system. Releasing too many orders or releasing them too early results in increased costs associated with excess inventory, bottles waiting in queues, and blocked forklifts or stations. The primary objective is to maintain a balanced system by efficiently releasing orders while aligning production capacity with customer demand.

The simulation-based game consists of five levels, including an introductory tutorial/onboarding level, a preparation level, and a final reflection level. As players progress through the levels, the system's complexity increases with the introduction of additional forklifts and multiple production lines, requiring more sophisticated decision-making and coordination. To support learning, players can take notes during gameplay and save them. In addition, SRL prompts are embedded throughout the experience, guiding students through planning, monitoring, and reflection phases as they interact with the system and refine their strategies.

**Participants**

Participants (N = 17) were recruited from an engineering course at Penn State Behrend to complete a research study outside of class time. Participants were primarily male (70.6%) and predominantly white (82.4% white, 11.7% Asian, 5.9% Hispanic/Latino), with an average age of 21.65 (SD = 1.80) years old. Additionally, the participants were mostly senior-level (76.5% seniors, 23.5% juniors) completing Industrial Engineering (70.6%) and Mechanical Engineering (29.4%) majors.

**Materials**

**Pre Survey**

Pre-survey administered via Qualtrics software and included the following:

*Demographics and Experience*. The pre-survey included a consent form, a demographics section, and two questions about prior professional work experience. Participants indicated whether they had previous professional work experience (1 = Yes, 2 = No) and, if applicable, were prompted to specify the duration of their experience. Agreement with statements concerning one's ability to learn (i.e., I can learn from online simulations) and enjoyment of learning through online simulations (i.e., I enjoy learning from online simulations) was rated on a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

*Big Five Inventory.* The Big Five Inventory included 10 statements for participants to rate on a scale from 1 (strongly disagree) to 5 (strongly agree). Each statement (e.g., I see myself as someone who is generally trusting) was evaluated on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree) and 6 (Can't Choose). The Big Five Inventory assessed how well statements described an individual's personality. Responses were used to calculate scores for each personality: Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism [29].

*Self-Efficacy*. The Engineering Self-Efficacy section included five questions concerning a participant's perceived confidence in their ability to complete tasks in the manufacturing simulation. Responses were given on a scale from 1 (Not at all Confident) to 5 (Extremely Confident). The items were used to create an average self-efficacy score for each participant [30]. The Cronbach's alpha for this section was .81, indicating good reliability.

*Pre-Knowledge*. The pre-knowledge section included seven questions about participants' pre-existing knowledge of the concepts covered in the game. The assessment included five multiple-choice items and two open-response items.

*Hexad-12 Scale*. Before beginning the simulation, participants completed the Gamification User Type Hexad-12 Scale [25]. The scale included 12 items rated on a 7-point Likert scale ranging from Strongly Disagree to Strongly Agree. Responses were used to identify participants' average scores across the Hexad player types: Philanthropist, Socializer, Free Spirit, Disruptor, Achiever, and Player.

**Post Survey**

A post-survey administered via Qualtrics software and included the following:

*System Usability Scale.* The System Usability Scale assessed participants' responses to the manufacturing simulation through 10 statements [26]. Responses given in this category were based on one's agreement with a presented statement. Statements included the degree to which an individual would like to use this manufacturing simulation frequently, the degree of complexity or simplicity presented, how well-integrated the functions of the simulation were, inconsistencies within the manufacturing simulation, confidence while participating in the manufacturing simulation, and the basis of knowledge needed to participate in the manufacturing simulation. The scale of these questions ranged from 1 (Strongly Agree) to 5 (Strongly

Disagree). Responses were scored to produce individual scores and an overall average for future comparisons. The Cronbach's alpha for this scale was .90, indicating excellent reliability.

*Situational Interest.* The situational interest [27] section was comprised of five statements concerning one's enjoyment and interest in the manufacturing simulation. Responses to these statements were rated from 1 (Strongly Disagree) to 5 (Strongly Agree). An average score was created for each participant. The Cronbach's alpha for this section was .87, indicating good reliability.

*Post-Task-Based Metacognitive Questionnaire.* The Post-Task Based Metacognitive Questionnaire was composed of 24 items answered on a 5-point Likert scale (Strongly Disagree to Strongly Agree) [28]. The items were used to create scores in three areas: Monitoring, Control, and Evaluation. Cronbach's alpha was .49 for the monitoring item, .60 for the control item, and .92 for the evaluation item.

**Procedures**

After participants signed up for the experiment, an introductory video was shared with them to prepare them for their manufacturing simulation session. During a participant's scheduled time slot, they completed the consent form and the Qualtrics pre-survey before beginning the manufacturing simulation.

Upon launching the simulation game, participants completed a user login followed by a series of statements from the Hexad-12 scale. The manufacturing simulation collected in-game data, including participants' clicks, time spent in the simulation, and notes taken during each level. Participants' actions and time spent in the simulation provided insights into how they navigate the environment. The recorded data included the number of times participants opened the order release interface to view orders, notes, and order fulfillment screens, the avatar's location at various time points, and the direction the avatar faced most frequently. Participant performance was assessed based on their ability to minimize costs while maximizing the overall balance. In the notes, SRL questions were posed based on the tasks being performed on the presented level. Responses to these questions were recorded and assessed for accuracy.

Upon entering the factory environment, users were cued to utilize different keyboard shortcuts to access various user interface (UI) menus. These menus included missions, a guidebook, an ordering screen, a demand interface, and a notes page (see Figure 1). The missions' menu allowed users to view completed and incomplete tasks (i.e., missions). The guidebook served as a reference for users seeking information on specific factory functions (e.g., forklifts). The release order UI allowed users to enter the amount needed to fulfill an order to meet customer demands. The customer demand UI enabled users to view and fulfill customer demands. The notes page allowed users to access SRL questions related to their current tasks and record responses accordingly (see Figure 1).

Participants first completed the Preparation Level, which required them to answer questions about the number of water bottles needed to meet customer demand, the number of order releases required to produce that amount, and the time required to produce that amount. Users were then prompted to create a plan for fulfilling customer demand. Then, users were prompted to begin Level 1, which required participants to fulfill the customer demand as they populated on the demand interface. During this level, the user had access to one water bottle production line. As users fulfilled the demands, they also had to answer questions on the notes page. These questions addressed the frequency of forklift deliveries, the hopper's capacity, whether order releases were causing congestion in the line, whether deliveries were meeting demand, and whether the forklift was waiting at the bottle-forming machine. Once these questions were answered and all demands were met, users were prompted to begin Level 2.

Level 2 of the manufacturing simulation functioned similarly to Level 1. Users were required to fulfill customer demand and answer questions in their notes. However, the amount and frequency of customer demand increased. During this level, the user had access to two water bottle production lines. In the notes, two questions remained the same concerning the frequency of forklift deliveries and the hopper's capacity. Additionally, questions were asked about whether the forklift was serving both lines or favoring one, whether a line was waiting for material, whether order releases were aligned with demand for both lines, and whether adjustments were needed in timing, batch sizes, or forklift priorities. Once these tasks were completed, users were prompted to Level 3.

Level 3 followed a similar structure to Levels 1 and 2, with further increases in customer demand and frequency. During this level, users had access to three water bottle production lines. Questions continued to focus on the frequency of forklift deliveries, hopper capacity, material availability across all lines, balance among production lines, and adjustments were required to timing, batch sizes, or forklift priorities. After fulfilling all customer orders and responding to the questions, users were prompted to complete a reflection activity.

The reflection activity provided participants with an opportunity to evaluate their performance in the manufacturing simulation. During this task, users responded to reflection questions by entering responses into the notes interface. These questions asked whether order releases kept the production line running smoothly, whether material flow was steady, whether forklift deliveries were efficient, whether production rates matched customer demand, which decisions helped improve the system, and what adjustments users would make in future attempts. After completing the reflection, participants completed the Qualtrics post-survey.

## Results

### Descriptive Statistics

Table 1 shows the means and standard deviations for pre- and post-assessments. The pre-knowledge assessment showed a ceiling effect, indicating the knowledge assessment was too easy for participants. Additionally, the average knowledge score decreased slightly from pre- to post-assessment; however, this difference was not statistically significant, [$t(16) = 1.60$, $p = .13$].

Table 1. Means and standard deviations for assessments.

| Measure | Mean (Standard Deviation) |
|---|---|
| Pre Assessments | |
| Efficacy for Engineering | 2.96 (.63) |
| Pre Knowledge | 6.29 (.77) |
| Extroversion | 3.47 (.86) |
| Agreeableness | 3.68 (.56) |
| Conscientiousness | 2.03 (.57) |
| Neuroticism | 2.59 (.80) |
| Openness | 2.24 (.77) |
| Hexad Player Scale | |
| Philanthropist | 6.20 (.71) |
| Socializer | 5.68 (.77) |
| Free Spirit | 5.94 (.79) |
| Achiever | 6.06 (.63) |
| Disruptor | 2.88 (1.05) |
| Player | 6.15 (.77) |
| Post Assessments | |
| Post Knowledge | 5.88 (.93) |
| Usability | 57.94 (21.85) |
| Situational Interest | 3.39 (.88) |
| SRL- Monitoring | 3.74 (.43) |
| SRL- Control | 3.83 (.49) |
| SRL- Evaluation | 3.24 (.89) |
| In-Game Performance | |
| Order 1 Profit | 224 (254.18) |
| Order 2 Profit | 1772 (295.62) |
| Order 3 Profit | 3361 (334.82) |
| Total Profit | 5346 (629.05) |

**Group Comparison by Situational Interest**

Participants' situational interest was used to create low-interest ($M = 2.55$, SD = .37) and high-interest ($M = 4.13$, $SD = .35$) groups using a median split [31]. The two groups' situational interest scores were significantly different, as indicated by a paired-samples t-test [$t(15) = -9.16$, $p = .001$]. They were therefore used as a grouping variable for subsequent comparisons.

The Hexad-12 scale was administered before students began using the simulation. An independent-samples t-test was conducted to examine whether the high- and low-situational interest groups differed in their player types. The results indicated a significant difference in the Player dimensions [$t(15) = -2.26$, $p = .04$]. Students with higher situational interest scored higher on the Player dimensions ($M = 6.50$, $SD = .43$) than those with lower situational interest ($M = 5.75$, $SD = .89$).

Independent-samples t-tests were used to compare high- and low-situational interest groups across pre-, during-, and post-assessments. There was no significant difference in pre-knowledge scores between the two groups ($p = .83$). However, there was a significant difference in post-knowledge [$t(15) = 2.33$, $p = .03$], with the low situational interest group scoring higher ($M = 6.38$, $SD = .74$) than the high-situational-interest group ($M = 5.44$, $SD = .88$).

There was also a significant difference in knowledge change between the high- and low-situational-interest groups [$t(15) = 2.18$, $p = .046$]. The low-situational-interest group showed a small increase in scores on average ($M = .13$, $SD = .83$). In contrast, the high-situational-interest group demonstrated an average decrease ($M = -0.89$, $SD = 1.05$), although this result was barely significant.

There were no significant differences between the low- and high-situational-interest groups on the self-regulation measures, including Monitoring ($p = .34$), Control ($p = .48$), and Evaluation ($p = .11$).

A significant difference was observed for Level 1 Profit [$t(14) = -2.19$, $p = .046$], with the high-situational-interest group ($M = 348.50$. $SD = 182$) achieving higher profits than the low-situational-interest group ($M = 99.50$, $SD = 264.07$). No significant differences were found for Level 2 Profit, Level 3 Profit, or Total Profit.

Finally, a significant difference in usability scores was observed between the high- and low-situational-interest groups [$t(15) = -3.39$, $p = .004$]. Participants in the low-situational-interest group reported lower usability scores ($M = 43.13$, $SD = 18.11$) than those in the high-situational-interest group ($M = 71.11$, $SD = 15.92$).

**Discussion and Conclusions**

The current study explored the implementation of a manufacturing simulation-based learning environment with undergraduate engineering majors. Simulation-based learning environments have been widely shown to support the development of decision-making and problem-solving skills in engineering education [2], [5], [23]. Situational interest, a precursor to long-term interest and an underlying component of motivation [27], was used as a grouping variable to examine the effects of the outcome variables in the simulation. Four important differences emerged between the high- and low-situational-interest groups that can inform future design decisions. Specifically, differences were observed in knowledge outcomes, early game performance, Hexad player type, and usability scores.

To begin, the ceiling effect on the pre-knowledge assessment posed challenges for data interpretation. Additionally, the average knowledge score decreased from pre- to post-assessment, suggesting potential issues with participants' knowledge levels and/or the measures used. When examining pre- and post-knowledge performance across situational interest groups, results showed that the low-situational-interest group achieved higher post-knowledge scores than the high-situational-interest group. This finding contrasts with previous research that suggests that increased interest is generally associated with improved learning outcomes [27]. One possible explanation is boredom or a lack of challenge among participants with higher prior knowledge, which may have contributed to lower situational interest during gameplay. A mismatch between users' prior knowledge and the level of challenge presented in the simulation may lead to disengagement with instructional activities. Previous research on game-based learning suggests that optimal learning occurs when task difficulty aligns with learners' skill levels, as insufficient challenges can lead to disengagement or superficial processing [23]. Essentially, learners often require an appropriate level of challenge to remain motivated in learning environments.

Another finding was a greater decrease in knowledge scores from pre- to post-assessment in the high-situational-interest group than in the low-situational-interest group. One possible explanation is that participants reporting higher interest may have focused more on specific gameplay elements than on content-related decision-making processes. This interpretation is supported by the finding that the high-situational-interest group also scored higher on the Hexad scale Player dimension, which is typically associated with a focus on maximizing rewards, such as in-game profit [25]. Prior research on game-based learning environments suggests that while gamification may increase engagement, it may shift learners' attention toward performance optimization rather than conceptual understanding if game mechanics are not aligned well with instructional goals [23]. As a result, these participants may have prioritized profit optimization over deliberate engagement with the underlying line balancing concepts.

Differences were also observed in usability scores, with participants in the high-situational-interest group reporting higher perceived usability than those in the low-situational-interest group. This finding aligns with previous research on user experience, which suggests that individuals who are more engaged or motivated are more likely to perceive systems as usable and accessible [26]. As usability reflects the accessibility and ease of use of the simulation environment, it is not surprising that participants who reported greater interest also perceived the system as more usable. In simulation-based environments, usability plays a crucial role in supporting engagement and sustained interaction, as complex or unintuitive systems can hinder learning and reduce motivation [2]. In contrast, participants with lower situational interest may have found the simulation less intuitive pr more difficult to navigate, which could have negatively influenced their overall engagement with the activity.

Overall, these findings suggest that situational interest is associated with meaningful differences in user experience and performance within a simulation-based learning environment, although the direction of these differences was not consistent across all outcome measures. While prior research emphasizes the role of simulations in supporting cognitive and non-cognitive outcomes [3], the current study highlights the complexity of balancing engagement, usability, and learning.

It is promising that there is a positive link between increased interest and increased usability. However, the simulation's main purpose is to increase content knowledge and metacognitive SRL skills. These results highlight the importance of carefully aligning assessment difficulty, instructional scaffolding, and game mechanics to support both engagement and learning. Findings from this study will be used to guide future iterations of the simulation, particularly with respect to adaptive scaffolding and the introduction of increasingly complex problem scenarios.

**Limitations**

There were three primary limitations in this study. First, the study was conducted at the end of the semester with upper-level engineering major students. The simulation is intended for students who have not yet learned all of the relevant operations management content; therefore, the timing and participant level may have limited the sensitivity of the knowledge assessment.

The second limitation was the misalignment between the difficulty of the knowledge assessment and participants' prior knowledge, as evidenced by the ceiling effect observed on the pre-assessment. This limitation reduced the ability to detect meaningful knowledge gains resulting from the simulation activity. Future studies will implement a revised knowledge assessment with greater difficulty and improved alignment with the simulation's learning objectives.

Finally, the study was limited by the small sample size. Future work will involve larger and more diverse samples of undergraduate engineering students further to examine learning outcomes and user differences across instructional contexts. The larger sample size will also allow for more robust statistical analyses.

**Acknowledgment**

The authors would like to thank the National Science Foundation (NSF) for funding this work under Grant # 22302813. Any opinions, findings, or conclusions within this paper are those of the authors and do not necessarily reflect the views of the sponsors.

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