Technology-enhanced Simulation for Developing Nursing Competencies and Digital Intelligence

Prakob Koraneekij[1] and Sresuda Wongwiseskul[2]
[1]Center of Excellence in Educational Invention and Innovation, Department of Educational Technology and Communications, Faculty of Education, Chulalongkorn University, Thailand
[2]Department of Community Nursing, Faculty of Nursing, Suan Dusit University, Thailand

prakob.k@chula.ac.th (Corresponding author)
sresuda_won@dusit.ac.th

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Abstract: In the context of digital disruption, nursing education requires approaches that integrate digital intelligence (DI) with professional competencies while addressing limitations of traditional simulation-based learning (SBL), which is often resource-intensive and constrained in large classes. This study developed and evaluated "Nurse Sims," a progressive web application that integrates with an Internet of Things (IoT)-enabled humanoid manikin (ESP32) to support real-time clinical training and automated feedback for nursing students. A four-phase research and development design was employed. Phase 1 assessed learning needs among 462 nursing students in Thailand using questionnaires and PNIModified analysis. Phase 2 involved the development of the SBL model and technological system. Phase 3 evaluated the intervention with 31 nursing students and six instructors using repeated-measures analysis of variance across three assessment points (Situations 1, 3, and 5). Phase 4 involved expert validation of the innovation. Results show a high need for SBL (PNImodified = 0.796). Significant improvements were observed in professional competencies (ηp^2 = .911) and DI (ηp^2 = .933) ($p < .001$). Students reported high acceptance of the system (M = 4.52, SD = 0.49), while experts rated the innovation as highly appropriate (M = 4.76, SD = 0.20). Qualitative feedback indicated improved digital self-efficacy and engagement with technology-enhanced learning. The findings suggest that IoT-integrated simulation systems can enhance nursing competencies, and DI and may serve as a scalable model for nursing education in resource-constrained settings.

Keywords: Learning innovation, Simulation-based learning, Disruptive educational technology, Nursing competencies, Digital intelligence

1. Introduction

Nursing education plays a critical role in preparing healthcare professionals to deliver safe, effective, and compassionate patient care (Pleshkan, 2025; Hou et al., 2025; Laugaland et al., 2025; Li & Cheung, 2024). As healthcare systems become increasingly complex and digitally driven, nursing education must evolve to incorporate technology-enhanced pedagogies that strengthen professional competencies and align with the demands of contemporary clinical practice (Hou et al., 2025; Hamilton, 2025; Jallad et al., 2024).

Technological advancement has expanded opportunities for innovation in nursing education. In particular, nurses are now expected to demonstrate digital intelligence (DI), which encompasses the competencies required to effectively use digital tools, interpret data, and navigate technology-enabled healthcare environments. DI is increasingly recognized as essential for ensuring safe and high-quality patient care. Emerging educational technologies such as mobile-assisted learning (Lim et al., 2024), generative artificial intelligence (AI) applications, virtual reality environments (Hou et al., 2025), and simulation robotics (Sighinolfi et al., 2023) have therefore gained attention as pedagogical tools. Among these approaches, simulation-based learning (SBL) has emerged as a particularly effective method for developing nursing competencies. SBL provides a safe, controlled, and experiential learning environment in which students can develop clinical knowledge, psychomotor skills, critical thinking, and decision-making abilities essential for high-quality patient care (Ylönen et al., 2025; Roettger et al., 2025; Thompson et al., 2024). In addition, SBL supports the development of DI by enabling self-directed, technology-mediated learning that can occur across time and space (Rungrangtanapol & Khlaisang, 2021).

DI is increasingly recognized as a key factor influencing educational outcomes in nursing. It has been shown to enhance academic motivation, lifelong learning capacity, and creative thinking, particularly in contexts involving AI and immersive digital environments such as the metaverse (Agaoglu et al., 2025; Amin et al., 2025).

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Despite these benefits, two major challenges persist. First, SBL remains resource-intensive, placing significant physical and cognitive demands on instructors and limiting scalability (Saito and Dal Sasso, 2023). Furthermore, large class sizes often reduce student engagement, with many learners adopting passive roles during simulation activities (Guinea et al., 2019). Second, there remains a persistent gap between nursing curricula and the digital competencies required in contemporary healthcare practice, particularly in relation to DI development (Agaoglu et al., 2025; Amin et al., 2025; Stunden et al., 2026). These challenges highlight an urgent need for disruptive educational approaches that reduce instructional burden, increase active learner participation, and provide real-time feedback while simultaneously strengthening both clinical competencies and DI. In response, this study explores the integration of SBL with disruptive technologies to enhance nursing education effectiveness. These approaches can enhance the effectiveness and efficiency of nursing education and better prepare nurses to meet patients' complex and evolving healthcare needs through DI in an era of digital disruption. More broadly, this study contributes to the evolving field of digital education by demonstrating how immersive simulation environments with advanced digital systems can support the development of 21st-century skills. By bridging simulation pedagogy and disruptive technology, the study proposes a scalable framework for cultivating nursing competencies, DI, and adaptive capacity in an increasingly globalized and technology-driven healthcare context.

1.1 Research Objectives

To examine the contextual conditions and learning needs within nursing education that inform the development of SBL innovation grounded in active and collaborative learning principles, aimed at addressing gaps in nursing students' professional competencies and DI in response to disruptive technological change.

- To develop a needs-based and theory-informed SBL innovation model integrating simulation pedagogy, Internet of Things (IoT)-enabled humanoid simulators, and web-based learning to support authentic clinical practice, real-time feedback, and collaborative knowledge construction.
- To investigate the effects of the developed SBL innovation model on nursing students' professional competencies and DI, with particular attention to the mechanisms through which technology-enhanced simulation supports skill acquisition, self-directed learning, and clinical readiness.
- To disseminate and validate the practical applicability of the SBL innovation model within nursing education contexts requiring feedback-rich, technology-supported, and resource-efficient approaches to professional competency development.

2. Literature Review

2.1 Disruptive Technology

Disruptive technology refers to sociotechnical processes through which digital innovations transform the delivery, access, and structure of education (Huang, Burton-Jones and Xu, 2024). Such technologies challenge established educational systems while simultaneously generating new opportunities and constraints for teaching and learning (Flavin, 2012; Huapaya et al., 2025). Disruptive technology is characterized by interrelated dimensions: 1) problem-solving capability, 2) system-level transformation, and 3) behavioral change in educational practice (Mills, 2018).

A range of disruptive technologies illustrates the transformation of education systems. Cloud computing enables scalable and distributed learning infrastructures that support collaboration and continuity of instruction, including Massive Open Online Courses (MOOCs) and remote learning environments (Al-Samarraie & Saeed, 2018; James & Weber, 2016; Sharma, Singh and Daim, 2023). Wearable Biosensor Technology enables real-time monitoring of cognitive and physiological states, supporting adaptive instructional responses based on learner engagement and stress levels (Hernández-Mustieles et al., 2024). The IoT connects physical learning environments with real-time data systems, contributing to the development of smart educational ecosystems (Paliktzoglou & Vlachopoulou, 2025). Digital twins and immersive technologies, including virtual reality (VR), augmented reality, and mixed reality, enable medical students to perform risk-free virtual surgeries, transform static textbooks by overlaying 3D holograms, and manipulate virtual objects as though they were tangible (Pandey et al., 2024). MOOCs expand access to education by reducing geographic and financial barriers (Sultan, 2019). Collectively, these disruptive technologies are reshaping education from a content-delivery model into a data-driven and interconnected learning infrastructure.

2.2 Learning Innovation for Nursing Education

Learning innovation involves the integration of emerging technologies, pedagogical strategies, and instructional designs to enhance learning effectiveness and engagement (Leslie, 2015; Redding, Twyman and Murphy, 2013;

Burke et al., 2025). In nursing education, it refers to the systematic use of digital and simulation-based tools to bridge theoretical knowledge and clinical practice. Technological integration in nursing education has led to multiple pedagogical innovations. Mobile Academic Electronic Medical Record (AEMR) systems enable students to practice clinical documentation and strengthen informatics competencies in simulated environments (Choi, Lee and Park, 2018). Cloud-based AEMR systems further enhance clinical reasoning by supporting complex patient data synthesis during simulation (Hong et al., 2022). Immersive tools further bridge the gap between theory and practice, including virtual reality mobile game-based applications (VR-MGBA), which improve long-term retention in disaster scenario training (Hu et al., 2022), while robotic patient simulators enhance procedural skill development (Huang et al., 2017). Smart glasses support real-time procedural guidance and reflective learning through video-assisted debriefing (Kim, Seo and Shin, 2024; Kopetz, Wessel and Jochems, 2020). Mobile applications such as E-MunDiabetes support evidence-based decision-making (Da Silva Negreiros et al., 2022), while clinical education platforms, such as the Clinical Education Management Information System, streamline the evaluation process between students and preceptors (Oxyandi et al., 2024). Exposure to sophisticated robotic surgery simulators further increases students' interest in modern surgical disciplines (Sighinolfi et al., 2023). Collectively, these technologies extend learning beyond traditional instruction and strengthen clinical preparedness.

2.3 Simulation-based Learning (SBL)

SBL is a pedagogical approach that provides a structured and safe environment for nursing students to develop clinical reasoning, decision-making, and procedural competence in nursing education (Holmes, 2024; Skedsmo et al., 2023; Thompson et al., 2024). It shifts learning from passive knowledge acquisition to active experiential engagement within controlled clinical scenarios. The four instructional models outline the essential steps for designing and implementing SBL as follows: 1) preparation, 2) presentation of objectives and guidelines, 3) assignment of learner roles and responsibilities, 4) execution of the simulation task, and 5) debriefing and discussion. This pedagogical approach transforms nursing education from a passive, theoretical exercise into a dynamic, psychologically safe, and structurally standardized learning framework. Instructional models for SBL, such as Tag Team Patient Safety Simulation (Guinea et al., 2019), have been introduced to empower students to challenge unsafe practices and advocate for patient safety within hierarchical clinical environments. High-fidelity SBL (HF-SBL; Lee et al., 2019) promotes learning through practice, enabling students to enhance self-directed learning, critical thinking, and confidence. Immersive Repeated Standard Simulation (iRS-Sim) and Team Deliberate Practice (iSim-TDP; Platt et al., 2024) evaluate repeated scenario engagement and progressively develop clinical self-efficacy without risk to patients. The Electronic Workflow for High-Fidelity Clinical Simulation (EWH-FCSN; Saito & Dal Sasso, 2023) provides a structured digital workflow tool that supports educators in designing and implementing simulations, reducing preparation time, standardizing simulation processes, and facilitating evidence-based practice.

However, several challenges limit the effectiveness of SBL. Early-stage nursing students may experience anxiety, cognitive overload, and emotional stress during high-fidelity simulations, which may negatively affect learning outcomes (Platt et al., 2024). In addition, large class sizes often result in student-based simulations that reduce individual participation and lead to passive observation (Guinea et al., 2019). Furthermore, SBL implementation places significant resource and instructional demands on educators, particularly those with limited experience in simulation pedagogy (Guinea et al., 2019; Saito & Dal Sasso, 2023).

2.4 Digital Intelligence (DI)

DI is a multidimensional competency framework encompassing technical, cognitive, metacognitive, and socioemotional skills grounded in ethical principles for effective participation in digital environments (DQ Institute, 2024). It includes competencies such as digital identity, use, safety, security, emotional intelligence, communication, literacy, and rights (DQ Institute, 2024; Terry et al., 2019). Recent research identifies DI as a key determinant of academic and clinical success in nursing education. Digital literacy mediates the relationship between AI use and creative thinking, particularly when supported by strong academic environments (Agaoglu et al., 2025). Immersive technologies such as metaverse environments enhance digital literacy and student motivation (Amin et al., 2025). However, significant gaps persist between technological advancement and institutional readiness. Nurse educators often lack sufficient digital deficiencies (Li et al., 2025), while nursing curricula remain misaligned with contemporary digital clinical requirements (Stunden et al., 2026). These findings highlight the urgent need for structured digital literacy development within nursing education systems.

2.5 Nursing Competencies

Thailand Nursing and Midwifery Council (2010) defines the core competency framework for registered nurses and midwives across eight key operational domains: 1) ethics, professional conduct, and legal practice; 2) core nursing and midwifery practice; 3) professional attributes; 4) leadership, management, and quality improvement; 5) academic and research competence; 6) communication and relationship mangement; 7) information technology competence; and 8) social competence. These competencies emphasize patient-centered care, communication, collaboration, and professional accountability, and collectively support the development of nurses capable of advancing healthcare quality and nursing practice.

3. Research Methods

This study adopted a research and development design aimed at developing an SBL innovation within the context of disruptive technology to enhance nursing students' professional competencies and DI. The research was conducted in four phases. Ethical approval was obtained from the Research Ethics Review Committee for Research Involving Human Research Participants, Chulalongkorn University. All participants provided informed consent, and confidentiality was strictly maintained. Data were reported in aggregate form only, ensuring that no participant could be identified.

Ethical approval was granted by Chulalongkorn University Research Ethics Committee with two Certificate of Research Approval numbers (COA No.) granted for each phase: COA No. 038/2564 for Phases 1–2 and COA No. 038/2564 for Phases 3–4. Participant confidentiality was ensured throughout all phases, and all findings were reported in aggregated form for educational and research purposes only.

3.1 Phase 1: Needs Analysis for SBL Innovation

Phase 1 involved two sample groups. The first group consisted of 12 key informants for focus group interviews, including instructors, administrators from the Faculty of Nursing, and educational technology specialists. Participants were selected through purposive sampling based on their relevant expertise and direct experience in nursing education, SBL, and educational technology. The second group comprised survey respondents. Based on Cochran's formula, a minimum sample size of 384 participants was required to ensure statistical adequacy; however, 462 complete responses were obtained and included in the analysis. These nursing students were recruited from the four regions of Thailand (north, northeast, central, and south) to enhance geographical representation.

Both sample groups were drawn from 89 nursing institutes certified by the Nursing Council of Thailand.

Data collection included focus group interviews and structured questionnaires. Instruments were developed based on a literature review and theoretical frameworks, then validated using the Index of Item Objective Congruence by three experts. All items met acceptable validity thresholds (Polit & Beck, 2004) and were refined before data collection. Data were analyzed using content analysis, descriptive statistics, and the Priority Needs Index Modified ($PNI_{Modified}$).

3.2 Phase 2: Development of SBL Innovation

Phase 2 involved the development of the SBL model and associated technological components based on findings from Phase 1 and relevant literature. The process comprised three stages.

First, an initial SBL model was developed and evaluated by seven experts in nursing education and educational technology, focusing on communication, content validity, usability, and system applicability. Five additional experts assessed content validity in terms of model appropriateness and workflow coherence.

Second, a web-based application integrated with simulation robotics and sensor-controlled systems was developed in alignment with the SBL model. The system was optimized for multi-device compatibility, including desktops, laptops, tablets, and smartphones. Three experts evaluated usability, functionality, and design suitability.

Finally, a focus group with nine experts, including nursing instructors and nursing institute administrators, was conducted to refine the SBL model and system. Feedback from this session informed iterative improvements to both pedagogical design and technological integration.

3.3 Phase 3: Evaluation of SBL Innovation

Phase 3 employed purposive sampling of voluntary participants, comprising 6 nursing instructors and 31 nursing students. Data were collected using four instruments: 1) SBL model, 2) web-based application, 3) sensor-controlled simulation robots, and 4) instructional manual, which was developed during Phase 2. A structured workshop was conducted using the developed SBL system. Students' competencies were assessed across three time points following simulation sessions: Session 1 (Respiratory System Conditions), Session 3 (Subcutaneous Injection), and Session 5 (Intravenous Injection). Descriptive statistics and repeated-measures ANOVA were used to examine changes in students' competencies and digital intelligence across three assessment points. Effect sizes and F value were also calculated to evaluate the magnitude of changes and consistent of improvement over time. Competency assessment instruments included 1) nursing professional competency rubrics, 2) DI rubrics, and 3) a questionnaire evaluating SBL usage. The nursing students' professional competency rubric assessed eight dimensions: ethics, professional conduct, and legal practice; core nursing and midwifery practice; professional attributes; leadership, management, and quality improvement; academic and research competence; communication and relationship management; information technology competence; and social competency. The DI rubric assessed eight dimensions: digital identity, use, safety, security, emotional intelligence, communication, literacy, and rights. Both rubrics used a three-level self-assessment scale: 1) Needs Improvement, 2) Fair, and 3) Good. All instruments were validated by three experts in nursing education, educational technology and communications, and educational measurement and evaluation. The researchers incorporated expert feedback and revised both rubric assessments to ensure their suitability for actual use. For the third instrument, a questionnaire assessing the use of SBL innovation in the era of disruptive technology to enhance nursing students' professional competencies and DI was designed using a five-point Likert scale. The instrument was reviewed by three experts who evaluated its content validity, as well as the completeness and comprehensiveness of its items. Following revision, the questionnaire was piloted with nursing students to assess reliability and ensure instrument quality before full implementation. Reliability analysis confirmed strong internal consistency, with a Cronbach's alpha coefficient of 0.981.

3.4 Phase 4: Diffusion and Validation

Phase 4 focused on refining and disseminating the SBL innovation based on findings from Phase 3. Iterative improvements were made to the learning model and technological system before expert validation. Seven experts in nursing, educational evaluation, and educational technology participated in the validation process. Qualitative feedback from experts was analyzed using content analysis to inform further system refinement. Quantitative evaluation of innovation acceptance was conducted using descriptive statistics based on a five-point Likert scale.

4. Findings

4.1 Research Results of Phase 1: Conditions and Needs of SBL Innovation

Most respondents reported prior exposure to SBL (n = 400, 80.6%) and expressed strong interest in SBL participation (n = 462, 93.1%). Participants indicated that technology-enhanced SBL would support flexible learning, real-time feedback, independent information retrieval, post-learning review, pre-class preparation, and improved accessibility during disruptions such as the COVID-19 pandemic.

In terms of learning needs, students prioritized simulation-based clinical scenarios as their preferred instructional approach, followed by blended online learning activities and structured practical assessments. Additionally, students expressed interest in collaborative learning through peer discussion and knowledge exchange.

Instructors reported that the proposed innovation would enhance nursing students' professional competencies and DI while also providing institutions with accessible and cost-effective tools for monitoring student performance in virtual learning environments in real-time.

4.2 Research Results of Phase 2: Development of SBL Innovation

The results of the literature synthesis on SBL, together with the analysis of Phase 1 needs assessment, informed the development of the learning model components and instructional processes. The model comprises five components: objectives, scenario content, participant roles, learning activities using the Nurse Sims system, and assessment. The instructional sequence follows the 5Ps framework: 1) preparation of equipment and the Nurse Sims applications, 2) presentation of simulations using Nurse Sims, 3) practice of simulations using Nurse Sims, 4) project discussion and debriefing, and 5) performing the assessment in Figure 1.

Figure 1: The components and 5Ps steps of the learning model

The SBL innovation comprises two integrated systems: the Nurse Sims web application and the Nurse Sims simulation equipment, which function together as shown in **Figure 2** and **Figure 3**. The Nurse Sims web application is accessible via https://nursing-sim.edii.in.th and is designed as a progressive web application with a responsive interface compatible across devices. The system architecture is presented in **Figure 5**, while the entity-relationship structure is shown in **Figure 6**.

Instructional manuals for both students and instructors are provided in **Figure 4**.

The hardware system includes 1) a vascular simulation arm model, 2) an IoT-enabled sensor system comprising an ESP32 microcontroller and total dissolved solids sensor, 3) respiratory and cardiac sound simulation modules, and 4) a web-based monitoring interface for data visualization and recording (**Figure 7**). The integrated system supports five simulations: 1) respiratory assessment, 2) cardiovascular assessment, 3) intramuscular injection, 4) intravenous injection, and 5) intravenous fluid administration (**Figure 8**).

Figure 2: Nurse Sims application (students' view)

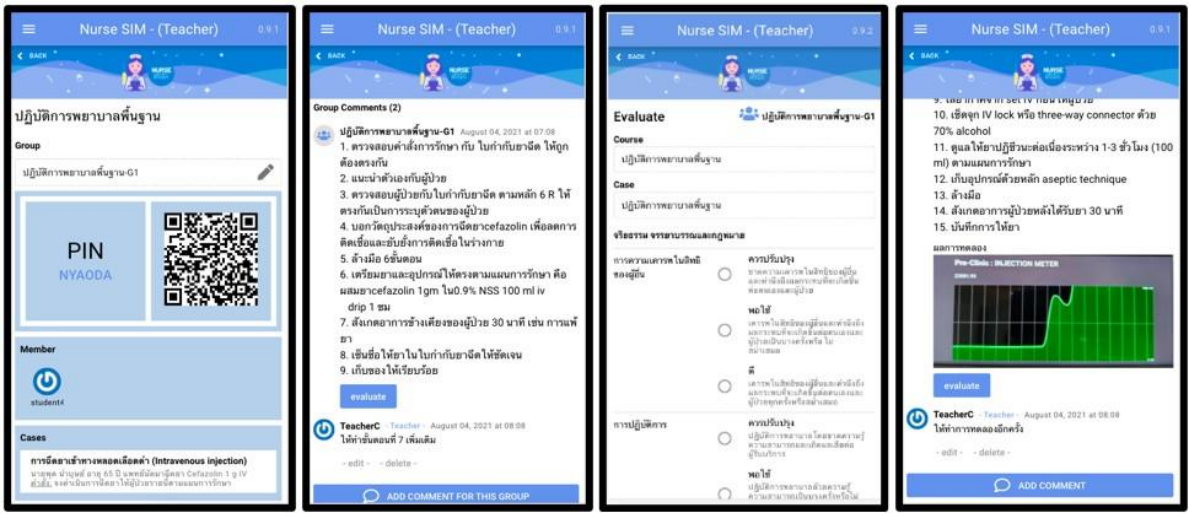

Figure 3: Nurse Sims application (instructors' view)

Figure 4: Manual for the Nurse Sims application for students (left) and instructors (right)

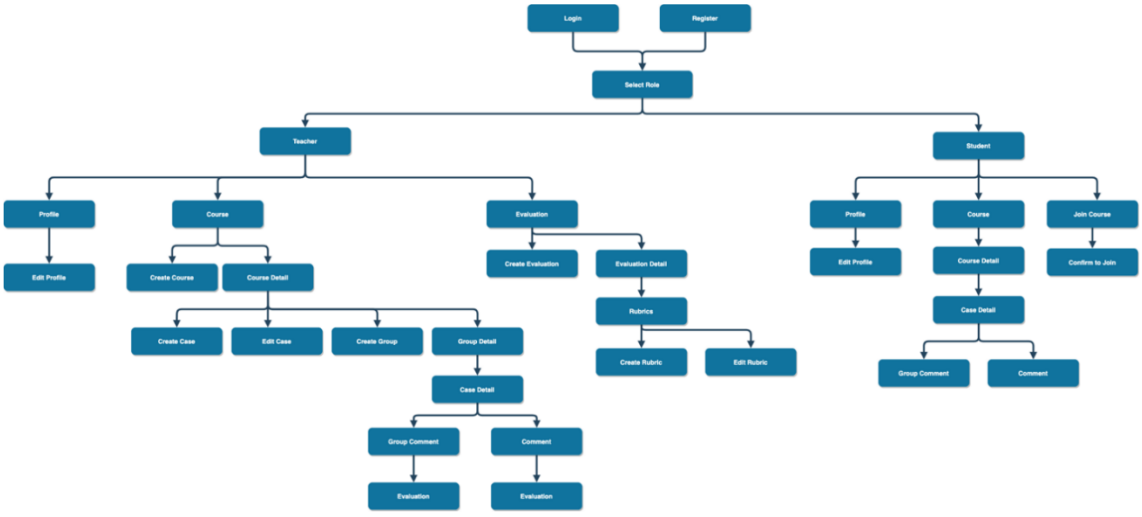

Figure 5: The structure of the Nurse Sims application

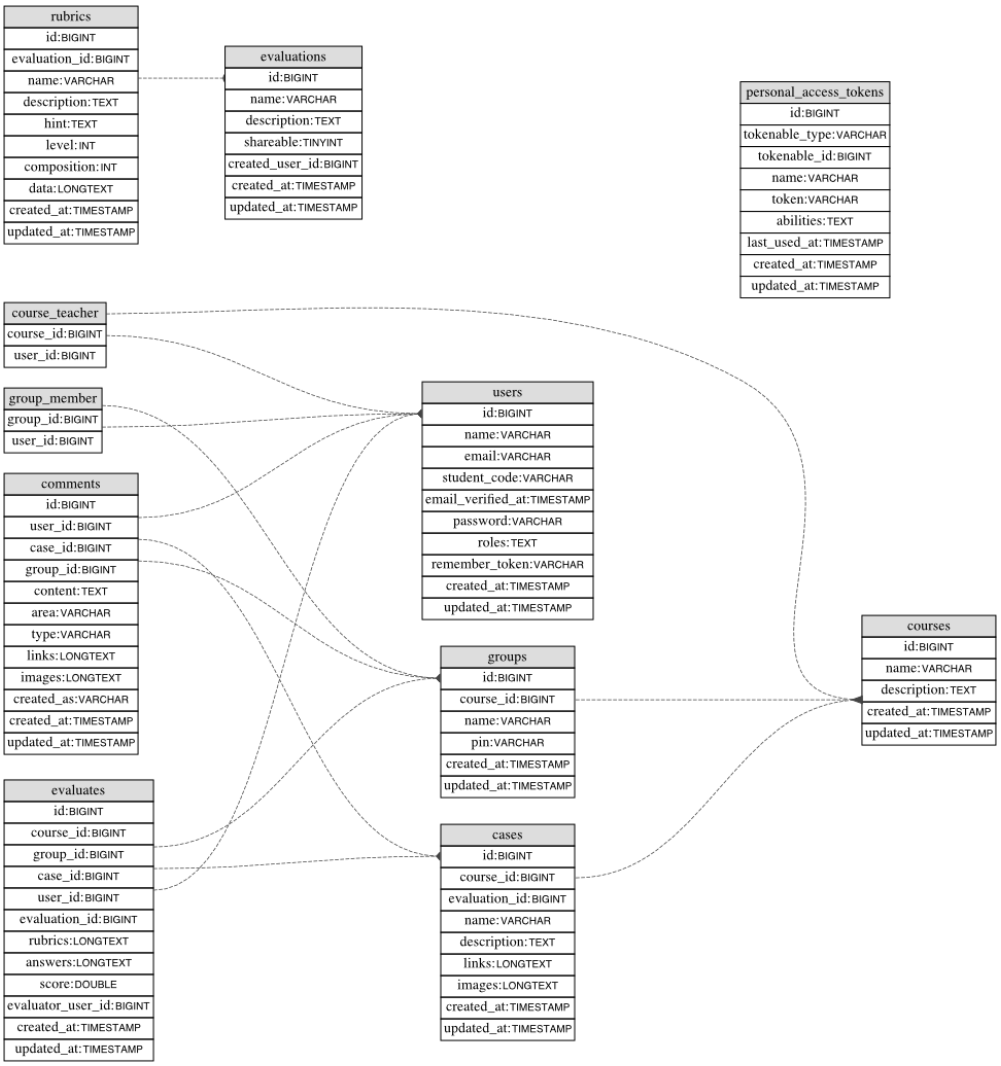

Figure 6: The entity-relationship of the Nurse Sims application

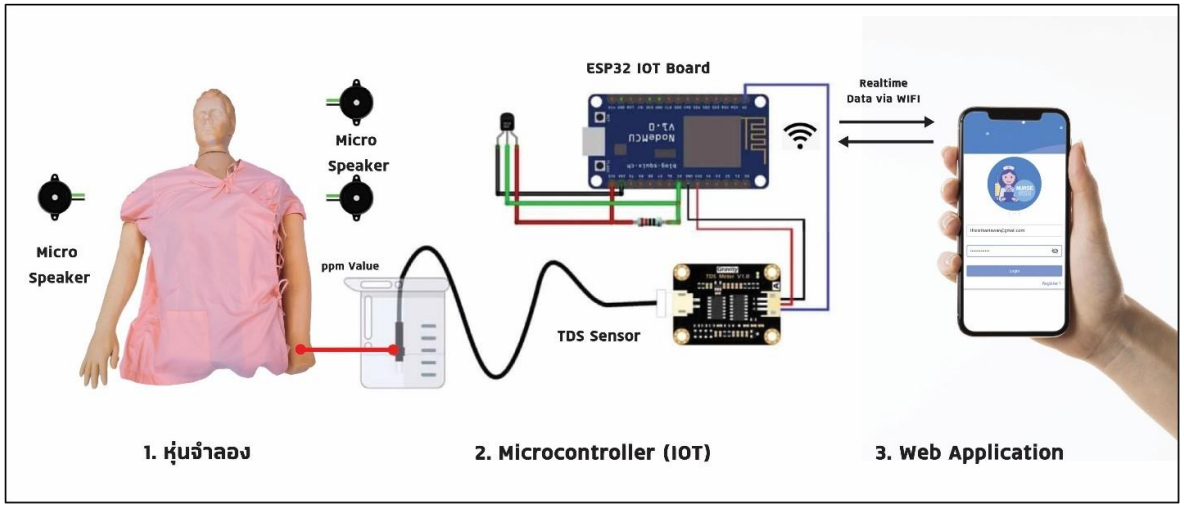

Figure 7: Technical components of the Nurse Sims application

Figure 8: Five simulations of the Nurse Sims application

4.3 Research Results of Phase 3: Effects of SBL Innovation

A repeated-measures ANOVA was conducted to examine changes in nursing students' professional competency scores across three assessment points. Data were collected using Likert scale assessments administered after Situations 1, 3, and 5 (descriptive analysis show in **Table 1**). These situations represented sequential simulation assessment points completed by the same participants during the intervention and corresponded to the early, intermediate, and final stages of learning progression. The results from Table 2 Situations 1, 3, and 5 indicated a statistically significant difference in the overall mean scores of nursing students at the .05 significance level (F = 1,293.430, p < .001). The highest mean score was recorded in Situation 5 (M = 2.84, SD = 0.14), followed by Situation 3 (M = 2.44, SD = 0.19) and Situation 1 (M = 1.42, SD = 0.24). Overall, nursing students demonstrated the highest competency level at the final assessment point (Situation 5; post-intervention), followed by the intermediate (Situation 3) and baseline (Situation 1; pre-intervention) assessments. The effect size analysis using partial eta squared (ηp^2) from the Tests of Within-Subjects Effects indicated a very large effect of Nurse Sims on nursing students' professional competencies. The ηp^2 value of 0.911 suggests that a substantial proportion of variance in competency scores across assessment points was attributable to the intervention, indicating both statistical and practical significance. These results indicate that nursing competencies improved following exposure to Nurse Sims.

Table 1: Descriptive analysis of nursing competency scores across three situations

Nursing competencies	Situation 1		Situation 3		Situation 5	
	Mean	SD	Mean	SD	Mean	SD
Ethics, code of conduct, and the law	1.71	0.36	2.82	0.24	1.71	0.36
Core nursing and midwifery practices	1.13	0.34	2.32	0.48	1.13	0.34
Professional characteristics	1.31	0.31	2.36	0.25	1.31	0.31
Leadership, management, and quality improvement	1.16	0.37	2.16	0.37	1.16	0.37
Academics and research competencies	1.10	0.20	2.19	0.25	1.10	0.20
Communication and relationship	1.57	0.38	2.32	0.24	1.57	0.38
Information technology	1.71	0.53	2.71	0.46	1.71	0.53
Social competency	1.61	0.50	2.68	0.48	1.61	0.50
Overall	**1.42**	**0.24**	**2.44**	**Overall**	**1.42**	**0.24**

Table 2: Repeated-measures ANOVA of nursing competency scores across three situations

Nursing competencies	Variance	SS	df	MS	F	sig	Results
Ethics, code of conduct, and the law	Estimate	23.536	1	23.536	419.322	.001	5>3>1
	Error	1.684	30	0.056			
Core nursing and midwifery practices	Estimate	35.629	1	35.629	276.125	.001	5>3>1
	Error	3.871	30	0.129			
Professional characteristics	Estimate	33.981	1	33.981	561.916	.001	5>3>1
	Error	1.814	30	0.06			
Leadership, management, and quality improvement	Estimate	40.323	1	40.323	328.947	.001	5>3>1
	Error	3.677	30	0.123			
Academics and research competencies	Estimate	42.778	1	42.778	803.712	.001	5>3>1
	Error	1.597	30	0.053			
Communication and relationship	Estimate	23.907	1	23.907	241.671	.001	5>3>1
	Error	2.968	30	0.099			
Information technology	Estimate	25.806	1	25.806	184.615	.001	5>3>1
	Error	4.194	30	0.140			
Social competency	Estimate	29.823	1	29.823	243.289	.001	5>3>1
	Error	3.677	30	0.123			
Overall	**Estimate**	**31.084**	**1**	**31.084**	**1293.430**	**.001**	**5>3>1**
	Error	**0.721**	**30**	**0.024**			

The repeated-measures ANOVA examined differences in nursing students' DI scores across three assessment points (Situations 1, 3, and 5) (descriptive analysis show in **Table 3**). The results indicated a statistically significant difference in overall DI scores at the 0.05 level ($F = 608.285$, $p < .001$). Mean DI scores increased from Situation 1 ($M = 1.43$, SD = 0.30) to Situation 3 ($M = 2.51$, SD = 0.35), and reached the highest level in Situation 5 ($M = 2.93$, SD = 0.10). The implementation of Nurse Sims was associated with a marked improvement in DI outcomes. The effect size ($\eta p^2 = .933$) indicated a very large effect, suggesting that the intervention accounted for a substantial proportion of variance in DI scores across time points. These findings demonstrate both statistical and practical significance in the development of DI through SBL. Consistent with the competency findings, the significant F-values (**Table 4**) confirm that DI improved significantly following the intervention.

Table 3: Descriptive analysis of DI scores across three situations

Digital intelligence	Situation 1		Situation 3		Situation 5	
	Mean	SD	Mean	SD	Mean	SD
Digital identity	1.71	0.46	2.61	0.50	1.71	0.46
Digital use	1.39	0.50	2.29	0.46	1.39	0.50
Digital safety	1.58	0.50	2.58	0.50	1.58	0.50
Digital security	1.55	0.51	2.55	0.51	1.55	0.51
Digital emotional intelligence	1.29	0.46	2.45	0.51	1.29	0.46
Digital communication	1.23	0.43	2.45	0.51	1.23	0.43
Digital literacy	1.23	0.43	2.48	0.51	1.23	0.43
Digital rights	1.48	0.51	2.48	0.51	1.48	0.51
Overall	**1.43**	**0.30**	**2.51**	**Overall**	**1.43**	**0.30**

Table 4: Repeated-measures ANOVA of DI scores across three situations

Digital intelligence	Variance	SS	df	MS	F	sig	Results
Digital identity	Estimate	25.806	1	25.806	242.424	.001	5>3>1
	Error	3.194	30	0.106			
Digital use	Estimate	28.452	1	28.452	240.545	.001	5>3>1
	Error	3.548	30	0.118			
Digital safety	Estimate	29.823	1	29.823	243.289	.001	5>3>1
	Error	3.677	30	0.123			
Digital security	Estimate	28.452	1	28.452	130.345	.001	5>3>1
	Error	6.548	30	0.218			
Digital emotional intelligence	Estimate	38.726	1	38.726	307.821	.001	5>3>1
	Error	3.774	30	0.126			
Digital communication	Estimate	45.306	1	45.306	425.606	.001	5>3>1
	Error	3.194	30	0.106			
Digital literacy	Estimate	45.306	1	45.306	324.115	.001	5>3>1
	Error	4.194	30	0.140			
Digital rights	Estimate	32.661	1	32.661	255.252	.001	5>3>1
	Error	3.839	30	0.128			
Overall	**Estimate**	**34.875**	**1**	**34.875**	**608.285**	**.001**	**5>3>1**
	Error	**1.720**	**30**	**0.057**			

Overall, nursing students reported a very high level of acceptance toward SBL innovation in a changing technological context for enhancing professional competencies and DI (*M* = 4.52, SD = 0.49). Instructors demonstrated a very positive attitude toward the use of SBL innovation for enhancing nursing students' professional competencies and DI. The overall level of agreement was high (*M* = 4.69, SD = 0.49).

4.4 Research Results of Phase 4: The Diffusion of SBL Innovation in the era of Disruptive Technology to Enhance Nursing Students' Professional Competencies and DI

In Phase 4, experts evaluated the SBL innovation and rated it as highly appropriate (M = 4.76, SD = 0.20). Experts further confirmed that the model had well-structured components, clearly defined learning steps, and a transparent implementation process. Additional feedback highlighted the practicality of the system in terms of usability, guidelines, and assessment, supporting its feasibility for real-world implementation.

5. Discussion

The effectiveness of Nurse Sims as an SBL innovation can be explained by its needs-driven and theory-informed design. The system was developed to address nursing students' demand for flexible simulation environments that provide real-time feedback, opportunities for post-learning reflection, and pre-class preparation. Nurse Sims integrates IoT-enabled sensor technology and a web-based platform, enabling students to engage in realistic, technology-enhanced clinical practice in a controlled environment. The intervention was delivered through a 5P learning process grounded in active and collaborative learning principles. Through structured activities including brainstorming, discussion, peer interaction, and hands-on practice, students co-constructed knowledge while developing both professional competencies and DI. The significant improvements observed in outcomes, together with expert validation of feasibility, indicate that Nurse Sims provides a practical model for integrating SBL, humanoid technology, and collaborative learning in nursing education.

The findings are consistent with previous studies demonstrating the effectiveness of SBL in nursing education. Kuesakul et al. (2024) and Platt et al. (2024) reported that SBL improves students' satisfaction, attitudes toward simulation design, knowledge acquisition, and self-efficacy by enabling safe practice environments and immediate feedback. In addition, Saito and Dal Sasso (2023) highlighted that technology-supported simulation systems enhance instructional efficiency by standardizing simulation design and reducing educator workload. Collectively, these findings suggest that technology-enhanced SBL improves both learning and teaching management efficiency.

Evidence also supports the effectiveness of manikin-based and high-fidelity simulation in nursing education. Li et al. (2024) found improvements in cooperative ability, learning motivation, and self-management among nursing students. Simulation-based environments also enhance critical thinking, problem-solving, and situational awareness by exposing students to complex clinical scenarios requiring team coordination (Hill et al., 2023). Furthermore, Brohard et al. (2021) demonstrated that simulation allows safe practice of emotionally challenging clinical communication without risk to patients. The integration of mobile and web-based learning tools in this study aligns with previous findings. Raurell-Torredà et al. (2025) reported that mobile simulation platforms significantly increased student satisfaction and self-confidence compared to traditional methods. Similarly, Khoshbakht-Pishkhani et al. (2024) found improvements in cognitive skills following mobile-assisted learning interventions. Carvalho and Sousa (2024), in interviews with 10 nursing students in Portugal, further demonstrated that mobile applications can enhance student engagement and understanding of patient self-practices in chronic disease management.

Additionally, the results align with studies on digital competence in nursing education. Abou Hashish and Alnajjar (2024) reported positive student attitudes toward digital transformation and confidence in using AI-based tools. Jallad et al. (2024) found that contemporary nursing students frequently use digital tools, including mobile applications, simulation platforms, and generative AI, to support learning. Reed and Dodson (2024) further emphasized that digital storytelling and AI-based visualization tools improve engagement and comprehension among Generation Z learners.

6. Limitations

Despite the promising findings of this study, several limitations should be acknowledged. First, the absence of a control or comparison group limits the ability to draw causal inferences regarding the relative effectiveness of the Nurse Sims intervention compared with traditional teaching methods. Second, the relatively small sample size in the implementation phase (n = 31) may restrict the generalizability of the findings to broader nursing student populations. Future research should employ larger samples and randomized controlled designs to strengthen internal validation and further examine the long-term impact of simulation-integrated technologies in nursing education.

7. Recommendations

7.1 Recommendations for the Application of Findings

To enhance the effectiveness of using simulation robots, along with controlling equipment and sensors, it is recommended that these tools be used in conjunction with the Nurse Sims application. The platform supports efficient scenario design, activity organization, and structured facilitation by instructors, while enabling students to engage meaningfully with simulated clinical situations.

When using the robotic simulator with integrated sensor-controlled systems alongside the Nurse Sims application, adherence to the 5Ps instructional framework is recommended. This structured process supports the systematic development of nursing students' professional competencies and DI.

7.2 Recommendations for Future Research

Future research should explore the development of simulation-based innovations using pediatric patient simulations. Such expansion would better prepare nursing students for specialized clinical contexts and improve readiness for pediatric care delivery.

Future research should enhance the realism and complexity of simulation interactions by incorporating dynamic patient behaviors, including noncooperative patients and spontaneous learner–patient dialogue. This would broaden scenario variability and strengthen clinical decision-making skills.

Future research is encouraged to adopt more robust methodological designs, including longitudinal studies and cross-disciplinary replications, to validate findings and strengthen the generalizability of the Nurse Sims innovation across diverse educational and clinical contexts.

AI Statement: The authors declare that they have used AI tools to enhance the spelling and readability of this manuscript.

Ethics Statement: This study involved human participants. Ethical approval was obtained from the Chulalongkorn University Research Ethics Committee (Multi-Institutional Group 2: Social Sciences, Humanities, and Fine Arts; reference numbers 038/2021 and 080/2022). Written informed consent was obtained from all

participants for participation and publication, with assurances of anonymity. Throughout the study, strict adherence to privacy, data protection, and confidentiality protocols was maintained. All participant data were anonymized and securely managed, and no identifying information was disclosed in this publication.

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