Low-Cost Simulations and Augmented Reality: Enhancing Practical Learning in e-Learning Environments

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Abstract: This study aims to enhance engineering education by introducing a cost-effective simulation approach that combines cardboard prototyping and augmented reality (AR) as alternatives to traditional wood-based practice. The primary objective is to determine whether these tools can improve students' technical skills, work attitudes, and overall learning performance in woodworking design within a vocational education context. The study addresses a critical challenge in e-learning: providing interactive and tangible experiences without relying solely on digital devices or high-cost materials. The study comprised 76 second-semester students from a vocational engineering program, separated into Group A (conventional learning using wood) and Group B (simulation-based learning utilizing cardboard and AR integration). Both groups adhered to the Conceive–Design–Implement–Operate (CDIO) structure throughout their learning sessions. Quantitative data were gathered using structured observation rubrics that evaluated four primary indicators: technical execution, planning accuracy, collaboration, and professionalism. The findings indicate that Group B, which employed cardboard simulations augmented with AR overlays, attained an average performance score of 8607, in contrast to 7350 for Group A. Group B exhibited enhanced planning, lower error rates, and more robust work attitudes. Feedback obtained from reflection sheets corroborated pupils' enhanced comprehension of spatial concepts and safety protocols. This study advocates for e-learning methodologies by introducing a novel hybrid paradigm that integrates physical simulation with digital support via AR. It mitigates the shortcomings of entirely online or exclusively digital learning systems by incorporating physical, manipulable elements into the virtual learning experience. This method enables students to engage with tangible items while obtaining digital instruction, connecting cognitive design with physical implementation. This work enhances the e-learning sector by integrating accessible physical simulation with AR technology, presenting a practical model suitable for low-resource settings. It illustrates that practical, low-tech resources—when enhanced by smart digital integration—can yield quantifiable educational improvements and promote the cultivation of vital engineering skills.

Keywords: e-Learning, Cardboard simulation, CDIO method, Blended learning, Engineering education, Practical skills development, Digital learning integration

1. Introduction

Amidst global technological progress and changing industry demands, engineering education pedagogy is evolving to equip students for real-world difficulties more effectively (Forcael, Garcés and Lantada, 2023; Al-Zoubi *et al.*, 2024). This change is evident in frameworks like Conceive–Design–Implement–Operate (CDIO), which synchronize educational experiences with professional engineering methods (Tanveer and Usman, 2022; Lenin, Siva Kumar and Selvakumar, 2023). In vocational education, pedagogical approaches must be based on theoretical frameworks and practical, scalable, and economical methodologies (Kang, 2024; Younis, 2025). In light of these changes, incorporating simulations and active learning technologies is becoming progressively vital.

A significant issue in engineering education is the financial expense and safety limitations linked to conventional workshop-based teaching, particularly with wood, metal, or electrical materials (Sahoo, Saraf and Uchil, 2025). These issues are particularly salient in resource-constrained institutions. Simulation-based learning has been thoroughly examined, encompassing computer-based modeling and physical prototyping (Demirel, Ahmed and Duffy, 2022; Cascella *et al.*, 2023; Shahrezaei *et al.*, 2024; Sounthornwiboon, Sriprasertpap and Nilsook, 2025). Nonetheless, digital simulations frequently necessitate advanced gear and comprehensive training for educators and learners (Brunzini *et al.*, 2022; Weis *et al.*, 2024). Consequently, a hybrid strategy employing economical physical media emerges as a pertinent answer.

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Despite extensive research on simulation and engineering pedagogy, scant attention has been afforded to cardboard prototyping as a simulation medium for engineering design within woodcraft education. Cardboard provides the benefits of being economical, lightweight, secure, and readily manipulable with basic tools (Sapienza *et al.*, 2022; Venkatesan *et al.*, 2023). These attributes are appropriate for introductory design training and quick prototyping, particularly in vocational settings.

This project tackles a significant pedagogical deficiency: enhancing student learning outcomes in wood-based design via simulation without dependence on expensive or hazardous materials. The subsequent research questions have been formulated:

- How does using cardboard-based simulation influence students' design performance and problem-solving in woodworking education?
- What differences in work attitude and craftsmanship can be observed between students using simulation-based tools and those applying direct wooden materials?
- To what extent does using simulation (cardboard) improve planning accuracy and professional behavior in workshop-based learning?

This research advances engineering education by showcasing an innovative, scalable simulation technique that uses cardboard as a substitute for timber components in vocational training. It also presents a preliminary AR integration to facilitate visual verification throughout the design phase. The proposed method seeks to connect digital learning with practical application, offering a cost-efficient, safe, and pedagogically robust option for developing technical skills.

2. Literature Review

The gap between theoretical knowledge and practical application is a well-known challenge in engineering education (Bühler, Jelinek and Nübel, 2022). Students often struggle to translate abstract design concepts into tangible, real-world products that meet professional standards (ElSayary, 2025). This disconnect can hinder their ability to effectively implement design ideas in practice, particularly in fields where hands-on skills are critical. Numerous studies have documented this issue, emphasizing the importance of developing teaching methodologies that allow students to bridge this gap more effectively (Resch and Schrittesser, 2023; Al-khresheh, 2024). While valuable for building foundational knowledge, traditional methods frequently fail when equipping students with the practical skills they need to succeed in the engineering industry (Malhotra, Massoudi and Jindal, 2023). As a result, there is a growing recognition of the need for educational strategies that balance theoretical instruction with experiential learning (Salinas-Navarro *et al.*, 2024), helping students to grasp the complexities of real-world engineering problems better.

One of the most widely explored solutions to this challenge has been using digital simulations, which provide students with virtual environments to interact with complex design tasks. These tools have improved students' understanding of engineering concepts by allowing them to visualize and manipulate models in a controlled setting—digital simulations, as highlighted by Rodríguez-Abitia et al. (2020), have become invaluable in helping students tackle complex engineering problems without the need for expensive physical materials. However, these tools come with significant financial and technical burdens. Many educational institutions, particularly those with limited resources, struggle to implement advanced simulation software due to the high acquisition, maintenance, and training costs required for both instructors and students. Additionally, the absence of physical interaction in these virtual environments can limit students' ability to develop crucial hands-on skills in disciplines like woodworking and mechanical engineering, where material properties and tactile feedback are essential for mastering practical techniques. Educators have sought more accessible, hands-on alternatives to supplement or replace digital tools.

2.1 The Role of Simulations in Engineering Education

Digital simulations have become essential in modern engineering education, providing students with immersive virtual environments to explore complex designs and engineering concepts. These simulations, as highlighted by Zhang et al. (2023), allow students to visualize and manipulate digital models of projects, offering insights into processes like construction, assembly, and systems operation. In fields like civil, mechanical, and electrical engineering, where theoretical knowledge is often abstract, simulations help bridge the gap by offering real-time feedback and experimentation. Students can engage in tasks such as stress testing, fluid flow analysis, or circuit design in ways that would be difficult or impossible in traditional classroom settings (Portillo *et al.*, 2025).

These tools allow for iterative testing, enabling students to modify their designs quickly and explore multiple scenarios without the risk and expense of physical materials.

However, digital simulations have notable limitations despite their benefits, especially regarding tactile and hands-on skills. As Ferguson et al. (2022) pointed out, the absence of physical interaction in virtual environments makes them less effective for skills like woodworking or mechanical engineering, where direct contact with materials is essential for mastering the craft. In fields requiring precise manual dexterity and material manipulation, such as carpentry or machining, the lack of haptic feedback can hinder the development of essential practical skills. Students may become adept at navigating digital environments but struggle when transitioning to real-world scenarios, where the physical properties of materials—such as weight, texture, and resistance—play a significant role in the success of a project.

In addition to their limitations in tactile learning, digital simulations often present challenges regarding accessibility and cost. As noted by Hippe et al. (2020), the financial investment required for advanced simulation software and the hardware needed to run these programs can be prohibitive for many educational institutions. The steep learning curve associated with these tools also requires significant time and resources for instructors and students to master the technology. This complexity, combined with the costs of purchasing and maintaining the necessary equipment, creates barriers to widespread adoption, particularly in resource-limited settings. These drawbacks highlight the need for alternative, more affordable simulation methods to complement or replace digital tools, especially in hands-on disciplines like woodworking.

2.2 CDIO Approach in Engineering Education

The Conceive, Design, Implement, Operate (CDIO) framework has gained recognition as a comprehensive methodology for enhancing engineering education by offering a structured approach that mimics real-world product development. By focusing on the complete lifecycle of a project, the CDIO model enables students to move beyond theoretical learning to practical application, fostering a deeper understanding of both design and implementation (Shuhaiber and Aldwairi, 2023). In the Conceive phase, students generate ideas and identify a project's needs, allowing them to develop problem-solving skills early on. During the Design phase, students create detailed plans and technical specifications, preparing them for the implementation phase, where they turn their designs into tangible products. The final operation phase involves testing and assessing the functionality and sustainability of their creations, ensuring they meet real-world demands and standards.

One of the key advantages of the CDIO approach is its emphasis on hands-on learning and experiential education. As Suksong et al. (2023) have demonstrated, this model not only enhances technical skills but also promotes the development of critical soft skills such as teamwork, communication, and project management. The collaborative nature of CDIO encourages students to work in teams, mimicking the dynamic environments of professional engineering projects. This teamwork aspect is especially beneficial in preparing students for the industry, where interdisciplinary collaboration is often necessary to solve complex problems. Furthermore, by allowing students to engage in the full cycle of product development, CDIO instills a sense of ownership and responsibility for the outcome of their projects, which can significantly improve their confidence and readiness for the professional world.

Previous research has shown that the CDIO framework significantly improves students' technical abilities and understanding of the product creation process (Suksong, Chomsuwan and Suamuang, 2023). Additionally, studies have demonstrated that practical simulations and structured project phases enhance students' ability to conceive, plan, and execute complex engineering tasks (Yang and Zhou, 2023). However, these studies often emphasize expensive digital tools, leaving a gap in the literature for more accessible and economical approaches to replicating real-world engineering assignments (Song, 2022). This research addresses this gap by introducing a novel method integrating cardboard simulations within the CDIO framework to teach woodworking skills.

While the CDIO framework has been extensively applied in mechanical and electrical engineering fields, its application to more craft-oriented disciplines, like woodworking, is relatively underexplored. Woodworking, which requires a high degree of manual skill and material familiarity (Lee, 2023), can benefit from CDIO's structured approach but also faces unique challenges in integrating this methodology. Incorporating physical simulations, such as using cardboard models, provides an innovative adaptation of CDIO to woodworking education, offering students a hands-on experience that aligns with the framework's emphasis on real-world application. This study explores how this adaptation can enhance woodworking education by providing the conceptual and practical skills needed for the industry.

2.3 Cardboard Simulations in Woodworking Education

Physical simulations, such as cardboard models, have emerged as a promising solution to some of the challenges associated with digital simulations and traditional teaching methods in woodworking education. Unlike digital simulations, which may lack the tactile feedback crucial for mastering manual skills (Singhaphandu *et al.*, 2024), cardboard simulations allow students to engage with their designs physically, better understanding spatial relationships, material properties, and construction techniques (Seiringer *et al.*, 2022). By working with cardboard, students can experiment with scale models of their projects, cutting, folding, and assembling the material to mimic the processes they will use with wood. This hands-on approach provides a low-risk environment where mistakes can be made and corrected without the expense of wasted wood (Suckling *et al.*, 2024), enabling students to refine their designs and improve their craftsmanship.

One of the primary benefits of using cardboard for simulations is its accessibility. As Song (2022) points out, cardboard is a readily available, inexpensive material, making it a practical option for educational institutions with limited budgets. It offers a sustainable alternative to wood, which can be costly and environmentally taxing, particularly for large-scale projects. Furthermore, cardboard is easy to manipulate, allowing students to modify their designs quickly and iterate on their ideas. This flexibility is crucial in the learning process, as it encourages creativity and problem-solving while reinforcing the technical skills required for woodworking. By integrating cardboard simulations into the CDIO framework, educators can offer a comprehensive learning experience that includes conceptual and practical aspects of engineering design.

Despite its advantages, cardboard simulations also have certain limitations that must be addressed. While they offer an effective way to simulate design and construction processes, cardboard lacks wood's structural integrity and material properties, meaning that students may not fully grasp the challenges they will face when working with actual timber. The time and effort required to create accurate cardboard models can also be significant, particularly for complex designs. However, reduced material costs, enhanced student engagement, and improved learning outcomes make cardboard simulations valuable in woodworking education, particularly when used with other hands-on learning methods. This study aims to evaluate the effectiveness of cardboard simulations within the CDIO framework and assess their impact on students' technical skills, creativity, and readiness for professional woodworking tasks.

2.4 VR vs. Hands-On Simulations

VR and hands-on simulations represent two prominent yet fundamentally different approaches to experiential learning for engineering education (May *et al.*, 2023). Both systems seek to reconcile theoretical knowledge with practical abilities; nevertheless, they markedly differ in sensory engagement, accessibility, cost, and educational outcomes.

From a cognitive engagement standpoint, VR provides an immersive digital world where students can navigate three-dimensional locations, mimic intricate operations, and obtain real-time feedback (AlGerafi *et al.*, 2023; Song, Shin and Shin, 2023). This digital immersion improves conceptual comprehension, particularly in abstract subjects such as stress analysis or circuit logic. Nevertheless, it frequently lacks haptic input, essential for cultivating fine motor skills and tactile awareness required in woodworking or mechanical activities. In contrast, tactile simulations—like cardboard prototyping—enable learners to interact with materials directly, enhancing kinaesthetic learning and spatial reasoning (Nazlidou *et al.*, 2024). This approach improves skill and practical insight, which are challenging to reproduce in a digital setting.

Regarding cost and accessibility, hands-on simulations like cardboard modeling are considerably more economical. Institutions can implement these strategies without investing in advanced VR technology or complex infrastructure. Physical simulations are especially beneficial in resource-constrained environments where digital fairness is ongoing (Kamdjou *et al.*, 2024). Conversely, VR entails substantial initial headgear, software, and training expenditures. Maintenance and upgrades hinder widespread application (Iqbal *et al.*, 2024).

From an instructional design perspective, VR provides scenario-based learning and virtual experimentation. It enables students to participate in repeatable, secure simulations replicating hazardous or high-stakes engineering activities. Nonetheless, as indicated in previous research, the lack of actual engagement may lead to shallow learning when the objective is to create physical objects (Wong and Liem, 2022). Practical methods, however, constrained in scenario adaptability, offer concrete problem-solving experiences—allowing learners to handle actual materials, identify manual errors, and progressively enhance their techniques.

The transferability of skills is another significant factor to consider. VR assists students in acclimating to digital tools and workflows prevalent in contemporary business, including CAD integration and virtual prototyping, thus augmenting their digital literacy. Conversely, practical simulations enhance physical dexterity, precision, and meticulousness, essential in craft-oriented and material-centric fields.

Numerous academics have advocated for integrated methodologies that merge the advantages of VR and practical simulations (Solmaz *et al.*, 2021; Abbas Shah *et al.*, 2024). To improve realism and immersion, cardboard simulations can be enhanced with AR overlays or virtual validation processes. These hybrid approaches demonstrate the potential to deliver a well-rounded educational experience that is both digitally proficient and substantively anchored.

The theoretical comparison of VR with hands-on simulations indicates a complementing relationship rather than a competitive one. Although VR excels in replicating intricate systems and surroundings, practical simulations are crucial for developing physical skills and enhancing tactile cognition. Optimal engineering education may benefit from strategic integration, contingent upon learning objectives, institutional capacities, and discipline-specific prerequisites (Beldad and Miedema, 2025).

3. Method

This study employed a mixed-method approach, combining both qualitative and quantitative data (Matović and Ovesni, 2023) to thoroughly assess the effectiveness of cardboard simulation in developing woodworking skills using the CDIO framework. The research was conducted over two months at Nusa Cendana University, with participants drawn from the Wood Practice course. Two groups of students were involved: Group A, which followed traditional woodworking methods, and Group B, which utilized cardboard simulations before working with wood. Seventy-six students participated in the study, with 36 students in Group A and 40 in Group B. Both groups were tasked with designing and constructing a bookshelf, following the exact technical specifications.

Each group was evaluated based on their performance across four distinct phases: product design, product manufacture, work attitude, and product assessment. These phases were chosen to reflect key CDIO framework aspects, ensuring that conceptual and practical competencies were adequately assessed (Alarcon-Pereira *et al.*, 2023). A detailed evaluation rubric assessed student performance in each phase, covering technical accuracy, creativity, teamwork, and problem-solving abilities. This comprehensive evaluation allowed for a deeper understanding of how cardboard simulations impact different facets of the woodworking process.

3.1 Research Design

The research was structured around the CDIO methodology (Martseva *et al.*, 2021). In the Conceive phase, students from both groups were asked to generate design ideas for a bookshelf with a branching structure, which would be produced during the later stages. This phase focused on creativity and innovation, with each group tasked with developing technical blueprints and preparing for the manufacturing phase. Group A moved directly from the design to the manufacturing stage using wood. At the same time, Group B utilized cardboard to simulate the design before moving to actual wood. In the Design phase, Group A created traditional technical drawings. In contrast, Group B first designed a scaled-down prototype using cardboard. The prototype allowed them to test the construction process and make necessary adjustments before working with wood. This approach gave Group B a hands-on, experimental opportunity to address potential issues in design, such as structural integrity or alignment problems, which they could rectify in the cardboard simulation (Hariharasakthisudhan *et al.*, 2025). This additional step aimed to reduce material wastage and improve final product quality in the later stages. Table 1 provides an overview of the research stages and their descriptions, outlining the tasks assigned to each group during each phase of the study.

Table 1: Research Stages and Their Descriptions

Stage	Group A Task	Group B Task
1. Conceive	Brainstorm design ideas and create technical drawings for bookshelves.	Brainstorm design ideas and create technical drawings for bookshelves.
2. Design	Create technical drawings and detailed specifications for wood products.	Design and construct cardboard models before finalizing technical drawings.
3. Implement	Build bookshelves using wood based on technical drawings.	Use cardboard prototypes to build the final bookshelf with wood.
4. Operate	Evaluate final product quality, structural integrity, and aesthetics.	Evaluate final product quality, structural integrity, and aesthetics based on prototype.

3.2 Participants and Sampling

The participants in the study were undergraduate students enrolled in the Wood Practice course at Nusa Cendana University. A purposive sampling method was used to ensure a balanced and representative sample (Zhao, 2021). Both groups included students with varying levels of prior experience in woodworking. Before the experiment, a pre-test was administered to gauge students' baseline knowledge and technical skills, ensuring comparability between Group A and Group B. This pre-test covered basic woodworking concepts like material selection, tool usage, and safety procedures.

Group A consisted of 36 students who worked solely with wood throughout the project. Group B, with 40 students, used cardboard to simulate their designs before transitioning to wood. Demographic data such as age, gender, and previous woodworking experience were collected to control for variables affecting performance. These variables were analyzed to ensure that no significant differences between the groups could skew the results.

3.3 Materials and Tools

Group A utilized traditional woodworking materials and tools such as saws, chisels, drills, and sandpaper to craft their bookshelves. The wood used was pre-specified in the design brief, ensuring uniformity in material selection across the group. Students were expected to follow the technical drawings they created in the Design phase and construct the bookshelf without any prior physical simulation. This group focused on directly translating conceptual designs into wooden structures.

Group B, on the other hand, first constructed their bookshelves using cardboard sheets, glue, tape, scissors, and box cutters. The cardboard simulation allowed them to prototype their designs in a less costly and more forgiving medium before moving on to wood. This allowed Group B to experiment with different techniques for creating wood joints and connections and test the overall stability and appearance of their designs. Once satisfied with the cardboard prototype, students transitioned to wood for the final construction. This approach was expected to reduce material wastage and improve the precision of the final product (Clancy, O'Sullivan and Bruton, 2023). Table 2 shows a detailed breakdown of the materials and tools used by each group, along with the evaluation criteria for assessing tool use and material handling.

Table 2: Materials and Tools Used by Each Group and Evaluation Criteria

Group	Material/Tool	Evaluation Criteria
A	Wood	Quality of wood preparation
A	Saw	Precision in cutting
A	Chisel	Skill in using chisels for joints
A	Drill	Accuracy in drilling
B	Cardboard	Accuracy in simulating design
B	Glue	Effectiveness in assembling
B	Scissors	Precision in cutting cardboard
B	Box Cutter	Safety and precision in cutting

This study mostly centers on cardboard simulations. However, an AR support pilot was implemented using a mobile-based AR viewer created with Unity and the Vuforia SDK. This AR component enabled students in Group B to scan their cardboard models using smartphones or tablets, receiving digital overlays with construction instructions and dimensional accuracy (McCord *et al.*, 2022). The technology delivered instantaneous feedback on prevalent faults (misalignment and joint gaps) using object identification markers affixed to the prototype. This experimental feature facilitated improved spatial verification and directed learning. The AR implementation was restricted to visualization and instructional overlays rather than comprehensive digital prototyping. It was utilized to augment design understanding during the "Design" and "Operate" phases of the CDIO cycle.

3.4 Procedure

The study adhered strictly to the CDIO framework, ensuring students engaged in all four stages: Conceive, Design, Implement, and Operate. During the Conceive phase, students were introduced to the design brief. They were encouraged to brainstorm creative solutions for the bookshelf design. In the Design phase, Group A created detailed technical drawings of their bookshelf. At the same time, Group B followed a similar process but then proceeded to build a scaled cardboard prototype. This simulation phase allowed Group B to identify potential design flaws, such as weak joints or unbalanced structures, and rectify these issues before working with wood.

In the implementation phase, both groups built their bookshelves. Group A worked directly with wood, while Group B transitioned from cardboard models to wood. The operation phase involved evaluating the final product. The assessment focused on several factors: structural integrity, aesthetic quality, and project completion time. Both groups were also evaluated on their work attitude, including teamwork, adherence to safety protocols, and problem-solving abilities. Table 3 outlines the assessment components and indicators used in the evaluation process. These criteria were applied consistently to both groups to ensure an objective performance comparison.

Table 3: Assessment Components and Indicators

Stage	Assessment Components	Indicators
Design	Product drawing, working drawings, simulation accuracy (Group B)	Accuracy of design drawings, completeness of details, simulation correctness
Product Manufacturing	Tool preparation, material preparation, cutting, and assembly accuracy	Efficiency in preparation, precision in cutting, assembly neatness
Work Attitude	Collaboration, discipline, honesty, responsibility	Level of collaboration in groups, adherence to project deadlines, integrity
Product Assessment	Product presentation, final product quality, adherence to specifications	Overall product quality, structural integrity, time management

3.5 Data Collection

Data were collected through objective product assessments, observational data, and self-reported student experiences. The objective evaluations focused on the quality of the final bookshelf, with specific attention to technical accuracy, adherence to design specifications, and material wastage (Li, Xiong and Qu, 2023). Students' work attitude, including teamwork, discipline, and responsibility, was also evaluated through observational data recorded by the instructors during the manufacturing process. This data was complemented by post-test scores, which assessed students' technical knowledge at the end of the project.

In addition to quantitative data, qualitative data were gathered through semi-structured interviews and questionnaires. Students were asked to reflect on their learning experiences, challenges, and perceptions of the cardboard simulation. These qualitative responses were coded thematically to identify common themes related to the usefulness of the cardboard simulation, the ease of transitioning from cardboard to wood, and any perceived improvements in problem-solving and technical skills.

3.6 Assessment and Evaluation

The assessment rubric used in this study included several categories: design accuracy, material preparation, construction technique, finishing quality, and work attitude (Amarasinghe, Hong and Stewart, 2024). Each category was rated on a scale from 1 to 5, with specific benchmarks for each score. For instance, a 5 in design accuracy score was given if the final product closely matched the original technical drawing. In contrast, a lower score indicated significant deviations. In addition to assessing the final product, teamwork and time management were also evaluated as part of the rubric, recognizing the importance of these skills in engineering education.

For Group B, an additional evaluation was conducted on their cardboard prototypes. This evaluation focused on the accuracy of the prototype compared to the final product, the insights gained during the simulation phase, and how effectively these insights were applied in the wood construction phase. The results from both groups were compared to determine whether the cardboard simulation had a measurable impact on the quality of the final product and the student's learning experience.

3.7 Data Analysis

Quantitative data were analyzed using statistical methods, including t-tests and ANOVA (Liu and Wang, 2021), to determine if there were significant differences in the performance outcomes between Group A and Group B. These tests helped identify whether the use of cardboard simulation had a statistically significant effect on the quality and efficiency of the final products. In addition to product assessment, data from the post-tests were also analyzed to measure the improvement in technical knowledge among students in both groups.

Qualitative data from the interviews and questionnaires were analyzed using thematic coding (Anderson *et al.*, 2022). The responses were categorized based on recurring themes, such as the perceived usefulness of the cardboard simulation, the challenges faced in transitioning from cardboard to wood, and the overall learning experience. This qualitative analysis provided valuable insights into how students felt about using simulation in woodworking education and its impact on their confidence and technical abilities.

Group A and B's comparative analysis yields significant insights. However, scientists recognize that cardboard and wood possess inherently distinct physical features. The investigation concentrated on the final product performance and process-based variables, including planning quality, tool preparation, and error reduction during execution. The evaluation criteria were modified to prioritize design precision and problem-solving in the initial stages, where material differences were less significant. This method facilitated a more equitable evaluation of cognitive and procedural learning outcomes, as opposed to solely material-dependent craftsmanship.

4. Results and Discussion

The study's findings are categorized into three groups: the researchers' assessment of student practical competence and the students' appraisal of wood product competency. Students were instructed to explain their response choices. Table 4 compares grades and items generated by classes A and B.

Table 4: Assessment results of making wood products

Stages	Assessment Components	Indicator	Group A	Group B
1	2	3	4	5
Stage 1 Product Feasibility Study - R&D **II**	Planning the task (Score 10%)	Drawing Product design Making working drawings (appearance - detail) Making pictures projection	76,60 78,50 74,50	76,50 78,50 76,80
	Mean value I		76,53	77,27
	Make a wood product task simulation (Score 20%)	2.1 Prepare cardboard boxes, glue, insulation, scissors, cutters, etc.	0,00	80.60
		2.2. Construction drawing in cardboard	0,00	78,20
		2.3. Cut the cardboard accordingly Image	0,00	74,60
		2.4 Assemble simulation products		
		2.5. Correctness of measure	0,00	78,80
		2.6. Correctness of construction	0,00	80.40
		2.7. Simulation time and results	0,00	78,80
Average value II			0,00	77,60
Stage 2 Product Manufacturing	Preparation of tools and materials (Score 10%)	3.1. Preparing the workplace	75,00	75,00
		3.2. Prepare tools and machine	72,00	78,00
		3.3. Preparing materials		
		3.4. Preparing tools	78,00	78,00
		work safety	72,00	82,00

Stages	Assessment Components	Indicator	Group A	Group B
1	2	3	4	5
Average value III			74,25	78,25
IV	Process (Systematics and Way of Working) (Score 20%)	4.1. Measuring materials	72,00	78,00
		4.2. Construction drawing in wood	72,60	78,60
		4.3. Correctness of construction	73,00	84,00
		4.4. Cutting, sawing, smoothing wood	76,00	84,00
		4.5. Assembling the product	74,80	86,40
		4.6. Tidying up the product	65,00	84,80
		4.7. Initial finishing of the product (smoothing, smoothing, caulking, polishing)	74,00	84.00
Average score IV			72,49	82,63
V	Wood product results and presentation (30% score)	5.1. Conformity of drawings to wood products	74,00	84,00
		5.2. Correctness of size and construction	72,00	88,00
		5.3. Product robustness	70,70	86,80
		5.4. Final finishing	74,40	88.80
		5.5. Time to complete the task	74,80	86,40
			72,00	85.00
Mean value V			72,98	87,07
	Product presentation (10% score)	6.1. Make a product report	78,00	86.00
		6.2. PPT making	82,00	85,00
		6.3. Task Presentation	76,00	86,00
		6.4. Answering questions from lecturers and students	76,00	84,00
			78,00	85,00
VI	Work Attitude (Maximum score 10)	6.1. Cooperation	72,00	84,60
		6.2. Discipline	72,00	86.80
		6.3. Hard work	74,00	88,60
		6.4. Honest	75,00	80.20
		6.5. Responsibilities	80,00	85,00
VI average value			74,60	86,07

Table 4 demonstrates Group B's superiority over Group A due to using cardboard simulations. During the product design stage, group B exhibited higher average scores in task planning and modeling the wood product work. This demonstrates that the cardboard simulation enhanced students' ability to visualize and engage in more intricate and meticulous planning (Chisunum and Nwadiokwu, 2024). Group B demonstrated exceptional performance in preparing tools and materials and the working process, achieving average scores of 7825 and 8263, respectively. This indicates that the cardboard simulation offers a superior comprehension of the necessary equipment and supplies and more organized and effective work procedures (Špirková, Straka and Saniuk, 2024). This demonstrates that using simulation can minimize inaccuracies and enhance work efficiency.

Furthermore, regarding the product results, group B exhibited superior scores in fit, sturdiness, and finishing, averaging 8707, as opposed to group A's average of 7298. This implies that using simulated cardboard contributed to creating a superior end product in terms of quality and aesthetics. The work attitude of Group B was exceptional, as evidenced by their average score of 8607. This indicates a higher level of discipline, collaboration, and responsibility. These results demonstrate that the cardboard simulation serves as both a visual assistance and a successful tool for enhancing students' technical skills, work processes, and professional attitudes in wood practice (Ortega-Gras *et al.*, 2023).

This study primarily concentrated on low-cost physical simulations utilizing cardboard while investigating an initial incorporation of AR support. A mobile AR viewer was utilized in a pilot study to enable students to superimpose digital guidelines over their cardboard prototypes. This technology, developed using Unity and Vuforia, allowed students to visualize assembly instructions and verify their designs in real-time (Kumar, Mantri and Dutta, 2021). While not a fundamental element of the primary intervention, the AR-assisted simulation effectively enhanced spatial comprehension and increased assembly accuracy. Future implementations may evolve this component into a comprehensive educational module, facilitating enhanced interaction between physical models and digital overlays.

Nevertheless, caution is warranted when assessing direct performance comparisons due to the intrinsic disparities in material properties between cardboard and wood. The results are more accurately interpreted as enhancing planning, visualization, and process precision rather than directly assessing physical production quality. Figure 1 displays both the simulation product and the final wood practice piece.

Figure 1: Simulation Results of the Cardboard

Figure 1 displays the outcomes of a simulation, including using cardboard to imitate a wooden product. Within the CDIO framework, this pertains to the "Conceive" and "Design" stages. During the "Conceive" phase, students engage in the process of conceptualizing and creating concepts for wood goods. They engage in sketching product designs and producing detailed technical drawings. During the "Design" step, the idea is transformed into an early physical representation using cardboard. This simulation enables them to assess the concept and design before moving forward with the physical wood substance. This minimizes the likelihood of design mistakes and guarantees the accuracy of all building components before subsequent execution. Moreover, employing cardboard for simulation is a cost-efficient and highly adaptable method, facilitating rapid and successful design iterations, , as demonstrated in the final product shown in Figure 2.

Figure 2 depicts the ultimate wooden product resulting from the implementation and operating process. This refers to the "Implement" and "Operate" stages of CDIO. During the "Implement" phase, students gather and organize the necessary equipment and materials and adhere to structured and methodical working methods. The cardboard prototype seen in Figure 1 provides a step-by-step demonstration of the precise actions involved in cutting, assembling, and refining the wooden product. This phase encompasses all the operations involved in the process, starting from cutting the wood, making the pieces, and concluding with the last finishing touches, such as polishing the surfaces and applying a protective coating. During the "Operate" phase, the completed wood items are assessed based on their functionality and appearance. Students showcase their final deliverables, demonstrating their ability to fulfill customer requirements and adhere to high-quality benchmarks. The superiority of group B, as shown by the cardboard simulation, was visible in the high quality and efficiency of their process and the superior end product they produced. The strengths and weaknesses of each CDIO phase, as observed in this study, are summarized in Table 5.

Figure 2: Bookshelf product

Table 5: Strengths and weaknesses of the study

Aspects	Pros	Disadvantages
Conceive	• Make it easier to visualize design ideas and concepts. • Reduce the risk of errors in the early stages of planning.	• Requires additional time to make simulations before making the actual product.
Design	• It provides an opportunity to refine and perfect the design before implementation. • Cardboard is cheaper and easier to modify than wood.	• It does not entirely reflect the actual strength and material characteristics of wood.
Implement	• Provides clear guidance for the cutting and assembly process. • Reduce technical errors in product manufacturing and improve artistry efficiency.	• Additional skills are required to create accurate and detailed simulations.
Operate	• The final product results are better in terms of quality and aesthetics. • Promote a more disciplined and collaborative work attitude.	• Simulations cannot thoroughly test the durability and performance of the product under actual use conditions.

Table 5 demonstrates that although cardboard simulation entails certain disadvantages, such as the requirement for extra time and specialized expertise, its benefits in streamlining visualization, enhancing efficiency, and generating superior quality goods are substantial. The limitations can be solved via training and knowledge, rendering cardboard simulation an invaluable tool in engineering education and product creation.

Student feedback on implementing the CDIO approach in the practical application of bookcase production using cardboard simulations. The favorable feedback from students emphasized the notable advantages of utilizing this simulation, such as the capacity to more effectively strategize and evaluate the product before commencing actual production. Additionally, they highlighted that using cardboard decreased manufacturing errors, enhanced the preparation of all materials, and accelerated production time and product completion. Furthermore, the end outcome of the bookshelf product created utilizing simulated cardboard is asserted to be superior, and the time needed is more optimized. The responses to the pupils' inquiries are seen in Table 6.

Table 6: Question Answers to Students

No.	Aspect Answer	Classification
1.	Make it easier for students to apply drawing plans to simulated cardboard products.	Positive
2.	Students better understand the final product that needs to be done.	Positive
3.	Students can better analyze the steps that must be done first, thus reducing errors.	Positive
4.	It is easier for students to replace the cardboard if they make size, cutting, or assembly mistakes.	Positive
5.	Reduce errors in work because you have prepared all the materials and work steps.	Positive
6.	Save time by doing the initial finishing before the wood is assembled.	Positive
7.	Assembling wood is faster because all parts are already prepared with the right size and construction.	Positive
8.	Removing and gluing wooden joints is faster because the construction is done correctly.	Positive
9.	The final finishing is done faster because of the pre-finishing before the wood assembly.	Positive
10.	The results of the bookshelf product are better, and the time required is faster.	Positive
11.	Students completed making a branching bookshelf faster and with better results.	Positive
12.	It takes 1 - 2 weeks to make a simulation by disassembling the parts of the bookshelf.	Negative
13.	Thin cardboard is not good because it is not as rigid as wood.	Negative
14.	It costs more to use cardboard, paper glue, and cutters.	Negative
15.	The simulation must be made correctly, as it will be the same as the resulting wood product.	Negative

Conversely, pupils who responded negatively emphasized the difficulties and disadvantages they encountered when using the cardboard simulation. It was observed that constructing the simulation involved more significant effort (Seiringer *et al.*, 2022) and intricacy in dismantling the cardboard bookshelf components. Furthermore, thin cardboard was deemed inadequate due to its lack of rigidity compared to wood and the added expenses associated with acquiring old cardboard, paper glue, and other necessary equipment. However, the data presented in this table indicates that despite a few challenges, the utilization of cardboard simulation offers numerous substantial advantages in both the educational experience and the enhancement of students' hands-on abilities in woodworking.

The CDIO idea is methodically employed in industry to create new goods that effectively fulfill market demands with superior quality and maximum production efficiency. The Conceive stage encompasses identifying the target market and conducting thorough trend research (Zabalawi, Kordahji and Mourdaa, 2022). This is followed by the Design stage, where Computer-Aided Design (CAD) software is utilized to create the product design. Additionally, digital simulations are performed to provide initial validation of the design (Wagg *et al.*, 2020). Implementation encompasses the process of manufacturing according to design specifications with rigorous quality control measures. On the other hand, the operation stage concentrates on conducting final testing, facilitating distribution, and providing customer support to guarantee optimal product performance and responsiveness to market feedback. This stage supports ongoing innovation and enables a quick time-to-market.

4.1 Enhancing Simulation-Based E-Learning with Augmented Reality (AR) and Interactive Digital Guides

Incorporating AR and interactive digital aids into simulation-based e-learning offers a revolutionary prospect for engineering and vocational education. Although physical simulations like cardboard modeling give beneficial practical experience, their efficacy can be improved by integrating AR technologies that deliver interactive overlays, instantaneous feedback, and customizable learning trajectories. By integrating these methodologies, students can cultivate technical competencies and digital literacy, equipping them for the industry's increasing requirements.

AR improves visualization by enabling students to superimpose 3D models over their physical simulations. Students can scan their cardboard prototypes using AR-enabled programs and obtain immediate advice on assembly methods, structural integrity, and design precision. This function mitigates prevalent errors during the first learning phase, lowering material loss and enhancing the quality of the final output (Joseph Nnaemeka Chukwunweike *et al.*, 2024). Furthermore, AR allows students to investigate alternate designs, examine cross-sectional details, and engage with virtual components before utilizing actual materials. This digital support layer facilitates a comprehensive comprehension of woodworking principles while preserving the advantages of practical experience.

Integrating interactive digital aids enhances the learning experience by offering organized, self-directed training. These guides may encompass video demonstrations, sequential lectures, and AI-powered assessment tools that monitor student progress and offer tailored recommendations. By including these components, students can obtain immediate feedback on their assignments, enhancing their capacity to recognize and rectify errors autonomously. Moreover, digital guides facilitate flexible learning, enabling students to interact with course materials remotely and enhancing e-learning accessibility.

Integrating AR with physical simulators fosters a more immersive and practical educational experience. Conventional cardboard models provide an economical method for design and assembly practice; however, when enhanced with AR overlays, they transform into potent instruments for interactive education. This method enables students to acquire immediate insights into their work while preserving the advantages of hands-on interaction. It also equips them for professional settings where digital technologies are progressively incorporated into engineering and manufacturing processes.

Notwithstanding its benefits, the execution of AR-assisted learning presents obstacles. Creating AR material necessitates technology infrastructure, software enhancements, and training for students and educators. Certain institutions may have financial limitations in implementing these technologies, requiring scalable and economical solutions like mobile-based AR apps. Moreover, it is essential to meticulously address the cognitive burden of transitioning between physical and digital worlds to guarantee a seamless and successful learning experience.

Integrating AR and interactive digital guides into simulation-based e-learning enables educational institutions to establish a more immersive and flexible learning environment. This integrated method increases student involvement, boosts error identification, and facilitates autonomous learning, ultimately elevating skill mastery. Future studies should examine the enduring effects of AR-assisted physical simulations on student performance and industry preparedness and assess the scalability of these technologies across various educational environments.

4.2 Comparison of Cardboard Simulations, Augmented Reality (AR), and Hybrid AR-Cardboard Approaches

The swift advancement of technology in education has resulted in several simulation-based learning methodologies designed to augment student engagement and enhance skill acquisition. In engineering and vocational education, conventional hands-on training techniques are progressively enhanced by digital tools, such as AR, to foster more engaging and immersive learning experiences. Although physical simulators, such as cardboard models, offer economical and hands-on educational experiences, they may be deficient in the technical advancements required for precise learning and immediate feedback. In contrast, AR-based simulations provide highly dynamic environments but frequently fail to accurately replicate the physical limitations and human dexterity necessary for real-world applications.

A hybrid strategy that combines cardboard simulations with AR technology has emerged as a possible way to address these gaps (Iqbal, Mangina and Campbell, 2022). This combination utilizes the advantages of tactile material interaction alongside digital overlays for improved visualization, evaluation, and direction. This review examines the advantages and limitations of three techniques in engineering education: cardboard-only simulations, AR-based learning, and hybrid AR-cardboard integration. The analysis evaluates factors such as cost, engagement, error detection, scalability, and industry preparedness to ascertain which method provides the most efficient and accessible learning experience. Table 7 presents a comprehensive comparison analysis of these three learning methodologies, emphasizing their advantages and disadvantages across diverse educational and technical criteria.

Table 7: Comparative Analysis of Cardboard, AR, and Hybrid AR-Cardboard Approaches in Engineering Education

Aspect	Cardboard Simulation	(AR)	Hybrid AR-Cardboard Simulation
Cost	Low-cost, accessible to all institutions	The high initial cost of software, hardware, and development	Moderate cost (uses AR with low-cost cardboard materials)
Material Representation	It simulates physical handling but lacks actual wood properties	Virtual visualization lacks honest tactile feedback	Balances digital visualization with hands-on material interaction
Learning Experience	Hands-on, encourages spatial awareness and craftsmanship	Interactive and dynamic, but lacks physical engagement	Best of both worlds: real-world interaction with digital enhancements
Error Identification	Manual error detection, trial-and-error process	Instant AI-based feedback, but may not detect hands-on mistakes	AR-assisted error detection with real material handling
Flexibility & Scalability	Easy to implement in any institution	Requires technological infrastructure, software updates	Scalable with mobile AR apps and physical materials
Engagement & Motivation	Engaging but may feel repetitive for tech-savvy students	High engagement due to interactive digital elements	It is most engaging as it blends tactile learning with digital interactivity
Collaboration & Remote Learning	Requires in-person interaction	Enables remote learning and collaboration	Supports both in-person and remote learning scenarios
Implementation Time	Requires time to create and test models	Quick access to simulations but with a learning curve for AR	It may take time to integrate both tools, but it offers long-term benefits
Industry Readiness	Improves manual skills but lacks real-world automation experience	Familiarizes students with digital tools used in industries	Develops both manual craftsmanship and digital competency
Cognitive Load	Medium – students focus on physical execution	High – requires cognitive adaptation to virtual spaces	Balanced – students experience both physical and digital learning modalities
Sustainability & Resource Use	It is environmentally friendly if recycled materials are used	Energy-intensive, dependent on electronic devices	Sustainable if combined with low-energy AR applications

From Table 7, each method—cardboard simulations, AR, and the hybrid AR-cardboard model—presents unique benefits and drawbacks in engineering education. Cardboard simulations offer students a practical, economical method to enhance spatial awareness, problem-solving abilities, and craftsmanship before engaging with actual materials. This approach is especially advantageous for resource-constrained institutions, as it obviates the necessity for costly software and hardware. Moreover, cardboard allows students to engage in hands-on design alterations, promoting creativity and iterative learning. A significant drawback is that cardboard does not entirely emulate the material characteristics of wood, including texture, weight, and durability. This may create a disparity between virtual practice and real-world application, necessitating further training to move effectively to practical woodworking. Moreover, error detection in cardboard simulations is contingent upon manual assessment, so relying on instructor oversight heightens the possibility of subjective evaluation.

Conversely, AR-based learning provides an interactive and visually rich method that improves conceptual comprehension and accuracy. AR enables students to superimpose 3D models onto practical environments, facilitating the exploration of design complexities, experimentation with various configurations, and acquisition of immediate feedback on inaccuracies. This minimizes trial-and-error methods and assists students in enhancing their designs prior to undertaking practical prototypes. Furthermore, AR-based simulations facilitate remote learning, rendering them accessible to students without access to conventional workshops. Despite these benefits, AR lacks the physical interaction essential for cultivating practical skills. Students utilizing AR simulations may encounter difficulties in material handling when applying concepts in real-world scenarios, as they lack exposure to the physical restrictions of weight, resistance, or texture. Moreover, the application of AR necessitates substantial technological investment, including appropriate gear, software development, and instructor training, rendering it less viable for institutions with financial limitations.

The hybrid AR-cardboard model aims to amalgamate the advantages of both methodologies, merging the cost-effectiveness and tactile involvement of cardboard simulations with the interactivity and accuracy of AR. This approach enables students to construct prototypes while employing AR overlays for immediate advice, error identification, and instructional assistance. Students may enhance accuracy and minimize design errors by scanning their cardboard models using an AR-enabled device to check their work against digital benchmarks. The hybrid method enhances industry preparedness by cultivating manual dexterity and digital literacy, which are vital in contemporary engineering and manufacturing contexts (Nithyanandam, Munguia and Marimuthu, 2022). This method necessitates extra preparation time and coordination since students must switch between physical and digital instruments. Moreover, although hybrid models diminish expenses relative to complete AR simulations, they still necessitate investment in AR apps and digital learning resources, which may present difficulties for specific institutions.

The selection between these methodologies is contingent upon educational objectives, resource availability, and student learning inclinations. Cardboard simulators are the most accessible and economical choice for practical training, yet they may lack accuracy and digital integration. AR-based learning shines in visualization and remote accessibility. However, it does not adequately facilitate the development of physical skills. The hybrid paradigm provides a balanced approach, augmenting physical education with digital accuracy, albeit necessitating a moderate technical investment. Future studies should investigate the effects of these methodologies on long-term skill retention and industry readiness, ensuring that engineering education adapts to the requirements of a technology-driven labor market.

4.3 Cardboard Models vs. Virtual Reality (VR) Models

In contemporary engineering education, simulation-based learning methodologies are essential for connecting theory with practice. Two increasingly popular methodologies are physical simulations employing cardboard models and digital simulations utilizing VR. Although both seek to improve conceptual comprehension and skill development, they vary in sensory engagement, learning outcomes, cost, and accessibility.

As mentioned in this study, cardboard models offer students tactile, three-dimensional representations of their creations. They are exceptionally proficient in woodworking and other material-centric fields where tactile manipulation and spatial precision are crucial. The tactile aspect of cardboard simulations enables students to acquire proficiency in cutting, assembling, and manipulating actual components—skills essential in technical disciplines that depend on manual craftsmanship.

Conversely, VR-based digital models provide comprehensive, immersive visualisations that enable students to engage with intricate ideas in a safe, simulated setting. VR facilitates real-time feedback, walkthroughs, and interaction with digital prototypes that would be challenging or costly to reproduce physically. This renders it exceptionally appropriate for tasks requiring high abstraction, perilous environments, or iterative design evaluation. Nonetheless, VR lacks material realism and tactile input, crucial for cultivating motor skills and comprehending physical limitations.

From an educational standpoint, cardboard simulations highlight iterative problem-solving and promote students' profound engagement with the creative process. They endorse experiential learning that aligns with the CDIO paradigm, facilitating seamless transitions from design to implementation. Conversely, VR simulations correspond more closely with cognitive load theory by minimising superfluous burdens, enabling students to visualise systems comprehensively and explore various perspectives dynamically. The selection between the two is contingent upon educational objectives, resource accessibility, and discipline emphasis. Table 8 provides a comprehensive comparison of these two methodologies.

Table 8: Comparison of Cardboard Simulations and VR Models in Engineering Education

Aspect	Cardboard Models	VR-Based Digital Models
Learning Style	Kinesthetic, tactile, hands-on	Visual, immersive, exploratory
Feedback Type	Manual, instructor-guided, peer-reviewed	Real-time system feedback, guided pathways
Skill Development	Manual dexterity, craftsmanship, tool handling	Spatial reasoning, digital fluency, systems thinking
Cost & Accessibility	Very low cost; accessible to all institutions	High initial cost; requires headsets, software, and infrastructure
Material Representation	Simulates real assembly, limited in material authenticity	Highly flexible, lacks physical feedback

Aspect	Cardboard Models	VR-Based Digital Models
Setup & Implementation	Easy setup, but time-consuming to build manually	Fast simulation deployment requires technical support
Error Detection	Human assessment and revision	AI-guided error identification, visual cues
Suitability by Discipline	Woodworking, product design, fabrication	Architecture, mechanical systems, high-risk simulations
Scalability	Scalable with recycled materials	Scalable with cloud-based access but limited by hardware needs
Student Engagement	Encourages hands-on creativity and teamwork	Enhances motivation through gamified learning
Cognitive Load	Moderate, distributed over manual and visual tasks	Potentially high, requires adaptation to virtual navigation
Industry Readiness	Strengthens material understanding and practical assembly skills	Builds familiarity with industry-standard design software

From Table 8, cardboard and VR-based simulations significantly enhance engineering education through different methods. Cardboard models are exceptional for imparting practical skills and spatial precision, rendering them suitable for fabrication-focused fields. VR models offer immersive visualisation and cognitive support, especially beneficial in intricate systems or conceptually dense subjects. Educational programs that optimise learning results should adopt blended methodologies, integrating physical simulations with digital visualisation tools to ensure student proficiency in handcraft and digital skills.

Cardboard models exemplify an economical, tactile methodology rooted in experiential learning. These simulations are fundamentally kinaesthetic, enabling students to handle materials, utilize hand tools, and perceive the spatial aspects of a design at an actual scale. This tactile interaction is particularly advantageous for fields such as carpentry or product design, where comprehending the physical properties of components, such as weight distribution, joint integrity, or manual alignment, is crucial. Cardboard models inherently promote patience, the development of fine motor skills, and an appreciation for craftsmanship—skills frequently overlooked in entirely digital environments.

Conversely, VR-based digital models primarily serve visual and spatial learners, providing an immersive experience that can replicate intricate systems and settings with negligible material risk. VR demonstrates exceptional conceptual clarity, enabling learners to manipulate, analyse, and engage with three-dimensional creations in ways unattainable in the physical world. This capacity renders VR exceptionally effective for comprehending abstract technical systems, such as fluid dynamics or circuit logic. Nevertheless, VR may prioritize visual learning to the detriment of tactile engagement, rendering it less successful for fields where sensory-motor connection is essential.

A frequently overlooked distinction pertains to the nature of feedback and reflection promoted by each strategy. Error detection with cardboard models predominantly depends on peer discourse, instructor oversight, and reflective practice, fostering collaborative learning and communication (Ataş and Yıldırım, 2025). Conversely, VR provides system-based feedback, frequently automated or AI-enhanced, which may expedite error correction but diminish opportunities for dialogic learning and peer evaluation (Rana and Chicone, 2025).

A further concealed layer pertains to learner autonomy and cognitive strain. Cardboard simulations enable learners to progress at their speed, physically arranging their concepts and modifying plans through iterative adjustments. This facilitates contemplative cognition and profound comprehension. Conversely, although VR can provide structured simulations for learners, it may also present a more challenging learning curve, necessitating users to acclimate to navigation controls and interface norms before engaging in substantive learning—thereby increasing cognitive demands, particularly for beginners.

From a sustainability standpoint, cardboard models constructed from recycled materials effectively correspond with environmentally responsible educational objectives (Ikemiyashiro Higa and Taki, 2024). Despite being paperless, VR systems depend on high-energy gadgets and regular updates, which raises worries regarding their long-term environmental impact and electronic waste. Institutions pursuing green education may favor physical models for economic considerations and their reduced ecological impact.

Regarding scalability and equity, cardboard models significantly outperform those used by under-resourced organizations. They necessitate no technical assistance and can be executed in virtually any classroom. VR, however, creates an accessibility gap—students lacking access to high-performance computers or VR equipment may face exclusion or disadvantage (Acevedo *et al.*, 2024). This component pertains to educational equity, an issue of growing significance in global dialogues around digital change.

Ultimately, both approaches have synergistic advantages when evaluating long-term alignment with industry standards. Cardboard simulations establish robust foundations in manual assembly, error resolution, and production planning—competencies pertinent to manufacturing, construction, or industrial design sectors. Simultaneously, VR provides students with proficiency in digital modeling, corresponding with modern architecture, systems engineering, and virtual prototyping practices. A hybrid methodology—initiating with cardboard for fundamental craftsmanship and augmenting with VR for systemic understanding—may offer the most thorough route to producing future-ready graduates.

4.4 Research Limitations and Future Research Directions

This study illustrates the efficacy of cardboard simulations in improving experiential learning in woodworking education; however, certain limitations must be recognized. A fundamental limitation resides in the portrayal of materials. Although cardboard offers a convenient and economical substitute for genuine wood, it fails to completely emulate the structural characteristics, including texture, weight, and durability. Consequently, pupils may not encounter the same degree of resistance and accuracy when engaging with authentic woodworking materials. This constraint may hinder the shift from simulation to practical applications, necessitating further practice with genuine materials to enhance students' skills.

A further constraint is the supplementary time and effort necessary for simulation preparation. Although cardboard simulations mitigate errors and enhance planning, they add a phase to the learning process, potentially prolonging the entire project duration. This may provide difficulties in educational environments with restricted class durations or stringent curriculum timelines. Moreover, fault detection in physical simulations predominantly relies on manual observation, necessitating vigilant oversight from instructors. In contrast to digital instruments that provide immediate feedback, students must depend on their judgment or peer evaluations, perhaps resulting in variations in assessment accuracy.

The research was performed at a single institution, rendering its findings context-dependent and possibly restricting generalizability. Differences in curriculum design, resource availability, and student demographics may affect the efficacy of cardboard simulations in various educational settings. Future research should investigate the efficacy of this strategy across diverse educational environments, including institutions with differing degrees of technological integration (Isaeva *et al.*, 2025). The study concentrated on short-term learning outcomes, evaluating immediate enhancements in skill acquisition. An extensive examination of the long-term effects of simulation-based learning, especially within industrial contexts, would yield a greater understanding of its efficacy in equipping students for professional careers.

Future studies should investigate the amalgamation of AR with physical simulations to mitigate these limitations (Crogman *et al.*, 2025). AR overlays enable students to obtain real-time feedback and interactive coaching, diminishing dependence on instructor oversight while promoting self-directed learning. The advancement of AI-driven assessment technologies may enhance the evaluation process by delivering automated input on design precision, construction methodologies, and project fulfillment. This hybrid methodology may address conventional physical simulations' limitations while preserving tactile involvement's advantages.

An interesting direction for future research is the scalability of simulation-based e-learning in distance education. The growing dependence on digital learning platforms necessitates the integration of affordable physical simulations with mobile AR applications to offer accessible training solutions for students in remote locations or institutions with constrained workshop facilities. Examining the efficacy of these models in hybrid and entirely online learning contexts would facilitate the broader implementation of blended learning methodologies in engineering and technical education.

Ultimately, longitudinal studies must be undertaken to assess the enduring advantages of simulation-based learning on students' preparedness for the business. Researchers can evaluate the effects of physical and AR-enhanced simulations on professional competencies, workplace flexibility, and technical proficiency over time by monitoring graduates who have participated in various training techniques. This research may provide significant insights for curriculum makers and educators aiming to enhance practical training methodologies in engineering education.

5. Conclusion

This study has shown that combining cardboard simulation and AR can improve engineering education quality, especially in vocational woodworking design. Utilizing the CDIO framework and segregating students into two learning cohorts revealed that the simulation-based methodology yielded significant technical correctness, planning precision, and student collaboration advantages. Students in Group B (simulation-based learning) quantitatively surpassed those in Group A (conventional learning) with an average score of 8607 compared to 7350.

Using cardboard as an economical, secure, and adaptable simulation medium allowed students to concentrate on design and problem-solving before interacting with actual materials. Despite the intrinsic distinctions between cardboard and wood, the simulation improved planning and visualization, resulting in superior real-world implementation. The preliminary application of AR technology, however, restricted in extent, enhanced value by delivering visual overlays for instructional assistance, thereby strengthening spatial comprehension throughout the prototype phase.

This research introduces a hybrid paradigm that integrates entirely digital and traditional learning methodologies from an e-learning perspective. It provides a pragmatic alternative for universities with restricted access to digital infrastructure or expensive materials, enabling them to adopt blended learning more inclusively and engagingly. The findings indicate that combining basic physical simulations with limited AR augmentation can enhance cognitive and technical results. Subsequent research may investigate the more profound integration of AR modules and extend the paradigm to more domains within engineering education.

AI Statement: The authors state that Artificial Intelligence tool was not used in thisstudy.

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References

Abbas Shah, S. F., Mazhar, T., Shahzad, T., Khan, M. A., Ghadi, Y. Y., & Hamam, H. (2024) 'Integrating educational theories with virtual reality: Enhancing engineering education and VR laboratories', *Social Sciences & Humanities Open*, 10, p. 101207. doi: 10.1016/j.ssaho.2024.101207.

Acevedo, P., Magana, A. J., Benes, B., & Mousas, C. (2024) 'A Systematic Review of Immersive Virtual Reality in STEM Education: Advantages and Disadvantages on Learning and User Experience', *IEEE Access*, 12, pp. 189359–189386. doi: 10.1109/ACCESS.2024.3489233.

Al-khresheh, M. H. (2024) 'Bridging technology and pedagogy from a global lens: Teachers' perspectives on integrating ChatGPT in English language teaching', *Computers and Education: Artificial Intelligence*, 6, p. 100218. doi: 10.1016/j.caeai.2024.100218.

Al-Zoubi, A., San Cristobal, E., Shahroury, F. R., & Castro, M. (2024) 'The Middle East Higher Education Experience: Implementing Remote Labs to Improve the Acquisition of Skills in Industry 4.0', *IEEE Transactions on Learning Technologies*, 17, pp. 982–991. doi: 10.1109/TLT.2023.3341490.

Alarcon-Pereira, G., Rampasso, I. S., Tapia-Ubeda, F. J., Rojas-Aguilar, K., & Rojas-Córdova, C. (2023) 'The evolution of sustainability in engineering education research: a longitudinal analysis through bibliometrics and the CDIO initiative', *International Journal of Sustainability in Higher Education*, 24(6), pp. 1266–1289. doi: 10.1108/IJSHE-03-2022-0073.

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023) 'Unlocking the Potential: A Comprehensive Evaluation of Augmented Reality and Virtual Reality in Education', *Electronics*, 12(18), p. 3953. doi: 10.3390/electronics12183953.

Amarasinghe, I., Hong, Y. and Stewart, R. A. (2024) 'Development of a material circularity evaluation framework for building construction projects', *Journal of Cleaner Production*, 436, p. 140562. doi: 10.1016/j.jclepro.2024.140562.

Anderson, R., Taylor, S., Taylor, T., & Virues-Ortega, J. (2022) 'Thematic and textual analysis methods for developing social validity questionnaires in applied behavior analysis', *Behavioral Interventions*, 37(3), pp. 732–753. doi: 10.1002/bin.1832.

Ataş, A. H. and Yıldırım, Z. (2025) 'A shared metacognition-focused instructional design model for online collaborative learning environments', *Educational technology research and development*, 73(1), pp. 567–613. doi: 10.1007/s11423-024-10423-4.

Beldad, A. D. and Miedema, H. A. T. (2025) 'Introducing a framework for designing an interdisciplinary engineering curriculum: educating new engineers for complex sociotechnical challenges', *European Journal of Engineering Education*, pp. 1–18. doi: 10.1080/03043797.2025.2507243.

Brunzini, A., Papetti, A., Messi, D., & Germani, M. (2022) 'A comprehensive method to design and assess mixed reality simulations', *Virtual Reality*, 26(4), pp. 1257–1275. doi: 10.1007/s10055-022-00632-8.

Bühler, M. M., Jelinek, T. and Nübel, K. (2022) 'Training and Preparing Tomorrow's Workforce for the Fourth Industrial Revolution', *Education Sciences*, 12(11), p. 782. doi: 10.3390/educsci12110782.

Cascella, M., Cascella, A., Monaco, F., & Shariff, M. N. (2023) ‘Envisioning gamification in anesthesia, pain management, and critical care: basic principles, integration of artificial intelligence, and simulation strategies’, *Journal of Anesthesia, Analgesia and Critical Care*, 3(1), p. 33. doi: 10.1186/s44158-023-00118-2.

Chisunum, J. I. and Nwadiokwu, C. (2024) ‘Enhancing Student Engagement through Practical Production and Utilization of Instructional Materials in an Educational Technology Class: A Multifaceted Approach’, *NIU Journal of Educational Research*, 10(2). doi: 10.58709/niujed.v10i2.2002.

Clancy, R., O’Sullivan, D. and Bruton, K. (2023) ‘Data-driven quality improvement approach to reducing waste in manufacturing’, *The TQM Journal*, 35(1), pp. 51–72. doi: 10.1108/TQM-02-2021-0061.

Crogman, H. T., Cano, V. D., Pacheco, E., Sonawane, R. B., & Boroon, R. (2025) ‘Virtual Reality, Augmented Reality, and Mixed Reality in Experiential Learning: Transforming Educational Paradigms’, *Education Sciences*, 15(3), p. 303. doi: 10.3390/educsci15030303.

Demirel, H. O., Ahmed, S. and Duffy, V. G. (2022) ‘Digital Human Modeling: A Review and Reappraisal of Origins, Present, and Expected Future Methods for Representing Humans Computationally’, *International Journal of Human–Computer Interaction*, 38(10), pp. 897–937. doi: 10.1080/10447318.2021.1976507.

ElSayary, A. (2025) ‘Enhancing teachers’ design thinking mindsets through reflective practice: Cultivating innovation in an upskilling STEAM training program’, *Eurasia Journal of Mathematics, Science and Technology Education*, 21(3), p. em2600. doi: 10.29333/ejmste/16048.

Ferguson, S., Lai, K., Chen, J., Faidi, S., Leonardo, K., & Olechowski, A. (2022) ‘“Why couldn’t we do this more often?”: exploring the feasibility of virtual and distributed work in product design engineering’, *Research in Engineering Design*, 33(4), pp. 413–436. doi: 10.1007/s00163-022-00391-2.

Forcael, E., Garcés, G. and Lantada, A. D. (2023) ‘Convergence of Educational Paradigms into Engineering Education 5.0’, in *2023 World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC)*. IEEE, pp. 1–8. doi: 10.1109/WEEF-GEDC59520.2023.10344026.

Hariharasakthisudhan, P., Logesh, K., Sathickbasha, K., & Kannan, S. (2025) ‘Enhancing project-based learning in engineering education: a hybrid DT-CDIO-RA framework for sustainable product design’, *Discover Education*, 4(1), p. 138. doi: 10.1007/s44217-025-00579-3.

Hippe, D. S., Umoren, R. A., McGee, A., Bucher, S. L., & Bresnahan, B. W. (2020) ‘A targeted systematic review of cost analyses for implementation of simulation-based education in healthcare’, *SAGE Open Medicine*, 8, p. 205031212091345. doi: 10.1177/2050312120913451.

Ikemiyashiro Higa, D. and Taki, A. (2024) ‘Examining Cardboard as a Construction Material for Sustainable Building Practices in Lima, Peru’, *Sustainability*, 17(1), p. 10. doi: 10.3390/su17010010.

Iqbal, A. I., Aamir, A., Hammad, A., Hafsa, H., Basit, A., Oduoye, M. O., Anis, M. W., Ahmed, S., Younus, M. I., & Jabeen, S. (2024) ‘Immersive Technologies in Healthcare: An In-Depth Exploration of Virtual Reality and Augmented Reality in Enhancing Patient Care, Medical Education, and Training Paradigms’, *Journal of Primary Care & Community Health*, 15. doi: 10.1177/21501319241293311.

Iqbal, M. Z., Mangina, E. and Campbell, A. G. (2022) ‘Current Challenges and Future Research Directions in Augmented Reality for Education’, *Multimodal Technologies and Interaction*, 6(9), p. 75. doi: 10.3390/mti6090075.

Isaeva, R., Karasartova, N., Dznunusnalieva, K., Mirzoeva, K., & Mokliuk, M. (2025) ‘Enhancing Learning Effectiveness Through Adaptive Learning Platforms and Emerging Computer Technologies in Education’, *Jurnal Ilmiah Ilmu Terapan Universitas Jambi*, 9(1), pp. 144–160. doi: 10.22437/jiituj.v9i1.37967.

Joseph Nnaemeka Chukwunweike, Andrew Nii Anang, Adewale Abayomi Adeniran, & Jude Dike. (2024) ‘Enhancing manufacturing efficiency and quality through automation and deep learning: addressing redundancy, defects, vibration analysis, and material strength optimization’, *World Journal of Advanced Research and Reviews*, 23(3), pp. 1272–1295. doi: 10.30574/wjarr.2024.23.3.2800.

Kamdjou, H. M., Baudry, D., Havard, V., & Ouchani, S. (2024) ‘Resource-Constrained EXtended Reality Operated With Digital Twin in Industrial Internet of Things’, *IEEE Open Journal of the Communications Society*, 5, pp. 928–950. doi: 10.1109/OJCOMS.2024.3356508.

Kang, L. (2024) ‘Revolutionizing Vocational Education: Information-Based Instruction and the Knowledge Economy’, *Journal of the Knowledge Economy*. doi: 10.1007/s13132-024-01797-0.

Kumar, A., Mantri, A. and Dutta, R. (2021) ‘Development of an augmented reality-based scaffold to improve the learning experience of engineering students in embedded system course’, *Computer Applications in Engineering Education*, 29(1), pp. 244–257. doi: 10.1002/cae.22245.

Lee, I.-J. (2023) ‘Applying virtual reality for learning woodworking in the vocational training of batch wood furniture production’, *Interactive Learning Environments*, 31(3), pp. 1448–1466. doi: 10.1080/10494820.2020.1841799.

Lenin, N., Siva Kumar, M. and Selvakumar, G. (2023) ‘Application of Conceive, Design, Implement and Operate (CDIO) Strategy for the Development of Engineering Education in Indian Perspective’, *Journal of Education*, 203(1), pp. 41–48. doi: 10.1177/00220574211016446.

Li, Y., Xiong, X. and Qu, M. (2023) ‘Research on the Whole Life Cycle of a Furniture Design and Development System Based on Sustainable Design Theory’, *Sustainability*, 15(18), p. 13928. doi: 10.3390/su151813928.

Liu, Q. and Wang, L. (2021) ‘t-Test and ANOVA for data with ceiling and/or floor effects’, *Behavior Research Methods*, 53(1), pp. 264–277. doi: 10.3758/s13428-020-01407-2.

Malhotra, R., Massoudi, M. and Jindal, R. (2023) ‘Shifting from traditional engineering education towards competency-based approach: The most recommended approach-review’, *Education and Information Technologies*, 28(7), pp. 9081–9111. doi: 10.1007/s10639-022-11568-6.

Martseva, L. A., Movchan, L. H., Vakaliuk, T. A., & Antoniuk, D. S. (2021) ‘Applying CDIO-approach at technical universities’, *Journal of Physics: Conference Series*, 1946(1), p. 012013. doi: 10.1088/1742-6596/1946/1/012013.

Matović, N. and Ovesni, K. (2023) ‘Interaction of quantitative and qualitative methodology in mixed methods research: integration and/or combination’, *International Journal of Social Research Methodology*, 26(1), pp. 51–65. doi: 10.1080/13645579.2021.1964857.

May, D., Terkowsky, C., Varney, V., & Boehringer, D. (2023) ‘Between hands-on experiments and Cross Reality learning environments – contemporary educational approaches in instructional laboratories’, *European Journal of Engineering Education*, 48(5), pp. 783–801. doi: 10.1080/03043797.2023.2248819.

McCord, K. H., Ayer, S. K., Perry, L. A., Patil, K. R., London, J. S., Khoury, V., & Wu, W. (2022) ‘Student Approaches and Performance in Element Sequencing Tasks Using 2D and Augmented Reality Formats’, *Education Sciences*, 12(4), p. 247. doi: 10.3390/educsci12040247.

Nazlidou, I., Efkolidis, N., Kakoulis, K., & Kyratsis, P. (2024) ‘Innovative and Interactive Technologies in Creative Product Design Education: A Review’, *Multimodal Technologies and Interaction*, 8(12), p. 107. doi: 10.3390/mti8120107.

Nithyanandam, G., Munguia, J. and Marimuthu, M. (2022) ‘“Digital literacy”: Shaping industry 4.0 engineering curriculums via factory pilot-demonstrators’, *Advances in Industrial and Manufacturing Engineering*, 5, p. 100092. doi: 10.1016/j.aime.2022.100092.

Ortega-Gras, J.-J., Gómez-Gómez, M.-V., Bueno-Delgado, M.-V., Garrido-Lova, J., & Cañavate-Cruzado, G. (2023) ‘Designing a Technological Pathway to Empower Vocational Education and Training in the Circular Wood and Furniture Sector through Extended Reality’, *Electronics*, 12(10), p. 2328. doi: 10.3390/electronics12102328.

Portillo, F., Soler-Ortiz, M., Sanchez-Cruzado, C., Garcia, R. M., & Novas, N. (2025) ‘The Impact of Flipped Learning and Digital Laboratory in Basic Electronics Coursework’, *Computer Applications in Engineering Education*, 33(1). doi: 10.1002/cae.22810.

Rana, S. and Chicone, R. (2025) ‘AI-Enhanced Virtual and Augmented Reality for Cybersecurity Training’, in *Fortifying the Future*. Cham: Springer Nature Switzerland, pp. 101–131. doi: 10.1007/978-3-031-81780-9_5.

Resch, K. and Schrittesser, I. (2023) ‘Using the Service-Learning approach to bridge the gap between theory and practice in teacher education’, *International Journal of Inclusive Education*, 27(10), pp. 1118–1132. doi: 10.1080/13603116.2021.1882053.

Rodríguez-Abitia, G., Martínez-Pérez, S., Ramirez-Montoya, M. S., & Lopez-Caudana, E. (2020) ‘Digital Gap in Universities and Challenges for Quality Education: A Diagnostic Study in Mexico and Spain’, *Sustainability*, 12(21), p. 9069. doi: 10.3390/su12219069.

Sahoo, P., Saraf, P. K. and Uchil, R. (2025) ‘Identification of challenges to Industry 5.0 adoption in Indian manufacturing firms: an emerging economy perspective’, *International Journal of Computer Integrated Manufacturing*, 38(5), pp. 649–674. doi: 10.1080/0951192X.2024.2382186.

Salinas-Navarro, D. E., Vilalta-Perdomo, E., Michel-Villarreal, R., & Montesinos, L. (2024) ‘Using Generative Artificial Intelligence Tools to Explain and Enhance Experiential Learning for Authentic Assessment’, *Education Sciences*, 14(1), p. 83. doi: 10.3390/educsci14010083.

Sapienza, V., Rodonò, G., Monteleone, A., & Calvagna, S. (2022) ‘ICARO—Innovative Cardboard ARchitecture Object: Sustainable Building Technology for Multipurpose Micro-Architecture’, *Sustainability*, 14(23), p. 16099. doi: 10.3390/su142316099.

Seiringer, W., Altendorfer, K., Castaneda, J., Gayan, L., & Juan, A. A. (2022) ‘Potential of Simulation Effort Reduction by Intelligent Simulation Budget Management for Multi-Item and Multi-Stage Production Systems’, in *2022 Winter Simulation Conference (WSC)*. IEEE, pp. 1864–1875. doi: 10.1109/WSC57314.2022.10015506.

Shahrezaei, A., Sohani, M., Taherkhani, S., & Zarghami, S. Y. (2024) ‘The impact of surgical simulation and training technologies on general surgery education’, *BMC Medical Education*, 24(1The impact of surgical simulation and training technologies on general surgery education), p. 1297. doi: 10.1186/s12909-024-06299-w.

Shuhaiber, A. and Aldwairi, M. (2023) ‘A Best Practice Model of CDIO Implementation in IT Classrooms: Gamification Crowdsourcing Approach’, in *2023 27th International Computer Science and Engineering Conference (ICSEC)*. IEEE, pp. 304–309. doi: 10.1109/ICSEC59635.2023.10329646.

Singhaphandu, R., Pannakkong, W., Huynh, V.-N., & Boonkwan, P. (2024) ‘A Manual Assembly Virtual Training System With Automatically Generated Augmented Feedback: Using the Comparison of Digitized Operator’s Skill’, *IEEE Access*, 12, pp. 133356–133391. doi: 10.1109/ACCESS.2024.3436910.

Solmaz, S., Dominguez Alfaro, J. L., Santos, P., Van Puyvelde, P., & Van Gerven, T. (2021) ‘A practical development of engineering simulation-assisted educational AR environments’, *Education for Chemical Engineers*, 35, pp. 81–93. doi: 10.1016/j.ece.2021.01.007.

Song, C., Shin, S.-Y. and Shin, K.-S. (2023) ‘Optimizing Foreign Language Learning in Virtual Reality: A Comprehensive Theoretical Framework Based on Constructivism and Cognitive Load Theory (VR-CCL)’, *Applied Sciences*, 13(23), p. 12557. doi: 10.3390/app132312557.

Song, X. (2022) ‘Application Research of CDIO Education Initiative in Reforming Online-Offline Hybrid Teaching of “Software Testing” Course’, in *2022 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)*. IEEE, pp. 270–275. doi: 10.1109/TALE54877.2022.00052.

Sounthornwiboon, P., Sriprasertpap, K. and Nilsook, P. (2025) ‘Simulation game-based learning for cognitive apprenticeship development: a focus on processing speed’, *Cogent Education*, 12(1). doi: 10.1080/2331186X.2024.2449280.

Špirková, S., Straka, M. and Saniuk, A. (2024) ‘VR Simulation and Implementation of Robotics: A Tool for Streamlining and Optimization’, *Applied Sciences*, 14(11), p. 4434. doi: 10.3390/app14114434.

Suckling, K., Patel, Y., Mann, K., & Collett, A. (2024) ‘Resilient Design with Upcycled Timber Within Architectural Design-Build Studio’, in *Integrating Resiliency into Future Sustainable Cities*, pp. 45–65. doi: 10.1007/978-3-031-63203-7_4.

Suksong, S., Chomsuwan, K. and Suamuang, W. (2023) ‘Work in Progress: Application of CDIO and Experiential Learning Theory for Developing the Problem Solving Ability of Technicians in Manufacturing’, in *2023 IEEE Global Engineering Education Conference (EDUCON)*. IEEE, pp. 1–3. doi: 10.1109/EDUCON54358.2023.10125201.

Tanveer, B. and Usman, M. (2022) ‘An Empirical Study on the Use of CDIO in Software Engineering Education’, *IEEE Transactions on Education*, 65(4), pp. 684–694. doi: 10.1109/TE.2022.3163911.

Venkatesan, S., Afroz, M., Navaratnam, S., & Gravina, R.(2023) ‘Circular-Economy-Based Approach to Utilizing Cardboard in Sustainable Building Construction’, *Buildings*, 13(1), p. 181. doi: 10.3390/buildings13010181.

Wagg, D. J., Worden, K., Barthorpe, R. J., & Gardner, P. (2020) ‘Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications’, *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 6(3). doi: 10.1115/1.4046739.

Weis, P., Smetanka, L., Hrček, S., & Vereš, M. (2024) ‘Interactive Application as a Teaching Aid in Mechanical Engineering’, *Computers*, 13(7), p. 170. doi: 10.3390/computers13070170.

Wong, Z. Y. and Liem, G. A. D. (2022) ‘Student Engagement: Current State of the Construct, Conceptual Refinement, and Future Research Directions’, *Educational Psychology Review*, 34(1), pp. 107–138. doi: 10.1007/s10648-021-09628-3.

Yang, Z. and Zhou, H. (2023) ‘Exploring and Construction On Practicality Instruction System in Engineering Education Based On CDIO Concept’, *World Journal of Educational Research*, 10(5), p. p269. doi: 10.22158/wjer.v10n5p269.

Younis, B. (2025) ‘Developing and Validating the Contextual Technology Andragogy/Pedagogy Entrepreneurship Work Content Knowledge Model: A Framework for Vocational Education’, *IEEE Transactions on Education*, 68(1), pp. 57–66. doi: 10.1109/TE.2024.3449636.

Zabalawi, I., Kordahji, H. and Mourdaa, R. (2022) ‘The “New” Normal of Business Education in a Post COVID Era: The CDIO Approach’, in *Higher Education in the Arab World*. Cham: Springer International Publishing, pp. 115–150. doi: 10.1007/978-3-031-07539-1_7.

Zhang, Z., Guo, B. H. W., Chang-Richards, A., Feng, Z., Jin, R., Zou, Y., & Miang Goh, Y. (2023) ‘Digital technology enhanced situation awareness for construction safety: Systematic review and future research directions’, *Safety Science*, 167, p. 106280. doi: 10.1016/j.ssci.2023.106280.

Zhao, K. (2021) ‘Sample representation in the social sciences’, *Synthese*, 198(10), pp. 9097–9115. doi: 10.1007/s11229-020-02621-3.