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Virtual practice as a complement to hands-on practice in mechatronics education: A thematic narrative literature review of effectiveness, limitations, and learning integration models

Rizal Taufik Wityasaputra[1]*, Hartoyo[2]

[1 2] Universitas Negeri Yogyakarta, Yogyakarta, Indonesia

*Corresponding Author: rizaltaufikwityasaputra@gmail.com

Abstract

Mechatronics education requires both conceptual understanding and the ability to operate, test, and troubleshoot physical equipment, while limited facilities constrain opportunities for hands-on practice. This study examines the uses, effectiveness, and limitations of virtual practice and develops an approach for integrating it with real-world practice in mechatronics education. It adopts a thematic narrative literature review, purposively selecting 30 articles published between 2018 and 2025 from five search sources. The articles were identified, screened, assessed for eligibility, mapped, and synthesized thematically. The findings indicate that virtual practice primarily supports conceptual understanding, programming, modelling, and learning motivation. However, its effectiveness varies, and evidence of skill transfer to physical equipment remains limited. This study contributes a four-stage integration model comprising virtual practice; reflection and mentoring; real-world practice; and competency assessment. The model positions simulation as a complement to, rather than a substitute for, hands-on experience.

Keywords: Mechatronics simulators; Virtual laboratories; Skill transfer; Hands-on practice; Competency assessment.

Abstrak

Pendidikan mekatronika menuntut penguasaan konsep sekaligus keterampilan dalam mengoperasikan, menguji, dan memperbaiki perangkat fisik. Sementara itu, keterbatasan fasilitas membatasi kesempatan peserta didik untuk melakukan praktik langsung. Kajian ini bertujuan menganalisis pemanfaatan, efektivitas, dan keterbatasan praktik virtual serta merumuskan model integrasinya dengan praktik nyata dalam pembelajaran mekatronika. Penelitian ini menggunakan kajian literatur naratif tematik dengan pemilihan sumber secara terarah terhadap 30 artikel yang diterbitkan pada periode 2018–2025. Artikel diseleksi dari lima sumber penelusuran melalui tahapan identifikasi, penyaringan, dan penilaian kelayakan, kemudian dipetakan dan disintesis secara tematik. Hasil kajian menunjukkan bahwa praktik virtual terutama mendukung penguasaan konsep, pemrograman, pemodelan, dan motivasi belajar. Namun, efektivitasnya bervariasi dan bukti transfer keterampilan ke perangkat fisik masih terbatas. Kontribusi kajian ini adalah model integrasi empat tahap, yaitu praktik virtual; refleksi dan mentoring; praktik nyata; serta asesmen kompetensi, yang menempatkan simulasi sebagai pendamping, bukan pengganti, pengalaman praktik langsung.

Kata Kunci: Simulator mekatronika; Laboratorium virtual; Transfer keterampilan; Praktik *hands-on*; Asesmen kompetensi.

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Introduction

Mechatronics education cannot rely solely on theoretical knowledge, as competence in this field is developed through activities involving the design, assembly, programming, testing, and troubleshooting of mechanical and electronic systems. These activities require repeated access to laboratory equipment, while laboratory time and the availability of equipment are often limited. Nolen and Koretsky (2018) demonstrated that virtual laboratory projects could generate higher levels of student motivation and engagement than physical laboratory projects in the engineering education context they investigated. However, greater engagement does not necessarily mean that virtual experiences can automatically replace hands-on experience with physical equipment. Viegas et al. (2018), through the implementation of the VISIR remote laboratory in two electrical and electronics courses at a higher education institution in Brazil, analysed the academic performance and perceptions of 471 students over three semesters. Their findings indicate that laboratory technologies can broaden learning experiences, but their implementation still requires appropriate instructional management.

Limited access to laboratories has encouraged educational institutions to adopt virtual and remote laboratories as a means of expanding opportunities for experimentation. The two approaches should be distinguished: virtual laboratories conduct experiments using models or simulations, whereas remote laboratories provide online access to physical equipment operated from a different location. Tho and Yeung (2018) tested a remote laboratory system comprising eight experiments with 32 students in Grades 7–9. Their findings demonstrated that the system could be used to enrich online experimentation and received positive responses from students, while complementing existing simulation activities. In mechanical engineering education, Kapilan et al. (2021) reported on virtual laboratory training involving 88 lecturers and the implementation of a virtual fluid mechanics laboratory for students. A total of 96% of the students reported satisfaction with their virtual experimentation experience, although some still required lecturer guidance and encountered difficulties accessing devices and internet connectivity.

The development of virtual environments has also expanded the range of instructional design options, from computer-based simulations to immersive virtual reality. However, technological success cannot be measured solely by visual appeal or ease of access; learning outcomes, retention, and transferable skills need to be assessed separately. Radianti et al. (2020) mapped the use of immersive virtual reality in higher education and emphasised the importance of design elements and learning objectives in its implementation. Hamilton et al. (2021) reviewed 29 experimental publications comparing immersive head-mounted display-based virtual reality with less immersive methods. Most studies reported improved learning outcomes, but many

interventions were conducted over short periods and did not assess knowledge retention. These findings indicate that the effectiveness of virtual technologies depends not only on device sophistication but also on instructional design and the quality of learning assessment.

Research on virtual and remote laboratories has been conducted in various engineering education contexts. Nolen and Koretsky (2018) found higher engagement in virtual projects, while Viegas et al. (2018) showed that the use of VISIR was associated with student performance and influenced by lecturer involvement. In secondary education, Tho and Yeung (2018) demonstrated the feasibility of eight remote experiments for 32 students, although the context involved school science rather than mechatronics competencies. Kapilan et al. (2021) reported positive acceptance of virtual laboratories in mechanical engineering education, while Hamilton et al. (2021) highlighted the limitations of retention measurement in many virtual reality studies. Furthermore, Van den Beemt et al. (2023), in a study of remote laboratories in higher engineering education, involved 58 students who completed 1,944 successful experiments in one of the learning activities. The study showed that active learning pedagogy could connect online experimentation with student engagement and the transfer of theory into practice. However, this relationship still needs to be examined specifically in mechatronics education, which requires physical competencies.

In light of these developments and limitations, this study aims to examine how virtual practice is used to complement real-world practice in mechatronics education. Specifically, it maps the types of simulators and technologies employed, analyses evidence of their effectiveness and limitations, and identifies how virtual activities can be connected to experiences involving physical equipment. This focus is important because successful mechatronics education extends beyond understanding concepts or completing tasks on a screen; it also involves the ability to operate, test, and troubleshoot real systems. By positioning virtual practice as a complement rather than a substitute, this study is expected to provide a conceptual basis for developing vocational learning that makes purposeful use of simulation while maintaining hands-on experience as a core component of competency development.

Method

This study adopts a qualitative approach using a thematic narrative literature review and purposive source selection. This approach is employed to identify, examine, compare, and synthesize previous research findings on virtual practice in mechatronics education. Snyder (2019) explains that literature reviews can be used to map the development of knowledge, integrate research findings, and develop conceptual frameworks based on available evidence. The literature search was conducted across five sources: Scopus, Google Scholar, Garuda, OpenAlex, and

Semantic Scholar, covering publications from 2018 to 2025. The keywords included *virtual laboratory*, *virtual practice*, *simulation-based learning*, *mechatronics education*, *vocational education*, *technical and vocational education and training* (TVET), *PLC simulator*, *robotics simulation*, *virtual mechatronics practicum*, and *PLC simulation in vocational high schools*. The search also incorporated the names of relevant software and platforms, including Factory I/O, TIA Portal, PLCSIM, CODESYS, Tinkercad, Wokwi, Proteus, MATLAB, Simulink, Webots, CoppeliaSim, LabVIEW, FluidSIM, and *digital twin*.

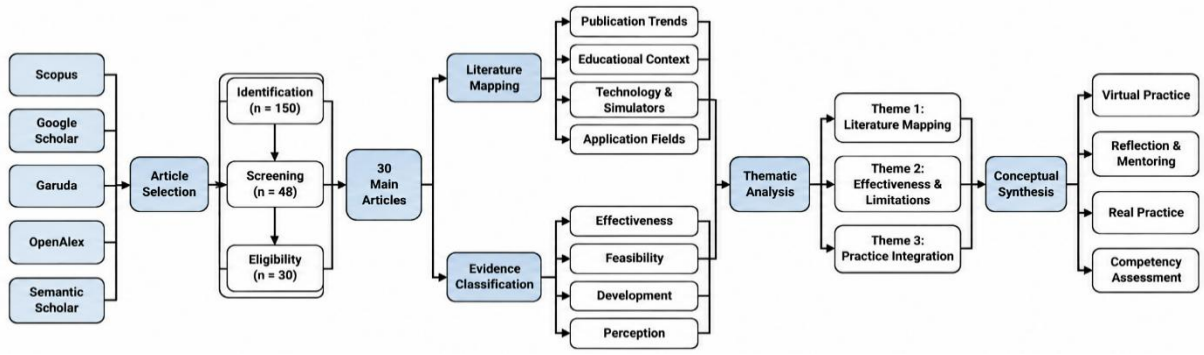

Figure 1. Literature Search, Selection, Mapping, and Synthesis Process

Source: Prepared by the authors based on the literature search, selection, mapping, and analysis conducted for the 2018–2025 publication period.

The literature selection process consisted of three stages: identification, screening, and eligibility assessment, as presented in Figure 1. The identification stage yielded 150 articles. These were subsequently screened based on the relevance of their titles, abstracts, and discussion focus, resulting in 48 articles for further examination. The eligibility assessment was then conducted using four criteria: (1) the article discussed simulators or virtual practice in mechatronics, PLCs, robotics, electronics, pneumatics, instrumentation, or *digital twins*; (2) the educational context involved vocational high schools, vocational education institutions, polytechnics, or technical higher education institutions; (3) the article presented findings, evidence, or analysis relevant to effectiveness, limitations, simulator types, or their application in learning; and (4) the article contributed to the diversity of technologies, educational levels, or research designs represented in the literature. Publications outside the specified period, general-purpose simulators without an educational context, and product promotional materials without learning evaluations were excluded. Bibliographic information and DOIs were also checked to ensure source traceability. The final selection process yielded 30 articles as the main corpus of this review.

All selected articles were subsequently mapped according to publication trends, educational contexts, types of technologies and simulators, and areas of application. To distinguish the characteristics and evidential contributions of the studies, the articles were classified into six categories: *effectiveness*, *feasibility*, *development*, *perception*, *review*, and *supporting*. The analytical process was guided by the Search,

Appraisal, Synthesis, and Analysis (SALSA) framework introduced by Grant and Booth (2009), particularly in connecting the processes of literature searching, appraisal, synthesis, and analysis. The findings were then thematically analysed across three main areas: literature mapping; the effectiveness and limitations of virtual practice; and the integration of virtual practice with real-world practice. The results of this analysis were synthesized into a four-stage conceptual learning framework comprising *virtual practice*, *reflection and mentoring*, *real practice*, and *competency assessment*. This framework represents the authors' conceptual synthesis based on patterns identified in the reviewed literature and has not yet been empirically tested.

Results and Discussion

Mapping the literature on virtual practice in mechatronics education

The literature mapping covered 30 articles published between 2018 and 2025. These articles addressed the use of virtual laboratories, PLC simulators, robotics, electronics, pneumatics, digital twins, LabVIEW, and remote laboratories in engineering and vocational education. The characteristics of each study are presented in Table 1, including the country and research participants, methods and technologies employed, and principal findings. This mapping does not treat all articles as providing equivalent evidence of effectiveness. Some studies examined learning outcomes, whereas others focused on system development, media feasibility, user perceptions, or the mapping of previous publications. This distinction is necessary to ensure that the contribution of each article is interpreted proportionately and that the conclusions of this review do not exceed the strength of the available evidence.

Table 1. Characteristics and main findings of the literature on virtual practice in mechatronics education

No.	Author(s) (Year)	Country and research participants	Methods and technologies	Main findings
1	Li & Liang (2024a)	Multinational; 46 studies from 22 engineering education publications	Meta-analysis; virtual laboratory	Hedges' g = 0.686, indicating a positive effect. However, substantial research heterogeneity suggests that effectiveness is not consistent across studies.
2	Niswah et al. (2024)	Indonesia; vocational high school students in civil engineering	R&D and controlled-group experiment; Android-based virtual laboratory	The experimental group achieved an N-Gain of 78.19%, compared with 54.07% in the control group. The findings support the effectiveness of virtual laboratories at the vocational high school level, although the study

				was not directly related to mechatronics.
3	Chamorro-Atalaya et al. (2024)	Multinational; 92 publications on digital twins in higher education	Bibliometric analysis; digital twins	Mapped the development of digital twin publications and highlighted the need to strengthen educators' competencies in their implementation.
4	Setyawan et al. (2025)	Multinational; 26 studies on robotic technologies in vocational education	Systematic literature review; robotic technologies and robot simulators	The use of robotic technologies is associated with the development of cognitive, psychomotor, and affective competencies in vocational education.
5	Vargas et al. (2023)	Chile; electrical engineering master's students studying industrial PID control	Competency-based learning evaluation; Factory I/O and MATLAB/Simulink	Factory I/O complements Simulink by providing a virtual industrial environment for practising fault detection and operating procedures.
6	Vu (2025)	Vietnam; 309 participants from three Electrical Automation campuses	Mixed methods; MATLAB/Simulink, Proteus VSM, TIA Portal, TwinCAT 3, and Factory I/O	The use of simulation was associated with active and project-based learning. The study is included as supporting evidence because of concerns regarding journal coverage and indexing status.
7	Ardana et al. (2024)	Indonesia; PLC control implementation in a polytechnic setting	System development and implementation; Factory I/O and Schneider PLC	Demonstrated the implementation of PLC-based simulation for sorting metallic and non-metallic objects. The study focused on system development rather than measuring learning outcomes.
8	Kucera et al. (2022)	Slovakia; case study in industrial automation education	Case study development; CODESYS, OpenPLC, Factory I/O, OPC UA, and cloud technology	Developed a case study on monitoring and controlling a discrete production system. The study demonstrated the potential for integrating

				simulators with industrial technologies.
9	Li et al. (2025)	China; development of a PLC experimental platform	Platform development; Siemens TIA Portal, S7-1500 PLC, and HMI	Produced a PLC and HMI experimental platform design for automation learning. The study did not comparatively examine improvements in learning outcomes.
10	Sahertian et al. (2021)	Indonesia; 50 eleventh-grade students at SMKN 2 Surabaya	Controlled-group experiment; CX-Designer and product-based project learning	The experimental group achieved a mean post-test score of 70.0, compared with 52.0 in the control group. The observed effect reflects the combined contribution of project-based learning and the use of CX-Designer.
11	Pebrianti et al. (2023)	Authors affiliated with institutions in Malaysia and Indonesia; quadrotor drone design and simulation. The research location was not explicitly stated.	Simulation experiment; Webots and PID control	Webots enabled the safe testing of drone control algorithms before their implementation on physical devices. The evidence primarily demonstrates the technical feasibility of simulation.
12	Zhang et al. (2024a, CoppeliaSim)	China; robotics course learning	Implementation case study; CoppeliaSim EDU	CoppeliaSim supports programming and experimentation with virtual robots and has the potential to reduce the costs and risks associated with using physical robots.
13	Kerimbayev et al. (2023)	Kazakhstan; secondary school students in robotics learning, with 120 participants across the overall programme	Experiment and collaborative learning; CoppeliaSim and educational robotics	Collaborative robotics learning supports computational thinking, programming, teamwork, and creativity. One experimental group examined separately consisted of 23 students.

14	Juanatey et al. (2021)	Spain; development of robotics and autonomous driving learning	Model development; CoppeliaSim, Robobo, and Python	Developed a simulation environment for testing robot navigation and behaviour before transferring them to physical robots.
15	Purnama et al. (2021)	Indonesia; eleventh-grade Industrial Electronics Engineering students at SMKN 1 Jetis	R&D and module validation; Proteus Professional and CodeVision AVR	Produced a Proteus-assisted microcontroller learning module. The findings focused on media development and feasibility.
16	Asbendri et al. (2024)	Indonesia; vocational high school students in industrial electronics	Quasi-experiment; Tinkercad	The experimental group demonstrated an 11.5% improvement in learning outcomes compared with the control group.
17	Maniar et al. (2021)	Indonesia; eleventh-grade students at SMK Negeri 1 Jetis	Pre-experimental one-group pretest-posttest; Proteus	Learning outcomes improved following the use of Proteus, and student responses reached 82%. The absence of a control group limits causal claims.
18	Tselegkaridis et al. (2024)	Greece; 110 university students learning circuit design and Arduino programming	Three-group comparative experiment; Tinkercad, breadboard, and modular board	No significant differences were found in several post-test outcomes across the groups. Simulation was not demonstrated to be categorically superior to physical practice.
19	Malik et al. (2025)	Indonesia; 27 tenth-grade students at SMK Muhammadiyah 1 Sukabumi in the Computer and Network Engineering (TJKT) programme	Quantitative quasi-experimental study; Wokwi and Tinkercad	The combined effect of both media was significant ($p = 0.016$). Individually, Wokwi had a significant effect ($p = 0.007$), whereas Tinkercad did not ($p = 0.100$).
20	Dimapilis & Andal (2025)	Philippines; 41 eleventh-grade students in mechatronics learning	Quasi-experiment with a pretest-posttest design; FluidSIM mobile application	Learning outcomes improved significantly following the use of FluidSIM. No control group was included.

21	Sukardjo et al. (2023)	Indonesia; development of electro-pneumatic practicum media for vocational high school students	R&D and expert validation; augmented reality and electro-pneumatic virtual laboratory	The media received expert ratings ranging from 4.4 to 4.8 and resulted in the development of a practical learning resource. The evidence demonstrates media feasibility.
22	Ortiz et al. (2025)	Ecuador; 16 university students in industrial process control learning	Learning experiment; digital twin, TIA Portal, S7-1200 PLC, and HMI WinCC	Task completion time decreased by 38%. The small sample limits the generalisability of the findings.
23	Flaga & Pacholczak (2022)	Poland; development of a digital twin demonstrator for education and training	System development; web-based digital twin	Produced a digital twin demonstrator to represent the behaviour of a production system in a virtual environment.
24	Otano et al. (2023)	Spain; vocational education and training teachers	Development and implementation study; digital twin and virtual commissioning	Presented five digital twin applications and highlighted the need to develop teachers' competencies in designing and using them.
25	Zhang et al. (2024b, digital twin)	China; 70 vocational high school students in landscape technology	Controlled-group experiment; digital twin learning system	The digital twin learning system demonstrated positive results in several learning aspects. The study is used as supporting evidence because it was not conducted in the mechatronics field.
26	Guajardo-Cuellar et al. (2025)	Mexico; engineering students in control systems learning	Development, validation, and implementation; mixed reality laboratory	The same control algorithm could be used with both simulated and physical plants. The study is relevant to the discussion of transfer, although its connection to mechatronics is indirect.
27	Jaya et al. (2020)	Indonesia; vocational high schools with limited practical facilities	Implementation study; remote laboratory and physical laboratory equipment	The availability of practical equipment at the schools studied was approximately 30%, with one piece of equipment shared by four to six

				students. Remote laboratories provided remote access to physical equipment.
28	Asraf et al. (2018)	Malaysia; Industrial Instrumentation learning	System development; LabVIEW, Arduino, and IoT platform	Developed an e-laboratory for remotely monitoring and controlling instrumentation equipment and configuring PID control.
29	Gergic & Hercog (2024)	Slovenia; electrical engineering and mechatronics students at the University of Maribor	Learning evaluation; LabVIEW, flipped classroom, and projects	In introductory courses, approximately 120 students in professional programmes and 100 students in university programmes (about 220 in total) participated in the laboratory work each year. Further evaluation reported 39 student projects over three academic years.
30	Ponce et al. (2022)	Mexico; 95 university students studying motor control and electric vehicle prototyping	Learning implementation study; MATLAB/Simulink and low-cost hardware	A total of 84% of students reported that the course met their expectations. This result represents an evaluation of the overall course rather than the isolated effect of the simulator.

Source: Authors' mapping and analysis of the 30 articles included in the review.

The publication-year mapping indicates that research on virtual practice has developed considerably over the past three years. As shown in Table 2, 2024 recorded the highest number of publications, with nine articles, followed by 2025 with seven articles and 2023 with five articles. Thus, 21 of the 30 articles, or 70% of the corpus, were published between 2023 and 2025. In contrast, the 2018–2020 period contributed only two articles. This pattern indicates growing academic interest in simulation and virtual laboratories, particularly alongside developments in digital twins, industrial automation, and technology-based learning. However, an increase in the number of publications does not automatically indicate stronger evidence of effectiveness. The quality of research designs and the measurement of practical skills using real equipment must still be examined separately.

Table 2. Distribution of the literature by publication year, educational level, field relevance, and publication type

Aspect	Category	Number	Percentage
Publication year	2018	1	3.3%
	2020	1	3.3%
	2021	4	13.3%
	2022	3	10.0%
	2023	5	16.7%
	2024	9	30.0%
	2025	7	23.3%
Total by year		30	100%
Educational level	Vocational high schools or secondary vocational education	10	33.3%
	Higher education, polytechnics, or general secondary schools	20	66.7%
Total by educational level		30	100%
Field relevance	Directly related to mechatronics	25	83.3%
	Related or cross-disciplinary fields	5	16.7%
Total by field relevance		30	100%
Publication type	Journal articles	28	93.3%
	Conference proceedings	2	6.7%
Total by publication type		30	100%

Source: Authors' mapping and analysis of the 30 articles.

In terms of educational level, Table 2 shows that 20 articles involved higher education institutions, polytechnics, or general secondary schools, whereas 10 articles focused on vocational high schools or secondary vocational education. This composition indicates that the available research evidence is not evenly distributed between higher education and secondary-level vocational education. This imbalance is important because learning characteristics, facility availability, student readiness, and competency requirements are not necessarily the same across educational levels. Regarding field relevance, 25 articles addressed areas directly related to mechatronics, while five originated from related or cross-disciplinary fields. These five articles remain useful for broadening the discussion, but they cannot be treated as primary evidence of the effectiveness of virtual practice in mechatronics education.

The publication composition also shows that the corpus is dominated by journal articles, comprising 28 articles, while the remaining two are conference proceedings.

The predominance of journal articles provides a relatively established publication basis, but it does not, in itself, guarantee methodological quality. Differences in research designs presented in Table 1 indicate that some articles examined learning outcomes through comparison groups or pre- and post-learning measurements. Other articles reported only system development, expert validation, or user responses. Therefore, the number of publications needs to be interpreted alongside the types of evidence they provide. This mapping also indicates that research involving Indonesian vocational high schools needs to be strengthened, particularly through more rigorous experimental designs, samples drawn from multiple schools, and assessments of practical skills using real equipment.

In terms of technology, Table 3 shows that digital twins were the most frequently reported technology, appearing in five articles. Factory I/O ranked second, appearing in four articles, while TIA Portal/PLCSIM, MATLAB/Simulink, Proteus, Tinkercad, and CoppeliaSim each appeared in three articles. Other technologies, including LabVIEW and pneumatic simulation, appeared in two articles each, whereas Webots, Wokwi, CX-Designer, remote laboratories, and CODESYS each appeared in one article. This distribution indicates that virtual practice in mechatronics education does not rely on a single software application. The technologies employed correspond to the competencies being developed, ranging from PLC programming and control system modelling to electronic circuit design and the testing of robot behaviour. Accordingly, simulator selection should be based on the alignment between technological functions and learning competencies, rather than solely on software popularity or ease of use.

Table 3. Distribution of simulators and virtual practice technologies

No.	Simulator/Technology	Number of articles	Percentage of 30 articles
1	Digital twin	5	16.7%
2	Factory I/O	4	13.3%
3	TIA Portal/PLCSIM	3	10.0%
4	MATLAB/Simulink	3	10.0%
5	Proteus	3	10.0%
6	Tinkercad	3	10.0%
7	CoppeliaSim	3	10.0%
8	LabVIEW	2	6.7%
9	Pneumatic simulation	2	6.7%
10	General virtual laboratory	2	6.7%
11	Webots	1	3.3%
12	CX-Designer	1	3.3%

13	Remote laboratory	1	3.3%
14	CODESYS	1	3.3%
15	Wokwi	1	3.3%

Source: Authors' mapping and analysis of the 30 articles.

The pattern of technology use also reveals an imbalance in research coverage. Digital twins and Factory I/O are discussed relatively frequently, whereas Webots, Wokwi, CX-Designer, remote laboratories, and CODESYS each appear in only one article in this corpus. The limited number of articles does not mean that these technologies are less useful; rather, it indicates that the available empirical evidence within the corpus remains limited. Overall, the mapping of the 30 articles yields two conclusions. First, virtual practice has been applied across various technical competencies, but the research evidence comes predominantly from higher education and technology development rather than from assessments of actual practical skills in vocational high schools. Second, the diversity of simulators demonstrates that virtual practice serves specific functions and that different simulators cannot simply be treated as interchangeable.

The effectiveness and limitations of virtual practice in mechatronics education

Virtual practice demonstrates its clearest benefits in the cognitive domain, particularly in helping students understand concepts, interpret circuits, and develop programmes. Prosser and Allen (1925) and Prosser and Quigley (1949) emphasized the importance of training environments that represent the world of work, whereas Camp and Hillison (1984) criticized the limitations of Prosser's theory for giving insufficient attention to higher-order cognitive and affective skills. The strongest empirical evidence comes from the meta-analysis by Li and Liang (2024a), which covered 46 studies from 22 publications and reported an effect size of Hedges' $g = 0.686$. However, the heterogeneity was very high ($I^2 = 94.8\%$), and the *funnel plot* was asymmetric. In the vocational high school context, Asbendri et al. (2024) reported an 11.5% improvement in learning outcomes, while Sahertian et al. (2021) obtained a mean *post-test* score of 70.0, compared with 52.0 in the control group. Thus, virtual practice provides strong support for conceptual understanding, but its effectiveness depends on the subject matter, technology, and instructional design.

In the psychomotor domain, the evidence remains less robust than that in the cognitive domain because some studies measure performance within simulators rather than skills in operating physical equipment. Ortiz et al. (2025) reported a 38% reduction in task completion time among 16 university students using a *digital twin*. Ponce et al. (2022) demonstrated an approach more closely connected to practical experience by integrating MATLAB/Simulink with low-cost hardware to develop an electric vehicle prototype. In the affective domain, Li and Liang (2024a) found a positive impact on motivation, Vargas et al. (2023) reported that Factory I/O supported learning interest,

while Kerimbayev et al. (2023) identified improvements in motivation and collaboration. Through *experiential learning*, Kolb (1984) emphasized a cycle of experience, reflection, conceptualization, and active experimentation. Dewey (1938) also stressed the importance of continuity of experience to ensure that learning remains educative. Therefore, positive responses and smooth task completion in virtual environments do not yet demonstrate mastery of *hands-on* skills; competencies must be assessed through the use of real equipment.

Comparisons with physical practice indicate that virtual practice does not always produce higher learning outcomes. Tselegkaridis et al. (2024) compared groups using Tinkercad, *breadboards*, and *modular boards*, but found no significant differences in their *post-test* scores. This finding does not establish that the three approaches are entirely equivalent; rather, it indicates that no differences in learning outcomes were detected within the context and measurements of that particular study. Tinkercad received positive responses regarding students' understanding of component interconnections, but this advantage was not reflected in the *post-test* scores for the circuit subdomain. Malik et al. (2025), as supporting evidence from the Computer and Network Engineering (TJKT) field, found a significant simultaneous effect of Wokwi and Tinkercad, whereas the partial effect of Tinkercad was not significant. These findings indicate that simulator effectiveness is related to the competencies being developed and the instructional strategies employed. Virtual and physical practice should not be treated as competing alternatives that replace one another: simulation facilitates exploration and repetition, whereas physical practice assesses the ability to deal with the characteristics of real equipment. A comparison of the effectiveness and limitations of virtual practice in terms of cognitive, psychomotor, and affective aspects, skill transfer, research design, facilities, costs, and educator readiness is summarized in Table 4.

Table 4. Effectiveness and limitations of virtual practice in mechatronics education

Aspect	**Main findings**	**Empirical evidence**	**Limitations or implications**
Cognitive	Virtual practice tends to improve conceptual understanding and learning outcomes.	Li and Liang (2024a) reported Hedges' g = 0.686. Asbendri et al. (2024) reported an 11.5% improvement in learning outcomes. Sahertian et al. (2021) obtained mean *post-test* scores of 70.0 in the experimental group and 52.0 in the control group.	Effectiveness varies according to the technology, subject matter, and instructional design.
Psychomotor	Simulators support procedural practice, system testing, and	Ortiz et al. (2025) reported a 38% reduction in task completion time. Ponce et al.	Improved performance in a simulator does not

	task completion in virtual environments.	(2022) integrated MATLAB/Simulink simulations with low-cost hardware to develop an electric vehicle prototype.	demonstrate mastery of *hands-on* skills using real equipment.
Affective	Virtual practice has the potential to increase interest, motivation, engagement, and collaboration.	Li and Liang (2024a) found a positive impact on motivation. Vargas et al. (2023) reported that Factory I/O supported learning interest. Kerimbayev et al. (2023) identified improvements in motivation and collaboration in robotics learning.	Motivation and positive responses cannot replace the assessment of practical competencies.
Comparison with physical practice	Virtual practice does not always produce higher learning outcomes than the use of real components.	Tselegkaridis et al. (2024) found no significant differences in *post-test* scores among the Tinkercad, *breadboard*, and *modular board* groups.	Simulators and physical practice serve different functions and should be selected according to the targeted competencies.
Skill transfer	Skills acquired through simulation have not been shown to transfer automatically to real equipment.	Pebrianti et al. (2023) did not examine the transfer of Webots simulation to a physical drone. Tselegkaridis et al. (2024) also identified the transfer from Tinkercad to a physical environment as an issue that had not been tested.	Virtual practice needs to be connected with practical training and direct assessment using real equipment.
Research design	Several studies still employ small samples, single-group designs, or research conducted at a single location.	Asbendri et al. (2024) used a non-equivalent control group quasi-experiment in a single school. Maniar et al. (2021) used a one-group design. Dimapilis and Andal (2025) involved 41 students without a control group.	The generalizability of findings and the strength of causal claims remain limited.
Facilities and costs	The use of simulators still requires supporting devices, licences, connectivity, and the availability of real practical equipment.	Jaya et al. (2020) found that the availability of practical equipment was approximately 30%. Vargas et al. (2023) and Vu (2025) identified software licensing costs as an obstacle.	Implementation needs to consider software costs as well as the maintenance of physical practical facilities.

Educator readiness	The use of digital twins and engineering software requires educator competencies and technology familiarization for students.	Otano et al. (2023) highlighted the time and technical competencies required by teachers to develop digital twins. Chamorro-Atalaya et al. (2024) identified educator competency as an issue in implementing this technology.	Teacher training and technical support need to be provided before the technology is implemented.

Source: Authors' synthesis based on the reviewed literature.

The issue of transfer represents a major limitation in evaluating virtual practice. The ability to assemble circuits or test algorithms on a screen does not necessarily translate into the ability to connect wires, calibrate sensors, and troubleshoot real equipment. Pebrianti et al. (2023) used Webots to test the mechanisms and control of an aerial vehicle, but the transfer of these skills to a physical drone was not examined. Tselegkaridis et al. (2024) also stated that transfer from Tinkercad to a physical environment was not included in their study. Juanatey et al. (2021) designed a simulation that allowed solutions to be implemented on real robots, but did not systematically examine skill transfer. Salomon and Perkins (1989) explained that transfer does not occur automatically; rather, it requires varied practice, the abstraction of principles, and connections between the training and application contexts. This is consistent with Prosser and Allen's (1925) emphasis on real work experience. Without practical training and assessment using physical equipment, improved performance in simulations is insufficient evidence of vocational competence.

The strength of conclusions regarding effectiveness is also constrained by research design. Several studies used small samples, involved only one school, or did not include control groups, making it difficult to establish that the observed improvements were caused solely by the simulator. Asbendri et al. (2024) used a non-equivalent control group quasi-experimental design at a single school (SMK Negeri 5 Padang), without random assignment. Maniar et al. (2021) employed a one-group design, while Dimapilis and Andal (2025) involved 41 students without a control group. In Sahertian et al. (2021), the simulator was combined with a project-based learning model, making it impossible to isolate the contribution of CX-Designer from the influence of the instructional model. These limitations do not invalidate the findings, but they restrict their generalizability. Thus, the available literature provides stronger evidence of the potential of virtual practice in specific contexts than of its widespread causal effectiveness. Future research needs to strengthen comparative designs, expand research locations and sample sizes, and assess competencies through direct performance using mechatronics equipment.

The implementation of virtual practice also depends on facilities, costs, and educator readiness. Jaya et al. (2020) reported that the availability of practical equipment in the

schools studied was approximately 30%. Simulators and *remote laboratories* can expand learning opportunities, although remote laboratories still require physical equipment. Vargas et al. (2023) and Vu (2025) identified licensing costs as one of the barriers to software use. Furthermore, Otano et al. (2023) demonstrated that developing *digital twins* requires time and teachers' technical skills, while Chamorro-Atalaya et al. (2024) highlighted the need for educator competencies in their implementation. Nasution and Jalinus (2024) linked the integration of information technology with curriculum development, instructional methods, and vocational education assessment. Therefore, the adoption of simulators needs to take into account hardware, licensing, connectivity, teacher training, and the sustainability of hands-on practice. Successful implementation is determined not merely by the sophistication of the simulator, but by the readiness of a learning ecosystem that connects technology, educators, facilities, and real-world experience.

Integrating virtual and real-world practice in the development of mechatronics education

Virtual and real-world practice should be positioned as two complementary learning experiences in mechatronics education. Dewey (1916) emphasized that education should connect experience with action and its consequences, ensuring that learning does not stop at the acquisition of abstract knowledge. Kolb (1984) reinforced this perspective through the experiential learning cycle, which comprises concrete experience, reflection, conceptualization, and active experimentation. Meanwhile, Lave and Wenger (1991) emphasized that skill mastery develops through participation in authentic practices and communities of practice. These three perspectives indicate that simulation needs to be connected with physical activities so that students not only understand how systems work but are also able to apply that understanding. Therefore, the integration of these two forms of practice needs to be designed as a structured learning sequence. To clarify how this integration can be implemented, Table 5 presents four learning stages that connect virtual practice with real-world practice, from preparation through simulation to the assessment of student competencies.

Table 5. Integration model of virtual and real-world practice in mechatronics education

Stages	Learning focus	Practical activities	Technologies or equipment	Forms of guidance	Assessment
1. Virtual practice	Conceptual understanding, modelling, programming, and preliminary testing	Designing circuits, testing algorithms, programming PLCs, and	Factory I/O, TIA Portal, Proteus, Tinkercad, Webots, MATLAB/Simulink	Instructions, demonstrations, and educator feedback	Conceptual tests, programme accuracy, and error identification

		identifying errors			
2. Reflection and mentoring	Connecting simulation results with the conditions of real equipment	Analysing simulation results, comparing possible errors, and planning implementation	Simulation results, circuit diagrams, programmes, and technical documentation	Discussions, demonstrations, and safety guidance	Explanations of procedures, error analysis, and practice plans
3. Real-world practice	Mastery of physical skills and work procedures	Assembling components, connecting sensors and actuators, operating systems, and performing *troubleshooting*	PLCs, sensors, actuators, electronic circuits, robots, and pneumatic equipment	Practical supervision and technical guidance	Performance observation, assembly accuracy, safety, and operation
4. Competency assessment	Integration of knowledge and skills	Completing mechatronics tasks or projects using physical equipment	Real mechatronics systems and work documentation	Evaluation and feedback based on competency criteria	Conceptual understanding, *hands-on* skills, procedural accuracy, and *troubleshooting*

Source: Authors' synthesis based on the reviewed literature.

The first stage is virtual practice, which prepares students before they use mechatronics equipment directly. Activities at this stage include system modelling, circuit design, programming, algorithm testing, and error identification. Pebrianti et al. (2023) used Webots to explore drone mechanisms and PID-based controllers, whereas Juanatey et al. (2021) developed a Robobo simulation model using CoppeliaSim as an initial testing environment before implementation on a physical robot. Ortiz et al. (2025) also reported the use of a TIA Portal-based digital twin in industrial process control learning, with a 38% reduction in task completion time among 16 university students. These findings indicate that simulation provides a safe and repeatable practice environment. Accordingly, virtual practice should be directed towards developing conceptual understanding and technical readiness before students work with physical equipment.

The second stage involves reflection and mentoring to connect simulation results with actual working conditions. At this stage, students do not merely receive outputs from

the simulator; they also analyse errors, explain their causes, and plan how to implement their solutions using physical equipment. The need for guidance is evident in the study by Gergic and Hercog (2024), which involved approximately 220 electrical engineering and mechatronics students and emphasized the need to introduce students to LabVIEW before they used virtual instrumentation. Juanatey et al. (2021) also demonstrated that the use of robotic simulations requires foundational skills in three-dimensional design and programming. As supporting evidence, Vu (2025) found that active, interactive, and project-based learning strengthened the use of simulation tools. These findings confirm that simulators are insufficient when used merely as independent practice media. Reflection and mentoring are necessary to help students connect virtual errors with technical problems that may arise when working with real equipment.

The third stage is real-world practice, which develops and assesses students' physical skills. At this stage, students apply the knowledge acquired through simulation by assembling components, connecting sensors and actuators, operating systems, and addressing technical malfunctions. Ponce et al. (2022) provide a clear example of integration through a learning approach that combined MATLAB/Simulink with low-cost hardware for 95 university students, ranging from understanding DC motors to developing an artificial intelligence-based electric vehicle control prototype. Jaya et al. (2020) demonstrated another approach through a *remote laboratory* that enabled vocational high school students to access real electronic equipment remotely, although the reported availability of practical facilities was only approximately 30%. Asraf et al. (2018) also developed a LabVIEW- and Arduino-ESP8266-based e-laboratory for temperature PID control. This evidence reinforces the need for interaction with physical equipment to develop practical competencies that cannot be replaced by simulation.

The fourth stage is competency assessment, which integrates conceptual understanding and practical skills. Assessment should not be based solely on students' ability to run programmes or complete tasks in simulators; it must also include their performance when using physical equipment. Tselegkaridis et al. (2024), through a comparison of Tinkercad, breadboards, and modular boards involving 110 university students, found no significant differences in the post-test scores of the three groups. This result indicates that simulation can support subject mastery, but does not establish its absolute superiority over physical practice. Limitations in skill transfer are also evident in Pebrianti et al. (2023) and Juanatey et al. (2021), neither of which systematically examined the transfer of skills to real equipment. Furthermore, the meta-analysis by Li and Liang (2024a) found very high heterogeneity in the results, with an I^2 value of 94.8%. The supplementary dataset published by Li and Liang (2024b) documents the data underlying this analysis. These findings reinforce the importance of assessment that goes beyond measuring performance in simulations to

examine assembly accuracy, operation, safety, and *troubleshooting* skills using physical equipment.

Implementing this integration model requires adjustments to the curriculum, educator readiness, and the availability of practical facilities. The curriculum needs to distinguish between competencies that can be developed through simulation and those that must be demonstrated using real equipment. The need for educator readiness is evident in Otano et al. (2023), who reported the development of five digital twin applications by vocational education teachers and an estimated development time of approximately seven months for each development edition. Kucera et al. (2022) demonstrated that integrating CODESYS and OpenPLC with Factory I/O through OPC UA and cloud applications can provide an alternative for developing digital practice environments. However, these technologies do not eliminate the need for physical equipment, as illustrated by the facility limitations reported in Jaya et al. (2020). Therefore, developing mechatronics education cannot be achieved merely by procuring simulators. Schools need to integrate virtual technologies, teacher guidance, physical facilities, and competency-based assessment within a unified curriculum design.

Conclusion

This study demonstrates that virtual practice plays an important role in mechatronics education, but its effectiveness depends on the type of competency being developed and how it is implemented. Simulators tend to support conceptual understanding, programming, modelling, and learning motivation because they allow students to conduct experiments repeatedly, safely, and relatively efficiently. However, these benefits do not demonstrate that skills acquired through simulation can automatically be applied to physical equipment. Differences in the functions of various platforms, learning outcomes that do not consistently favour simulation, and limited assessments of skill transfer indicate that virtual practice cannot replace direct practical experience. Therefore, this study positions simulation as a preparatory stage that must be followed by real-world practice through a structured learning sequence, accompanied by reflection and mentoring. Such integration is necessary to transform conceptual understanding into technical skills that can be applied in actual workplace situations.

The contribution of this study lies in clarifying the role of virtual practice as a complement to real-world practice and developing a four-stage integration model comprising virtual practice, reflection and mentoring, real-world practice, and competency assessment. This model represents a conceptual synthesis based on the reviewed literature rather than a model that has been empirically validated. The limitations of this study include the use of a narrative literature review with purposive article selection, a corpus of 30 articles, and limited empirical evidence concerning the transfer of skills from simulators to physical equipment. Future research should

examine this integration model through experimental or multi-site studies in vocational high schools and vocational higher education institutions, including assessments of practical skills using real equipment and investigations of skill transfer over a specified period. In practice, educational institutions need to align the use of simulators with the curriculum, teacher readiness, the availability of physical equipment, and performance-based assessment to ensure that virtual technologies genuinely support the attainment of vocational competencies.

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