

Article

Combining Virtual Reality with the Physical Model Factory: A Practice Course Designed for Manufacturing Process Education

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Abstract

Diverse model factories have been established in universities and enterprises to support practical education across various fields. Increasingly stringent health and safety regulations have made practical equipment more complex and costlier. With the advancement of digital infrastructure, virtual reality (VR) technology has been widely adopted in education to simulate real-world environments. This study explores the application of VR technology in enhancing manufacturing process education. To achieve this, an interaction methodology based on the OPC UA standard is proposed to enable data exchange between virtual and physical environments. Additionally, a detailed workflow of the practice course, conducted in a physical model factory at North China University of Technology, is presented. This approach is particularly noteworthy because it allows students to validate simulated results using a physical system, rather than relying solely on virtual scenes to mimic real-world settings. Students were divided into two groups: a practice group using the proposed digital method, and a control group without digital tools. The number of mistakes from the practice group was 37% less than that of the control group. Statistical analysis of students' grades and questionnaire responses concludes that the proposed methodology is valuable to improve students' engagement and practical skills. The presented course is replicable for other training institutions.

Keywords: engineering education; VR; learning factory; digital education system

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1. Introduction

Educating students in science and engineering involves both theoretical and practical components. However, as health and safety regulations become increasingly stringent, and equipment along with associated digital systems grow increasingly complex and costly, ensuring students acquire the necessary practical skills and understanding to move effectively into industry is becoming ever more challenging.

This paper builds on previous work that has explored the use of virtual reality (VR) in teaching practical subjects, with the aim of addressing the challenges outlined above. VR refers to a simulated experience that can be similar to or entirely different from the real world. This technology immerses users in a three-dimensional environment, allowing users to interact with digital elements in ways that can enhance gaming, training, education, etc.

1.1. The Application of VR in Education

VR is well-established in the gaming industry [1], with headsets commonly used. This technology has also been applied in education, enabling students to engage in immersive

experiences and feel as though they are fully interacting with their environment [2]. Hai [3] developed a virtual field trip system, which utilizes 360-degree panoramic virtual reality to teach construction engineering students about health and safety. The system allowed students to fully comprehend the consequences of safety breaches without the risk of fatalities that would occur in real-life scenarios.

Similarly, Krupnova [4] developed a virtual environmental chemistry laboratory to provide descriptions and simulations of water treatment and toxic gas diffusion. Liang [5] developed an educational game to teach safe approaches for underground rock-related hazards. Gao [6], through the development of a VR system to train students in the maintenance of electric locomotives, addressed the issues of very large and expensive system training. Typically, very few educational institutions would be able to purchase, house, and maintain a fully functioning system.

In the context of manufacturing process education, Ivanova [7] developed an interactive 3D virtual learning environment for measuring the geometrical parameters of gear hobs in cutting tool courses. Peidró [8] introduced an interactive web-based virtual laboratory (m-PaRoLa) to help students understand the movement principles of five-bar and 3RRR robots. Mogessie [9] created a VR-based technician training system for additive manufacturing technology.

The latest literature reveals numerous examples of digital scenario development for training in manufacturing processes, including PLC programming [10], maintenance [11], assembly [12], quality assurance [13], casting processes [14], and welding [15].

1.2. Changes in Physical Model Factories with Digitization

In recent years, the digital infrastructure associated with manufacturing processes has significantly expanded. This is evidenced by national strategic initiatives, such as Germany's Industrie 4.0 [16], France's Nouvelle France Industrielle [17], the United States' Advanced Manufacturing Partnership [18], the United Kingdom's High-Value Manufacturing [19], and China's Made in China 2025 [20].

Within this digital envelope are, inter alia, the Internet of Things (IoT), Cyber-Physical Systems (CPS), industrial automation, cybersecurity, intelligent robotics, Product Lifecycle Management (PLM), industrial big data, and computational vision.

As a consequence, it could be argued that the original learning factory (LF) concept, introduced in 1995 [21], has evolved to incorporate digital elements. Examples include the Coventry-based Manufacturing Technology Centre in the United Kingdom [22], which collaborates with the University of Birmingham [23] and Loughborough University [24] and launched a model factory showcasing how advanced industrial digital technologies can benefit manufacturers and supply chains. Similarly, the University of Nottingham developed a demonstration facility known as Omnifactory [25], a multi-purpose training center aimed at addressing the digital skills gap. Other examples include the Experimentation and Digital Factory at Chemnitz University of Technology in Germany [26]; the ETAT Smart Labs in Thailand [27], funded by the Education and Training for Automation 4.0 (ETAT) project; and the SETP Learning Factory at McMaster University in Canada [28].

Learning within these new environments is facilitated through the use of multidisciplinary teaching methodologies. One example is the virtual learning factory toolkit [29], which supports students in leveraging simulation and virtual reality technologies in their manufacturing studies.

In addition, Bashir [30] proposed a VR-based methodology that supported students in understanding the complexities of designing, implementing, and evaluating the performance and operation of reconfigurable manufacturing systems. Cole [31] introduced a hybrid, integrated, system-based experiential learning approach aimed at enhancing

students' ability to diagnose faults in mechatronic systems, an area that requires an understanding of multiple interrelated disciplines.

1.3. "New Engineering Education" in China

To enhance engineering education, the Chinese Ministry of Education [32] developed the concept of "New Engineering Education" [33]. The aim is to transform engineering education through the integration of technologies like VR, big data analytics [34], artificial intelligence (AI) [35], and digital twins (DT). A DT is a digital model that mirrors a physical entity, enabling various forms of data interaction with its real-world counterpart. This approach is being adopted widely across China. Examples include the Nanjing University of Aeronautics and Astronautics, Tianjin University, and the Beijing Forestry University, which have developed educational systems for aviation [36], biochemistry [37], and forestry [38], respectively. The North China University of Technology (NCUT) has also developed a virtual environment that simulates a real manufacturing production line.

It is this project at NCUT that forms the focus of this paper. It is of particular interest because the virtual environment developed is capable of real-time data interaction with an actual manufacturing production line. This allows students to verify simulated results directly through the physical system, unlike other approaches that merely construct isolated virtual scenes to mimic real-world settings. This paper presents a methodology that utilizes this interactive virtual environment to enhance students' practical skills and understanding of manufacturing processes.

2. Methodology

The integration of the virtual environment with the actual manufacturing production line is based on the promising open platform communications unified architecture (OPC UA) standard [39]. The proposed OPC UA standard aims at achieving two key objectives: (1) collecting data from the production line and (2) transmitting commands to control the production line. The methodology focuses on integrating industrial networks following the OPC UA standard to realize real-time data interaction.

The OPC UA standard follows the client/server paradigm. The architecture of the paradigm is shown in Figure 1. The OPC UA server contains a server application, real objects, address space, a subscription, a server application programming interface (API), and a communication stack. The server is distributed in each device of the production line. The OPC UA client contains a client application, a client API, and a communication stack. The client is integrated into the virtual environment application.

The interaction between the client and the server is as follows. The request message from the client is sent to the communication stack in the server. The server application invokes the response service and executes specified task on the nodes in the address space and then returns a response message to the client. The published message from the client is sent to the communication stack in the server and then transmitted to the subscription. When the specified subscription detects events or alerts, a notification message is generated and sent back to the client. The API is an internal interface that separates the client/server application from the communication stack.

Based on the OPC UA standard, this study presents a practice-based course titled Intelligent Manufacturing Process Training, which integrates a virtual environment with a physical model factory. Specifically, teams of three students complete the full production cycle from raw materials to the final product through a series of modular tasks.

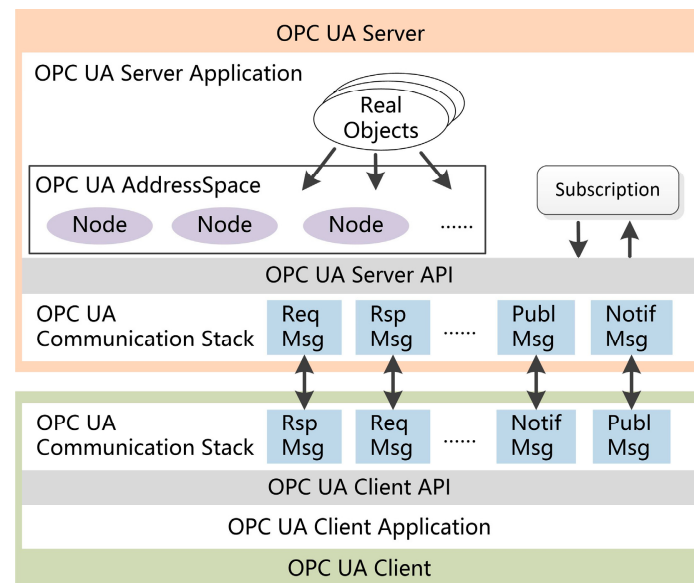


Figure 1. The architecture of the OPC UA standard [40].

Unlike traditional simulation-only approaches, this course combines virtual and physical operations, enabling students to apply their knowledge in a realistic setting. The design not only emphasizes the integration of digital tools but also aims to cultivate students' ability to solve complex, real-world problems, preserving the original intent of hands-on engineering education.

The course's design draws on the framework proposed by Heman [41], which outlines six phases for replicating discrete events in manufacturing processes. These six phases form the foundation of the course's workflow and are detailed in the following subsections.

Phase 1: Understanding the Problem

Teachers assign task sheets to students, mirroring the process of setting production tasks in real factories. These sheets contain detailed product specifications, including functions, dimensions, raw materials, accuracy requirements, and operational descriptions. Students clarify their tasks through group discussions.

Phase 2: Collecting Information

Information gathering is a critical skill in industrial settings. In this phase, students are guided to collect key parameters and identify operational methods related to the production line equipment. Foundational concepts relative to the manufacturing process are introduced through integrated software. For more in-depth knowledge, students are encouraged to consult library resources, online databases, and digital learning platforms.

Phase 3: Building Digital Models

Students create digital models of both the factory environment and the components to be manufactured. Factory modeling lays the groundwork for digital operations and maintenance, while part modeling involves designing 3D components using computer-aided design (CAD) software and generating numerical control (NC) code via computer-aided manufacturing (CAM) tools.

Phase 4: Validating Digital Models

Before proceeding to physical manufacturing, students must identify and correct errors. This stage is implemented through process simulation. Mistakes at this stage can pose serious safety risks, such as potential injury or equipment damage. Teachers play a crucial role in reviewing student work, providing feedback, and explaining corrections.

Phase 5: Manufacturing Process

Once validation is complete, students transmit their NC codes to computer numerical control (CNC) machines via the industrial internet to begin real manufacturing. Additionally, they are required to use robot teaching software to program motion sequences for automated loading and unloading tasks. Upon completion of assembly, students obtain the final product.

Phase 6: Result Analysis

In the final phase, each student prepares a report summarizing their contributions and outcomes across all stages. Reports include detailed descriptions of their work, engineering drawings, process plans, NC code, and so on.

3. Layout and Framework of the Learning Factory

3.1. Layout of the Learning Factory at NCUT

The layout of the LF is illustrated in Figure 2 and comprises two main sections. The left-hand side of the figure depicts the production line, which includes CNC machines, industrial robots, and various non-standard pieces of equipment used for transportation and assembly. The production line is divided into six stations based on their functions. While the layout differs slightly from that of a typical industrial production line, it has been optimized to better support engineering education.

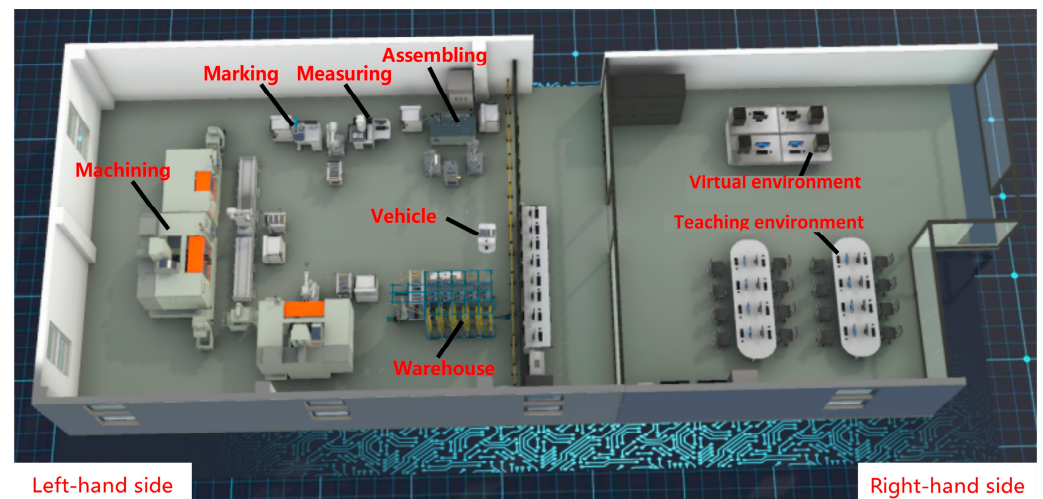


Figure 2. The layout of the LF at NCUT for manufacturing process education.

The right-hand side of Figure 2 features two environments, including a teaching environment and a virtual environment. In the teaching environment, students design the manufacturing process using CAD software to create part models, followed by CAM software to generate NC machining codes. Then, the processes are simulated in the virtual environment before being executed on the physical production line.

The operation of the production line is shown in Figure 3. The warehouse serves as both the starting point for raw material delivery and the endpoint for storing finished products. Raw materials are processed through four stations—machining, measuring, marking, and assembly—to produce the final product. Industrial robots and automated vehicles are used to transfer workpieces between stations.

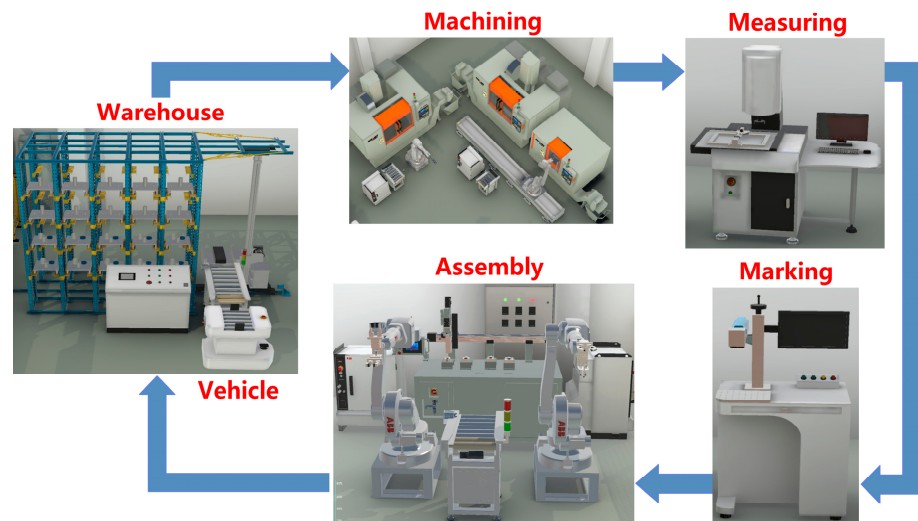


Figure 3. The raw materials are processed through machining, measuring, marking, and assembly in the production line.

Detailed Descriptions of Each Station

1. Warehouse Station

As shown in Figure 4, the warehouse is equipped with shelves, a palletizer, and a control cabinet. The shelves are arranged in two rows: the front row stores raw materials sourced from suppliers, while the back row holds finished products. The palletizer, positioned between the rows, automatically transfers items. A Siemens® (S7-1214C sourced from Munich, Germany) programmable logic controller (PLC) is installed in the control cabinet and connected to the server via a local area network (LAN) for centralized control.

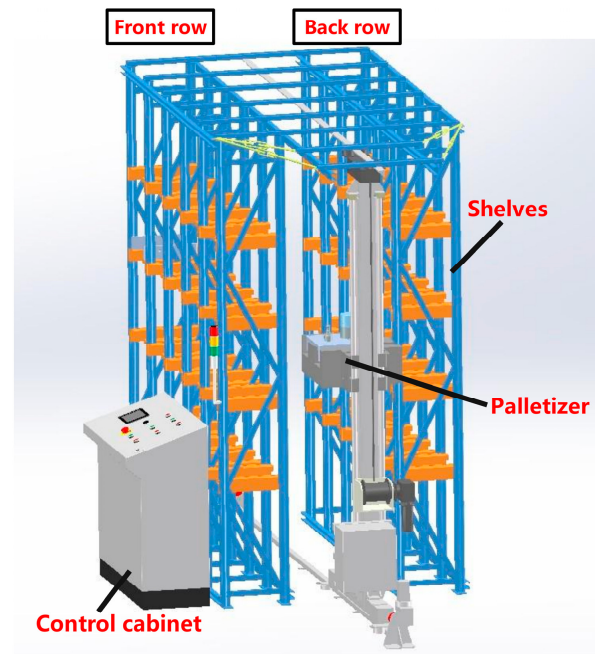


Figure 4. The structure of the warehouse station includes shelves, a palletizer, and a control cabinet.

2. Machining Station

This station includes CNC lathes, three-axis CNC milling machines, and four-axis CNC milling machines. The CNC controllers, provided by FANUC, are connected to the server through the LAN.

3. Measuring Station

The measuring station is equipped with a visual measuring instrument used for geometric inspection. Key dimensions of the manufactured parts are measured to verify compliance with design specifications. For instance, in the case of a rotary part (see Figure 5), the cone angle is measured using the instrument. These measurements are used as a key reference for evaluating student performance.

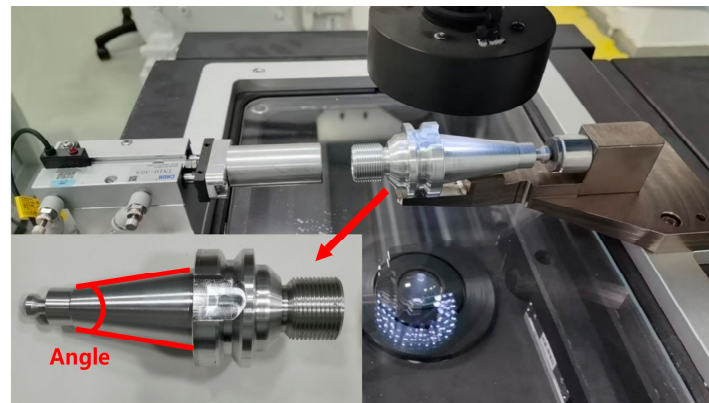


Figure 5. The angle of the cone part was measured by the instrument.

4. Marking Station

This station features a laser marking machine used to engrave two-dimensional codes onto component surfaces. Each code typically represents a unique serial number for inspection, traceability, and inventory management.

5. Assembly Station

At this station, components are assembled into the final product and packaged. The station includes a ball screw, guide rail, servo motor, air cylinder, proximity sensor, and operating screen.

3.2. Framework of the Learning Factory at NCUT

The LF is divided into five layers for illustrative purposes, based on the ANSI/ISA-95 standard [42] formulated by the International Society of Automation, as shown in Figure 6. These layers include the equipment, functional, application, network, and control layers.

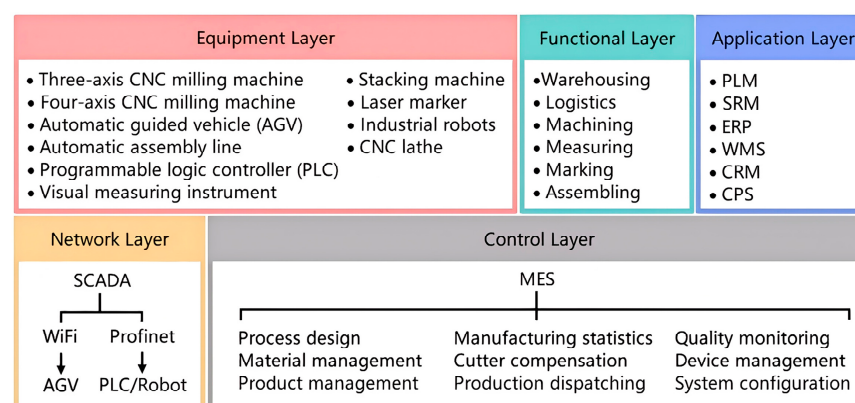


Figure 6. The architecture of the LF based on ANSI/ISA-95 standard.

3.2.1. Equipment Layer

The equipment layer comprises a variety of machinery and tools used to perform manufacturing tasks. This includes CNC milling machines, an automatic guided vehicle

(AGV), an automated assembly line, PLCs, a visual measuring instrument, a stacking machine, a laser marker, industrial robots, and a CNC lathe. All equipment is equipped with either wired or wireless communication capabilities and can be controlled via LAN. Among the most essential equipment for manufacturing are CNC machines and industrial robots.

CNC Machine: The CNC machines used in the learning factory are equipped with FANUC Series controllers (sourced from Yamanashi, Japan) supporting secondary development through a dynamic link library. This development encompasses three key areas: network connectivity, data exchange, and interface development. The controller is physically connected to the server via Ethernet cables. TCP/IP connectivity is established using the *cnc_allclibhndl3* function from the *FWLIB32/64.DLL* library. Functions from the *DataCollection* and *MachinePosition* classes are then used to retrieve tool coordinates and machine status.

Industrial Robot: The learning factory is equipped with five ABB® IRB1600 series industrial robots. These are strategically positioned near the CNC machine, visual measuring instrument, laser marking machine, and assembly station to facilitate the loading and unloading of machined parts. The robots are programmed and simulated using ABB's RobotStudio® (v.6.04.01) software—a comprehensive development platform that supports offline programming, motion simulation, parameter configuration, and other essential functionalities [43]. This software is also used in the practice course to support student learning.

3.2.2. Function Layer

Manufacturing enterprises are generally categorized into two types based on the characteristics of their production processes: flow type and discrete type. Flow-type enterprises handle materials in a continuous and uniform manner, which is typical in industries like metallurgy, chemical engineering, and pharmaceuticals—particularly when chemical reactions are central to production.

In contrast, discrete-type enterprises organize manufacturing through distinct operations, such as cutting, grinding, and drilling. These processes are typically distributed across various locations within a factory, such as workshops, departments, and stations. Components and semi-finished products are transferred between these locations and ultimately assembled into finished goods. This approach is common in industries like automotive manufacturing, electronics, and household appliance production.

Reflecting the characteristics of discrete manufacturing, the equipment within the LF at NCUT is categorized according to its functional role, forming what is referred to as the function layer. The key functional categories include storage, logistics, machining, measuring, marking, and assembly. The relationship between these functions is illustrated in Figure 7.

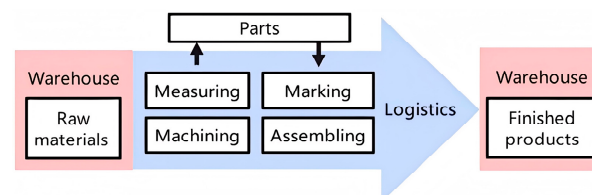


Figure 7. Raw materials start in the warehouse, undergo processing to form parts, and are then assembled into final products. These finished products are subsequently returned to the warehouse. Movement of the parts between each area is managed by a logistics system.

3.2.3. Network Layer

The network topology of the LF is illustrated in Figure 8. At the upper level, the network server functions as the central node, responsible for data collection, processing,

and instruction transmission. Equipment at the lower level communicates either via wired or wireless connections.

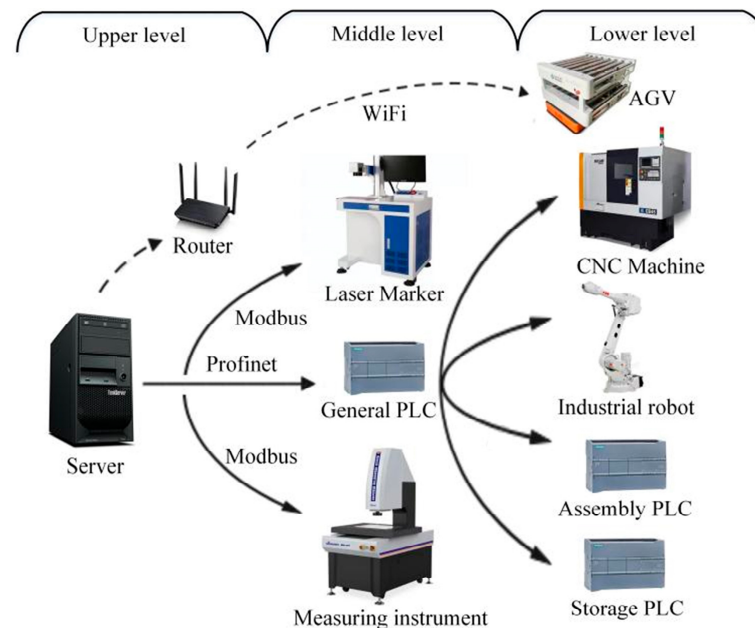


Figure 8. The network topology of the LF is divided into upper, middle, and lower levels.

For instance, fixed equipment establishes wired communication with the server using industrial protocols, such as Profinet or Modbus, which offer superior real-time performance. Profinet is an industrial Ethernet protocol that complies with TCP/IP standards and uses a standard RJ-45 interface. It is widely employed in process automation, status monitoring, and motion control applications [44].

In contrast, mobile equipment, such as the AGV, which moves between different stations, uses the Wi-Fi (IEEE 802.11) protocol to maintain wireless communication with the server.

At the intermediate level, a general-purpose PLC acts as an instruction dispatcher, facilitating data mapping, processing, and transmission between the upper-level server and the lower-level equipment.

The supervisory control and data acquisition (SCADA) system, operating on the central server, enables centralized management and decentralized control of all equipment within the learning factory. It supports a wide range of protocols and ports to facilitate both wired and wireless communication, accommodating various transmission media, such as coaxial cables, optical fiber, and microwave links. The SCADA system integrates seamlessly with PLCs, remote terminal units, microcontrollers, and other devices to ensure robust and flexible network connectivity.

3.2.4. Control Layer

The transformation of raw materials and components into finished products in manufacturing involves a wide range of activities, including the management of materials, machinery, and information related to planning, scheduling, procurement, and finance. To ensure effective coordination among personnel, equipment, materials, and energy, a robust control system is essential.

In this paper, these management activities are categorized under the control layer. A manufacturing execution system (MES) has been implemented on the server of the LF. The MES provides a comprehensive suite of functions, including process design, production

scheduling, tool parameter configuration, material and product management, equipment monitoring, system configuration, production statistics, and quality inspection.

In accordance with the ISA-95 guidelines for the hierarchy of manufacturing operations management, the MES functions are grouped into four categories, production management, storage management, maintenance management, and quality management, as illustrated in Figure 9.

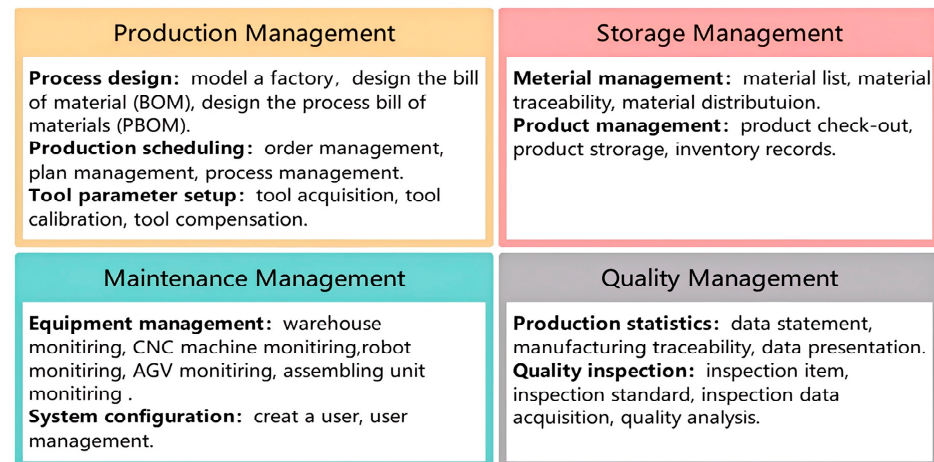


Figure 9. Grouping of MES functions based on the ISA-95 standard.

3.2.5. Application Layer

A variety of digital resources are installed onto the computers of the teaching environment, including CAD, CAM, PLM, PDM (product data management), CRM (client relationship management), SCM (supply chain management), WMS (warehouse management system), CPS (Cyber-Physical System), OA (office automatic), and ERP (enterprise resource planning) software. These applications are compatible with multiple devices, such as PCs, tablets, mobile phones, and cloud platforms, and are categorized under the application layer. Their full names are presented in Figure 10.

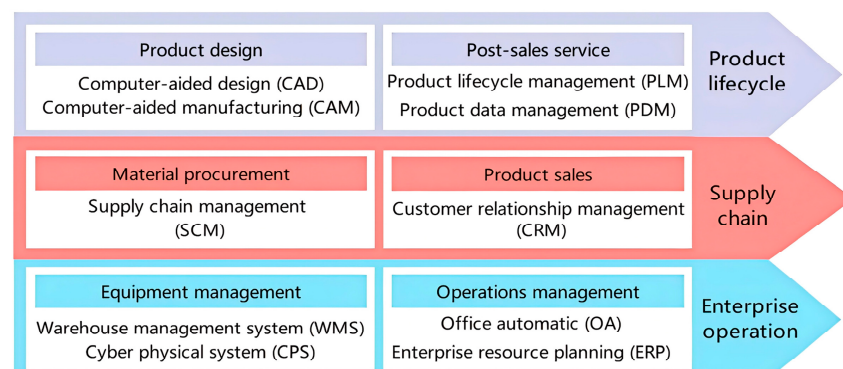


Figure 10. All of the digital resources installed in the teaching environment are divided into three main classes and six sub-classes according to their usage.

CAD, CAM, PLM, and PDM are used throughout the product life cycle—from initial design to post-sales service [45,46]. CRM and SCM manage the entire supply chain, covering everything from material procurement to product sales [47,48]. WMS, CPS, OA, and ERP are employed to enhance operational efficiency [49–52]. Seamlessly integrated, these software tools play a vital role in modern manufacturing and are incorporated into the digital enterprise system to help students understand enterprise-level operations.

4. Course Implementation and Outcome Assessment for Manufacturing Process Education

Actual views of the layout presented in Section 3.1 are shown in Figure 11, including the production line, server, console, virtual environment, and teaching environment. The practice course focusing on key technologies in the manufacturing process has been designed and implemented at NCUT. The key innovation of the presented course is the integration of a virtual environment with hands-on practice. Students learn and design manufacturing processes in a virtual environment and then validate these processes on the actual production line. The implementation of the course is detailed, and the outcomes are evaluated for ongoing improvement.



Figure 11. Actual views of the LF at NCUT, including the overall perspective of the production line, server, console, and students' operation in the virtual environment and the teaching environment.

4.1. Implementation of the Practice Course

A rotating part in blue shown in Figure 12 was chosen as a manufacturing case. It is a tool holder with one end connecting the CNC machine and the other end connecting the cutting tool.

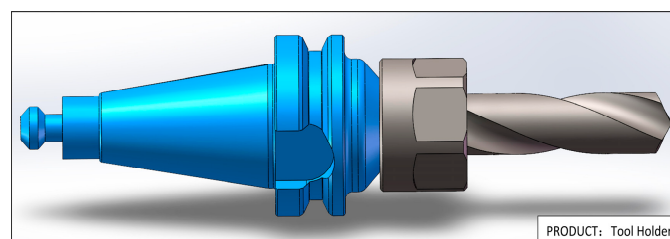
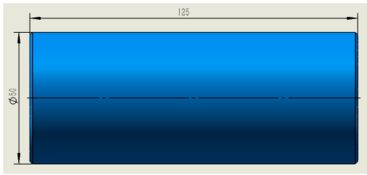
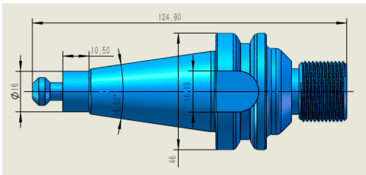


Figure 12. The tool holder in blue is a task example in the practice course that needs to be manufactured.

Table 1 presents operation steps and the specific content that the students have to carry out. The task sheet in Table 1 includes the step number, operation description, evaluation method, proportion of the grade, and machine or software students used in each step. Software used in these courses includes SolidWorks® (v.2024 Premium SPS5.0), MasterCAM® (v.2024 26.0.7108.0) [53], RobotStudio® (v.6.04.01), and the discrete event simulation (DES). Main hardware includes a CNC machine (FANUC® oi-MF Plus sourced from Yamanashi, Japan), PLC (SIEMENS® 1214C v.4.6 sourced from Munich, Germany), and an industrial robot (ABB® IRB1600-v.522861 sourced from Zurich, Switzerland).

Table 1. The task sheet of the tool holder for students.

Task No.:1 Part Name: Tool Holder Raw Material: Aluminum Alloy Functions: Connect the Cutting Tool to the CNC Machine Time: Totally 9 h		Initial State of the Part	Final State of the Part
			
Step Number	Machine or Software Used	Operation Description	Proportion of the Grades
1	Solidworks®	Design 3D model of the part	5%
2	MasterCAM®	Design cutting paths and generate NC codes	10%
3	ABB RobotStudio®	Design motion path of the robot for loading and unloading the part and generate NC codes	10%
4	DES software	Design digital model of the production line and simulate the manufacturing process	10%
5	CNC Machine and Industrial Robot	Transmit the codes to the equipment for real production	15%
6	Measuring Instrument	Measure the finished part	10%
7	DES software	Write the report and transmit to the DES	40%

4.1.1. Design 3D Model of the Part

Using SolidWorks (v.2024 Premium SP5.0), students develop 3D models and corresponding engineering drawings of the assigned part based on the specifications outlined in the task sheet. These drawings are subsequently reviewed and evaluated by the supervising instructors.

4.1.2. Design Cutting Paths of the Part

Students import their 3D models into MasterCAM (v.2024 26.0.7108.0) to configure key CNC machining parameters, including spindle speed, feed rate, cutter path, and tool compensation. The machining toolpath is first simulated within a virtual environment, allowing for verification and refinement. Once adjustments are made, the finalized NC code is generated and uploaded to the CNC machine for physical manufacturing. The simulation process and the corresponding real machining process are illustrated in Figure 13a and Figure 13b, respectively.

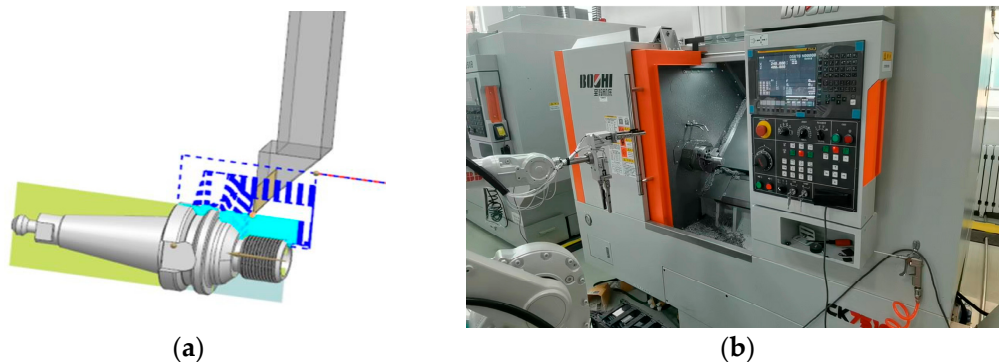


Figure 13. Contrast of design cutting paths in the virtual environment (a) and the corresponding real machining process using the CNC machine (b).

4.1.3. Design Motion Path of the Robot

Students design the motion paths of industrial robots using RobotStudio (v.6.04.01) and simulate their operations within a virtual environment. Once validated, the corresponding NC code is transferred to the physical industrial robots to automate part loading and

unloading tasks. The robots' I/O signals are synchronized with the server to enable real-time monitoring and control. The virtual simulation and its real motion on the production line are depicted in Figure 14a and Figure 14b, respectively.

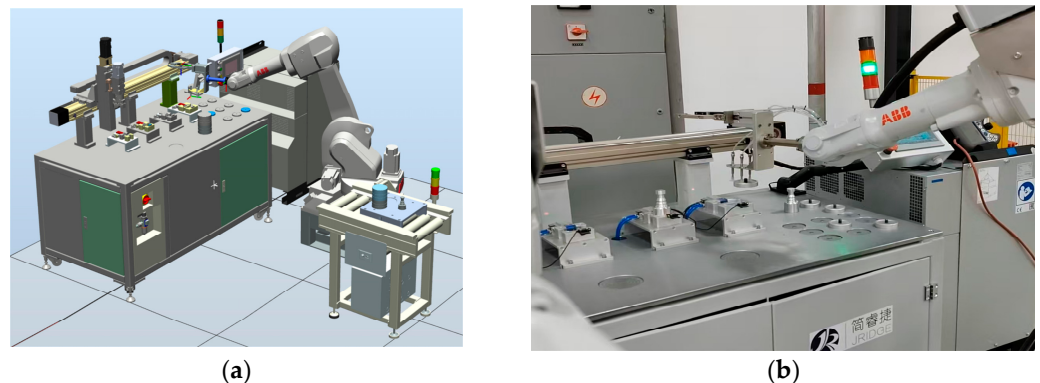


Figure 14. Contrast of design motion paths of the robot in the virtual environment (a) and the corresponding real loading process on the production line (b).

4.1.4. Design Digital Model of the Production Line

Students construct a virtual production line using DES software to simulate the manufacturing process. The key functions of the DES software are as follows:

1. *Production Line Construction:* Students can drag and drop predefined models from a component library to assemble a production line within a virtual factory environment, as illustrated in Figure 15a.
2. *Process Simulation:* Students can transmit NC code to the DES platform to simulate the manufacturing process, enabling them to visualize and analyze operations before physical execution, as shown in Figure 15b.
3. *Integrated Learning Resources:* DES software also includes built-in reference materials, instructional content, and quizzes to support student learning and reinforce key concepts.

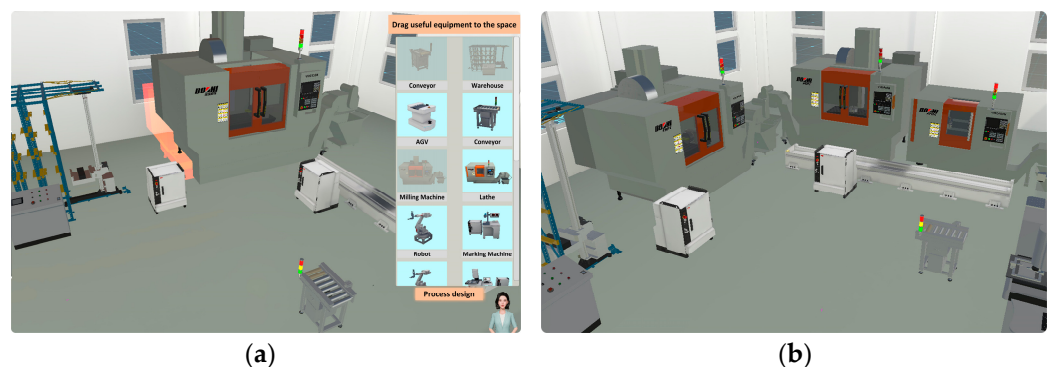


Figure 15. Students drag and drop predefined models to assemble a production line (a) and then transmit NC code to simulate the manufacturing process (b).

Following the practical session, each group submits a report to document and demonstrate their achievements. Instructors evaluate the reports based on three main criteria: technical accuracy, formatting, and writing quality. The detailed grading scheme is presented in Table 1, with a maximum score of 100 points.

4.2. Outcomes Assessment of the Practice Course

4.2.1. Contrast Experiment on Students' Performance

To assess the effectiveness of the proposed approach in enhancing students' performance, participants were divided into a practice group and a control group. The practice group used the aforementioned software to complete the design and programming processes. The manufacturing process could be verified and modified within the virtual environment. In contrast, the control group was not permitted to use the software. Students in this group had to complete the design process manually and write program code directly on the machine panels. Additionally, they were unable to verify the manufacturing process in the virtual environment.

Sixty students from the same grade and major academic discipline were selected to participate in the assessment. To eliminate the influence of students' prior academic performance on the final results, they were ranked according to their grade point average (GPA). Students with odd-numbered rankings were assigned to the practice group, while those with even-numbered rankings were assigned to the control group. Each group consisted of thirty students.

Each group was divided into ten teams of three students, with each team focused on completing their assigned tasks. Table 2 presents the average and the standard deviation (SD) of each team's completion time, the number of mistakes, and the percentage completion in the practice course. The mistakes in Table 2 were evaluated by teachers according to criteria with some key points relative to real production processes and finished parts. The key point not finished or size not reached was recorded as a mistake. The operations relative to simulation were excluded in mistake evaluation to ensure consistency of the two groups.

Table 2. Summarized performance of each team from the two groups.

Group	Completion Time (Hours)	Number of Mistakes	Completion (%)
	Mean (SD)	Mean (SD)	Mean (SD)
Practice	2.53 (0.271)	2.36 (0.142)	100%
Control	8.01 (0.557)	6.25 (0.673)	90% (0.316)

Figure 16a illustrates the completion time of each team in the two groups. The completion time was limited to 9 h, which had been specified in the task book. Teams in the control group required more time to complete the tasks and made more mistakes. Some teams were even unable to finish within the specified 9 h. Figure 16b displays box plots comparing the completion times of the two groups, revealing a significant difference between the practice group and the control group.

Furthermore, the positive impact of the practice course is also reflected in students' improved performance in subsequent related courses. Student grades were analyzed in three follow-up courses, Manufacturing Processes, Machine Design, and Computer-Aided Design, taken after the completion of the practice course.

Figure 17 illustrates the number of students who achieved a grade of B+ (60–65%) or higher in these courses. The results indicate that students in the practice group consistently outperformed those in the control group, suggesting a broader transfer of skills and knowledge gained through the integrated learning experience.

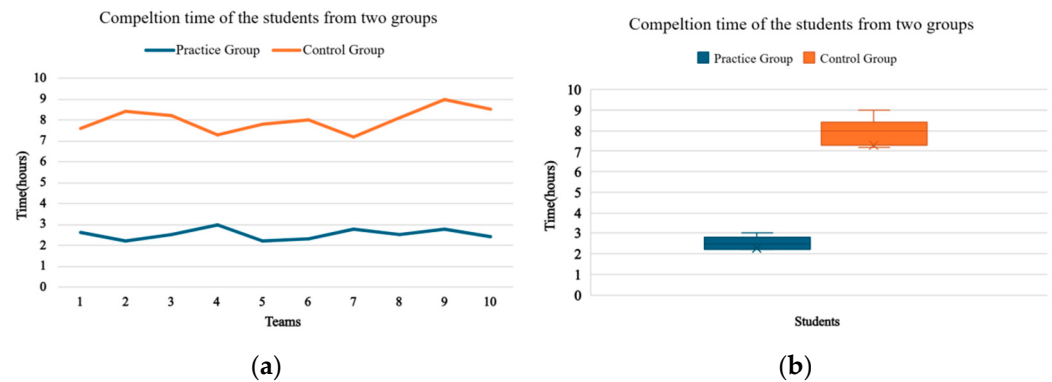


Figure 16. Contrast of completion times of the practice group and the control group; the control group is higher than the practice group. (a) Completion time of each team in the two groups. (b) Average completion times of the two groups.

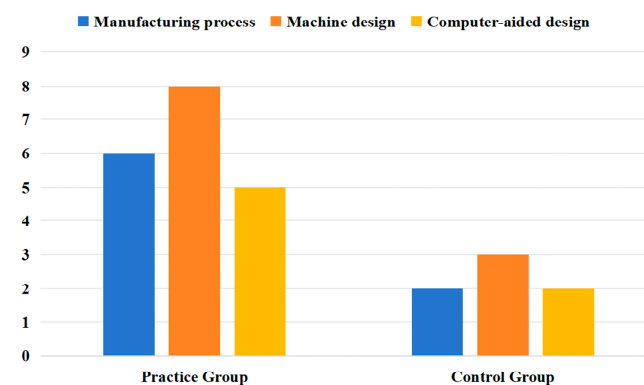


Figure 17. Number of students who got B+ or above in the practice group is higher than in the control group.

4.2.2. Satisfaction Assessment of the Students

To gather student feedback, a questionnaire was developed using the Likert scale [54], a widely adopted tool in psychological and educational research. The questionnaire comprised eight questions, as outlined in Table 3.

Table 3. Evaluation of the usability of the practice courses.

Question	Strongly Agree to Not Sure
1. I understand the principle behind the operation of CNC machines and industrial robots.	⑤ ④ ③ ② ① ① ① ① ① ①
2. I understand the role of the PLC in the production line for logic control.	⑤ ④ ③ ② ① ① ① ① ① ①
3. I have an intuitive understanding of the manufacturing process.	⑤ ④ ③ ② ① ① ① ① ① ①
4. My confidence in handling the equipment independently has improved.	⑤ ④ ③ ② ① ① ① ① ① ①
5. My teamwork and communication skills have improved.	⑤ ④ ③ ② ① ① ① ① ① ①
6. My interest in setting up and operating the equipment has improved.	⑤ ④ ③ ② ① ① ① ① ① ①
7. The task of the practice course is challenging.	⑤ ④ ③ ② ① ① ① ① ① ①
8. I would recommend these courses to my classmates.	⑤ ④ ③ ② ① ① ① ① ① ①

- Questions 1–3 focused on evaluating students' perceptions of their learning outcomes;
- Questions 4–6 assessed the quality of student interactions during the course;
- Questions 7–8 gathered students' overall recommendations and impressions.

Responses were rated on a 5-point Likert scale, ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), with an additional "Not Sure" option for students who preferred not to respond. For statistical analysis, responses marked as "Not Sure" were excluded.

The survey results from the experimental and control groups are presented in Tables 4 and 5.

Table 4. The survey results from the practice group.

Question	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
① Strongly Agree	24.6%	20.6%	20.6%	72.6%	51.6%	81.2%	58.6%	72.0%
② Agree	72.9%	35.9%	59.9%	21.9%	23.2%	11.5%	20.9%	25.6%
③ Neutral	1.1%	20.1%	10.1%	3.1%	13.3%	4.1%	19.1%	2.2%
④ Disagree	0.9%	17.9%	7.9%	1.4%	10.2%	3.2%	0.9%	0.2%
⑤ Strongly Disagree	0.5%	6.5%	1.5%	1.0%	1.7%	0.0%	0.5%	0.0%

Table 5. The survey results from the control group.

Question	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
① Strongly Agree	25.8%	10.4%	10.2%	22.3%	31.6%	9.1%	68.7%	22.1%
② Agree	39.1%	31.3%	42.3%	31.5%	44.0%	16.5%	28.8%	35.7%
③ Neutral	20.8%	25.7%	27.4%	33.6%	21.0%	18.1%	1.9%	36.3%
④ Disagree	12.4%	26.4%	17.9%	11.4%	8.9%	51.2%	0.6%	2.8%
⑤ Strongly Disagree	1.9%	6.2%	2.2%	1.2%	5.5%	0.1%	0.0%	3.1%

Figure 18 illustrates the responses to Questions 1–3 from the practice group, focusing on perceived learning outcomes. Notably, students expressed a lower level of agreement with Question 2, suggesting that the practice course was less effective in supporting their understanding of PLC concepts—an area identified for improvement.

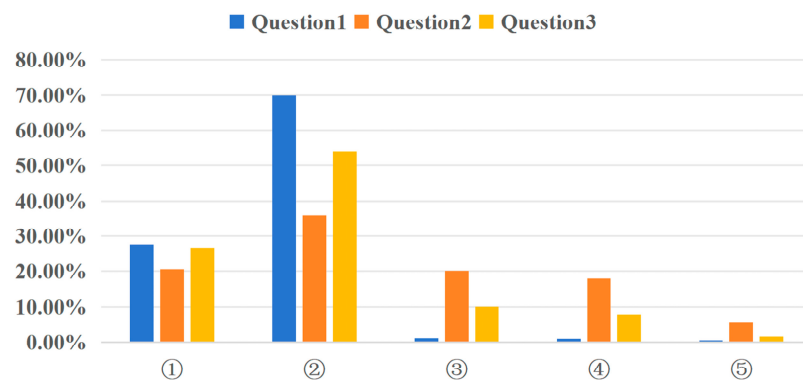


Figure 18. The survey results for Questions 1–3 from the practice group.

Figure 19 displays the percentage of “Strongly Agree” responses to Questions 4–6 from both groups. The results indicate that the integration of the virtual environment significantly enhanced students’ confidence, collaboration skills, and engagement.

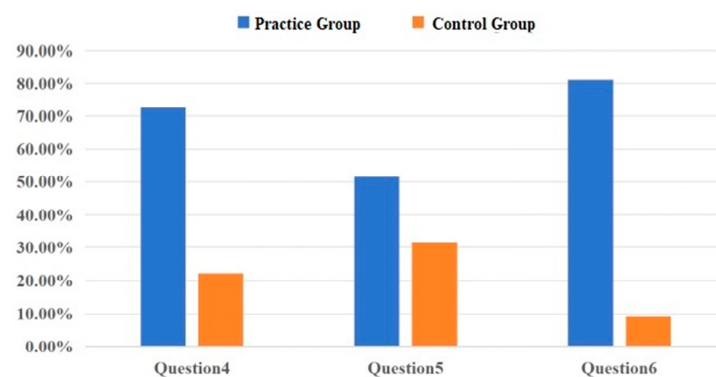


Figure 19. The strongly agree results of Questions 4–6 from the two groups.

Figure 20 presents the “Strongly Agree” responses to Questions 7–8. While students in both groups acknowledged the challenging nature of the course, those in the practice group were more likely to recommend the course to others. This suggests that the methodology proposed in this study is more appealing and impactful from the students’ perspective.

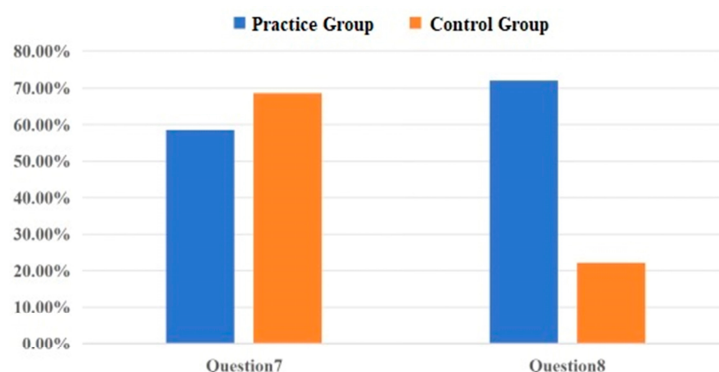


Figure 20. The strongly agree results of Questions 7–8 from the two groups.

5. Discussion

This research focuses on integrating virtual infrastructure with physical equipment via the OPC UA standard. The cross-platform feature in the OPC UA standard enables real-time communication between different hardware and software. Then, the real-time data are fed back to operators through visual interface, reducing hands-off time between different platforms. The OPC UA standard integrates multiple protocols in industry 4.0 and unifies data formats. The process of subscribing to a standard data stream eliminates protocol conversion. Information in the data stream is transformed into a visual model and presented in a virtual environment, reducing cognitive load on the operators.

Based on industrial networks adhering to the OPC UA standard, the proposed practice course integrates VR technology with a physical model factory to enable data interaction between virtual and real environments in the context of manufacturing processes. During the practice course, teams of three students complete tasks, including 3D model design, engineering drawing, code programming, robot operation, and process design.

The designed course was grounded in experimental learning theory [55], which emphasizes the importance of active exploration in learning. Constructivist grounded theory [56] informed the development of the interactive modules, encouraging students to build knowledge through active explore, invention, and problem solving in the course. Balalle [57] reviewed a lot of the literature about using VR, augmented reality, and mixed reality in higher education. The innovation of this presentation lies in the fact that students will engage in real production after practice, which is different from a totally virtual operation. The presented methodology aligns with situated learning [58], in which knowledge is acquired in an active way, rather than passive observation.

Another theory is that interest promotes learning, which plays a crucial role in the design of the course. Interest is closely related to intrinsic motivation and is often a measure of motivation. Some researchers argue that all behavior is driven by external rewards, while other theories emphasize the importance of intrinsic motivation, where the activity itself is the reward [59]. In that case, interest can be regarded as the extent to which VR enhances students’ motivation in learning. To evaluate students’ experience in the course, a questionnaire using a five-point Likert scale was designed. Of course, the collected data have a certain degree of psychological subjectivity comparing the consumed time and the number of mistakes. Studying how to objectively assess psychological states through a questionnaire is a valuable research direction in educational psychology.

6. Limitations

Comparative experiment and student satisfaction assessment demonstrated that the course effectively enhances students' engagement and practical skills. However, the experiment also revealed certain limitations. The lack of individual accountability within teams may negatively impact overall team performance. For example, if one member fails to complete the engineering drawing, it can delay the entire team's progress. As a result, some students questioned the objectivity of the final scores. Peer assessment among team members may be a potential solution, but it may introduce certain conflicts of interest.

7. Future Research

The sample size used in the study is relatively small (30 students in total, excluding the control group). Future research will aim to improve the validity and scientific rigor of the assessment methods employed in this study. The experiment results, along with promising comments, prompt more careful design of the control experiment (e.g., random sampling, use of a large sample) and a more formal evaluation with objective statistics. Additionally, it is valuable to implement the control experiment in other training institutions and incorporate diverse populations to obtain more comprehensive understanding of the study.

8. Conclusions

This paper presents a hands-on methodology that integrates VR technology with a physical model factory via the OPC UA standard. The study's findings demonstrate that the integration of VR significantly improves students' learning efficiency and outcomes. The main argument highlights the significant potential of VR as an innovative educational tool capable of integrating with the existing physical environment to enhance students' cognition of new knowledge and maintain a hands-on process simultaneously.

Key findings and evidence are as follows:

1. Integrating the virtual environment with a real production line not only improves learning efficiency but also preserves the hands-on nature of practical training. Students in the practice group consumed 2.53 h to finish the task, which was obviously lower than that of 8.01 h in the control group.
2. Students demonstrated greater mastery of knowledge compared to traditional hands-on methods, which was reflected in their performance in subsequent courses. Nineteen students in the practice group got B+ or above in three subsequent courses, which was obviously higher than that of seven students in the control group.
3. Surveyed students provided positive feedback, and more than 70% of students from the practice group strongly recommended the presented courses to classmates. The feedback indicates that the proposed methodology is a feasible innovation for manufacturing process education.
4. The presented methodology is more suitable for practice education. However, the shortage lies in the high cost to build the production line. So, it is more suitable for the renovation of existing LFs, workshops, or devices.

To date, more than 4000 students have participated in NCUT's practice courses using this methodology. The combination of virtual and real environments has significantly enhanced student engagement and provided an intuitive understanding of operations in modern enterprises. The presented methodology, framework, course design, and assessment approach offer a valuable reference for other training institutions, including universities and industry-based programs.

For training institutions that wish to replicate the presented course, the minimum requirement is MES software referring to the OPC UA standard. In addition, the virtual

environment that simulates the real scene is crucial. For instructors who wish to transform a traditional course into a VR-assisted course, the key infrastructure relies on the construction of the network architecture and the virtual environment. Of course, these tasks can be entrusted to professional software engineers. The key consideration for instructors is to design the workflow of the course combining VR technology and conforming to the teaching objectives. It is recommended to write a script and have it implemented by the software engineers. In general, researching the opportunity to increase the use of VR in various educational settings would guide the future development of VR in training initiatives.

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Abbreviations

The following abbreviations are used in this manuscript:

VR	virtual reality
IoT	Internet of Things
CPS	Cyber–Physical Systems
PLM	Product Lifecycle Management
LF	learning factory
AI	artificial intelligence
DT	digital twins
NCUT	North China University of Technology
APT	application programming interface
CAD	Computer-aided design
NC	numerical control
CAM	Computer-aided manufacturing
CNC	computer numerical
PLC	programmable logic controller
LAN	local area network
AGV	automatic guided vehicle
SCADA	supervisory control and data acquisition
MES	manufacturing execution system
PDM	product data management
CRM	client relationship management
SCM	supply chain management
WMS	warehouse management system
CPS	Cyber–Physical System
OA	office automatic

ERP	enterprise resource planing
DES	discrete event simulation
SD	standard deviation
OPC UA	open platform communications unified architecture

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