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Investigation and practice of evaluation methods for virtual simulation experiments in intelligent manufacturing within mechanical engineering

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Abstract: Virtual simulation experiments in intelligent manufacturing serve as an effective extension and complement to theoretical courses and physical experiments in manufacturing disciplines. Relying on the Internet, students engage in experimental operations such as process planning, production control, and logistics management on virtual intelligent manufacturing production lines that integrate CNC machine tools and robotic arms. Conducting reasonable evaluations on the correctness of students' experimental designs and operations, as well as their mastery of knowledge, is an effective way to improve the quality of teaching. Considering the characteristics of virtual simulation experiments in intelligent manufacturing, this study proposes a structured evaluation method, including classification and evaluation based on knowledge points, evaluation of engineering operation skills, and overall evaluation of process rationality and safety. By using automated evaluation by virtual simulation software, in addition to manual evaluation by instructors and self-evaluation by students, a standardized and practical experimental evaluation method was established. After implementation across multiple courses and semesters, the evaluation results were found to be reliable and accurate, demonstrating the rationality and universality of the proposed method.

1. Introduction

In order to cultivate equipment manufacturing talents with solid theoretical knowledge and innovative practical skills, it is essential to incorporate necessary experimental and practical components into the teaching process. Among them, the virtual intelligent manufacturing workshop, based on large-scale equipment manufacturing environments, facilitates a series of virtual simulation experiments in intelligent manufacturing. These experiments can be integrated with various theoretical courses and physical experiments in the field of mechanical engineering, making virtual simulation experiments in intelligent manufacturing an important part of undergraduate laboratory education in mechanical engineering [1-3].

Via the Internet, students can perform experimental operations such as process planning, production control, and logistics management on virtual production lines that include equipment such as CNC machines and robotic arms. These operations require careful consideration of the rationality of process and control design, as well as the correctness of production operations.

Intelligent manufacturing virtual simulation experiments are conducted through modular experiment combinations, selection of processing objects, adjustment of preset experiment parameters, and changes in production process parameters. This approach aims to meet the skill requirements associated with related theoretical courses and physical laboratory sessions. Given the integration of virtual and physical elements, as well as the adjustable and flexible nature of these experiments, conducting a scientific and comprehensive evaluation of such virtual simulation experiments serves as an effective guarantee for improving the quality of experimental teaching

Many universities have actively explored and implemented effective reforms regarding the evaluation methods for online courses or virtual simulation experimental courses, with positive results [3-7]. Based on the existing methods, this study focuses on developing a targeted evaluation system for virtual simulation courses in intelligent manufacturing by combining software-based automated evaluations with active evaluations from both instructors and students. This approach aims to improve the effectiveness of evaluation and promote the integration of students' theoretical knowledge with practical skills.

2. Evaluation methods for intelligent manufacturing virtual simulation experiments

(1) Overview of the evaluation methods

The virtual simulation experiment of intelligent manufacturing serves as an effective extension and supplement to theoretical courses and physical experiments in mechanical manufacturing, while maintaining a close relationship with them. Therefore, the virtual simulation experiment should focus on evaluating students' mastery of knowledge points related to theoretical courses, as well as their skill and accuracy in experimental operations. This will ensure that the evaluation requirements of the knowledge points of theoretical courses and the skill points of comprehensive practical courses are aligned. The relationship and evaluation structure of the intelligent manufacturing virtual simulation experiment evaluation system are shown in Fig. 1.

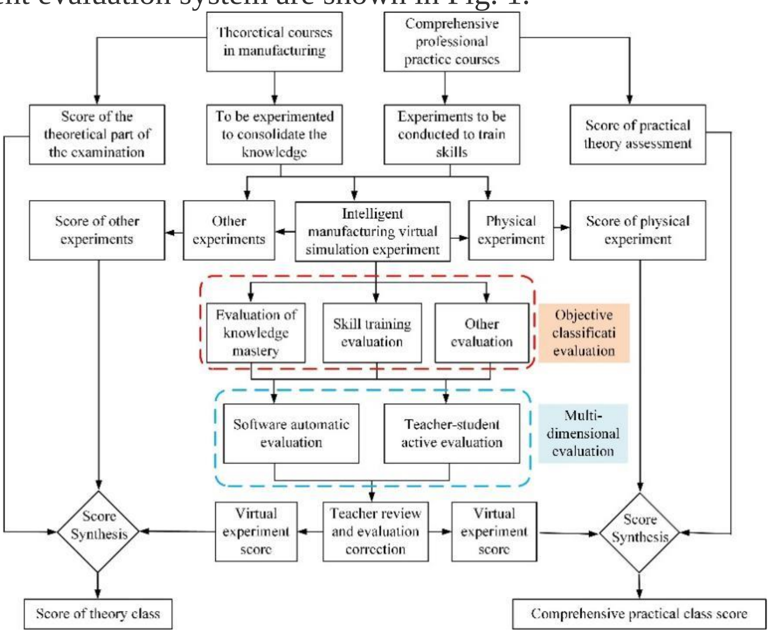

Fig.1 Evaluation system of intelligent manufacturing virtual simulation experiment

Manufacturing theory courses typically include experiments and knowledge points related to intelligent manufacturing technology. Examples include programming, driving, testing, and operation experiments in “Numerical Control Machine Tools”; control software and hardware design, programming, and operation in “PLC Technology”; experiments on equipment, processes, fixtures, cutting tools, and control in “Mechanical Manufacturing Technology”; and experiments on equipment and production line control in “Automation Control”.

Professional comprehensive practice courses also integrate content related to virtual technologies, focusing on students' mastery of related theoretical knowledge points and their proficiency and accuracy in experimental operations. Such courses include “Virtual Design and Manufacturing of Machinery”, “Comprehensive Experiments in Mechanical Engineering”, and intelligent manufacturing-related sections of “Internships”. The breadth, depth, or emphasis of the knowledge points covered in different courses vary, resulting in differences in the evaluation criteria for lab scores and the contribution of those scores to the overall course grade.

The evaluation of virtual simulation experiments can be classified according to objectives, including assessments of knowledge mastery, engineering operating skills, and other general aspects such as rationality, discipline, safety, and extensibility of the experimental process. The weight of these evaluation dimensions can be adjusted based on the specific requirements of each course.

Course evaluation methods include automated software grading and active grading involving both instructors and students. Virtual simulation experiment courses based on B/S architecture network software should mainly focus on automated software evaluation. The software calculates appropriate scores by weighting theoretical evaluation scores, virtual experiment scores, and other specified experiment scores according to the evaluation policies of each course. Instructors conduct their review, evaluation, and grading based on students' experimental process records, report quality, individual or team performance, and adherence to safety protocols. Student evaluation, on the other hand, focuses primarily on assessing team collaboration and individual contributions as part of the active assessment process.

(2) Classification evaluation of virtual simulation experiment goals

1) Classification and scoring based on knowledge point requirements

The knowledge points in theoretical courses that require reinforcement and extension through experimentation can be categorized based on the depth of mastery into knowledge points for understanding, familiarity, and proficiency. The software expresses and automatically scores these knowledge points according to the requirements of the course syllabus, as detailed in Table 1.

Table 1 Requirements for automatic evaluation of the mastery of knowledge points and evaluation methods

request	experimental expression	Evaluation methodology
Understanding Class Knowledge Points	Demonstration of simulation operation	Number of demo items viewed, length of time viewed
	Structural principle cognitive operation	The simulation operation logic is reasonable and the operation sequence is correct
	Knowledge Base Randomized Quiz	Knowledge quiz questions answered correctly
Familiarity class knowledge point	Individual design tasks for processes, fixtures, controls, etc.	Reasonable design basis, reasonable analysis and calculation, correct design results
	Processing unit or logistics unit operation	Correct parameter setting, correct equipment operation, correct process flow, correct control logic, electromechanical safety compliance
Mastery Class Knowledge Points	CNC machine tool drive and inspection design Automatic fixture design	Reasonable selection of hardware parameters, software design is correct, equipment and parameters are correct, tool parameters are

	Design of machining process and logistics of the section Workshop control design	correct, timing and beat is correct, positioning and clamping is correct, the clamping automation ≥ 1, the control logic is correct, productivity balance ≥ 75%
	Design Rationality Check	Design parameter-driven runs, simulation runs with correct results
	optimization and refinement	Improvement of optimized design parameters ≥ 1
	Extended Applications	Expanded application recommendations ≥ 1

2) Evaluation of experimental operating skills

The evaluation of students' experimental operating skills consists of two parts: teacher-initiated scoring and software-automated scoring. (1) For the physical equipment integrated in the virtual production line, such as CNC machine tools, clamping fixtures, tool libraries, robotic arms for loading and unloading, and AGV carts for transportation, students are guided to operate these physical devices in the lab based on the production rhythm parameters of the logistics process of the virtual production line. Teachers actively evaluate students' operation behaviors according to the detailed operation guidelines in the experiment manual, and the scores are incorporated into the overall virtual experiment score. (2) Students' operations within the virtual production line are automatically evaluated by the software. The requirements and methods for automatic evaluation of operation skills are detailed in Table 2.

Table 2 Operational skills evaluation requirements and evaluation methods

Virtual experiment operation content	**Evaluation methodology**
Operation object selection	Score by menu itemization
sequential operating class	Template calibration in established sequence
Process Operation Logic	Conforms to predefined process logic
Control Logic Operation	Conforms to pre-programmed electrical control logic
tool-based operation	Select, use, and place correctly
Operational Safety Category	Compliance with major electromechanical safety regulations

Taking virtual simulation experiments in mechanical control design as an example, the method of virtual machine and physical device simulation verification evaluation is applied. In intelligent manufacturing system experiments, control design for processing and logistics equipment or production lines is a crucial component. Evaluating the rationality of these designs not only ensures practical training for students, but also enhances the functionality of software-based automatic evaluation, which promotes students' self-checking and self-improvement awareness and skills. Students design control timing diagrams and build physical PLC control systems based on the control objects, production processes, and rhythm parameters. They then connect the physical PLC controllers and programming designs to the virtual production line for simulated operation and output. The experimental terminal software compiles and recognizes the control program in real time, and collects the operation signals and sends them to the corresponding virtual ports of the I/O ports of the hardware PLC system. The server program evaluates the rationality and correctness of the port mapping and I/O signals. Next, the control program drives the operation of the virtual equipment or production line, and the accuracy of the program is reflected in the actions of the virtual equipment. If the design is correct, the equipment operation and production processes meet the requirements, and the software assigns an appropriate score. Conversely, if there are errors in the design, such as mismatched timing between material unloading from the processing equipment and the robotic arm, or AGV route interference, the virtual robotic arm may mishandle materials or the AGV may encounter collisions or traffic accidents. The software's automatic scoring system applies the predefined rules in the scoring database to issue warnings and deduct points accordingly. The simulation and verification technology has been developed and refined over the years, with the scoring rule database and algorithms continuously enriched by real-time automatic additions and manual input. This has greatly improved the accuracy of the software's automatic scoring system.

During students' experimental operations, the experimental software automatically records the design processes and results, generating a draft experimental report. This draft is saved in the .dot template format on the server, with one copy stored per student account. After the experiment, students can manually complete the remaining sections, such as result discussions, experimental conclusions, analytical reflections, summaries and outlooks, answers to reflection questions, self-evaluations, peer reviews, and suggestions or feedback. Once finalized, the report is uploaded to the course website.

The software conducts an initial evaluation of the report and assigns a preliminary score, which is later combined with the teacher's review to determine the final grade. The system's automatic assessment employs four evaluation methods:

①Exact Content Comparison – Evaluates the inclusion of required elements, such as experimental objectives, principles, instruments, and preset parameters, based on standards stored in the database.

②Record Equivalence – Compares experiment processes, results, design data, and operations for consistency with server-stored records.

③Keyword Matching– Verifies the presence of indexed keywords in sections like analytical reflections, summaries, and answers to reflection questions.

④Exact Matching– Assesses multiple-choice answers related to course knowledge points by checking for direct equivalence.

3) Generalized evaluation

The generalized evaluation of virtual simulation experiments primarily assesses students' subjective initiative and enthusiasm for learning, as well as their teamwork and collaboration skills. It focuses on the rationality, discipline, safety, and extensibility of experimental designs during the experimental process. Specific evaluation contents and recorded items are detailed in Table 3.

Table 3 Generic evaluation content and matters of record

Evaluation content	Automatic logging of account logins
length of experiment	Automatic recording, time-limited or time-unlimited items
repetition	Automatic recording, limiting or encouraging repetition
network security	Automatic monitoring and recording
teacher-student exchange	Automatic recording of inter-account information and attributes
Cluster synergies	Automatic recording of necessary synergies and accounts
self-esteem	Manual, based on awards and penalties related to the difference in final scores
peer review	Manual, peer assessment, self-assessment reference

(3) Course evaluation total score calculation

According to the course syllabus requirements, the overall course grade is determined by weighting the process assessment score and the final assessment score. The Process Assessment Score includes the Virtual Experiment Score (SV), the Physical Experiment Score (SE), and the Regular Performance Score (SR) during the course. The final assessment score consists primarily of the theoretical exam score (SF) (all scores are on a 100-point scale). The overall course grade (ST) is calculated as follows:

$$S_T = W_P(W_V S_V + W_E S_E + W_R S_R) + W_F S_F$$

Within this structure, WP and WF respectively represent the weighting coefficients for the process assessment score and the final assessment score towards the total course grade, summing to unity. WV, WE, and WR denote the proportional weights of the virtual experiment score, the physical experiment score, and the regular performance score within the process assessment, with the sum of WV+WE+WR equaling 100%. The specific proportions for each part are determined based on the course syllabus's emphasis on critical and challenging knowledge points, and are clearly communicated to the students. For theoretical courses with examinations, WF typically has a larger weighting, usually 70% or 60%, whereas for comprehensive practical courses, WF has a smaller weighting, generally 10% or 20%.

3. Evaluation methodology in educational practice

(1) Applying Evaluation Methods

Due to the differences in content, nature, and number of teaching hours among different courses, the processes and results of evaluation implementation also differ. The aforementioned evaluation methods have been applied to six theoretical courses related to intelligent manufacturing virtual experiments. This paper summarizes the application of these methods in three typical courses in recent semesters.

1) Application in the "CNC Machine Tools" course

The CNC Machine Tools course is 32-48 hours in total, with 6 hours devoted to a combination of physical and virtual labs. These labs integrate four key components: ①the structural principles of various CNC machine tools, ②machining centers and tool magazines, ③servo drive and sensing, and ④interpolation and CNC programming experiments. The course assigns weighted coefficients as follows: WP=30%, WF=70%, WV=40%, WE=40%, and WR=20%. In virtual experiments, for components①and②, demonstrations and operational logic are automatically and instantly evaluated, achieving an accuracy rate of approximately 98%. For component③, a virtual electrical simulation verification method is used, where drive methods, component selection, parameter settings, and electrical connections are automatically evaluated, achieving an accuracy rate of about 90%. Some aspects require manual assistance from the instructor for evaluation, especially for drive recognition schemes and substitutable components, where the program's automatic evaluation is not yet perfected. For component, through independently developed CNC programming wizards, simulation compilation, verification, and drive verification processing functions, the automatic evaluation accuracy exceeds 95%. However, for experiments involving physical machine tools and drive detection hardware, as well as bidirectional virtual-real interactive operations, the evaluation still relies mainly on manual teacher intervention. In addition, students' self-assessment scores are generally about 16% lower than their final grades, and peer assessment scores are generally higher, indicating that students' confidence and self-assessment skills need to be improved, and the objectivity of peer assessment needs to be strengthened.

2) Application in the PLC Technology course

The "PLC Technology" course focuses primarily on motor control using physical PLCs and the "Smart Manufacturing Automation Control" segment in virtual experiments, which includes unit control and section production logistics control. The course has set weighted coefficients as follows: WP=40%, WF=60%, WV=50%, WE=40%, WR=10%. The unit control section is basically similar to parts ③ and ④ of the above "CNC Machine Tools" course and will not be explained further.

For the production logistics control section, students are tasked with designing the hardware and software of the production logistics control system based on the given production line equipment, production task parameters, and production process diagrams. During the experiments, the automatic evaluation of the software by the students accounts for about 55%, the combined automatic and teacher evaluation accounts for about 20%, and the part requiring teacher evaluation is about 25%.

3) Application in the Mechanical Manufacturing Technology class

The Mechanical Manufacturing Technology course includes 48 hours of theoretical lectures and a one-week fixture design project. Practical components include hands-on equipment assembly and disassembly, measurement, testing, and virtual experiments in intelligent manufacturing processes. The course is structured with the following weighted coefficients: WP=30%, WF=70%, WV=45%, WE=35%, WR=20%. The virtual experiments mainly include the design of the milling process for integral forming of turbine engine impellers, the design of automatic clamping fixtures for impeller forming on CNC machining centers, the machining of 300MW generator main shafts, and the dynamic balance testing of 300MW generator rotors. The experiments use guided step-by-step procedures with selective parameter input and are evaluated using a database of process programs, allowing an automatic evaluation rate of approximately 80% with an accuracy of over 95%. Since this course is offered after the above courses, students benefit from increased experimental experience. Coupled with a new system of reliability rewards and penalties for self- and peer-assessment (where the reward or penalty is proportional to the accuracy error), there has been a significant improvement in the accuracy of self- and peer-assessments, increasing by 6.8% and 9.1%, respectively.

(2) Questions and reflections

After conducting approximately 21,000 student virtual experiments in six courses over four semesters, both inside and outside the school, the evaluation methods for virtual experiments have been progressively optimized. However, there are still areas that need to be strengthened and improved:

a) The course syllabus needs to be revised to gradually increase the content of virtual simulations, especially the integration of virtual and real experiments, and to appropriately increase the proportion of experimental grades;

b) Given the mismatch between course content and experimental knowledge, future efforts should focus on improving the connectivity and correlation between experimental content and knowledge points. This should form the basis for the development of targeted assessment methods and technologies;

c) We recommend increasing the proportion of automated system assessments, with the long-term goal of progressively moving toward fully automated assessment.

4. Conclusion

Virtual simulation experiments in the field of intelligent manufacturing serve as an effective extension and supplement to theoretical courses and physical experiments. The use of online platforms for virtual experiments has created favorable conditions for automated evaluations. Virtual simulation experiments are designed and implemented around the mastery of course knowledge points, engineering operational skills, and generic assessments. By integrating instructor evaluations with student self-assessments and peer evaluations, a standardized and practical course evaluation method has been established. After several courses over several semesters, the evaluation results were found to be reliable and accurate, confirming the rationality and universality of this evaluation method.

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