



## Article

# Experiment Information System Based on an Online Virtual Laboratory

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**Abstract:** In the information age, MOOCs (Massive Open Online Courses), micro-classes, flipping classroom, and other blended teaching scenes have improved students learning outcomes. However, incorporating technologies into experimental courses, especially electronic and electrical experiments, has its own characteristics and difficulties. The focus of this paper is to introduce virtual technology into an electronic circuit experiment course and to explore its teaching strategy, thereby realizing the informatization of experiment teaching. First, this paper explores the design concepts and implementation details of the digital circuit virtual laboratory, which is then developed based on previous literature and a prequestionnaire to users. Second, the informatization process of the experiment learning model based on traditional custom lab benches is shown through a blended learning scheme that integrates the online virtual laboratory. Finally, the experiment information system is verified and analyzed with a control group experiment and questionnaires. The blended program turned out to be an effective teaching model to complement the deficiencies in existing physical laboratories. The research conclusions show that the virtual experiment system provides students with a rich, efficient, and expansive experimental experience, in particular, the flexibility, repeatability, and visual appeal of a virtual platform could promote the development of students' abilities in active learning, reflective thinking, and creativity.



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**Keywords:** virtual laboratory; experimental design; blended learning

## 1. Introduction

Traditional engineering experiments are often carried out in small groups, at specified times and in fixed laboratories, with custom lab benches. The traditional experiment teaching model is widely recognized in the long-term teaching practices, and it provides users with hands-on and intuitive experiences with experiment components and measuring equipment based on a universal or custom lab bench. With the development of computer graphics and visual technologies, more conceptual applications are emerging in the field of education. Among them, virtual laboratories have been broadly accepted as a potentially effective alternative to traditional engineering courses, such as science simulation [1,2], process technologies [3–5], signal and control systems [5–7], and robotics and teaching models [8–10]. Experience has shown that students can benefit from the flexibility of virtual experiments and strengthen their innovative capability and logical thinking. However, fully software-based virtual laboratories also have inherent drawbacks; for example, students may feel as if they are playing a video game [11–13]. This study, therefore, agrees that the final training process still needs real equipment [11] and attempted to explore a blended learning scheme that mixes a virtual laboratory and real-world experience based on a university digital circuits course, to achieve a balance in learning enjoyment [14] and knowledge acquisition.

In recent years, there have been two main viewpoints on implementing virtual laboratory systems: web-based remote laboratories [7,8,15–17] and fully software-based

virtual laboratories [1–10,18–24]. A remote laboratory tries to carry out online experiments by operating physical equipment from a distance. They are usually complex, consume large amounts of bandwidth, and have high requirements for sensory-control hardware and software. Hence, this paper primarily discusses fully software-based virtual laboratories. A number of studies have elaborated their methods to implement virtual laboratories [1–10,18–24] in various educational applications. Few virtual platforms aim to realize generalized software that may be applicable to multiple disciplines. Two representative works include the “Go-Lab” project [18,19] and the “Lila” project [20], while most of the rest are specific to different fields. A virtual chemical vapor deposition (CVD) laboratory [4] emphasizes the training of students in experimental design abilities. The Virtual Laboratory for Robotics (VLR) [9] is a classic example of robot simulation. More recently, an instrument-based virtual laboratory [21] simulates an environment for electromagnetic phenomena. Work in Reference [22] realized a cloud-server-based virtual laboratory used in network security teaching and practice. The literature from Reference [23] proposed two methods to help implement virtual laboratories. In Reference [24], an NCSLab (Network-Based 3D control laboratory) was reported for a control system, and then Liang et al. [25] presented a design approach to facilitate the establishment of virtual laboratories in an HIL (hardware-in-the-loop) control system. An investigation in Reference [26] verified that students’ learning with virtual laboratories in experimental courses could achieve similar effects as using traditional laboratories.

However, some improvements may still be possible. The main implementation tools in Reference [25] include 3dsMax and Matlab, which could be updated by new ones. Additionally, most courses with a virtual laboratory are too dependent on the online section. Therefore, the main contribution of this study lies in two aspects: using the new technologies to design and implement a virtual laboratory and adopting a blended learning scheme to balance the online and offline sections in light of the investigations on blended learning approaches [27–29].

## 2. Design and Methods

This section discusses the creation of the digital circuit virtual laboratory. Section 2.1 elaborates the design concepts of the digital circuit virtual laboratory, including a pre-questionnaire to users in Section 2.1.1, and a design methodology to provide students a renewable experiment process presented in Section 2.1.2. Then the development details of virtual laboratory are shown in Section 2.2, system architecture is discussed in Section 2.2.1, and implementation is covered in Section 2.2.2.

### 2.1. Design of the Digital Circuit Virtual Laboratory

#### 2.1.1. Pre-Questionnaire

As mentioned in Reference [30], for a virtual experiment, students always pay more attention on the features of the virtual lab itself, such as the visual appeal, easy usability, and so on, rather than whether this virtual lab can be online timely. In addition, based on the study in Reference [13], teachers and students usually have different views for the same concept. Through a structural equation modeling approach [14,31], work in Reference [14] explores the importance of some hypothetical variables in an affective and cognitive path, which interact in a learning process with the desktop virtual world. With deep investigations on the above studies, a survey with teachers and students about the virtual lab is necessary prior to design and implementation, and, therefore, a questionnaire is generated. Considering the natures of digital circuits course and its experiments, this work selectively adopted some factors described in the literature works in Section 1 to construct this questionnaire. Moreover, the survey was conducted in two groups: students, 258 participants in two grades, of which one grade level of students has taken the digital circuits course, while another grade will have the digital circuits course; and 5 teachers, who have been teaching digital circuits all year round. Table 1 shows a sample of a simplified

version of the questionnaire. Table 2 illustrates the factors and their sources used in this survey. Furthermore, the statistic result of this survey can be seen in Section 3.1.

**Table 1.** A sample of a simplified version of the questionnaire.

Fields	1 to 100 Importance	Comments and Suggestions (Optional)
Like game		
Open Questions (Optional)		
How about applying the game-style to the virtual lab?		

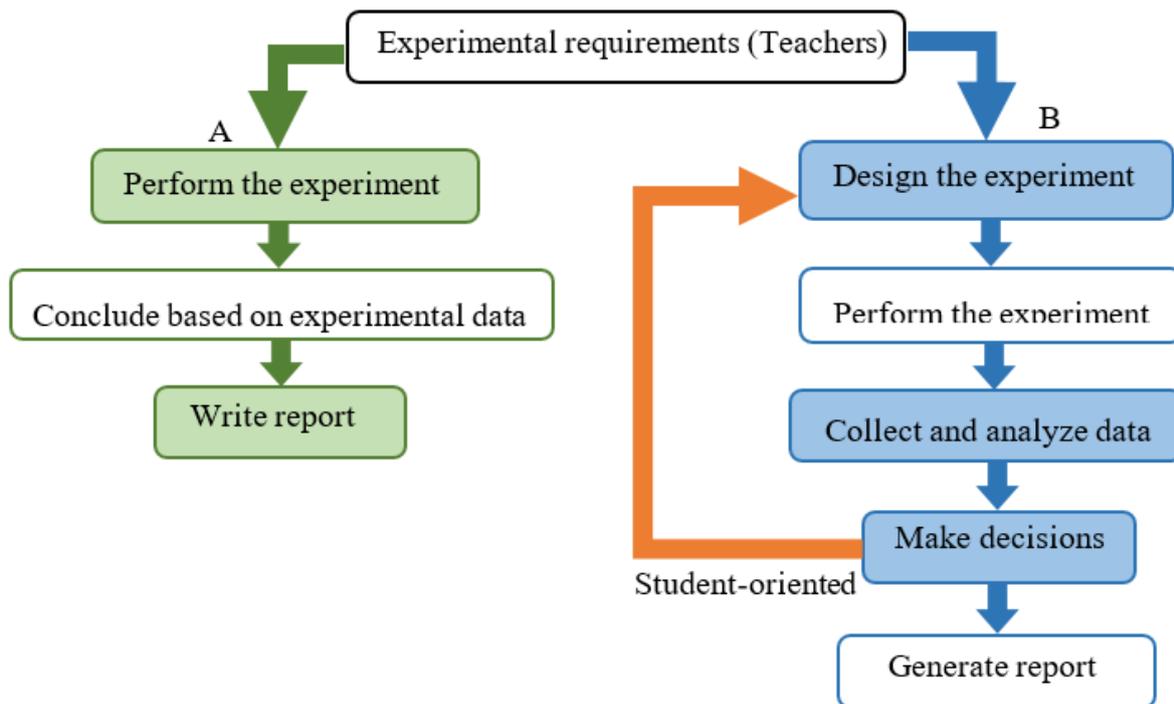
**Table 2.** Factors to construct the questionnaire.

Factors	Interpretation	Source
Experimental design	Through the virtual laboratory, students can obtain trainings on experimental design.	[4]
Loop process	Unrestricted by a laboratory space and laboratory rules, students can perform experiments multiple times.	[4]
C1	Virtual equipment must correspond to the real device.	[11,14]
C2	The theory and operation must correspond to those in a real physical laboratory.	[11,14]
C3	The visualization of laboratory scenes must be as real as possible.	[11,14]
C4	Communication and collaboration between students and teachers should be provided.	[11,14]
Immediate control	The virtual environment should be able to respond to user requests in time.	[14]
Appealing visually	The visualization of laboratory scenes should be visually appealing.	[30]
Usability	The interface should be easy to use.	[14,30]
Game-like	The virtual laboratory should be developed in a game-like manner.	[12]
Immersion	Students should be engrossed in the virtual platform.	[31]
Enjoyment	The virtual experiment should make students feel happy.	[14]
Reflective thinking	Through the virtual laboratory, students can think more on the relationship between the new experience and early theoretical knowledge, not just the operation.	[14]
Easy to evaluate	Practical, complete, and intelligent assessment systems should be offered.	[4,32]

### 2.1.2. Design Concepts

From References [11–14], one of the teaching objectives of an undergraduate experimental course is to train students in experimental design. However, the design experience brought to students by traditional experiments is always limited. The basic experimental process of a traditional experiment is described in Figure 1, flow A, where the shaded boxes represent the steps that students spend the majority of their energy and time. It can be seen that, when students start a traditional experiment, the consumption of their energy and time is primarily occupied by successfully conducting the experiment and writing a good report. The thinking activities that can be allocated for experimental design and data analysis become very few. In fact, the experimental design portion in a traditional experimental teaching program is typically determined by the teacher. In other words, the probability that students can use the results of the previous round of experiments to make decisions and design the next round of experiments is almost zero. Therefore, inspired

by the work in References [4,33], a method of problem-based learning (PBL) was applied in this study. PBL emphasizes a student-centered learning approach and can incorporate teaching aids to help students complete real and open questions or projects independently and successfully. One of the suggested principles for the effectiveness of PBL is to provide a support platform for students and teachers to learn. It is through simulating the actual experimental environment, equipment components, and running processes of the circuit that the virtual laboratory provides students and teachers with a support platform to strengthen the learning and training of students in experimental design.



**Figure 1.** Comparison between the process of traditional experiments (Flow A) and that of virtual experiments (Flow B). The shaded boxes show the steps that students spend the majority of their energy and time. Flow A is a sequential process as the traditional experiments do, while Flow B provided by the virtual experiments presents a loop process, where students can be trained in the thinking of experimental design through repeatable operations for experimental activities, such as checking experimental design, proposing and verifying new problems, testing parameters, and so on.

The complete experimental design process for using a virtual laboratory is shown in Figure 1, flow B. It can be seen that now the focus of the students' work turns to developing an experimental strategy, and the actual implementation process is accomplished by simulation. This redirects the time and energy a student normally invests in performing the experiment and thus is no longer emphasized by shading in flow B. Instead, students can assign more learning energy in the experimental design phase, which includes the experimental requirements analysis, overall design, implementation details, and parameter selection, while also placing extra emphasis on the analysis and interpretation of data. The data-analysis process helps students to actively examine and think about the experimental design and implementation process, propose and verify the potential problems, understand the theoretical and practical significance of the experiment, and determine accordingly the next experimental steps. This process continues until the student believes that the problem has been solved and generates an experimental report. Through this platform, students receive training in high-level thinking activities, thereby guiding the successful completion of the experimental design process.

In addition, it should be mentioned that Flow A, presented in the traditional experiments, cannot achieve the process shown in Flow B, offered by the virtual experiment

platform due to some non-recurring factors. First, host institutions (such as universities, research institutes, and factories) need to provide space to build laboratories, require funding to purchase and maintain laboratory equipment, and incur labor costs to support laboratory management. Therefore, a huge number of instruments in the physical lab usually cannot be provided at the same time. Second, because of the high degree of lab bench integration, most hardware components are fixed installations and are not conducive to the development of new experiments and loop tests, and they inhibit the development of innovative capabilities in studies. Besides this, traditional experimental methods require users to perform experiments at specified times and designated locations. This results in poor experimental flexibility, and it is difficult to mobilize the subjective initiative of the students.

## 2.2. Development of the Digital Circuit Virtual Laboratory

### 2.2.1. System Architecture

The implementation of the virtual laboratory software needs to ensure that the software is portable and adaptable so that different experimental projects can be applied. Browser/Server (B/S) architecture was adopted in the current implementation. The user can log in to the virtual laboratory system anytime and anywhere through the browser, and can select different experimental items to operate. Meanwhile, since the virtual experiment does not involve physical devices, users can test various innovative experiments according to their own ideas without worrying about damaging the devices. Thus, the main components of the virtual laboratory include the client side (such as the 3D (three-dimensional) student client and the web-based teacher interface) and the server side, as shown in Figure 2. Specifically, after logging in the student client, students would enter a 3D virtual reality laboratory and develop the virtual experiments. Comparatively, the teacher client is not a 3D virtual environment but a web-based interface, mainly handling data from students' virtual experiments. In addition, the teacher also has permission to log into the 3D virtual laboratory for experiment design, development, and test. Finally, the server side is responsible for the computations and the data transmissions between the 3D virtual laboratory and server side, and the teacher interface and server side.

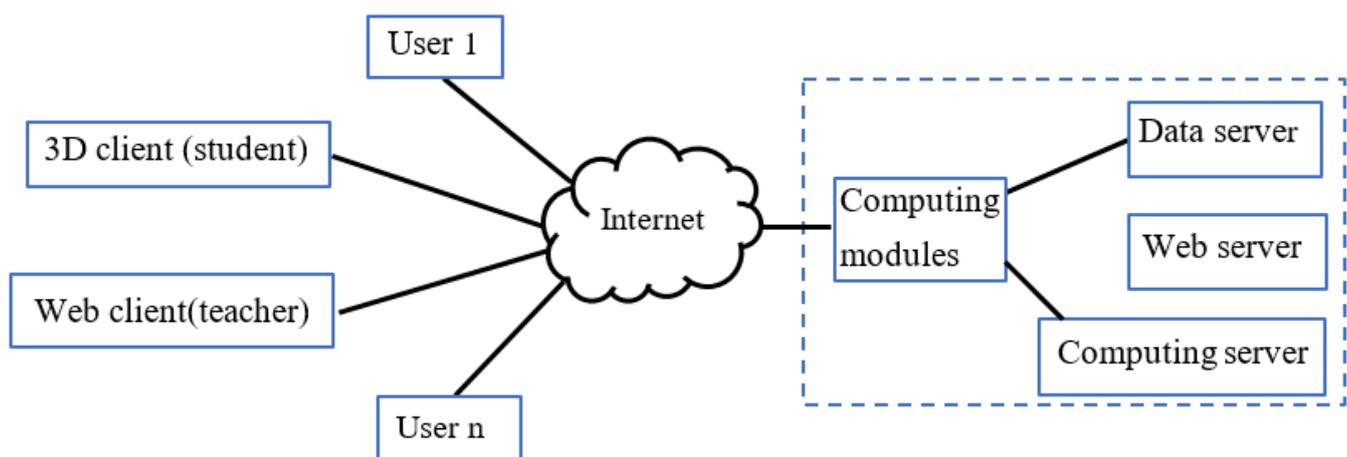


Figure 2. System architecture of the virtual laboratory.

### 2.2.2. Implementation Details

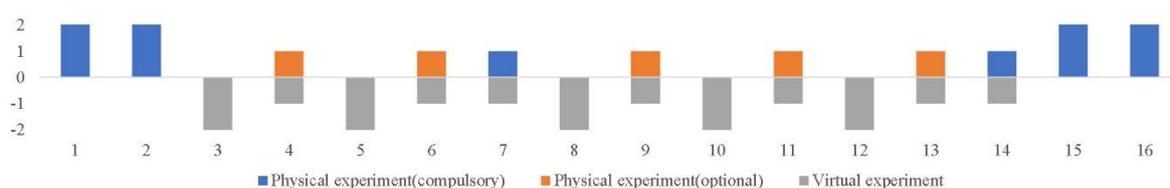
Taking the university experimental project as an example, we see that the 3D student client is a 3D-graphical interface that provides a typical virtual experiment environment, where students can perform tasks such as circuit design, testing, obtaining output data, performing data analysis, and completing experimental reports. In this study, the virtual experimental platform was created based on the 3dsMax and C4D modeling software and the powerful Unity3D game engine. Moreover, 3dsMax and C4D are primarily used

to implement the static model framework of the platform, the virtual instruments and equipment, the virtual laboratory classroom environment, etc. The dynamic interaction control module, the logic control mechanism between the circuit connection input and the experimental output, the data communication mechanism, the experimental operation feedback mechanism, and the wiring simulation are implemented in Unity3D with C#. Moreover, the teacher web client was implemented with C# because of its powerful abilities in interaction programming and data handling. In addition, it is generally considered that the limitation of the effectiveness of the physical laboratory is the difficulty of real-time evaluation. Therefore, enlightened by the work in Reference [32], we also implemented an integrated assessment function in the teacher web client.

### 2.3. A Blended Learning Model

A benefit of the 3D virtual laboratory is that teachers are able to design and develop reasonable blended teaching plans for experimental courses. Blended courses typically involve a certain number of regular courses published on the Internet, as well as a small number of face-to-face courses that are held in a real laboratory. In our case, the course implementer can split the course and deliver part of the experiments on the virtual laboratory and retain other parts in the physical laboratory. The regular online experiment part is also equipped with online courseware and micro-classrooms, to provide students the corresponding experiment guidance. In the experimental course design process, it is unnecessary to fix the ratio of the number of the real experiments and the virtual experiments. The ratio of these two parts can vary. According to the investigations on blended-course cases [13,26–28], it is reasonable that, at the initial step, the number of the online parts should be at least equal to the number of those in the physical laboratory, that is, the ratio can be set to be 1:1. As the course progresses, the ratio of the two is ultimately determined by the experiment types and specifics, about to 10% floating variation.

Specifically speaking, in the physical laboratory part, students must attend the following sections: the first introduction class, the midterm seminar, the last class, the pre-exam review class, and the final exam. These sections aim to help students get familiar to the real devices and the virtual environment, make midterm and last-term summaries and reviews, and prepare for the final exam. That is, it is helpful for students to construct a complete knowledge system bridging real experiments and virtual ones. The rest of the physical laboratory courses are planned before and/or after each online unit experiment. They are designed as the complementary lessons to the corresponding virtual experiments, for instance, a preview lesson before a virtual experiment or a review course after a virtual experiment, and are, thus, set to be optional. Whether or not to attend this part of courses depends on students' completion of the virtual experiment and their understanding of it. Based on the experimental data received from the virtual experiment platform, the teacher can advise the students whether to choose the corresponding physical laboratory course. In this manner, the ratio is approximately 1:1 for students who can participate in all recommended physical laboratory courses. Figure 3 shows an example of the blended-model course arrangement. The abscissa represents a typical 16-week instruction block. The ordinate represents the number of class hours. The minus sign distinguishes between different experiment types without mathematical meaning. This schedule is only a sample, and the specific time can be adjusted according to the students' abilities and their mastery of the experiments. Table 3 gives the detailed teaching plan according to Figure 3.



**Figure 3.** An example course arrangement of the blended learning model for digital circuit course.

**Table 3.** An example teaching plan under the blended mode.

	Stage	Participants	Specifications
Lesson 01	On class	Teacher	Introduction to the course Introduction to the physical laboratory Introduction to the virtual laboratory
		Students	Get familiar to the real devices Test and get familiar to the virtual system
		Interaction	Face-to-face question-and-answer
	After class	Teacher	Summary and evaluation of students' overall performance
		Students	Get familiar to the virtual lab ➤ Read the manual and/or watch the introduction video of the virtual system ➤ Run the demo of the virtual system
		Interaction	Online question-and-answer
Lesson 02	Before class	Teacher	Release the next lesson and materials
		Students	Prepare the next lesson
	On class	Teacher	Nonlinear Resistance Voltage Ampere Characteristics
		Students	Theory learning and practice in the physical lab
	After class	Interaction	Face-to-face question-and-answer
		Teacher	Summary and evaluation of students' overall performance Examine problems and develop solutions
Lesson 03	Flexible	Students	Prepare for the corresponding virtual lab
		Interaction	Online question-and-answer
		Teacher	Online virtual experiment, as supervisor
Lesson 04	Before class	Students	Online virtual experiment in lesson 02 before due date
		Interaction	Online question-and-answer
		Teacher	Evaluation of lesson 03
	On class	Students	Prepare for class discuss and communication for lesson 03
		Interaction	Online communications between students and teacher, as well as between students and students
		Teacher	Summary and evaluation of lesson 03 to students Important tips for next lesson
After class	Students	Class discussion and communication	
	Interaction	Face-to-face communication	
	Teacher	Release the next lesson and materials	
Lesson 05	Flexible	Students	Prepare for the next lesson ➤ Watch the introduction video of the virtual experiment in the next lesson ➤ Run the example demo
		Interaction	Online question-and-answer
		Teacher	Release the next lesson and materials
Lessons 06–13	Flexible	Students	Virtual experiment: spectrum analysis of periodic signals in series resonant circuits
		Interaction	Online question-and-answer
		Teacher	Online virtual experiment, as supervisor
Lesson 14	Have the similar process as Lesson 04 and Lesson 05, except for a midterm discussion in Lesson 07		
Lesson 14	A virtual experiment with the last class in the physical lab		
Lesson 15	Review before the final exam		
Lesson 16	Final exam or other additional arrangements before the final exam		

#### 2.4. Validation with a Control Group

In order to verify the effect of the blended learning model, this study designed and conducted a project for the blended course development in digital circuit experimental courses, enrolling students who were majoring in multimedia engineering in the second semester of the 2018–2019 school year. A control group experiment was arranged for this project: one group of students selected the blended program, designed as the experimental group, while the others selected the traditional course, specified as the control group. Of the 132 students enrolled in the control group experiment, 67 selected the blended course, and 65 selected the traditional course. In order to respect the wishes and preferences of students, the creation of these groups was not a randomized process; instead, it was decided by the students.

An evaluation process based on the control group experiment was also carried out, looking at various fields, including physical laboratory lessons, online lessons, routine tests, and final exams. The quality of the developed curriculum was assessed by observing and recording the experimental process performed by different groups of students, comparing the scores of students who participated in different experimental schemes, and collecting feedback from anonymous questionnaires and interviews with students and teachers. By listing not all the fields and omitting the interpretation section considering the typesetting, Table 4 gives a sample of a simplified version of the questionnaire for the satisfactory survey of the virtual teaching materials, and Table 5 shows the one for the quality survey of the blended course. Here, participants are required to give their marks to related fields, on a level of 1 (poor) to 5 (excellent). Optionally, they could also leave comments and suggestions in the Comments and Suggestions box, and answer the questions in the Open Question box. As for the traditional course, similar questionnaires are provided to the control group, just without the Comments and Suggestion section and the Open Question section.

**Table 4.** A questionnaire sample for the satisfactory survey of the virtual teaching materials.

Fields	1 (Poor) to 5 (Excellent)	Comments and Suggestions (Optional)
Content		
User friendly		
Easy to design		
Visually appealing		
Open Questions (Optional)		
Do you think it is easy to use? Why?		
Do you think it is good for design? Why?		
If the game style is more attractive? Is there something to worry about?		

**Table 5.** A questionnaire sample for the quality survey of the blended course.

Fields	1 (Poor) to 5 (Excellent)	Comments and Suggestions (Optional)
Enough practices		
Communications		
Active learning		
Enjoyment		
Open Questions (Optional)		
Which kind of practice do you think is better?		
Only traditional experiment, only virtual experiment, or combined ones.		
Is real-time communication important and helpful?		
Does game-like teaching model help students learn actively?		
Is enjoyment helpful to students' active learning? What other factors can you think of?		

### 3. Results

#### 3.1. Pre-Questionnaire

Figure 4 gives the statistic result of this pre-questionnaire, which reveals the impact of those factors shown in Table 2 on virtual laboratories from the perspective of students and teachers separately. Table 6 shows an example result of the pre-questionnaire presented in Table 1. It can be seen that teachers are more concerned about the learning outcomes the virtual labs can offer. They also agree that virtual laboratories should provide real authentic equipment and operating processes as that in the real physical laboratories, including the factors of experimental design, loop process, reflective thinking, C1 to C4, and so on.

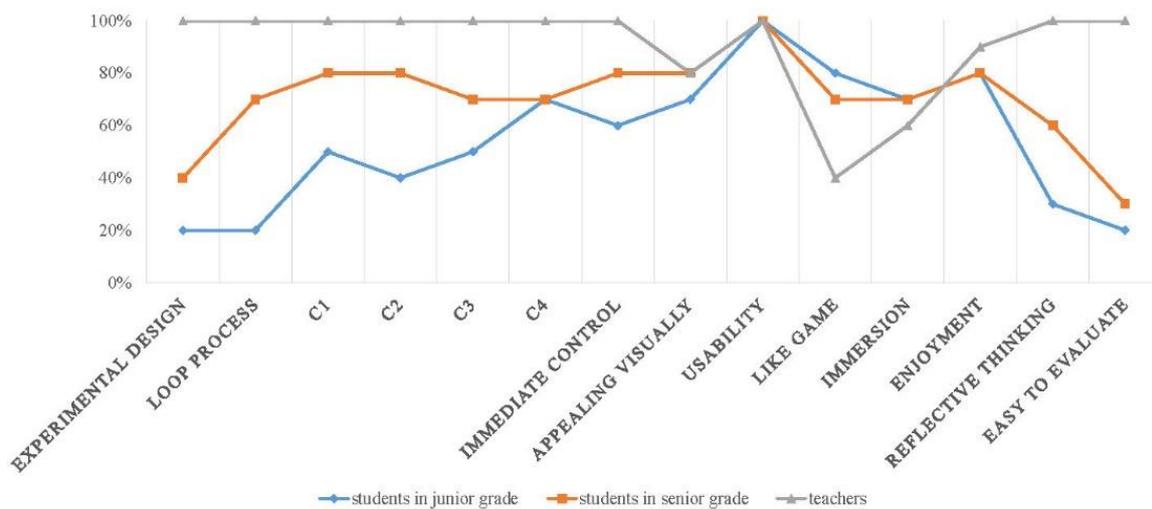


Figure 4. Survey results of the questionnaire with the factors in Table 2.

Table 6. An example result of the pre-questionnaire shown in Table 1.

Fields	1 to 100 Importance	Comments and Suggestions (Optional)
Like game	85	
Open Questions (Optional)		
How about applying the game-style to the virtual lab?		As for me, a student, I think the game-style will be more interesting.

From the students’ view, their attention to the learning outcomes is not very high, which is more obvious in the lower-grade students who have not taken the course, but they may be more directly attracted by the experience provided by the simulated environment, such as the factors of enjoyment, like game and so on. A more controversial factor lies on whether it should be “like game”. Most students explain that they would be more interested in the virtual experiments if the virtual world could have the interaction in the game style, while more than half of the teachers worry that students will regard the experiments just as playing video games; however, the teachers also believe that enjoyment is a significant factor to encourage students’ development in intrinsic motivation, self-efficacy, and knowledge learning. These investigations tell the story that factors related to the learning achievements and virtual lab requirements should be preserved. As for controversial factors, the game mode was not employed to develop the virtual lab; instead, some entertainment factors unrelated to the lab requirements were added, like the cartoon appearance, cartoon virtual characters, and so on.

### 3.2. The Virtual Laboratory

According to the system architecture of the virtual laboratory system, Figure 5 shows the typical process of a user performing experiments in the virtual experiment system. First, the user logs in from the website with a username and password. Different users have different permissions. Once opening an experiment, the user can build a new scene, using the existing components in the virtual experiment panel. Then the experiment plug-in encapsulates the user's request and the relevant data of the experiment, which are sent to the computing server through the data-exchange layer of the system. Subsequently, the computing server forwards the request to the specific computing node, to complete the calculation. Finally, the computed data are transmitted back to the experiment plug-in along the opposite data link direction, to display the result visually.

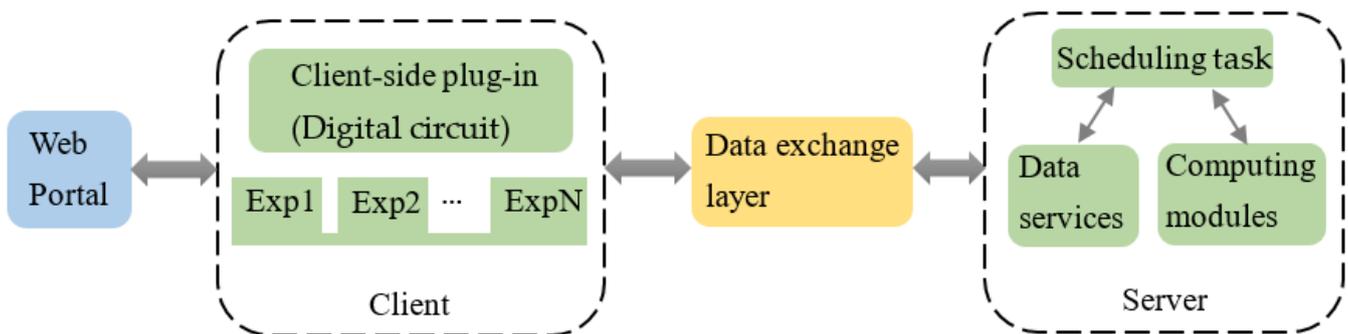


Figure 5. A typical work process under the above architecture.

Figure 6 presents some screenshots of the 3D-virtual laboratory with the student client. The image in Figure 6a is an example of the real experimental environment. The image in Figure 6b is of the classroom environment of the virtual laboratory. As an attempt and validation, the laboratory appearance, virtual characters, and other things unrelated to the real devices and authentic operation flows are cartoon-like, to test whether a cartoon-style can attract students more. The image in Figure 6c shows the browser of the virtual experimental equipment. Students can select and take experimental equipment in this interface. These devices have been implemented to be fully identical to their corresponding real devices. In order to completely reproduce the real digital circuit experimental process—that is, students operate the real devices, and observe the experimental response on the computer screen in real time, such as signal response, parameter debugging, and so on—our virtual experiment platform realizes the function of invoking the simulation software on the virtual computer without exiting from the 3D client and entering another software interface. The image in Figure 6d shows the computer screen of a virtual computer in the virtual laboratory, when the student is conducting an experiment. In this interface, students can call and utilize simulation software commonly used in electronic circuit experiments, such as EasyEDA and Multisim.

The second part is the teacher web interface, in which teachers can set up and manage student accounts and view their behavior and performance in the virtual lab as well as add, modify, and delete experiments as required, and also teachers could provide real-time communication to students. The image in Figure 7a shows an example of a set of experimental arrangements, and the image Figure 7b shows an example of a circuit diagram being viewed. The experimental data can also be exported to the spreadsheet files as a measurement set which can be running separately. When students complete a task and the teacher finishes the scoring, the evaluation tool will automatically generate a personal summary report.



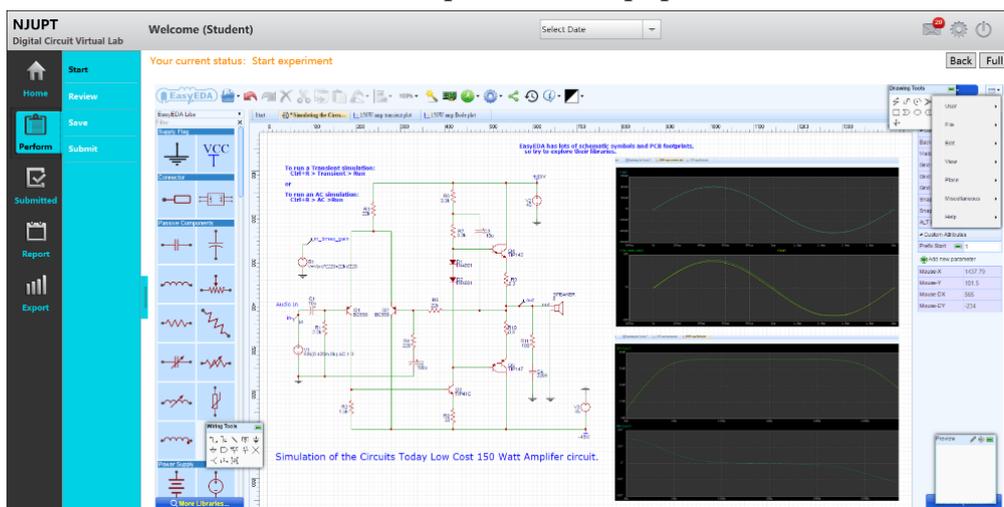
(a) Real experimental environment.



(b) Classroom environment of the virtual laboratory.

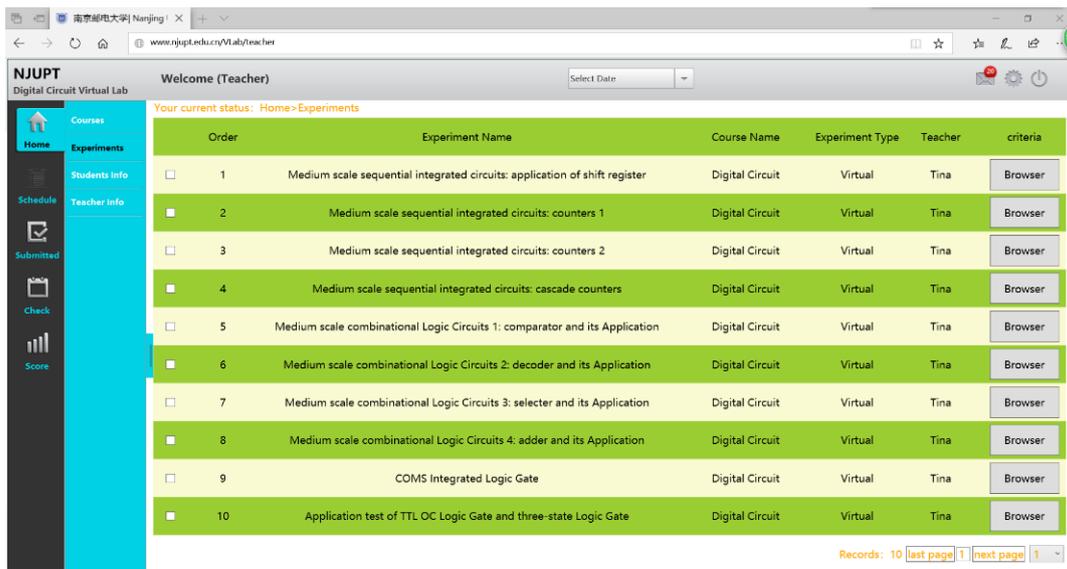


(c) Virtual experimental equipment.

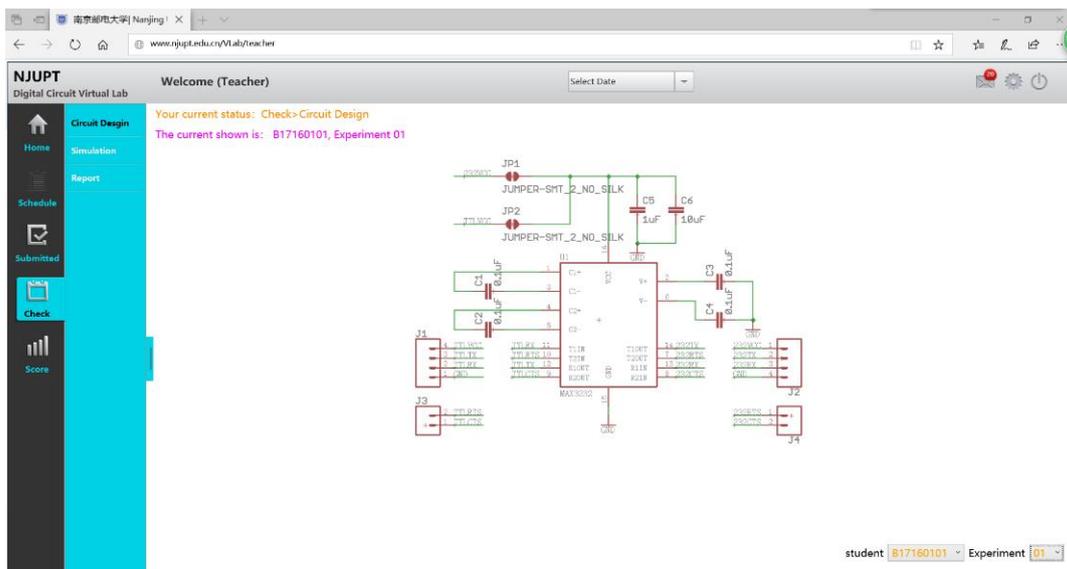


(d) The computer screen of a virtual computer in the virtual laboratory.

Figure 6. Some screenshots of the student client of the 3D virtual laboratory.



(a) Teacher web interface screenshot for experiments arrangement.



(b) Teacher web interface screenshot for experiments review.

Figure 7. Some screenshots of the teacher client of the 3D virtual laboratory.

The above clients are finally supported by the computation module, which is composed of three separate servers, namely the data server, the web server, and the computing server. The data server is mainly responsible for user information management, such as login information and privilege control. Besides this, it also stores the data related to the relationships among the user accounts and the measured data in each experiment, and it provides a library of mathematical models for circuit-related calculations. The web server carries the resources of the site, including web pages, pictures, experimental plug-ins, and others. Meanwhile, it primarily responds to the requests from the 3D student clients and the teacher web interface through the feedback mechanism. The computing server is in charge of all the calculations requested from the experimental plug-in and maintains the collaborative work with the data server.

### 3.3. Validation with a Control Group for the Blended Learning Model

Under the blended learning scheme, students can use the virtual experiment to correct and improve the experimental design continuously through the iterative process, as an example shown in Figure 8. The task sequence is represented by a number, and the second-level subtask under the primary task is connected by the “.” operator. For example, the subtask under Task 1 is labeled as “1.1”, and so on. A student group from the control group just completed five runs (Tasks 1.1–1.7) for a specified Task 1 (i.e., the teacher-defined task) and then directly went to the report stage. Instead of giving an experimental report right away (branch from Decision stage directly to Report stage), the students from the experimental group then proposed a new research problem to assess the consistency of the experiment, that is, Task 2 generated along the branch of the outer loop from Decision stage back to Design stage. Task 2 was carried out in ten runs (Tasks 2.1–2.10), with 12 sets of parameters being measured repeatedly in each turn (Tasks 2.1.1–2.1.12, Tasks 2.2.1–2.2.12, etc.). Conclusions were validated in the following proposed tasks, like Task 3 and Task 4, based on the measurement results from the previous tasks, like Task 1 and Task 2, finally generating an experimental report (Task 5) in the end.

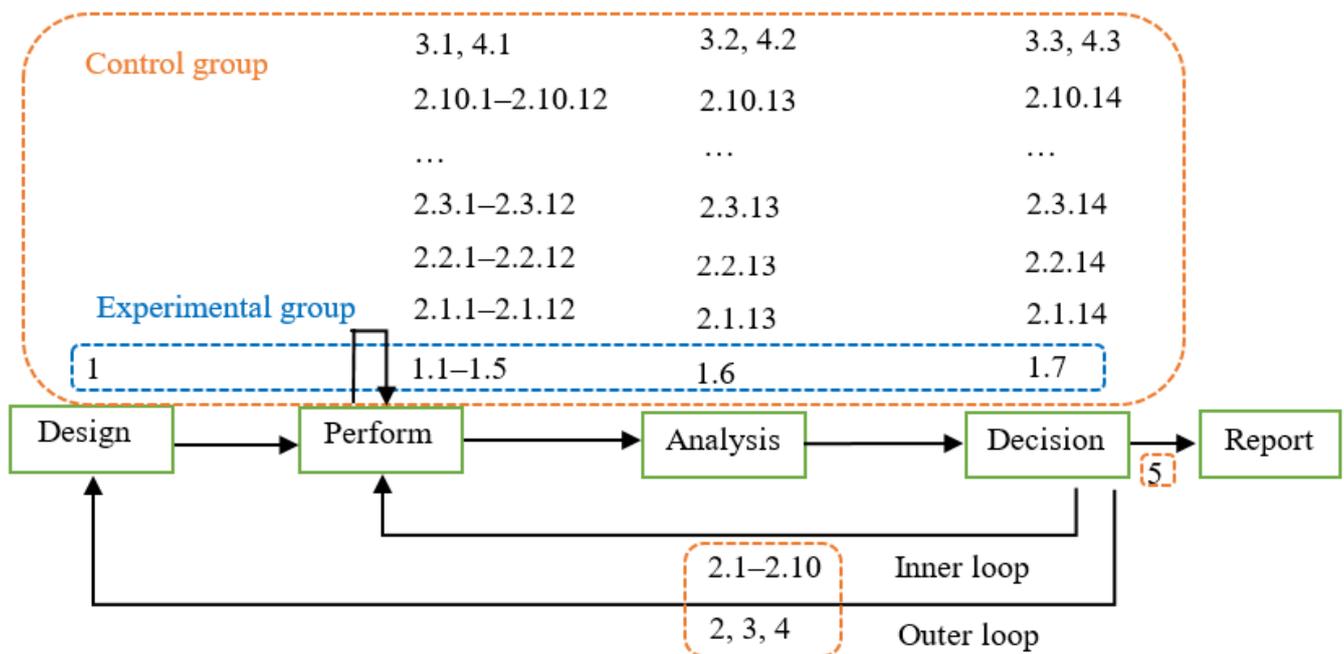


Figure 8. Experimental steps scheduled by student group who used the loop design process.

In view of the teaching process and teaching effect, the blended curriculum required students to have a higher level of participation in before-class preparation and after-class discussions and to do more work in the pre-examination review. However, the requirement for attendance in the classroom is lower. In contrast, students choosing traditional courses were required to spend more time in classroom lectures and experimental exercises in the fixed laboratories (see the first three indicators from below, that is, attendance, activities, and review, in Figure 9). The student groups then conducted three relatively structured unit operation experiments. The test results show that the blended course provided students with all the necessary levels of experimental knowledge. Compared with the traditional course, students obtained more satisfactory results in the knowledge test, with the pass rate increasing from 40–50% to 50–60%, and achieved a higher average mark, 75.3 against 70.5. At the same time, the number of students who dropped the course was less in the blended course (see the last three indicators from below, that is, pass one test, pass three tests, and give up courses, in Figure 9).

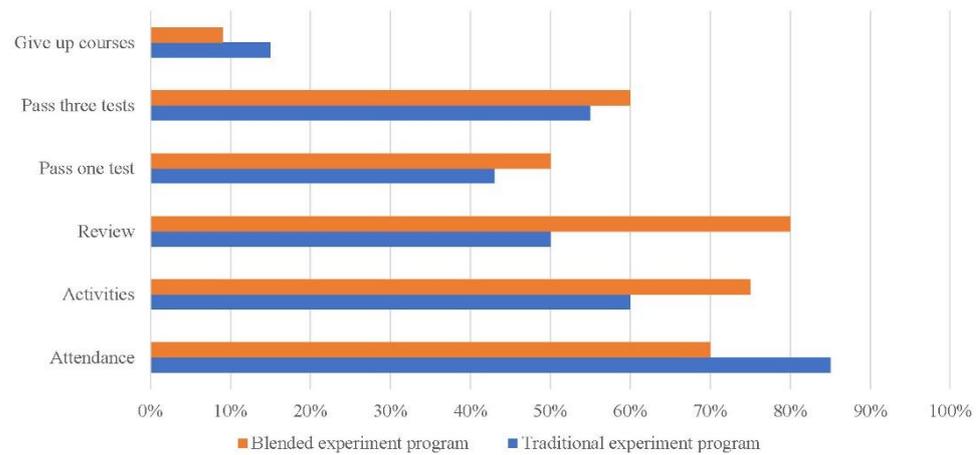
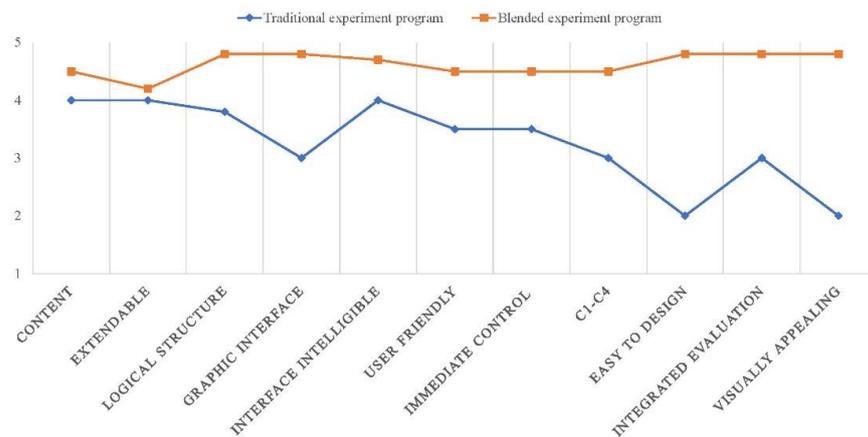
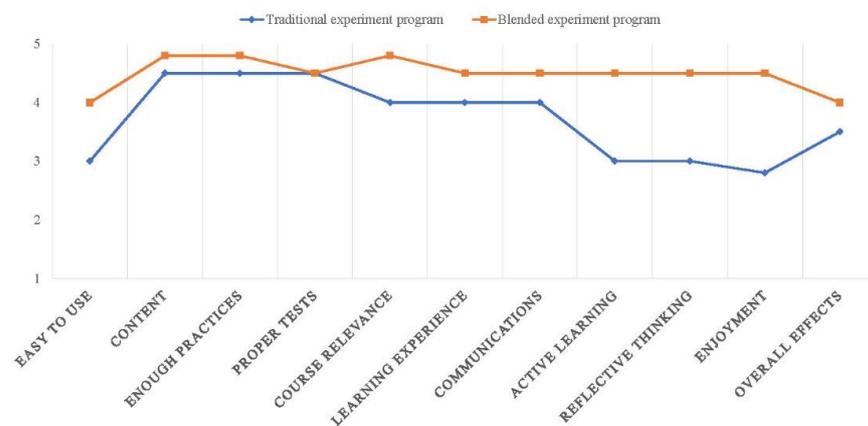


Figure 9. Results in the group experiment.

Then, this paragraph presents the results on another survey of the quality of the virtual teaching materials (image in Figure 10a) and that of the blended course teaching effects (image in Figure 10b). The detailed method can refer to Section 2.4. Correspondingly, Tables 7 and 8 give the example results of the questionnaire shown in Tables 4 and 5.



(a) Survey result of the teaching materials.



(b) Survey result of the teaching effects.

Figure 10. Survey results of the teaching materials and teaching effects.

**Table 7.** An example result of the questionnaire shown in Table 4.

Fields	1 (Poor) to 5 (Excellent)	Comments and Suggestions (Optional)
Content	4	Could be richer.
User friendly	4.5	Easy to use.
Easy to design	4.8	
Visually appealing	4.5	Appearance could be further improved.
Open Questions (Optional)		
Do you think it is easy to use? Why?		Yes, only computers are required, and easy to manipulate with the user guideline.
Do you think it is good for design? Why?		Yes, an experiment can be repeated any number of times.
If the game style is more attractive, is there something to worry about?		I think so. No.

**Table 8.** An example result of the questionnaire shown in Table 5.

Fields	1 (Poor) to 5 (Excellent)	Comments and Suggestions (Optional)
Enough practices	4.3	The loop process is good. I can test several ideas of mine, and verify parameters many times.
Communications	4.5	It would be even better if the communication function has reminders.
Active learning	4.5	It is helpful for active learning that students can make decisions on experimental design and implementation strategies.
Enjoyment	4	
Open Questions (Optional)		
Which kind of practice do you think is better? Only traditional experiment, only virtual experiment, or combined ones.		Combined ones.
Is real-time communication important and helpful?		Yes.
Does game-like teaching model help students learn actively?		I have reservations. I worry about that students will operate virtual experiments as playing video games.
Is enjoyment helpful to students' active learning? What other factors can you think of?		Yes. Many students have shown greater interest in using the virtual lab.

In terms of teaching materials, the three-dimensional realistic experimental environment gives students a good sensory experience, thereby obtaining higher scores on some factors like graphic interface, user friendly, and visually appealing. Comparing Figure 4 and the orange line in Figure 10a, it can be seen that factors considered in the design stage do get good scores in the implemented virtual laboratory. As for teaching effects, factors with higher scores mostly happen in the blended course project (the orange line), and the overall teaching effect earned more agreements from the participants. The students who completed the open questions in the teaching material questionnaire (Table 7) indicated that the demands of the physical conditions of the virtual experiment are low and easy to meet. They can turn on the computer at any time, to carry out the experimental simulation, verify the classroom teaching content, strengthen the consolidation and understanding of knowledge, and communicate and discuss with the teachers and other classmates conveniently. Teachers think it, indeed, provided a platform for students to train their creative and design thinking, so that students can study actively and think reflectively.

#### 4. Discussions

From the results of the pre-questionnaire, it can be seen that those factors shown in Table 1 have positive significance to help us design and develop the virtual lab. For instance, if students could pay more attention on experimental design, they may be more likely to think actively about the relationship between operational experience and theoretical knowledge. That is, we can observe the active learning and the reflective thinking happening in students. Another case is that the virtual laboratory is a very good medium for students to perform experiments repeatedly and flexibly, since it is not restricted by the lab location, lab space, and lab rules, especially on security. It is this loop process that realizes the function of experimental design.

With the implementation of the virtual laboratory system, the entire virtual laboratory not only replicates the functions of a traditional laboratory but also retains the ability of system simulation and analysis, with strong immersion and good interaction. We additionally compared it with other related virtual platforms. As elaborated in Section 1, in the recent two decades, there are kinds of virtual laboratories and/or remote laboratories presented for large-scale applications. This section compares our system with several related work in the most recent years. Work in Reference [15] reports a remote laboratory project called VISIR (Virtual Instrument Systems in Reality) for the wiring and measuring of electronic circuits. It had been applied in several universities and received overall satisfactory feedbacks. However, the VISIR system [15] highly depended on physical devices to collect experimental information and data, for example, using web cameras to obtain the videos or diagrams of the devices, and using the DAQs (Data Acquisition Cards/Boards) to handle the signals, which results in high hardware and transmission costs and inflexible operations.

Another work covered in Reference [16] employed the augmented reality animations on the static images, to get the states of the real devices. Its implementation was based on the EJS (Easy Java Simulations) for the client, and Lab-VIEW for the server. Although this method alleviates the problem of high costs in hardware and transmission consuming, the contradiction still exists. An NCSLab framework was proposed in Reference [24], which implemented 3D animation in a remote laboratory platform. Then, by replacing the real physical devices with virtual ones, the NCSLab was extended to the 3D-NCLab, as described in Reference [25], which offered powerful virtual equipment and integrated control hardware. Compared with Reference [25], more than fifty virtual devices have been implemented in our system, offering more resources and experiment possibilities for students. Meanwhile, our platform is structured on the B/S architecture and is implemented by using Unity3D and C#, considering that Unity3D has the merits of better 3D performance, being easy to program, and having multi-platform portability. A specific comparison of the methods is presented in Table 9. For the sake of the cite, we named our system 3D-DCLab.

**Table 9.** Comparison of virtual 3D experiment systems.

Systems	Virtual Devices	Simulation Implementation	3D Performance	Collaborative Experiments	Easy to Program	Multi-Platform
VISIR	none	PHP, C++, and LabVIEW	no	No	no	no
System in Reference [16]	none	EJS, JIL Server, and LabVIEW	no	No	no	no
NCSLab	several	Flash 3D, and HTML5	yes	Yes	no	no
3D-NCLab	30	3dsMax, and Matlab	yes	Yes	no	no
3D-DCLab	50	3dsMax, C4D, Unity3D and C#	yes	Yes	yes	yes

VISIR, Virtual Instrument Systems in Reality; NCSLab, Network-Based 3D control laboratory; EJS, Easy Java Simulations.

The validation results from the control group experiment reveal that those new tasks proposed in the iterative experimental design process (Tasks 2, 3, and 4 in Section 3.3) enabled students to determine the repeatability and reproducibility of the device and allowed them to understand the statistical uncertainty of the experimental process and measurements, thereby giving students the space to design and think. Meanwhile, the possible reason behind the better pass rate, higher average mark, and lower rates of abandonment in the blended course is that students could use the virtual laboratory to repeat and optimize the experiment process any number of times and could arrange their study time more flexibly. On the other hand, the survey results during the development of the blended learning program suggest that, in the process of interacting with the virtual instrument, the enthusiasm of students to participate in digital circuit experiment is potentially improved.

## 5. Conclusions and Future Work

The purpose of developing digital circuit 3D-virtual online laboratories is to complement the limitations of existing physical laboratories, not to replace them. Hence, the potential benefits of this work include the creation of the 3D-DCLab and a blended learning model. On the one hand, the virtual laboratory is designed to offer students complete involvement in all aspects of the experimental design process, including experimental strategies, data analysis, and interpretation, along with an iterative design process. The software application includes a 3D student client with a simulation environment, a web-based teacher interface with an integrated assessment tool, and a database server with a calculation engine. This application also has an integrated assessment tool that can be used directly to support formative and summative evaluation. The implementation of the 3D-DCLab, indeed, provides higher numbers of virtual instruments, better simulation mechanism, more friendly user interface, and more powerful operation performance to students and instructors.

On the other hand, compared with the traditional course, the control group experiment shows that the blended program gives better results in the learning effects, such as higher rate of attendance, lower rate of course dropout, and higher scores on exams. Besides this, the blended learning scheme obtains better reviews both on the teaching materials and teaching quality. Most students considered the virtual laboratory to be an attractive and effective learning medium. Furthermore, teachers think that the flexible and convenient learning mode brought by the virtual experiments is helpful for students to think and study actively and independently. Meanwhile, the preservation of physical experimental operations in the blended teaching program can compensate for the inherent shortcomings of a pure virtual laboratory (being unskilled in practical operations). Thereby, it achieves more effective learning results and outcomes.

However, there is additional work to be done. Future work includes realizing a virtual system in full game-like style and investigating its learning scheme and learning effects. Another direction is to further develop a flipped classroom. Moreover, deep-learning-based methodology [34,35] could be considered further. Finally, more work is needed to determine how to make the virtual platform more universal to various experimental courses.

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