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Exploration and Practice of Online−Offline Blended Teaching in Process Simulation Courses

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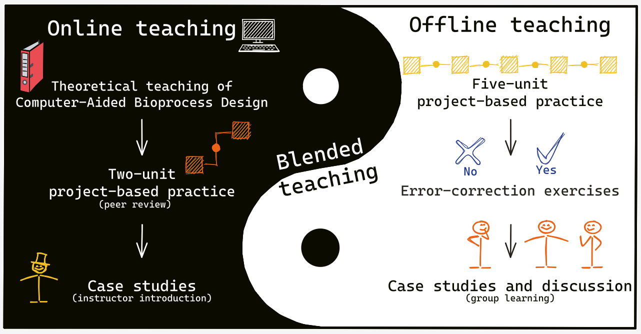

ABSTRACT: While process simulation tools offer immense potential in chemical engineering, effectively integrating them into the educational curriculum poses challenges. This work explored and practiced online−offline blended teaching in process simulation courses. The design of this blended course was based on a comparison of students' performances in fully online courses, Massive Open Online Courses (MOOCs) and Small Private Online Course (SPOCs). Approximately 2000 students from academic institutions or industries have participated in these online courses since 2021. The comparison between MOOCs and SPOCs encompassed participation rates and scores, revealing a preference among participants for hands-on software lectures over theoretical ones in the process simulation course. Based on the outcomes of online learning, we redesigned the online−offline blended course to optimize course arrangements, leveraging the complementary advantages of both online and offline instruction. This blended approach manifested in two key aspects: first, the online segment served as a precursor to the offline component, with the offline component acting as an evaluative measure of the online segment; second, the two-unit project-based online learning led to the redesigned five-unit offline instruction, which served as both a supplement and expansion to the two-unit online teaching. Furthermore, offline activities, such as error-correction exercises and case studies conducted through group learning, enhanced students' ability for open-ended and independent thinking and reinforced their understanding of innovation on process simulation, which was lacking in online learning.

KEYWORDS: *Upper-Division Undergraduate, Computer-Based Learning, Testing/Assessment*

Process simulation stands as one of the important cores of chemical engineering, offering users a virtual playground to explore and comprehend the complexities of real-world industrial processes.[1−4] In recent years, much attention has been paid to practical and hands-on learning experiences with these process simulation tools.[5−7] However, traditional chemical education has predominantly relied on theoretical instruction, often lacking a tangible connection to the practical applications of their studies. Process simulation can bridge this gap by immersing students in a virtual environment that mirrors the challenges and decision-making processes they will encounter in their professional careers.[8−12] This not only enhances their grasp of theoretical principles but also cultivates problem-solving skills essential for success.

Among the numerous process simulation tools available, SuperPro Designer stands out as a robust and versatile solution.[13,14] This software is a comprehensive process simulation software package developed by Intelligen, Inc. It is not only used for modeling and simulating various chemical and biological processes, including batch, continuous, and hybrid processes, but also used in industries such as chemical engineering, pharmaceuticals, food and beverage, and environmental engineering. SuperPro Designer offers a variety of key features, including process modeling, batch and continuous operations, material and energy balances, cost analysis, environmental analysis, and process optimization. With its comprehensive features, SuperPro Designer has facilitated the modeling of an expanding array of processes. Figure 1 shows the growth in publications and citations related to SuperPro Designer from 2014 to 2023. In particular, it excels in addressing bioprocess applications such as fermenters, chromatography, and strainers—where other process simulation tools like Aspen Plus might have limitations.[5] SuperPro Designer offers a publicly available evaluation version, as well as an academic version open to universities. Compared with other free or open-source software, it boasts a more user-friendly interface. Hence, it is capable of serving as an ideal platform for introducing students to the intricacies of process

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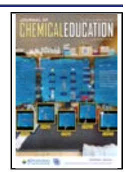

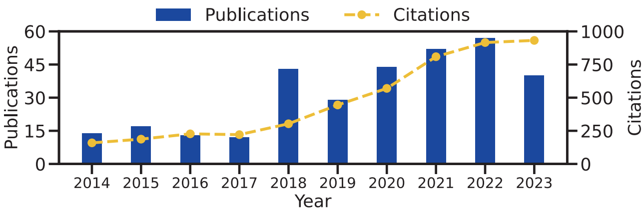

Figure 1. Number of publications and citations related to SuperPro Designer over the past decade (2014−2023) from Web of Science.

simulation in a controlled and instructive manner. The core of this study lies in the exploration and implementation of online−offline blended teaching in process simulation courses. The proposed methodology is adaptable to other software besides SuperPro Designer.

While process simulation tools such as SuperPro Designer hold immense potential, integrating them effectively into the educational curriculum presents challenges. As a form of computer-based learning, it involves various computer-related operations and multimedia content. Relying solely on an offline instruction may not be a robust choice. Traditional paper-based materials for software learning are often intricate and lack intuitiveness, posing challenges in capturing direct software interactions within students' notes. However, these issues can be addressed through online teaching methods which offer vivid video lectures or clear screencast notes.[15,16] Among the most prevalent approaches are Massive Open Online Courses (MOOCs) and Small Private Online Courses (SPOCs). MOOCs are large-scale online courses accessible to all, while SPOCs are designed for more specific groups of participants. One of the key features of MOOCs is their accessibility; anyone with an Internet connection can enroll in a course and learn at their own pace.[17] This flexibility makes it convenient for working professionals, students, and lifelong learners to acquire new knowledge and skills. Unlike MOOCs, SPOCs are designed for smaller groups of learners, allowing for more personalized attention and tailored instruction.

Nevertheless, entirely online computer-based learning might lack the crucial element of face-to-face feedback. In online teaching, some novice learners in process simulations may tend to replicate steps from video tutorials without fully grasping the underlying implications of the software operations. SPOCs are often used in blended learning environments, where online components complement the face-to-face instruction. By combining the best aspects of traditional classroom learning with the convenience of online education, such a blended course can provide a flexible and effective way for learners to acquire new knowledge and skills of computer-based learning. While the benefits of such blended teaching have been extensively reported during the COVID-19 pandemic,[5,18,19] its applicability in the context of computer-based learning remains to be fully explored.

■ COURSE DESCRIPTION

In this study, to explore and practice the online−offline blended teaching in process simulation courses, "computer-aided bioprocess design", we implemented three instructional methods: MOOCs, SPOCs, and online−offline blended courses. All three methods were conducted in mixed formats of Chinese and English. The term "online−offline blended courses" refers to the online segment serving as a precursor to the offline component. The blended courses were designed based on the performances of students in fully online courses (MOOCs and SPOCs).

Table 1 provides the details of our online−offline blended process simulation courses. After the introduction of the course, the initial four online lectures would center around theoretical teaching of computer-aided bioprocess design, accompanied by an introduction to SuperPro Designer. Subsequent to these, the following four online lectures would encompass a two-unit SuperPro Designer project-based practice, an introduction to SchedulePro, case studies of SuperPro Designer, and an online final exam. This is followed by the offline course including a five-unit SuperPro Designer project-based practice and error-correction exercises, case studies, and discussions of SuperPro Designer. The eight online lectures were conducted in the format of MOOCs or SPOCs.

■ METHODS

Theoretical Teaching of Computer-Aided Bioprocess Design

The online teaching of the computer-aided bioprocess design course targets the general public. It starts with four lectures designed to systematically introduce fundamental concepts to bioprocess design and process simulation. A comprehensive understanding of these concepts and principles is pivotal to ensuring students' proficiency in subsequent lectures. These four lectures cover an overview of bioprocess design, bioprocesses and bioproducts, process development and analysis, and techno-economic evaluation. Throughout these instructional lectures, we interspersed insights into the practical use of SuperPro Designer software, including the official tutorials provided by SuperPro Designer and recent scientific literature employing this software.

Table 1. Online−Offline Blended Process Simulation Courses

Method of course delivery	Contents of course
Offline	Introduction of course
Four online lectures	Theoretical teaching of Computer-Aided Bioprocess Design as well as introduction of SuperPro Designer
One online lecture	Two-unit SuperPro Designer project-based practice (peer review)
One online lecture	Introduction of SchedulePro
One online lecture	Case studies of SuperPro Designer (instructor introduction)
One online lecture	Summary and final exam
Offline	Five-unit SuperPro Designer project-based practice
Offline	Error-correction exercises (instructor evaluation)
Offline	Case studies and discussion of SuperPro Designer (group learning)

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SuperPro Designer Project-Based Practice

The online practice lecture of MOOCs/SPOCs and the offline practice lecture of the blended course are centered around a SuperPro Designer project-based practice.

In the fully online MOOCs/SPOCs, we provided guidance to students on operating the SuperPro Designer software through instructional videos and assigned them the task of developing a two-unit SuperPro Designer project. The two-unit project is embedded in the section “2.2 Developing a Process Model” of the SuperPro Designer tutorial. This simple process includes an upstream unit (stirred reactor with a chemical reaction of A + B → C) and a downstream unit (plate and frame filtration), both operated in batch modes. The evaluation of this two-unit project learning adopts a peer review approach.[20] The approach involves students assessing their peers’ project files for criteria such as completeness in process construction, adherence to material and energy conservation calculations, and the soundness of economic evaluations.

During the blended course, students were also required to complete the two-unit project mentioned above in online SPOC. However, students were additionally tasked with developing a five-unit project. This five-unit project is a simplified version derived from a monoclonal antibody production example. It comprises an upstream bioreactor with a bioreaction of 150 O_2 + 100 SF Media → 20 Biomass +120 CO_2 + 10 Impurity + 5 mAb + 95 H_2O and four downstream units (centrifugation, dead-end filtration, storage tank, and chromatography). The evaluation of this five-unit project was carried out by the instructor. Furthermore, in order to enrich the learning experience, we provided engaging error-correction exercises based on common mistakes observed during construction of the five-unit project.

Figure 2 illustrates the flowchart for developing a process model. To begin, the project construction involves the registration of components, configuration of the unit, and configuration of the operation. Following their completion, material and energy balances are conducted. If the balancing results are reasonable, the subsequent steps involve process analysis and techno-economic assessment. Detailed handouts for developing a process model can be found in the Supporting Information.

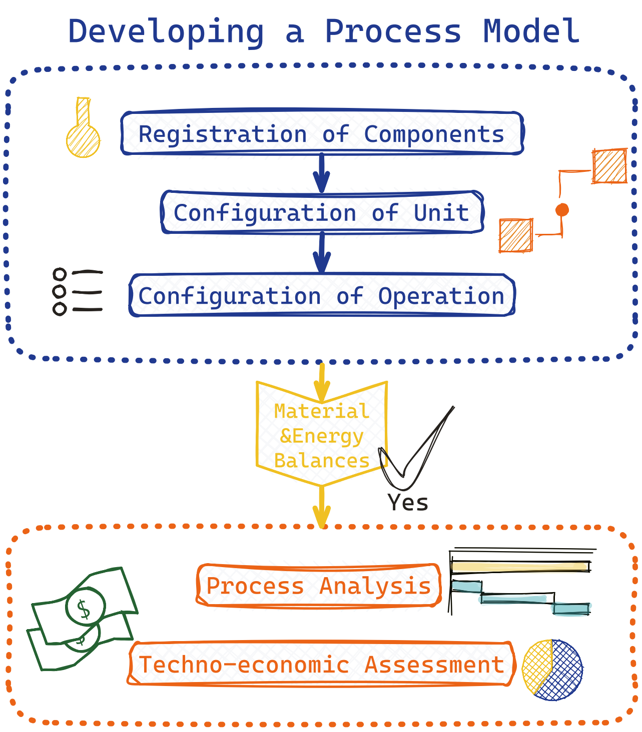

Figure 2. Flowchart for developing a process model.

Case Studies of SuperPro Designer

Both online MOOCs/SPOCs and the blended course involve case studies. However, the difference lies in the fact that in the two online courses the analysis and research of the cases primarily rely on the guidance provided by the instructors.

In contrast, during blended instruction, students were grouped based on the type of case (such as biofuels, biomaterials, biopharmaceuticals, etc.), forming six teams in total. Each student was assigned an independent study case. They were required to present their case study results in a 15 min presentation using slides. Additionally, based on their understanding of the case study results, they were tasked with optimizing the implementation process, building upon the official basic cases.

Software

The latest version, Version 13, of SuperPro Designer was utilized in the course. Based on the number of units supported for saving, this software is categorized into the evaluation edition (two units), academic edition (25 units), and commercial edition (unlimited units). It is noteworthy that the limitation refers to the number of units that can be saved while the processes of editing and opening units are unrestricted. Despite this limitation, the evaluation and academic editions encompass all functionalities available in the commercial edition. Therefore, the evaluation and academic editions were employed in the MOOCs/SPOCs and the blended course, respectively. Participants, guided by teaching assistants, installed the software on their personal computers.

Data Collection and Analysis

MOOCs/SPOCs have been offered for three terms and two terms, respectively. All online course materials (including video-based learning, textbooks, software installer, lecture quizzes, project-based learning, final exams, and discussion forums) are distributed to students through the Chinese university MOOC platform (www.icourse163.org). MOOCs and SPOCs had different participants: the participants in SPOCs were the fourth-year undergraduate students majoring in bioengineering at Zhejiang University, while those in MOOCs were public participants from other universities (undergraduate/master/doctoral students) and industries. These public participants possess a certain background in biotechnology. We disseminate promotional information on the icourse163 platform, encouraging members of the public interested in computer-aided bioprocess design to engage in MOOCs learning. Detailed information about the term schedule and the number of participants in the different terms is presented in Table 2.

For project-based practice, students were obligated to submit their developed project files (.spf) to the icourse163 platform for evaluation by either the instructor (blended courses) or their peers (online courses). Additionally, each of the lectures was accompanied by a brief quiz that students were required to complete on the online platform. The quiz

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Table 2. Term Information about Computer-Aided Bioprocess Design

Term	Duration (YYYY−MM−DD)	Enrollment for course
MOOC-1	2021−01−28 to 2021−03−21	517
MOOC-2	2022−03−07 to 2022−04−30	687
MOOC-3	2023−03−06 to 2023−04−30	725
SPOC-1	2021−09−13 to 2021−11−14	26
SPOC-2	2023−09−01 to 2023−10−30	24

formats include objective questions, such as multiple-choice, fill-in-the-blank, and true/false questions. Scores for each section of the online learning as well as participation rates and the final course grade can be directly exported from the online platform. The final grade for students consisted of the following components: lecture quizzes (30%), project-based learning (20%), a final exam (30%), and performances in the discussion forums (20%). In the case of SPOCs, which do not have a dedicated discussion forum, the scores for this component are incorporated into the project-based learning, increasing the weight of the component to 40%.

To analyze and test the collected data, including scores, participation rates, and final course grades, the Wilcoxon method was employed with a significance level set at 5%.

EVALUATION OF STUDENTS' PERFORMANCES

The course was offered in three formats: MOOCs, SPOCs, and online−offline blended courses. In this section, the students' performances in MOOCs and SPOCs were compared. Based on the outcomes of fully online learning, we redesigned an online−offline blended course.

Teaching in MOOCs

Across the three terms, a total of 1929 students participated in the MOOCs. The results of process analysis and techno-economic assessment are presented in Figures S1, S2, and S3 (Supporting information). Figure 3 illustrates the participation and score statistics of the three MOOC terms.

From Figure 3a, it can be observed that students initially showed high enthusiasm for video-based learning. However, as the courses progressed, the number of participants gradually declined, with the final participation rate stabilizing at around 25%. This trend highlights a significant drawback of online learning, where some students may lack motivation in a fully online learning environment due to the absence of direct face-to-face supervision and encouragement. Additionally, proposing an online course that consistently maintains student interest in learning remains an ongoing challenge. A surprising finding is evident in the practice lecture, the two-unit SuperPro Designer project-based practice, where the video-based learning participation rate is higher compared with other lectures. This suggests that students are more attracted to practical operations in process simulation software than to theoretical lectures.

Despite the relatively high video-based learning rates for certain lectures, the participation rates in quizzes for almost all lectures are around 20%, as presented in Figure 3b. The participation rate in practice lectures, however, does not mirror the elevated levels observed in video-based learning. Instead, it tends to be slightly lower than those of other lectures. As a robust and versatile software, SuperPro Designer is developed for diverse participants, ranging from academia to industry, undergraduate students to doctoral candidates. The official

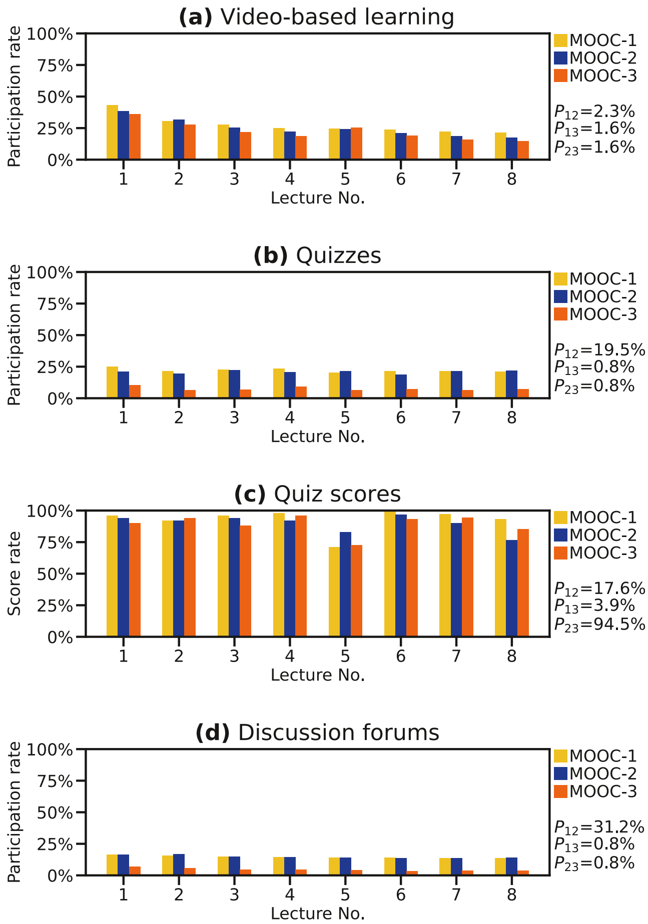

Figure 3. Statistical analysis of three MOOC terms: participation rates in video-based learning (a), quizzes (b), and discussion forums (c), along with score rates in quizzes (d). Bottom right corner: *p*-value of the Wilcoxon test, where P_{12} represents the test results between MOOC-1 and MOOC-2, and so forth.

two-unit project-based instruction proved to be ineffective in engaging the public from diverse backgrounds.

The corresponding quiz scores are shown in Figure 3c. All score rates of objective quizzes are approximately 90%. In contrast, the two-unit project-based learning exhibits an unusually low score rate. This could be attributed to the online peer review evaluation method, given the significant variations in students' educational backgrounds. Future improvements may involve training on how to consistently evaluate assignments among students to ensure fairness and uniformity in the evaluation process.[21]

To address the drawbacks of limited social interaction and face-to-face feedback in online learning, we established a dedicated MOOC discussion forum. Students were encouraged to pose questions and engage in discussions related to the course activities. The participation rate in the forum stands at approximately 15%, as shown in Figure 3d. An examination of the forum discussions reveals that approximately 50% of the issues raised are related to installation problems with SuperPro Designer. On one hand, this highlights the pressing need to address technological and equipment limitations in online process simulation instruction. Such differences in technological resources may lead to unfair learning outcomes. On the other hand, it underscores compatibility issues of the process

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simulation software across different student computers, necessitating future improvements.

The Wilcoxon test results from Figure 3a, 3b, and 3d show a significant difference in participation rates between MOOC-3 and the previous two terms, with a p-value less than 2%. Particularly notable is the remarkable decrease in participation rates for quizzes and discussion forums compared with a minor decline in video-based learning. Despite the decrease in participation rates, the number of enrolled students for MOOC-3 (725) is higher than those of the previous two MOOCs (MOOC-1: 517 students, MOOC-2: 687 students). As a MOOC catering to a diverse audience ranging from academia to industry, we were not entirely certain of the students' motivations for taking this course. If their objectives were solely to familiarize themselves with process simulation software, they may be more inclined to engage in video-based learning, which requires less time investment.

Teaching in SPOCs: A Comparative Analysis with MOOCs

The targeted participants of SPOCs comprise the students majoring in bioengineering at Zhejiang University, for whom computer-aided bioprocess design is a mandatory course, leading to a 100% participation rate across all lectures. Noteworthy for analysis are the quiz scores. Figure 4a

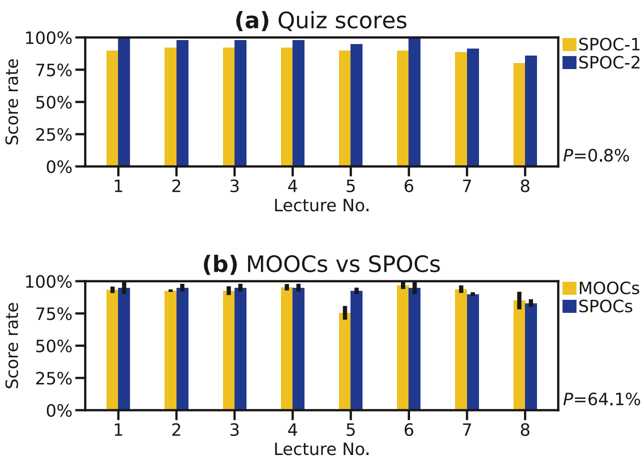

Figure 4. Statistical analysis of two SPOC terms: score rates in quizzes (a) and a comparison between MOOCs and SPOCs (b). Bottom right corner: p-value of the Wilcoxon test.

illustrates the quiz scores for each lecture. Similar to MOOC participation rates, SPOCs exhibit a trend of initially high and subsequently decreasing quiz scores. This phenomenon is observed in both SPOC terms, further highlighting the drawback of students lacking subjective initiative in online learning. Despite both participants being from our institution, students in SPOC-2 outperformed those in SPOC-1, with a p-value of 0.8%.

The weighted scores for all objective quiz questions in MOOCs/SPOCs are 53.3% and 52.9%, respectively, with no significant differences. Similarly, a p-value of 64.1% indicates no difference in the average course scores between MOOCs and SPOCs. However, a notable distinction arises in the score of the fifth quiz, where students in SPOCs significantly outperformed those in MOOCs, as shown in Figure 4b. We attribute this difference largely to the fact that students participating in SPOCs are from our institution and possess prior experience with process simulation software, such as Aspen Plus, rendering them proficient in utilizing SuperPro Designer. It is undeniable that the shift in the evaluation method from peer review in MOOCs to instructor evaluation in SPOCs may also contribute to this discrepancy.

Exploration and Practice of Online–Offline Blended Teaching

The performances of students in fully online courses, including MOOCs and SPOCs, prompted us to reconsider our course design. Therefore, we redesigned the course structure into an online–offline blended format with the course schedule outlined in Table 2. The design principle of this blended course aims to leverage the strengths of online learning in the process simulation course while addressing its shortcomings through the advantages of offline learning.

A comparison of Figure 3a–c in MOOCs reveals several insights. First, students exhibited a lower interest in theoretical knowledge related to process simulation but were more focused on practical software applications. As a computer-based learning course, emphasis should be placed on software practice rather than theoretical teaching, although the latter remains essential. A particularly challenging aspect is that educators should deal with the balance between theoretical foundations and practical applications, ensuring that students not only comprehend the software but also develop a deeper understanding of the underlying engineering principles. Second, video-based learning stands out as a significant advantage in online instruction, while online quizzes and online discussion forums may not be suitable. Consequently, in the design of blended courses, we replaced traditional offline theoretical learning with SPOC video-based learning, covering a substantial portion of theoretical learning in process simulation. Online video-based learning serves as a precursor to the offline component, capitalizing on its advantages. For instance, students can take notes using video screenshots and reinforce their understanding through repeated video playback.

The term "precursor" implies that online and offline learning is not isolated. For example, the offline assessments students participated in the classroom are related to their online learning experiences. This blended approach allows for a more comprehensive assessment of the effectiveness of students' online learning.[22,23]

The evolving target participants of the course prompted us to redesign the teaching approach for the offline two-unit project-based practice. The online two-unit project-based practice is highly suitable for non-bioengineering students and learners from the industry, enabling them to quickly familiarize themselves with process simulation software. However, for students majoring in bioengineering, the two-unit project-based instruction limits their exploration of the advanced functionalities of process simulation software, preventing them from grasping the significant advancements the tool brings. Therefore, students were tasked with developing a five-unit process within 12 given hours of offline instruction. The comparison between two-unit and five-unit projects is presented in Figure 5. This assignment was built upon the concepts they acquired online through the two-unit project, exemplifying another instance of a "blended" course. Further details on the five-unit process can be found in the Supporting Information.

Compared to the two-unit official tutorials of SuperPro Designer, our proposed five-unit project takes into account its practicality and comprehensiveness in bioengineering educa-

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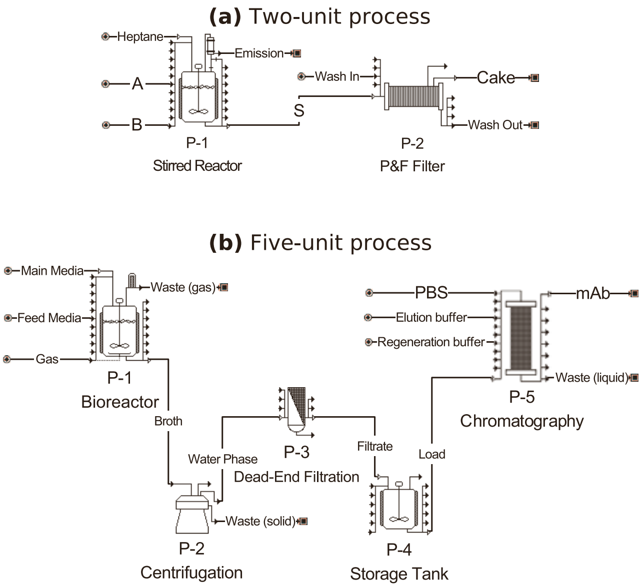

Figure 5. (a) Two-unit process comprising a stirred reactor and a plate and frame filter. (b) Five-unit process comprising a bioreactor, centrifugation, dead-end filtration, storage tank, and chromatography.

tion. In addition to experiencing most introductory features of SuperPro Designer as the two-unit instruction, students gained exposure to advanced functionalities, such as fine-tuning key parameters for optimal performance and identifying process bottlenecks in this five-unit instruction. The project also introduces advanced debottlenecking techniques, such as staggered equipment operation, to enhance overall annual throughput. The flowchart for developing the five-unit project follows the procedure outlined in Figure 2 as well. During the development of the five-unit process in the classroom, students could seek assistance from teachers, thereby improving their learning efficiency. In contrast, the efficiency of seeking assistance through online forums during online learning is not as pronounced. Students' active engagement in the classroom in the five-unit practice can significantly enhance their comprehension of process simulation concepts.

After all students submitted their five-unit process assignments, we aimed to introduce exercises that differ from online quizzes and effectively leverage the advantages of face-to-face offline teaching, thereby stimulating students' interest in process simulation learning. To achieve this, we continued to focus on the most interesting project-based practices. This time, we provided them with erroneous processes to correct (see the Supporting Information). These errors were collected during the offline five-unit project-based learning when students were developing processes. The collected errors fall into three major categories, corresponding to the errors in the three sections of Figure 2: process development, material and energy balances, and process analysis and techno-economic assessment. The difficulty of correcting these three types of errors increases incrementally, with the most challenging being process analysis and techno-economic assessment. Some novice users of process simulation may erroneously believe that the absence of errors or warnings implies flawless process construction. For the third type of error, which often lacks any errors or warnings, students need to locate and rectify errors through alternative means. This approach effectively enhances their ability to identify and rectify errors encountered during process simulation. The correction methods for these three types of errors are not limited to a single answer but are open-ended. This allows students to fully exercise their ability for open-ended thinking in process simulation courses. An intriguing point is that some students' proposed correction methods are even beyond the teacher's imagination. Furthermore, this error-correction exercise could enhance students' ability to think independently and reinforce their understanding of process simulation concepts. Effectively, it mitigates the phenomenon where some students may tend to replicate steps from tutorials without fully grasping the underlying implications of the software operations.

Additionally, we transformed the approach to case studies, shifting from predominantly teacher-led instruction to group learning and discussion. Students, organized into different groups, presented their case study results in the form of slides. They were required to provide creative improvement suggestions for their presented cases and engaged in discussions with other students. This collaborative case study method can enhance students' ability for creativity and effectively reinforces the advantages of face-to-face communication and interaction in offline learning. Consequently, online discussion forums have been eliminated in the blended courses.

A summary framework of blended teaching, comprising both offline and online components, is illustrated in Table 2. The online component primarily involves online SPOCs, while the offline component encompasses five-unit project-based learning, error-correction exercises related to the five-unit project, and case studies with group learning and case discussions. The above exploration of online−offline blended teaching holds promise as a blueprint for educators seeking to seamlessly integrate advanced process simulation tools into their courses.

■ CONCLUSION

This work explored and practiced the online−offline blended teaching in process simulation courses. The design of this blended course was based on a comparison of students' performances in fully online courses, MOOCs, and SPOCs. The comparison encompassed participation rates and scores, revealing a preference among participants for hands-on software lectures over theoretical ones in the process simulation course.

Based on the outcomes of online learning, we redesigned the online−offline blended course to optimize course arrangements, leveraging the complementary advantages of both online and offline instruction. This blended approach manifests in two key aspects: first, the online segment served as a precursor to the offline component, with the offline component serving as an evaluative measure and enhancement of the online segment; second, the two-unit SuperPro Designer project-based online learning led to the redesigned five-unit offline instruction, which serves as both a supplement and expansion to the two-unit teaching.

Furthermore, offline activities, such as error-correction exercises and case studies conducted through group learning, enhance students' ability for open-ended and independent thinking and reinforce their understanding of process simulation concepts, which are lacking in online learning. The above exploration of online−offline blended teaching holds promise as a blueprint for educators seeking to seamlessly integrate advanced process simulation tools into their courses.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00095.

Instructor's notes; student handout (PDF, DOCX)
SuperPro Designer project with two-unit process (ZIP)
SuperPro Designer project with five-unit process (ZIP)
Economic assessment report (PDF)
SuperPro Designer project file with erroneous processes for error-correction exercises (ZIP)

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Author Contributions

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Notes

The authors declare no competing financial interest.

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