Modeling-Eliciting Activities in an Online Engineering Course for Improving Conceptual Learning, Professional Skill, Interaction

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ABSTRACT

This empirical research aims to propose and examine an online teaching approach that embeds modeling-eliciting activities (MEA). The approach guides teachers to create a well-interactive online learning environment and improve the conceptual learning and professional skills of engineering undergraduates. The professional skills are defined as critical thinking and collaboration. A structured teaching procedure was implemented sequentially by task introduction, problem description, performance analysis, structural optimization, and solution discussion. The six principles of MEA were organically integrated with the teaching procedure, creating an inspiring, open-ended, and teamwork learning environment. The instruments used to collect data included conceptual learning tests, design report evaluations, learning reflection analyses, and interaction statistics. The findings suggested that the MEA-embedded online courses have significant advantages for improving learners’ conceptual learning and professional skills. The proposed approach guides the learners to make appropriate decisions and practical actions, enhancing their critical thinking. The MEA inspires learners’ positive attitudes and high participation, providing an emotional basis for group collaboration. The discussions on the open topics and thought process reflections create a collaborative environment. Besides, the statistics on the online teaching platform show that the MEA has a significant role for interaction promotion in the online course.

INDEX TERMS

Modeling-eliciting activity, online course, engineering education, teaching approach.

I. INTRODUCTION

Engineering education aims to cultivate the competency of potential practitioners to address real context challenges. To this end, it is not only necessary to predict the future industry demand but also the development trend of science and technology. The education and industry communities should jointly define the practitioners’ core competence framework. Enterprise managers usually undertake four core tasks: orientation, reaching consensus, executing pilot projects, and embedding results. The individual competencies relevant to the core tasks include systematic thinking, embracing diversity and interdisciplinary, interpersonal skills, action skills, and strategic management [1]. The American Management Association conducted a critical skills survey of engineering practitioners from the entrepreneurs’ perspective in 2012. The 21st-century business requires high-level skills such as critical thinking and problem-solving, effective communication, collaboration and team building, creativity and innovation, beyond the basics of reading, writing and arithmetic [2].

A well-designed teaching strategy is a key to enhancing engineering students’ conceptual learning and professional skills.

A modeling-eliciting activity (MEA) shows learners with an inspiring, open-ended, real context, demand-driven, aiming to improve their conceptual learning and problem-solving skills. Unlike traditional teacher-centred lectures, the MEA encourages learners to create mathematical models and
provides a mechanism to explore learners’ thought processes [3]. Like problem-solving in the real world, the MEA guides learners through simplification, assumption, assessment, simulation, and prototype. This series of operations is essentially in line with the structured thinking in engineering [4]. The MEA focuses on guiding learners to discover and define design problems based on the real challenge. Compared with applying simulation tools or discipline principles to solve abstract problems, it may more contribute to learners’ core professional skills.

The MEA was initially developed by mathematics educators to improve K12 students’ mathematics problem-solving ability. Recently, the MEA was gradually introduced into engineering courses in higher education. One of the challenges is to develop efficient strategies integrated with the current teaching paradigm [5]. In the past two decades, online teaching has become increasingly popular in engineering education. Academia and education believe that online teaching is vital to the future of engineering education [6]. The accessibility of the Internet and the flexibility of online courses support online teaching as an indispensable part of engineering education [7]. The empirical researches identified and tested the key factors affecting online teaching effects from various aspects, such as communication technology, time management, teaching strategies, and effect evaluation [8], [9], [10]. The interaction between learners and teachers, learners and course contents is considered a significant limitation of online teaching [11]. Lack of immediate feedback and limited communication between learners are the two primary factors affecting interaction in online courses [12], [13]. The open-ended scenario and group collaboration included in the MEA provide opportunities for instructors’ immediate feedback and learners’ group discussions. It is expected to promote interaction in online courses.

Few educators explored the integration of MEA into online engineering courses, and there is a lack of high-quality empirical research. To fill the research gap, we followed the general paradigm of empirical study and proposed an MEA-embedded online teaching approach for engineering education. In the next section, we review the literature on the engineer’s competence framework and MEA teaching practice. Besides, the research hypothesis of this study is briefly explained.

II. LITERATURE REVIEW

A. COMPETENCE FRAMEWORK FOR FUTURE ENGINEERS

With the development of intelligent manufacturing in the industry, future engineers face new skills requirements in an ever-changing environment. The competency framework involves not only specific technical skills but also soft skills, such as problem-solving, systematic thinking, collaboration, presentation, and willingness to explore new knowledge [14]. According to the critical skills survey of the American Management Association, the competence framework of highly skilled employees was defined as critical thinking, effective communication, collaboration and team building, creativity and innovation [15].

Critical thinking refers to the ability to make decisions, solve problems, and take appropriate actions. It is described as a cognitive endeavour, providing the organization with value-added high-order reasoning capabilities [16]. The process of critical thinking includes problem identification and analysis, clarifying meaning, collecting evidence, evaluating evidence, inferring conclusions, considering other relevant information, and making overall judgments [17]. Effective communication is the ability to synthesize and disseminate ideas in written and oral forms. Communication skills are an essential part of engineering education, which can promote teaching effects and prepare students for their future careers. Communication skill development should be integrated into the engineering curriculum but not set up as a separate curriculum [18]. Collaboration and team building are defined as collaborating effectively with others, including people from different groups and holding opposing views. Teamwork activities promote member participation by dividing responsibilities among participants. Each participant is responsible for solving part of a complex problem or project [19]. Creativity and innovation refer to perceiving things that do not exist and make things happen. Innovative activities encourage learners to design, research and develop creative and innovative solutions [20].

Professional skill development can promote the proposal of solutions, thereby improving any services, processes, systems and practices to maximize the resource usage. Employees’ skills become increasingly crucial for businesses to keep up with rapid changes and participate in global competition. Business managers and executives believe that it is easier to develop the skills in undergraduates than experienced employees [15].

B. MEA IN ENGINEERING EDUCATION

The MEA enhances learners’ conceptual learning and problem-solving skills by inspiring, open-ended, real context, demand-driven problems [3]. In addition to improving learning effects, the MEA provides engineering educators with a mechanism for evaluating the thought processes in problem-solving and conceptual learning [21]. The concept of MEA was proposed by mathematics educators and first applied to engineering students at Purdue University in 2004 [22]. Then, the MEA was gradually introduced into engineering education at various levels and may become a widely used teaching strategy [23], [24], [25].

A well-designed MEA should comply with six principles, including modeling, reality, self-assessment, documentation, generalization, prototype [26]. Applying the MEA in engineering courses helps to improve students’ core professional skills, such as conceptual learning, problem-solving, communication, and teamwork. The MEA creates a learning environment, emphasizing the application and adjustment of conceptual tools to formulate, describe, and analyze complex problems through effective communication and collaboration.
MEA requires students to develop engineering models or procedures instead of using traditional prescribed equations and models. The modeling and solving process with real context can help students clarify the misunderstanding of engineering concepts, thereby deepening the conceptual understanding [28]. The design and implementation of MEA can encourage experienced and novice engineering educators to embrace the student-centred teaching approach [29]. The model formulation and modification provide students with opportunities for in-depth cognitive reasoning. The explanatory and evaluative reasoning induced by the MEA prompts students to explore the underlying mechanisms of complex systems [30].

Existing research supports the MEA potential in engineering education, and the possible challenge lies in how to integrate with popular teaching models. Recently, online courses received widespread attention in engineering education, providing various opportunities for teachers, students, and institutions [31]. However, there is little literature on the combination of MEA and online engineering courses, especially high-quality empirical studies.

C. RESEARCH HYPOTHESES OF THIS STUDY

This paper proposes and tests a teaching approach combining the MEA and online engineering courses for improving the teaching and learning effect, including conceptual learning, professional skills, and interaction. Conceptual learning refers to students’ understanding of the discipline and engineering concepts. The professional skills involve critical thinking and collaboration. The interaction occurs between students and teachers, students, and course content during the online teaching. The empirical research was implemented in the online course of sensor design. The course adopts a mixed-mode of classroom and online teaching. The course target is to cultivate students’ design and optimization skills for typical sensor structures. Classroom teaching content is the basic principles and design methods of various sensors (eight weeks, four hours per week). Online courses are about the design and application of specific sensors (one week, eight hours per day).

The six principles of MEA were employed to create the design activities in the empirical study [26]. The Modeling Principle ensures that the activity requires the construction of an explicit description, explanation, or procedure for a mathematically significant situation. The Reality Principle requires that the activity be posed in a realistic context and designed so that students can interpret the activity meaningfully from their different levels of mathematical ability and general knowledge. The Self-Assessment Principle ensures that the activity contains criteria the students can identify and use to test and revise their current ways of thinking. The Documentation Principle requires students to create some form of documentation that will reveal explicitly how they are thinking about the problem situation. The Generalizability Principle requires students to produce solutions that are shareable with others and modifiable for other situations. The Prototype Principle ensures the model produced is simple to implement but based on sound application of scientific principles.

The literature suggested that modeling and solving engineering problems in real context from different perspectives can significantly improve learners’ conceptual learning and problem-solving skills [3], [28]. Self-assessment of thought processes and standardized documents may make team collaboration smooth and efficient [24], [27]. Overcoming the challenges of generalization and prototype construction can promote interaction and students’ critical thinking [22], [30]. Therefore, we establish a hypothetical model as shown in Figure 1 and propose the following hypotheses.

H1: In conceptual learning enhancement, MEA-embedded online teaching is better than teacher-centred online teaching.

H2: In professional skill enhancement, MEA-embedded online teaching is better than teacher-centred online teaching.

H3: In interaction promotion, MEA-embedded online teaching is better than teacher-centred online teaching.

III. METHODOLOGY

A. PARTICIPANTS

Participants in this empirical research were 147 junior undergraduates majoring in mechanical engineering from an applied-oriented university in China. They signed informed consents to participate in this study. Of the participants, 122 (83%) were male, and 25 (17%) were female. The average age of the participants was 21.0, and the standard deviation was 0.66. They came from four actual teaching classes. In the empirical research, two classes (75 students) were designated as the experimental group, and the others (72 students) were the control group. Because this study was limited by the real classroom scenarios, the participants were not randomly assigned to the experimental and control groups. To ensure validity, a pre-test was employed to determine the knowledge and skill levels of the two groups.

The pre-test data were extracted from the participants’ test scores in the pre-courses of the curriculum program, including mechanical design, mechanical principles, and material
mechanics (see Table 1). They involved a series of abstract concepts and emphasized problem-solving skills. Thus, the course scores can roughly indicate the knowledge and skill levels of the participants. The independent samples t-test was adopted to compare the course scores of the experimental group and the control group. $p \geq 0.05$ means no significant difference. It shows no significant difference in pre-courses’ scores between the two groups, and the p-values are higher than 0.05. Therefore, this experimental grouping can be equivalent to random allocation.

**B. MEASURING INSTRUMENTS**

Instruments were proposed to measure the performance of MEA-embedded online courses in the participants’ improvement of conceptual learning, critical thinking, and collaboration. Also, this study tested whether the MEA can improve the interaction between students with teachers, students with course contents in online teaching. Conceptual learning tests, design report evaluations, learning reflection analyses, and interaction statistics were used to collect data.

1) **CONCEPTUAL LEARNING TEST**

The concept learning test was developed to measure participants’ learning effects on discipline and engineering concepts. The researchers created a question bank containing 100 closed-end questions. A pilot study was performed on 120 junior undergraduates to calculate the difficulty index and discrimination index. The means of the two indexes were 0.65 and 0.41, and the standard deviations were 0.08 and 0.05. The internal consistency coefficient was 0.71. We implemented two conceptual learning tests. For each test, 40 questions were randomly selected from the question bank.

2) **DESIGN REPORT EVALUATION**

This study uses the submitted design reports to measure the participants’ critical thinking. The design report required a problem description, performance analysis, structural optimization, and solution discussion. Each item involves several elements, constructing a critical thinking framework from the three dimensions of affection, cognition, and behaviour [32]. Table 2 lists the scoring criteria for each item and the critical thinking elements involved. The researcher scored on a five-point scale, i.e., one point (lowest level) to five points (highest level).

3) **LEARNING REFLECTION ANALYSIS**

The Participants were required to submit a 500-word reflection on the online course, attached to the end of the design report. The researchers provided reflection guidance, including expectations for the online course contents, teaching approach, impressive thought processes, challenges encountered and solutions, issues and results of group discussions. The researchers performed semantic analysis on the learning reflections and defined coding topics in response to the research hypotheses.

4) **INTERACTION STATISTICS**

The online course relied on the online teaching platform titled “Classroom Pie”, serving the whole-process management of online and offline mixed teaching. The researchers delivered the teaching materials on the platform, such as teaching videos, courseware, technical documents, and references. The participants interacted with the course content by browsing the teaching materials. There is a discussion area on the platform, where the participants proposed topics to discuss the challenges and gains in task execution with the instructors and other participants. The platform automatically counts the interaction data of browsing teaching materials and participating topics.

**C. MEA-EMBEDDED ONLINE TEACHING APPROACH**

The MEA was implemented in the actual online courses of sensor design. The online course lasted for one week (five working days, eight hours/day), including task introduction, problem description, performance analysis, structural optimization, and solution discussion. Design report writing is also a necessary part of MEA. Six principles were used to guide the MEA creation. How to embed each principle into the online course is described below.

The modelling principle ensures that the activity requires the construction of an explicit description, explanation, or procedure for a mathematically significant situation. It is applied in performance analysis and structural optimization. Take the acceleration sensor design task of this study as an example, as shown in Figure 2. The mechanics model is used to analyze the structural performance of the sensor under a specific design option, such as weight, sensitivity and natural frequency. In engineering applications, various structural performances are usually conflicting objectives. The mathematical model is formulated to balance the design objectives and achieve the optimal solution that meets the design requirements. The modeling principle uses the structural optimization method to guide participants to create mathematical models by defining design variables, objectives, and constraints. Therefore, the principle ensures the generation of open-end questions, providing an opportunity for students to compare their thought processes with engineering practices. The participants learned related mechanics and mathematical

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**TABLE 1. The t-test results for the pre-test scores of the groups.**

| Pre-courses             | Mean/standard deviation | Difference in means | $p$-value |
|------------------------|-------------------------|---------------------|-----------|
|                        | Experimental group       | Control group       |           |
| Mechanical design      | 3.21/0.53               | 3.17/0.48           | 0.04      | 0.65 |
| Mechanical principle   | 3.39/0.47               | 3.47/0.46           | 0.08      | 0.30 |
| Material mechanics     | 3.13/0.64               | 3.18/0.50           | 0.05      | 0.60 |
TABLE 2. The scoring criteria and critical thinking elements.

| Items                  | Description and Weight | Elements of critical thinking                                      |
|------------------------|------------------------|---------------------------------------------------------------------|
| Problem description    | According to the given task, establish appropriate assumptions, define design objectives, constraints, design variables, and parameters (25%) | Defining problems accurately; Resisting over-generalization; Employing precise terms; Welcoming divergent views |
| Performance analysis   | Describe the principles and steps of performance analysis, define input parameters and give the evidence, provide solution and interpretation. (25%) | Analyzing data for value and content; Gathering data; Accepting change |
| Structural optimization| Determine the highly sensitive parameters and variables, define the design space, formulate and solve the optimization model. (25%) | Employing a variety of thinking processes in solving problem; Synthesizing; Modifying judgement in light of new information |
| Solution discussion    | Comparatively analyze the sensor performance before and after optimization, discuss the similarities and differences with other team members' thought processes, and explain the advantages and disadvantages. (25%) | Delaying judgement until adequate data are available; Distinguishing fact from opinion; Encouraging critical dialogue; |

FIGURE 2. The design task of an acceleration sensor.

modeling methods in the pre-courses. The modeling methods are integrated into the course to practice sensor design.

The reality principle requires that the activity be posed in a realistic context and designed so that students can interpret the activity meaningfully from their different levels of mathematical ability and general knowledge. The reality principle runs through the entire process of online teaching. To reveal the design principles, the conventional courses show students the sensor prototype after abstraction and hypothesis. In this study, the researchers delivered the manufacturer background, manufacturing process, and application scenarios of the accelerometer on the online platform to enhance participants’ intuitive experience of actual requirements. In the introduction and feedback, the instructors consciously emphasized the influence of design decisions on the actual manufacturing process and application effects. In the topic discussion, the instructors guided participants to explore and solve the problems from an engineering perspective.

The self-assessment principle ensures that the activity contains criteria the students can identify and use to test and revise their current ways of thinking. The self-assessment is reflected in the four parts except for the task introduction. The criterion of problem description is to transform the general client’s demands into analytical expressions with physical meaning. For example, the assembly compatibility required by the client can be converted to the expression that the sensor weight does not exceeding the rated value. The criterion of performance analysis is to obtain performance responses from analyzing a design option containing a series of variables. The process should be packaged as a standard input/output function, i.e., performance function. The criterion of structural optimization is to construct a standard optimization mathematical model, including design variables, design space, objectives, and constraints. Accurate descriptions should be provided to explain the meaning of the mathematical expressions for engineering practice. The criterion of solution discussion is to respond to given requirements through quantified design output and further explore alternative paths.

The documentation principle requires students to create some form of documentation that will reveal explicitly how they are thinking about the problem situation. The design report should be submitted in response to the documentation principle and organized with structured content. The principle is similar to conventional design-based learning, but the difference lies in the emphasis on the thought process reflection. The task introduction usually provides critical information while ignoring some potential influencing factors. These factors may be hidden in the real context, requiring participants to discover from existing knowledge, experience, and teaching materials. In problem-solving, the participants should describe their thought processes while establishing assumptions about potential factors. In the solution discussion, the instructors encouraged students to focus on the hypothesis rationality and possible engineering impact. The purpose is to clarify the engineering application of the design option and seek more reasonable and objective solutions.

The generalizability principle requires students to produce solutions that are shareable with others and modifiable for other situations. The generalizability is primarily reflected in the performance analysis, structural optimization, and report writing. The performance analysis is usually created based on
discipline principles or numerical simulation. Structural optimization applies mathematical models to balance conflicting objectives. Creating a reusable model is a challenge for participants, which is more difficult than providing a highly specialized solution. The instructors provided scaffolding to help students achieve generalization, including the structured modeling flowchart, annotated code examples, and design report templates. The performance analysis and structural optimization should be packaged into standard input/output functions. A series of test cases were provided to guide participants to strengthen the model robustness and understand the value of general solutions.

The Prototype Principle ensures the model produced is simple to implement but based on sound application of scientific principles. The prototype is a crucial topic in the solution discussion. The participants should list the hypotheses in the problem-solving and propose the prototype options to verify the hypotheses. The group discussions provide opportunities for peer feedback. Limited by knowledge level and engineering experience, it is a challenge for participants to propose a simple and effective prototype. The participants were encouraged to summarize the challenges into topics and post them to the discussion areas of online platforms. The instructor responded to the topics by providing essential clues to guide the participants step by step to complete the prototype design.

**D. PROCEDURES**

The empirical research was implemented in the actual classroom, and the procedure is summarized as shown in Figure 3. Firstly, 147 participants passed the knowledge and skill test to achieve equivalent random grouping, i.e., the experimental group and the control group. The two groups implemented a one-week practice course in the sequence of five parts. The MEA constructed with the six principles was used for the experimental group. The control group adopted the conventional teacher-centred teaching approach. Subsequently, the conceptual learning test was performed on all participants. One week later, the participants were required to submit the design reports and learning reflections. The second conceptual learning test was performed two weeks later to test the durability of the learning effect.

Unlike MEA, the instructors in the control group applied their favourite strategies, such as direct introduction, case study, individual guidance, and discussion. In the first class of each day, the instructors used the presentation to teach the current part directly. In the following six hours, they guided students to implement the design task through case studies and individual guidance. The last hour is discussions and concentrated Q&A.

**IV. FINDINGS**

This study collected data through the concept learning test, design report evaluation, learning reflection analysis, and interaction statistics. The SPSS software was adopted for data analysis to highlight meaningful outcomes. The independent samples t-test was used to measure the difference between the experimental and control groups, and \( p < 0.01 \) represents a significant difference. Cohen’s \( d \) was calculated for the effect sizes, \( d < 0.2 \) means a small effect size, \( d > 0.8 \) indicates a large effect size, and \( 0.2 \leq d \leq 0.8 \) denotes a medium effect size [33]. Besides, semantic analysis was performed on the learning reflections. The qualitative data were coded into several themes, responded to the research hypotheses. To ensure inner-coder reliability, two researchers combed the qualitative data. Cohen’s Kappa (\( \kappa_c \)) was used to measure the
consistency between coding results, and $\kappa_c \geq 0.6$ indicates that the consistency satisfies the requirement.

A. CONCEPTUAL LEARNING TEST

The two test results of the experimental group and the control group are listed in Table 3. In the first test, the average score of the experimental group (3.92 points) is 15.6% higher than that of the control group (3.31 points), and $d = 1.32$ indicates a large effect size. The result shows that the MEA-embedded online courses are significantly better than the teacher-centred online courses for enhancing participants’ conceptual learning. The results of the second test were similar to the first, and the conceptual learning of the experimental group was significantly better than that of the control group. The average score of the former (3.68 points) is 14.9% higher than that of the latter (3.13 points), and $d = 1.18$ presents a large effect size.

B. DESIGN REPORT EVALUATION

The results of the design report evaluation are listed in Table 4, which reflects the participants’ critical thinking in the online course. In general, the average score of the experimental group (3.83 points) is 13.8% higher than that of the control group (3.39 points). The differences were 12.7%, 15.9%, and 15.8%, respectively. It further demonstrates the significant advantages of MEA-embedded teaching in critical thinking enhancement.

C. LEARNING REFLECTION ANALYSIS

As listed in Table 5, five coding themes are defined from two aspects: behaviour and improvement source. In terms of behaviour, the percentages of participants in the experimental group who reported positive attitudes and high participation in online courses were 84.0% and 90.7%, respectively. In terms of improvement sources, 78.7% of participants in the experimental group mentioned peer support, and 85.3% of participants reported the topic discussion. The percentages of the two groups saying instructor feedback were close, i.e., 92.0% and 95.8%, respectively. It shows that the MEA-embedded online courses can promote collaboration (e.g., peer support, topic discussion) for participants’ competency improvement. However, the teacher-centred online course relies more on instructor feedback.

D. INTERACTION STATISTICS

The interaction statistics provided by the online teaching platform are listed in Table 6. The average number of browsing teaching materials in the experimental group is 6.7, 1.8 times that of the control group (3.7). The average number of topic
V. DISCUSSION
To investigate the performance of the MEA-embedded online teaching approach, three hypotheses are outlined. According to the experimental findings, the research questions involved in the hypotheses are discussed as follows.

A. CONCEPTUAL LEARNING IMPROVEMENT IN THE MEA-EMBEDDED ONLINE COURSE
The two test results support the first hypothesis that the participants’ conceptual learning in the experimental group is significantly better than that of the control group. It supports the conclusions of existing research that the MEA can strengthen learners’ conceptual learning [3], [25], [29], [32]. The six principles for creating the MEA in the online course are the primary sources for conceptual learning improvement. For example, the mechanics modeling includes the comprehensive application of disciplines and engineering concepts such as structural features, material properties, assembly, boundary conditions, loads, meshing, and solvers. Structural optimization considers design variables, parameters, constraints, and objectives. These elements establish a direct and analytical link between concept and practice. The modeling can deepen conceptual learning and cultivate learners’ higher-order thinking, which is supported by the literature [23], [24], [25]. The reality principle vividly reflects the challenges in the real world by the engineering contexts involving working conditions, client demands, and manufacturing processes. It helps learners understand the abstract and hypothetical concepts in the course. In terms of self-assessment, the MEA provides criteria to examine and modify the learners’ thought process, thereby clarifying specious understanding of concepts. The documentation in the MEA emphasizes the reflection on the thought process. The learners explore the potential impact of idealized assumptions in practice, thereby discovering the application scope of subject concepts in actual engineering. The principles of generalizability and prototype guide learners to return to general thinking from specific problems and realize meaningful learning of abstractions and assumptions in concepts.

B. PROFESSIONAL SKILL IMPROVEMENT IN THE MEA-EMBEDDED ONLINE COURSE
The findings of the design report evaluation and learning reflection analysis support the second hypothesis. The professional skill improvement of the experimental group was significantly better than that of the control group in terms of critical thinking and collaboration. Critical thinking is the problem-solving skill to make decisions and implement actions. The MEA guides learners to solve real design problems with a structured flowchart integrating the six principles. The flowchart is designed to link problem description, performance analysis, structural optimization, and solution discussion. The design report is employed to record the participants’ thought processes in each link. The problem description of MEA emphasizes that participants should transform the general descriptions into precise mathematical expressions. The current literature concluded that mathematical and physical modeling has a significant impact on critical thinking improvement [17], [32]. The performance analysis and structural optimization in the proposed MEA are based on the physical and mathematical models, respectively. It emphasizes different modeling

| Table 5. The learning reflection analysis results and statement instances. |
|--------------------------|--------------------------|--------------------------|--------------------------|
| Aspects                  | Coding themes            | Number (%)               | Instances extracted from the reflections |
|                          |                          | Experimental group       | Control group             |
| Behavior                | 63 (84.0%)               | 46 (63.9%)               | The acceleration sensor design is an interesting and meaningful design task. |
|                          | High participation       | 68 (90.7%)               | Each member of our group is responsible for a part of the task. For example, I conducted simulation modeling. |
|                          | Peer support             | 59 (78.7%)               | We decompose the task to each member and discuss solutions together when encountering problems. |
| Improvement source       | Instructor feedback      | 69 (92.0%)               | In the performance analysis, we are not familiar with the operation of simulation software. The teacher immediately provided guidance. |
|                          | Topic discussion         | 64 (85.3%)               | Most of the topics in the discussion area were common issues. By participating in the discussion, my confusion was answered. |

| Table 6. The results of interaction statistics between the experimental and control groups. |
|-----------------------------------------------|-------------------------------|--------------------------|
| Interaction                          | Mean / standard deviation | Difference |
|-----------------------------------------------|-------------------------------|--------------------------|
|                                     Experimental group | Control group |                       |
| Browsing teaching materials | 501/6.7                      | 264/3.7                  | 1.8 times |
| Topic discussions                    | 763/10.2                     | 231/3.2                  | 3.2 times |
strategies to achieve general solutions, which may be the source of problem-solving skill improvement. The solution discussion primarily focused on the reasonableness of assumption and the possible results. The participants were guided to explore the engineering applicability of the solution and review the potential defects in problem-solving. Thus, it may contribute to the participants’ critical thinking and supports the conclusions of the existing literature [30], [31], [32], [33], [34].

In collaboration enhancement, the learning reflection analysis indicates that MEA-embedded online courses have significant advantages over the teacher-centred online courses. The participants in the experimental group exhibited stronger positive attitudes and higher participation levels, providing a solid emotional foundation for collaboration. The literature suggested that the attitude and participation of members are important factors to promote the collaboration [19]. The participants in the experimental group reported that the improvement sources include peer support, topic discussions and instructor feedback. The participants in the control group said that the improvement primarily relies on instructor feedback. The proposed MEA emphasizes open-end problem modeling and thought process reflections, providing a beneficial environment for group collaboration. It may be the reason for the collaboration improvement. Consistent with the literature findings [27], the MEA promotes group collaboration in practical courses.

C. INTERACTION IMPROVEMENT IN THE MEA-EMBEDDED ONLINE COURSE

The interaction statistics of the online teaching platform support the third hypothesis. The interaction of the experimental group was significantly better than that of the control group in terms of content browsing and topic discussion. Also, the participants’ behaviour and improvement sources reflected in the learning reflection analysis confirm this finding. The intuitive and vivid information in the real context is more interesting than the abstract principles. It may be a reason for attracting participants to learn actively. The MEA requires to create the reusable models and propose the simple and effective prototypes. It is more challenging than conventional practical courses, driving the participants to study teaching materials repeatedly for solutions. The challenges may prompt participants to propose topics and participate in discussions. Unlike direct introductions, the MEA instructors provide vital clues to respond to the topics. The heuristic guidance may further promote interaction between participants. The instructor guided participants to discuss open-end topics, such as solutions to different requirements and possible results due to subjective assumptions. The collision and communication of various thoughts may be a source of interaction improvement. The literature suggested that interaction is an essential factor affecting the learning effect of online courses [12], [13]. The findings of this study provide evidence for the MEA to promote interaction in online courses, and fill the gaps in the existing researches of MEA and online course.

VI. CONCLUSION

This empirical study proposes and examines an MEA-embedded online teaching approach. The purpose is to help teachers create a good and interactive online learning environment and improve the undergraduates’ conceptual learning and professional skills in engineering education. The contribution of this study is to provide a practical approach and experimental evidence for integrating the MEA into online courses, and to respond to engineering education’s concern to the interaction improvement in online teaching. The proposed approach followed the general paradigm of design-based learning, i.e., a structured flowchart for sequential implementation with task introduction, problem description, performance analysis, structural optimization, and solution discussion. Unlike teacher-centred teaching, the teaching links were organically integrated with the six principles of MEA, including modeling, reality, self-assessment, documentation, generalization, and prototype. The conceptual learning testing, design report evaluation, learning reflection analysis, and interaction statistics were used to collect data to verify the effectiveness of the proposed teaching approach.

The experimental evidence show that the MEA-embedded approach has significant advantages in the participants’ improvement of conceptual learning and professional skill compared with the conventional online courses. In terms of interaction improvement, it also shows better performance. The six principles embedded in online teaching are the primary sources for the learners’ conceptual learning improvement. The MEA-embedded structured flowchart guided the learners to make appropriate decisions and take effective actions in dealing with real challenges, enhancing their critical thinking. Besides, the MEA inspired learners’ positive attitudes and high participation, providing an emotional foundation for group collaboration. The discussion on the open-ended topics and thought process reflections created opportunities for group collaboration. Therefore, the MEA-embedded approach is expected to enhance students’ collaboration. The Teaching materials in the real context and the challenges involved in implementing MEA enhanced the interaction between students with course contents. The heuristic guidance promoted topic proposal and discussion, thereby enhancing the interaction between learners. In short, the proposed MEA-embedded approach provides an effective tool for online teaching in engineering education.

VII. LIMITATIONS AND FUTURE RESEARCHES

This empirical study contains two limitations. Firstly, the online course content of this experiment is the practical teaching module of an engineering course. The students learned theories and concepts through the previous lectures, reducing the learning burden of online courses. Future researches should consider the teaching and learning challenges introduced by the MEA-embedded and explore the adjustment mechanism of MEA creation. Secondly, this study is limited to the undergraduates at the same level. To ensure generality,
future researches should be implemented at various educational levels, such as vocational education and postgraduate education. Considering the impact of economic development on education, we will conduct comparative studies on students from different regions in the future.

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