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Article

Multidimensional Characteristics of Design-Based Engineering Learning: A Grounded Theory Study

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Abstract: Design-based engineering learning is an important learning model in the field of engineering education research, and also an important embodiment of sustainable development engineering education. At present, the research is still in the stage of conceptual discussion, and its connotation has not been effectively clarified. In order to construct a theoretical model of design-based engineering learning, this study adopted grounded theory to carry out exploratory research. First, we selected the advanced class of engineering education in Chu Kochen Honors College of Zhejiang University as a follow-up case, conducted interviews with front-line teachers and students, and collected relevant data; second, we adopted the three-level coding technology of open coding-axis coding-selective coding and used NVivo software to extract concept categories from open codes, and established the connection between categories through the axis coding; and finally, multidimensional ideas were developed through core categories, including design practice, interactive reflection, knowledge integration, and circular iteration. The multidimensional conception of design-based engineering learning constructed in this study aims to provide theoretical support for promoting engineering education research. At the same time, it puts forward some useful suggestions on the training of engineering talents for sustainable development in practice.

Keywords: design-based engineering learning; multidimensional conception; grounded theory

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1. Introduction and Background

Since the second half of the 20th century, the contradiction between economic development and ecological environmental protection has become increasingly prominent. As a practical activity for humans to explore and transform the world, engineering is regarded as an important means to protect the ecological environment and improve the quality of life. This new generation of engineers has an important mission and responsibility in advancing the global Sustainable Development Goals for engineering education. Without their wisdom and contributions, these goals would not be possible. While leading the reform of international engineering education, the concept of sustainable development education has increasingly become an important choice to improve the quality of engineering education. In order to support the country's long-term innovation capacity and the sustainable development of the social economy, we must promote the innovative development of global engineering education and cultivate a large number of sustainable competitive innovative talents.

Engineering education is intended to train engineers [1,2]. In the field of engineering education, scholars have been concerned about "how people learn engineering" and "the nature of engineering knowledge". Engineering learning is a process of knowledge acquisition, knowledge creation, and ability development that learners develop around the engineering subject field [3–5].

Engineering is a systematic activity of artificial creation, whose essence lies in design [6–8]. In modern engineering practice, design is an important step from overall planning to concrete implementation and a process of technology integration and engineering synthesis [9]. Only design can create a sound engineering framework and make engineering activities form an organic whole [10]. "Engineering design and training is a creative, repetitive and often endless work", according to China's Certification Standards for Engineering Education (Trial). The Board for Certification in Engineering Technology (ABET) states that engineering design is a decision-making process that requires engineers to apply basic science, mathematics, and engineering science to optimize resource conversion and achieve specific goals. In fact, engineering design has rich connotations: at the scheme level, it is the artificial object to achieve the optimal decision combining entity and intention [11,12]. At the process level, it has multidimensional characteristics such as individual reflection, knowledge integration, and social interaction [13,14]. At the activity level, it integrates resources to implement goal-oriented engineering activities [15,16]. For engineering education, design is the core of training engineers [17,18]. Engineers are different from scientists. "Scientists discover the world that has already existed, while engineers create the world that has never existed" [19]. The function of engineers is to solve complex engineering problems in industry, including new products, new processes, and new technologies [2,20]. A teaching and learning process for engineering education that lacks design activities will lead to a lack of students' intersubjectivity, engineering practical ability, and innovative thinking [10].

Influenced by the trend of scientism, the global higher engineering education system has been turning to a "scientific paradigm" since the 1990s [21,22]. Engineering teaching under the scientific paradigm positions the teacher–student relationship as the subject–object relationship, making the focus of engineering education shift to acquiring formal knowledge, and students gradually become "automated" knowledge containers, unable to achieve deep learning, high-level thinking, or conceptual innovation. In the early 20th century, some scholars proposed "design-based learning" (DBL) in the field of education, in which teachers put forward questions to students based on practical problems and adopt a bottom-up approach to enable students to construct and deepen existing knowledge meaningfully while completing design tasks. Furthermore, they constantly learn new knowledge in a repeated cycle and finally obtain the learning mode of products that meet the task requirements [23–26]. Since then, design-based learning has been regarded as an innovative learning mode combined with engineering education practice and has gradually evolved into a unique design-based engineering learning (DBEL) method.

As a powerful inductive learning method, scholars have studied the concept and connotation of design-based engineering learning from multiple perspectives, such as the learning process, teaching means, and learning mode. Some scholars define DBEL as a learning process that is based on authentic engineering design practice and encourages students to construct knowledge in the process of solving engineering problems [23,27,28]. Some scholars define DBEL as a teaching method in which teachers assign challenging tasks to students and create interactive environments so that students can repeatedly memorize and practice the learned knowledge [29,30]. Some scholars believe that DBEL is a brand-new learning mode. Engineering students design specific engineering models by using prior experience and knowledge learned and then modify and redesign the models and schemes in a circular manner to acquire new knowledge in practice [31,32]. Some scholars believe that DBEL is a collaborative optimization engineering learning mode, in which students constantly analyze and design the existing engineering technology system and make improvements in quality, function, cost, price, and other aspects, thus significantly improving the performance of engineering products [30]. Furthermore, some scholars believe that DBEL enables students to design science content in the context of design challenges, thus promoting deep learning [24,33,34]. Based on the existing research and practice, this paper regards "design-based engineering learning" as an extension of the core of "design-based learning" and "engineering learning", and defines it as a learning mode; that is, in the real-engineering problem situation, according to the specific design task, students use their existing knowledge and experience, through several iterations, to create a certain object model to acquire new knowledge and improve their engineering problem-solving ability using a dynamic learning mode. Design-based engineering learning is a learner-centered learning model that helps to highlight the centrality of engineering students in sustainable engineering education.

In the past two decades, design-based engineering learning has been widely promoted in undergraduate engineering education around the world. Famous universities in the United States have reconstructed engineering curriculum systems with design as the main line. For example, the University of Utah has set a "spiral" introduction to engineering courses for freshmen [35], there has been the construction of integrated design courses in the Mechanical Engineering Department of MIT [14], and Purdue University has integrated engineering design into undergraduate and postgraduate education [36]. In China, Professor Gu Peihua, an academic from the Canadian Academy of Engineering, introduced the CDIO engineering learning mode in 2005 and explored and implemented it at Shantou University [37]. Later, the global CDIO initiative cooperation alliance successively attracted Shantou University, Tsinghua University, Yanshan University, Chengdu University of Information Technology, and other universities to join, and successively formed an innovative engineering education model based on the CDIO represented by Shantou University. Since then, many colleges and universities in China have also promoted design-oriented engineering education reform. For example, Xi'an Jiaotong University has set up a basic general core course named "Innovative Thinking and Robot Maker Practice" with design thinking as the main line [38], Chongqing University has carried out a curriculum teaching innovation design based on the BOPPPS teaching mode [39], and Shanghai Jiao Tong University offers the course "Innovative Thinking and Modern Design" based on Kolb's experiential learning cycle theory [40].

Although design-based engineering learning has demonstrated some achievements, the research on design-based engineering learning is still in the stage of connotation exploration, and the question "what are the core characteristics of design-based engineering learning?" has not been well answered. Therefore, the research question to be solved in this study is as follows: what are the core characteristics of design-based engineering learning, and how can the students' learning process be dynamically deduced? In addition, among the three necessary steps of engineering training (engineering knowledge learning, engineering practical experience, and engineering professional training), engineering learning is the study of engineering-related theoretical knowledge, which mainly takes place in undergraduate education [41]. Therefore, in order to solve the above problems, this study longitudinally tracked typical undergraduate engineering education cases, hoping to build a design-based engineering learning feature model, which is of great significance for promoting the construction of sustainable development engineering education theory and practice system.

2. Research Methods and Data Collection

2.1. Grounded Theory

Grounded theory is a type of research method that draws theories from experience from the bottom up, constantly summarizes, compares, connects, and concentrates the collected empirical data, and finally forms theories [42,43]. This study adopted the grounded theory method and collected research data through in-depth interviews and the observation of research objects. Then, the collected research data were coded and analyzed to determine the characteristics of design-based engineering learning and dynamically deduce the design-based engineering learning process model. As an inductive method, grounded theory needs to relate everyday facts and phenomena to theoretical explanations and interpretations, achieving the ability to understand observational relationships and to dynamically explain reality. It focuses on gaining knowledge about the processes behind complex phenomena from qualitative data [44]. The grounded theory combines the flexibility and pragmatism of qualitative methods [45,46]. After 1967, as many authors developed different perspectives [47], the method evolved into different versions, with different terminology and implementation paths. Currently, there are three approaches to grounded theory: inductive framework, interpretive framework, and constructivism framework [48]. In this study, we follow an interpretive framework.

Since the grounded theory was proposed, the academic circle has had a lot of discussion on its research process, among which the "programmed grounded theory" gradually developed around three-level coding and has been widely applied due to its clear process and easy operation [43,49,50]. In this study, we selected "programmed grounded theory" and followed the research process of "defining object–literature discussion–data collection and analysis–establishing preliminary theory–testing theoretical saturation–constructing theory". Using the "open coding–axial coding–selective coding" coding process, the category was gradually abstracted through the analysis of materials, and finally, the core relationship was established to achieve the theoretical construction (see Figure 1) [51].

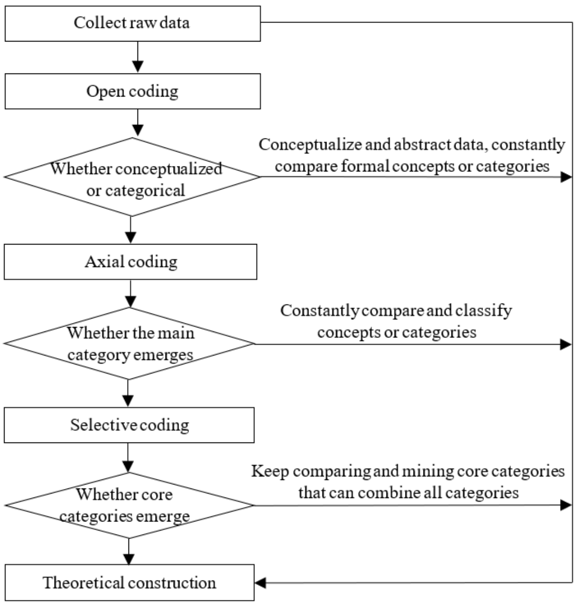

Figure 1. The thinking framework of grounded theory research.

Open coding refers to the process of coding the initial material sentence by sentence, continuously clustering and integrating the key information of the content, and gradually abstracting to form the "conceptual category". The principal axis coding is a process of induction and correlation of related concepts based on open coding, so as to form the "main category". Selective coding is to sort out the relationship and abstract the theory of the spindle coding results and finally form a clear storyline. In the process of operation, we used the software NVivo 12 as the coding tool. NVivo is the most mainstream analysis tool for qualitative research; it supports qualitative research methods and mixed methods. It can collect, organize and analyze interviews, focus group discussions, questionnaires, audio, etc. It is very suitable for analyzing the interview materials for this paper. Through the functions of open coding, node coding, relationship coding, reliability, and validity testing, etc., open coding (through NVivo 12 open coding and node coding) and spindle coding (through relationship coding in NVivo 12) in the research process of the rooted theory were realized. Combined with the literature, actual interviews, and other processes, open coding and spindle coding were constantly abstracted and refined to achieve selective coding and the construction of the final theory.

2.2. Purposeful Sampling

This study adopted purposeful sampling and selected the advanced engineering education class of the Chu Kochen Honors College of Zhejiang University as the tracking case. This class is a pilot reform of engineering education at Zhejiang University. Every year, 40 students are selected from the engineering students in the second semester of the freshman year to prepare separate classes and carry out two-year engineering design courses, aiming at cultivating high-level interdisciplinary talent with innovative abilities. This study conducted in-depth interviews with students and teachers who participated in engineering high school classes and obtained first-hand data. The sample of students included sophomores and juniors who had participated in engineering high school programs, and the sample of teachers included frontline teachers and teaching managers who had participated in engineering high school classes for a long time. Among them, the sample teachers had at least two semesters of engineering design teaching experience and had been unanimously recognized by students and peers in engineering design teaching. Based on this criterion, 20 interviewees were selected, including 7 teachers and 13 students (see Table 1).

Table 1. Basic information table of interview samples.

Basic Information	Characteristics	Teacher	Student	Total
Gender	Male	4	8	12
	Female	3	5	8
Grade	Sophomore year	/	9	9
	Junior year	/	4	4
Number of years of teaching or participating in DBEL	One year	/	9	9
	Two years	/	4	4
	Over two years	7	/	7
Total number		7	13	20

2.3. Interview Design and Implementation

Focusing on the "core characteristics and functional process of design-based engineering learning", the interview outline (see Appendices A and B for the interview outline) was studied and prepared. A semi-structured interview method was adopted, with face-to-face interviews as the main method and telephone interviews as the auxiliary method. Through face-to-face and telephone interviews, 1140 min of interview recordings were obtained. The recording time of teachers' and students' interviews was 431 min and 709 min, respectively. The content of the interviews was transformed into text through "IFLYREC". After collation and modification by two researchers, about 230,000 words of interview manuscripts were finally formed, including 59,000 words for teachers and 172,000 words for students. This laid the foundation for the coding and analysis of the follow-up interview text. In the study, the interviewees were coded as T01–T07 for teachers and S01–S13 for students. See Appendix A for the outline of the teacher interview and Appendix B for the outline of the student interview.

3. Data Coding and Analysis

In this study, qualitative text content analysis and keyword clustering induction methods were used, and NVivo software, a qualitative text analysis tool, was used as the research tool to complete the content analysis of research literature by using its text coding, data visualization, clustering comparison, and other functions. There are two common coding methods: one is to determine the coding node according to the research topic and form a research framework, which is called deductive coding; the second is to code the original text first and integrate it after generating multiple subnodes, that is, inductive coding. In terms of practical operation technology, the layered coding method was adopted, which was divided into three stages: open coding (first-level coding), node coding (second-level coding), and relationship coding (third-level coding) (see Figure 2).

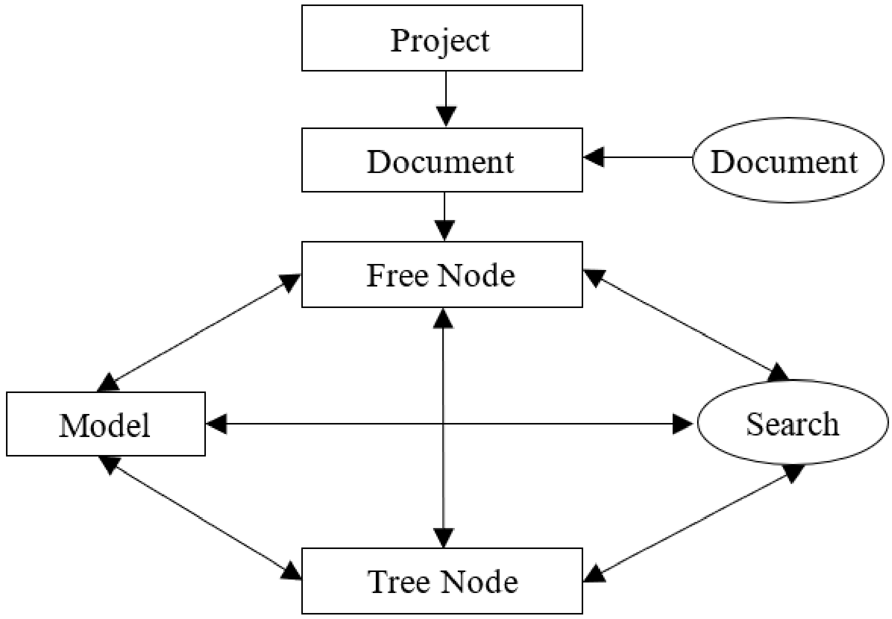

Figure 2. The coding process of NVivo12.

3.1. Open Coding

Using three methods of "line by line coding", "sentence by sentence coding", and "paragraph by paragraph coding", through the process of refining, induction, and comparison, all 20 samples of text were "labeled", 271 initial tags were extracted, and then 271 initial tags were filtered, combined, and classified to form 76 "initial concepts". An example of open coding is shown in Table 2.

Table 2. Examples of DBEL open coding.

Sample Source Data		Initial Concept
S2: I think it's important that you know what to do and what the details are during the design process. Hands-on skills are acquired, and trial and error are crucial.	T3: During the design process, I will give feedback to students as soon as possible to help them adjust and iterate.	aa10 Students' hands-on practice aa67 Trial and error
S9: I like to participate in design projects. Doing projects gives me a sense of accomplishment. When I finish a project, I feel very happy because I can learn a lot.	T6: Our analog integrated circuit and robotics courses are usually held in the first or second year of junior year. At this stage, students have a lot of practical design content, which is relatively difficult.	aa3 Design project
S10: Whenever I have a problem in the learning process, I want to solve it, no matter what the problem is or what the teacher said in class. No matter how many times I try and make mistakes, if I can't solve them, I will keep thinking until I solve them.	T6: The design process is to iterate through the whole process to stimulate students to consider some underlying practical engineering problems.	aa67 Trial and error aa74 The problem is rectified
S12: Making plans with classmates can deepen my impression. When you can explain the whole scheme in its entirety, you will understand the problem very well; If I don't know how to do it, at this time, other students may come to tell me their thoughts and ideas, which can also help me understand what I didn't understand before. This process is very effective.	T1: Engineering students should not only have the professional ability but also have the spirit of teamwork. Integration and innovation are very important for engineering students, and these things need students to practice daily communication and cooperation.	aa41 Student exchange and cooperation

3.2. Axial Coding

In order to further form the main category and subcategory, main axis coding (secondary coding) was carried out in this study, as shown in Table 3. Spindle coding is a more abstract concept, which requires a profound distinction between the relationships and meanings between concepts and categories, thus forming multiple dimensions of the theory. We further abstracted 76 "initial concepts" and finally formed 28 "initial categories", such as real engineering problems, real project content, and challenging tasks. Then, the "initial categories" were classified into 12 "subcategories", and finally, the "subcategories" were further classified and merged into 4 core categories.

Table 3. Axial coding results.

Core Category	Subcategory	Initial Category	Dimension
Design Practice	Challenging task	Real engineering problems, real project content, challenging tasks	Suitable–Not suitable
	Hands-on practice	Students do hands-on experiments; students make the finished product by hand	Attention–Neglect
	Scheme design	Student participation in program design; students use design methods	Suitable–Not suitable
Interactive Reflection	Peer interaction	Group negotiation, class discussion, group cooperation	Abundant–Deficient
	Teacher–student interaction	Teachers interact with students; the teacher gives guidance to the students	Abundant–Deficient
	Social interaction	Physical interaction in the external environment; school–enterprise interaction in foreign cooperation	Abundant–Deficient
Knowledge Integration	Information recognition	Students understand information; students identify external knowledge	Sufficient–Insufficient
	Knowledge correlation	Students identify deficiencies in the design process; students promote knowledge understanding; students relate and integrate knowledge points	Sufficient–Insufficient
	Opinion generation	Students extract knowledge elements; students generate relevant opinions; students consolidate relevant knowledge	Sufficient–Insufficient
Circular Iteration	Trial and error	Students try and make mistakes along the way	Strong–Weak
	Scheme iteration	Redesign based on trial and error results; participate in many design cycles and design scheme iterations	Strong–Weak
	Result from perfection	Students constantly improve the design products; implement the new learning plan according to the adjustment plan	Strong–Weak

3.3. Selective Coding

In the coding process, we constantly consulted the original data and literature, classified and divided the contents of open coding and spindle coding, and then linked the core categories together according to the storyline and used theoretical analysis to condense them into four axis codes, namely design practice, interactive reflection, knowledge integration, and cyclic iteration. Finally, a "storyline" that runs through all materials, categories, and relationships was constructed. Engineering learning based on design emphasizes process rather than results, which is essentially a closed-loop learning mode; that is, engineering students take design practice as a starting point, observe, think from different perspectives, and incorporate them into their own logical system, so as to gain new experiences through constant trial and error and concept transformation. In design-based engineering learning, learners conduct design inquiry based on design projects, further promote learners' self-reflection and development through "interaction" with other learners, teachers, or experts, and finally, obtain systematic knowledge in inquiry action and cycle iteration to achieve knowledge construction. Figure 3 shows the process.

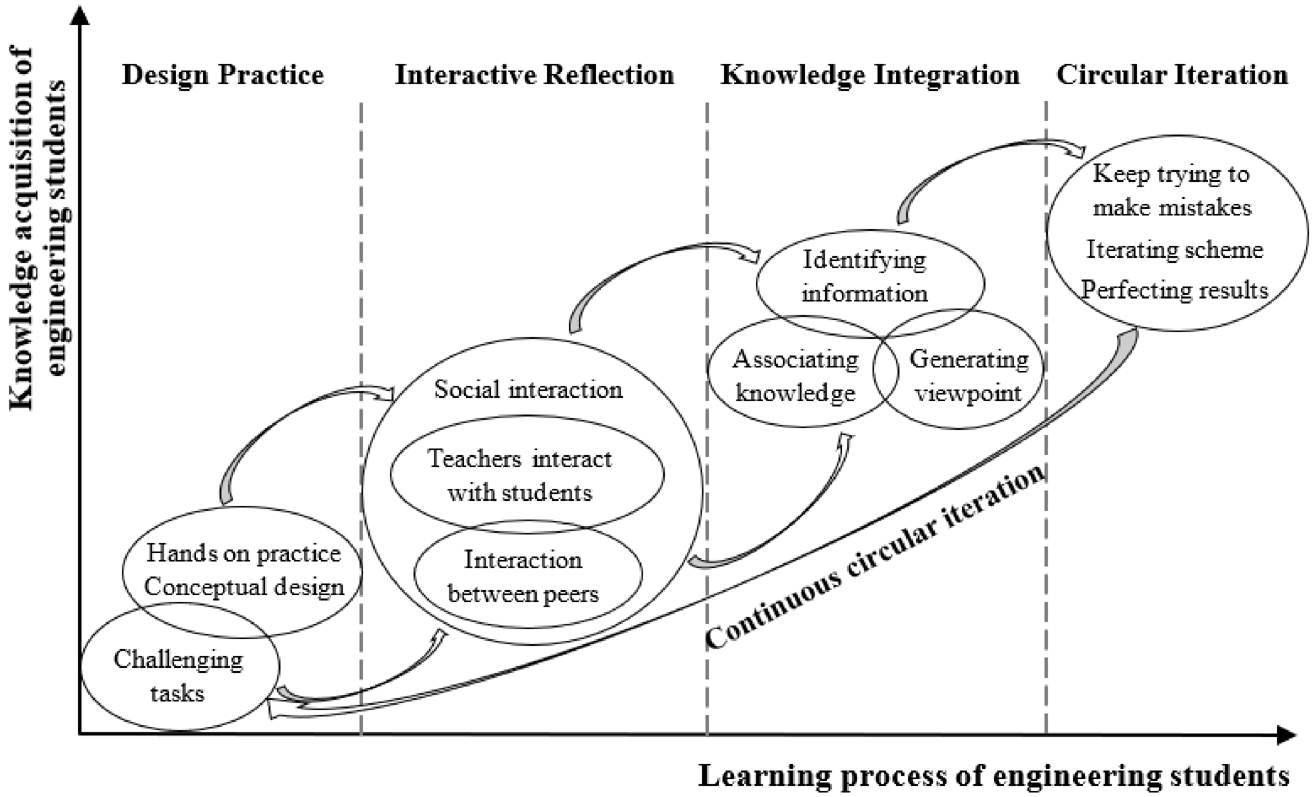

Figure 3. The multidimensional feature model of design-based engineering learning.

3.4. Test of Theoretical Saturation

A theoretical saturation test is a key step to verify whether the interview information is saturated [43]. When new data do not add meaningful contributions to the theory being developed, and no new categories appear [52], it is determined that saturation has been reached. Generally, most of the code can be built and data-saturated in the first 15 interviews [53–56]. In this study, we used the random sampling method to recode the contents of three coded interview materials and found that no new classification concept was formed. In other words, the new document was covered by the previous 43 "initial concepts", proving that it had basically reached theoretical saturation [57]. In addition, NVivo's "coding comparison" function [58] was used in this study to sample the text materials independently coded by two researchers, and the "code consistency percentage" was used to measure the objectivity of the coding. It was concluded that the consistency of 20 original materials in the four dimensions was more than 82.33%, thus ensuring the reliability and validity of the data analysis.

4. Results and Discussion

Through grounded research, this paper refines the multidimensional characteristics of design-based engineering learning and explains the relationship between the four characteristics. In order to further explore learners' understanding and feelings in design-based engineering learning, interview minutes and interview materials of 20 learners were analyzed in detail, and node contents of NVivo were read through the node coding query function of NVivo12. The keywords and key texts in the reference points of design practice, interactive reflection, knowledge integration, and cyclic iteration were analyzed successively.

4.1. Design Practice

Through careful reading and analysis of the node content of the learners' design practice category, it was found that the characteristics of the learners' design practice were mainly manifested as design tasks, process optimization, hands-on practice, etc. (see Figure 4).

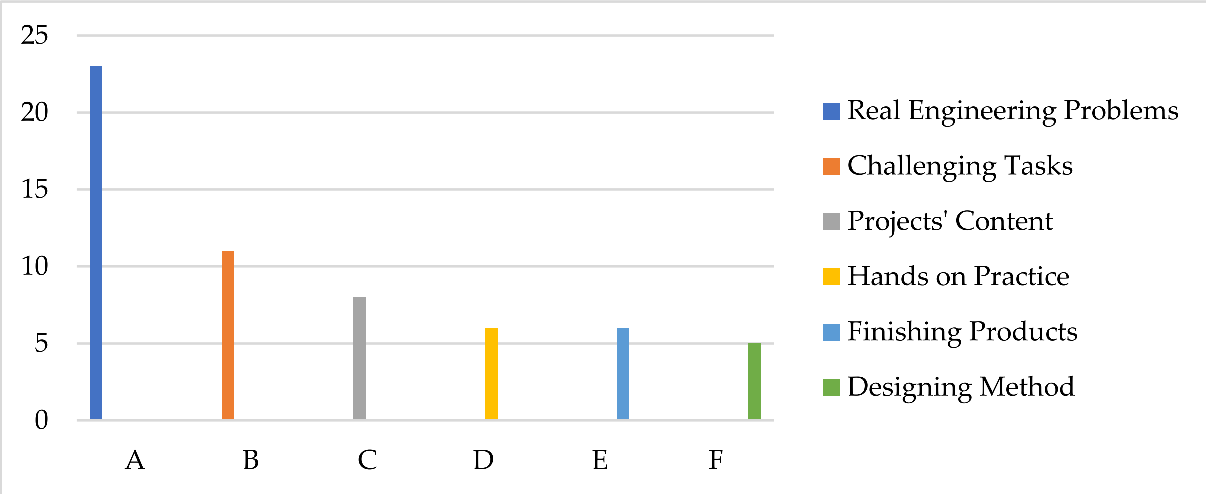

Figure 4. Statistics and analysis of the number of coding nodes in design practice (top 6).

Design practice is an exploratory activity carried out by students around the design situation. It is based on scientific principles or theories, aiming to conceive and implement some practical new products, and the final result is to produce innovative methods to solve problems. The connotation of design practice mainly includes the following aspects: The first is challenging tasks. Learners' learning often requires the support of the environment. In design-based engineering learning, this environment takes the form of challenging and specific engineering design tasks, which can introduce students to the real engineering environment. The second is scheme design. Scheme design is an important way for learners to complete challenging tasks. Learners make use of multidisciplinary knowledge to design, organically integrate learning content with hands-on practice, realize the true meaning of learning, and gradually move from "passive acceptance" to "active exploration". The third is hands-on practice. Engineering learning needs practical "people", who are living individuals with initiative and creativity, rather than machines with only "pure theory". The practicability of the learning subject in the design context is related to the effectiveness of the whole learning process, which reflects the construction of the learning process with "behavior" as the link and "situation" as the bridge.

In interviews, students and teachers clearly expressed the importance of design practice in improving engineering learning outcomes:

> *Sometimes the teacher tells me a lot of things, and I listen to the fog, then forget. However, for a specific example in the course, if I do it by hand, I will be deeply impressed after the experience, and then I will know how to go further after I find the problem, so practice is very important. (S3)*

> *Engineering design is biased towards practice. Through the design scheme and physical model, I fully practice the engineering knowledge I have learned. (S7)*

> *For engineering students, practical ability should be the most basic. It is very effective to cultivate students' practical ability in design-related practical projects, which can help students simulate the engineering environment. (T03)*

> *Our philosophy is that students in the lower grades should be exposed to robots early. Students will understand the difficult points, key points, and core points of robots in practice. When students have a basic understanding of the whole knowledge point, and*

then go back to learning machinery, computers, and other related courses, students will know how to combine relevant knowledge to solve engineering problems. (T07)

4.2. Interactive Reflection

It was found that learners' interactive reflection features mainly include group cooperation, peer learning, communication, and discussion. In order to further explore the characteristics of learners' interactive reflection in design-based engineering learning, the number of reference points in learners' interactive reflection was obtained (see Figure 5).

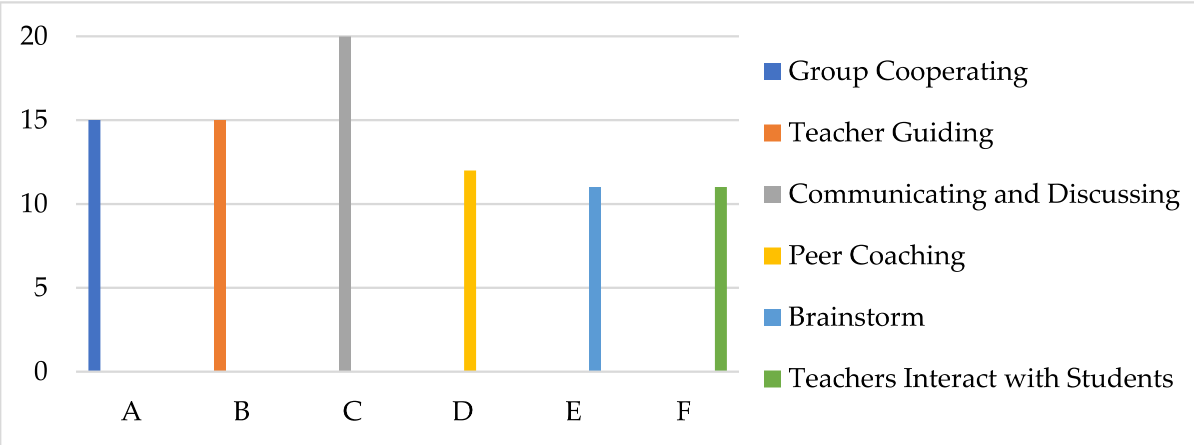

Figure 5. Statistics and analysis of the number of coding nodes in interactive reflection (top 6).

Although many scholars have recognized the role of "reflection" in learning, they all regard reflection as an individual's spontaneous behavior and fail to consider how external stimuli affect the individual's thinking and how reflection affects the behavior of those studied. Through the above coding analysis and theoretical analysis, we know that "design task" and "community interaction" are important forms of design-based engineering learning. The "design task" puts learners into a thinking deadlock where they cannot find a solution to real engineering problems. In this state, individuals' cognitive input and learning efficiency will be very high. At this stage, interactive reflection helps students have an epiphany.

The interaction of design-based engineering learning is mainly manifested in three ways: The first is the interaction between students and students. Discussion and communication among students are effective ways for students to carry out design-based engineering learning, and their own experience is also an important learning context for design-based engineering learning. Design-based engineering learning should make full use of learning resources among students, carry out cooperative learning, and establish a community. In this "community" learning environment, the student's learning process is influenced by teachers' guidance and evaluation, and students' cooperation and sharing. The second is teacher–student interaction. Teacher–student interaction is the interaction between students, teachers, and teaching content. Teachers and students will have a different understanding of the same course content, and they can help improve students' knowledge acquisition and problem-solving abilities by expressing and discussing different viewpoints. This can also further strengthen the emotional communication between teachers and students so that students can obtain positive emotional experiences in the learning process. The third is social interaction. Students are brought together by design activities, and they make full use of engineering drawings and the physical environment of engineering materials in the design process to form a situation of social interaction.

Students can deeply feel the atmosphere of group cooperation in the process of learning. Teachers and students recorded their thoughts on design-based engineering learning in a journal.

> *The process of completing the design task usually involves the cooperation of students from multiple majors. Students from different majors will be responsible for different modules. In the process of task docking, there must be a lot of work in communication and connection, and interaction is very common. (S9)*

> *The biggest goal of group cooperation is to obtain more satisfactory results after constantly revising the program! (S13)*

> *We don't care about the form of classroom teaching but focus on the content and effect of the lecture, which is the most fundamental. The reality is that students are more likely to take the initiative to learn, be inspired, and gain from cooperation. I think teamwork is very effective. (T05)*

4.3. Knowledge Integration

It was found that learners' knowledge integration features mainly included knowledge application, association integration, and association consolidation. In order to further explore the characteristics of learners' knowledge integration in design-based engineering learning, the number of reference points in learners' knowledge integration was obtained through research and analysis (see Figure 6).

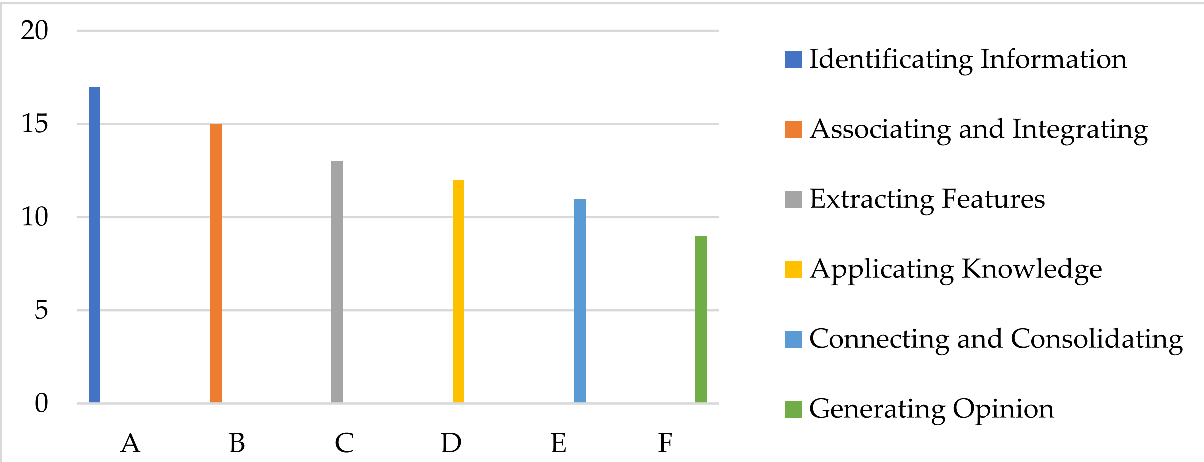

Figure 6. Statistics and analysis of the number of coding nodes in knowledge integration (top 6).

The purpose of design-based engineering learning is to help learners identify real engineering problems and apply knowledge to solve them. The knowledge integration stage is an important stage to promote learners' learning and produce behavioral changes. In this stage, students can not only extract feasible ideas but also combine these ideas with what they have learned and make plans for the next step with new actions, thus promoting changes in their behavior patterns. Therefore, design-based engineering learning has strong interdisciplinarity, and its interdisciplinary integration is equally important to engineering design. Knowledge integration in design-based engineering learning is mainly manifested in the following two ways: The first is knowledge association and integration. Design-based engineering learning is complex and integrated, and students need to fully integrate engineering-related knowledge. The second is the integration of process and result. Design-based engineering learning is not a single static process, but a comprehensive dynamic learning process that advocates learning for the purpose of problem-solving and cultivates a series of high-level abilities of learners.

The teachers and students in the interview reflected on the integration and application of knowledge:

> *I was deeply impressed when I finished the big design assignment. One of my classmates directly made a small program of an artificial intelligence volleyball team, in which two volleyball teams designed by him could play together. This program requires a lot of*

knowledge, and I admire it. It seems that to make a great thing, one must have strong knowledge integration ability, this requirement is very high. (S1)

I think knowledge integration is crucial in the realization of engineering design. The design process is not monolithic, but multidisciplinary, and you need to constantly evaluate how students are applying their knowledge, and provide appropriate guidance based on feedback. (T3)

4.4. Circular Iteration

It was found that learners' cyclic and iterative characteristics mainly showed continuous trial and error, scheme adjustment, correlation integration, and so on. In order to further explore the characteristics of learners' cyclic iteration in design-based engineering learning, the number of reference points in learners' cyclic iteration was obtained through research and analysis (see Figure 7).

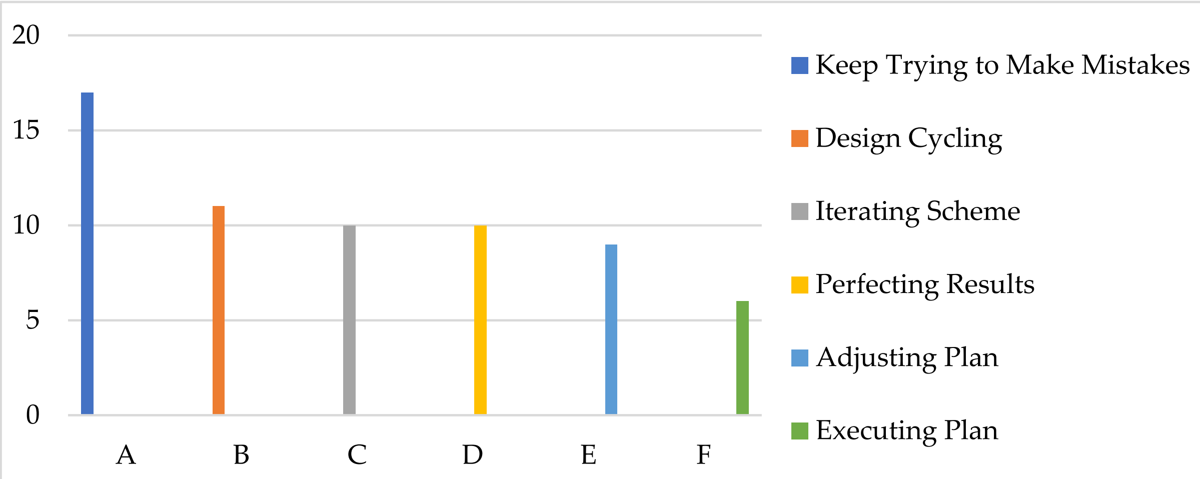

Figure 7. Statistics and analysis of the number of coding nodes in circular iteration (top 6).

The core of engineering is design, and the key to design is iteration. In design-based engineering learning, learners need to constantly try and make mistakes, take active actions, diagnose and debug the information generated by actions, and thus promote their own deep learning. In this process, learners deduce possible interpretations (logical reasoning), anticipate some results (reasoning), or summarize (generalization) existing information from other information, which is exactly the learning process based on engineering problems.

On the whole, in the learning context of design-based engineering learning, the outside world constantly gives feedback on the learning process of students, and students constantly reflect on their own design methods and promote the absorption of implicit thinking by constantly clarifying the underlying thinking process, basic principles, and progress.

In the interview minutes, there were more than 30 descriptions of timely feedback from the course teachers, teaching assistants, and peers, such as the following:

Engineering and design is a process of trial and error. Experience has taught me that trial and error have a cost. If I obtain results after some tries, then I will be happy. If I keep trying and making errors without finding a solution, I find the process very boring. (S7)

Sometimes I get caught up in self-inspired learner mode, where I've spent a lot of time but the feedback isn't satisfactory. There is definitely a problem with this process. You may think you have learned it, but you may not have understood it at all. At this time, we need to reflect on our own practice process and then communicate with classmates to understand the reasons, and finally establish a connection with the knowledge system, or apply it to practical problems. (S1)

Design-oriented curriculum teaching emphasizes a closed loop in teachers' instructional design before, during, and after class, as well as a self-cycle in students' individual learning. (T6)

4.5. Operational Definition

Based on the grounded theory, this paper proposes that design practice, interactive reflection, knowledge integration, and circular iteration should be dynamically deduced in the process of DBEL. Students can realize personal knowledge construction and professional ability improvement by connecting old experiences, engaging cognition, summarizing reflection, and other cognitive cycles. In the early coding, we identified key nodes of DBEL features, and we made operational definitions for each feature construct through detailed analysis of key behavior examples in the learning process of the interview cases, as shown in Table 4.

Table 4. Operational definition of DBEL feature constructs.

Characteristic Dimension	Operational Definition
Design Practice	Engineering students participate in real design projects and hands-on solutions to real engineering problems.
Interactive Reflection	Engineering students interact with people and products in the process of design practice and seek new perspectives to solve design problems.
Knowledge Integration	Engineering students receive external information, integrate internal knowledge, and transform knowledge and information into problem-solving strategies.
Circular Iteration	In the process of design, engineering students constantly apply trial and error, iterate, verify the design scheme, and finally, solve the problem.

When sorting the interview data, the researchers selected 67 coding units from the interview data that were in line with the characteristics of DBEL and expressed them in a relatively independent and complete form. The selected codes follow the classification exclusion principle, where each encoding unit has only one classification. If a particular coding unit is classified as "other characteristics", the reason should be stated. Finally, this study formed the feature coding table of each dimension shown in Table 5.

Table 5. Operational coding of DBEL feature constructs.

Characteristic Dimension	Operational Coding
Design Practice	Engineering students design experiments and optimize the design process and methods
	Engineering students learn through real projects and challenging assignments
	Engineering students carry out hands-on experiments and make finished products Engineering students apply technology and tools to design engineering problem solutions
Interactive Reflection	Engineering students integrate internal information to generate new ideas
	Engineering students identify external perspectives and integrate them
	Engineering students use multidisciplinary approaches and tools to solve engineering problems
	Engineering students integrate theoretical knowledge with practical experience

Table 5. *Cont.*

Characteristic Dimension	Operational Coding
Knowledge Integration	Engineering students participate in group cooperation and group negotiation
	Engineering students reflect on the learning process in collaboration
	Engineering students share and exchange ideas and generate new ideas
	Engineering students share solutions with their classmates
Circular iteration	Engineering students are constantly experimenting with trial and error, trying new solutions
	Engineering students identify the deficiencies in the design process and constantly improve and practice
	Engineering students seek the best solution to improve the learning effect

5. Conclusions

5.1. Theoretical Contributions

This study deconstructed the core features of design-based engineering learning through grounded theory, proposed a new concept of design-based engineering learning, and constructed a circular learning circle that integrates design practice, interactive reflection, knowledge integration, and circular iteration. It was found that design-based engineering learning is a new concept that starts with the process of seeking solutions to ill-structured problems in engineering learning under uncertain conditions. In essence, DBEL is a process in which engineering students constantly practice and construct the design task, thus promoting the continuous improvement of their professional ability. In this study, design-based engineering learning's operational definition and operational coding have laid a foundation for the subsequent measurement of DBEL and testing of DBEL learning effects. The exploration of feature conception in this study contributes to the theoretical development of design-based engineering learning and is of great significance for promoting the construction of higher engineering education system based on the concept of sustainable development.

5.2. Practical Enlightenment

This study provides practical enlightenment for engineering students to learn. Due to the lag effect of practical feedback, engineering students' personal behaviors in the learning process will have a certain degree of blindness. Most students' learning behaviors stay in a certain stage of learning, but cannot reach the cycle and iteration phase. The multidimensional characteristics proposed in this study provide methodological guidance for engineering students to participate in engineering learning. Based on this, on the one hand, engineering students can continuously accumulate relevant knowledge and ability through design practice and iterative attempts and constantly improve their ability to solve engineering problems. On the other hand, continuous reflection can broaden new horizons and optimize problem solutions through knowledge integration.

At present, the field of engineering education has begun to try to promote the deep integration of the sustainable development concept and engineering education through multidisciplinary integrated engineering project design. The situational nature of design-based engineering learning makes it possible to integrate cognitive skills and professional knowledge into specific situations. To carry out the study practice of design-based sustainable development engineering, firstly, an integrated knowledge framework containing professional knowledge and sustainable development content should be provided, and modular training should be implemented for engineering students to realize the visualization of knowledge content related to sustainable development. Secondly, specific problem scenarios should be provided; for example, civil engineering students could be provided with a study project on the construction of a hydropower station, and the students could be encouraged to consider various issues from a sustainable perspective during the project design process, including the biodiversity around the hydropower station, resident relocation, transportation, etc. Thirdly, it provides the “scaffolding” to understand and become familiar with the requirements of sustainable development engineering. Software simulation, video learning, and group communication are used to help students grasp the rich connotation of sustainable development engineering education and meet specific sustainable development goals in real engineering design and practical project operation. Finally, it examines engineering design activities from the perspective of constructivism, focuses on the process of establishing the connection between individuals and society with engineering knowledge of sustainable development, promotes the interaction between teachers and students in engineering design and engineering products, and promotes cooperative learning and open sharing in the process of design activities.

5.3. Limitations and Prospects

As an exploratory study, this study still has some shortcomings. For example, since the coding materials in this study are mainly interview records, supplemented by a small number of internal materials, the coverage of interviewees and the richness of primary data have limitations in the coding conclusions. In view of this, future research needs to expand the scope and number of interviewees, and further improve the interview outline in multiple rounds of interviews, so that the research can show the implementation of design-based engineering learning to the greatest extent and scope. Future studies need to further explore the influence mechanism of different dimensions on engineering students’ learning performance.

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Appendix A

Semi-structured interview questions for the teachers:

(1) What do you think is the position of design-based engineering learning in engineering education?
(2) From your teaching and management experience, what principles should be followed in the implementation of design-based engineering teaching, and what kind of learning environment should be created?
(3) Based on your teaching and management experience, can design-based engineering learning improve the learning outcomes of engineering students, and what is the key to improving their performance?

(4) According to your teaching and management experience, what difficulties have you encountered in teaching engineering design courses? How was it solved?
(5) What are the key elements to the success of design-based engineering learning besides the efforts of teachers?
(6) What do you think is the development stage of design-based engineering learning in China compared with foreign countries? What foreign countries are worth our learning and referencing?
(7) What are your suggestions for the development of design-based engineering learning in China?
(8) How does the Teaching Steering Committee of Chinese colleges and universities promote the development of design-based engineering learning?

Appendix B

Semi-structured interview questions for the students:

(1) Have you ever participated in design-based engineering studies during your four years at university?
(2) Can you introduce the situation of the learning project that you participated in (participation mode and period, course content, teaching method, organization method, the evaluation method of student learning outcomes, etc.)?
(3) What do you think are the main points and characteristics of design-based engineering learning? Can you describe your learning process, the key stages and key events in your learning of design-based engineering?
(4) What problems and challenges have you experienced in the learning process? How did you solve it? Could you share with me in detail the process of solving this problem?
(5) How did you communicate with team members during the learning process of design-based engineering? What benefited most from communication with team members?
(6) Do you think the practice of design-based engineering learning in your current major can meet your needs for employment or further study in the future? If not, what are the problems? How can it be improved?
(7) Are you satisfied with the supply of various teaching resources and organizational management provided by colleges and universities? If not, what are your suggestions?

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