A Study of the Implementation Effectiveness of the CDIO Education Model

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Abstract: The CDIO education model is the latest achievement in the reform of international engineering education in recent years. China introduced the model and initiated pilot implementation in late 2005. After more than ten years of investigation and practical experience, the higher education institutions that participated have developed and consolidated their own training characteristics. Through the analysis of the evaluation standards for engineering personnel as well as elements of the CDIO curriculum, this paper employed the catastrophe evaluation method to constructs the evaluation index system, and to assess the effectiveness of the CDIO engineering education model at the university.

1 INTRODUCTION

The conceive-design-implement-operate (CDIO) engineering education model was initiated by a multinational research team comprising members from the Massachusetts Institute of Technology (MIT) and several Swedish universities. It focuses on providing students with a realistic engineering setting that embodies the entire life cycle of a product, from conceptual design to operational implementation and even maintenance. This allows students to study engineering in a proactive and hands-on way, through courses that are organically connected, thereby enabling them to develop into engineers capable of solving practical engineering problems in today's complex environment[1-2]. In late 2005, Shantou University was the first Chinese institution that introduced this model to pilotimplementation in five departments of its College of Engineering. In April 2008, a study group, established by Department of Higher Education of China's Ministry of Education, dedicated to develop the research and practice related to the CDIO engineering education model[3]. These two steps pronounce the construction of CDIO, which highlight the best of talent cultivation in engineering colleges.

Although researchers consistently have investigating the theory of CDIO, the deployment of this model is not scaled and the implementation is beyond the college capacities. The investigation of working principle of CDIO is the foundation of application, which exploits the best of both by defining engineering education strategies. The focus on the study of CDIO principles in recent years has called for corresponding support research in this field. Effectiveness evaluation is one such field , with technical approaches exploring the potential of CDIO for engineering education. Thus, in this study, graduates of the mechanical departments of YS University were selected as participants. The Catastrophe Evaluation Method (CEM) was adopted to comprehensively evaluate and verify the effectiveness of the CDIO engineering education model through empirical research. The paper is arranged as follows. Section 2 introduces the basic principle of catastrophe evaluation method. Section 3 presents a general overview of system for indicator evaluation. Methodology of data collection as well as the sample preprocessing approach is depicted in section 4. Section 5 provides a modeling based on the theory of CEM to examine the CDIO application and the testing outcome is given. Section 6 shows the discussion, conclusion and future steps to be taken.

2 CATASTROPHE EVALUATION METHOD

2.1 Fundamental Concept

Learning is a highly complex psychological activity. The evaluation of students' learning effectiveness is inevitably provisional and largely depending on the subjective experience as well as the specific evaluation criteria. CEM(Catastrophe theory evaluation method) is a comprehensive evaluation method developed on the basis of catastrophe theory. Traditional evaluation process considers merely the relative importance of evaluation indices without assigning weights to other parts.CEM can effectively avoid errors in artificially determining weights on quantitative evaluation. Therefore, the evaluation results reduce subjectivity without limiting overall robustness and are calculated in a simple and convenient way[4-7]. This study adopted CEM to assess each student's achievement of the expected learning.

CEM is an evaluation method considering the purpose of an evaluation system, which constructs the evaluation index system and breaks down its contradictions in a multi-level manner consistent with the mechanism of the system itself. The overall indicator is gradually broken down into sub-indicators, and the target units are presented as an inverted tree. By determining the grade of the underlying evaluation index,and the state variable is normalized using the catastrophe fuzzy subordinate function. Hereafter, the decision-making outcome is evaluated[8-10].

2.2 Evaluation Method

The common catastrophe models contain the fold, cusp, swallowtail, and butterfly catastrophe systems. We employ the swallowtail and butterfly catastrophe systems in this paper. Swallowtail catastrophe is utilized for the condition of three control variables while butterfly catastrophe for four. A potential function f(x) can be used to express the state variable x for each system[11-12].

The swallowtail catastrophe potential function is:

$$f(x) = \frac{1}{5}x^5 + \frac{1}{3}ax^3 + \frac{1}{2}bx^2 + cx \qquad (1)$$

The butterfly catastrophe potential function is:

$$f(x) = \frac{1}{6}x^6 + \frac{1}{4}ax^4 + \frac{1}{3}bx^3 + \frac{1}{2}cx^2 + dx \qquad (2)$$

The coefficients a, b, c, and d indicate the control variables of x.

The swallowtail catastrophe equilibrium surface could be obtained by a first derivative of f(x), Again, f^'(x) =0,thus:

The swallowtail catastrophe equilibrium surface was:

$$x^4 - ax^2 + bx + c = 0 \qquad (3)$$

The butterfly catastrophe equilibrium surface was:

$$x^5 + ax^3 + bx^2 + cx + d = 0 \qquad (4)$$

The singular point set of the equilibrium surface could be obtained by a second derivative of f(x), Again $f''(x) = 0$, eliminating the state variable x through simultaneous equations f^'(x) =0 and f^" (x) =0. Thus, a bifurcation equation of the catastrophe system is obtained.

The swallowtail catastrophe bifurcation equation was:

$$\begin{cases} a = -6x^2 \\ b = 8x^3 \\ c = -3x^4 \end{cases} \qquad (5)$$

The butterfly catastrophe bifurcation equation was:

$$\begin{cases} a = -10x^2 \\ b = 20x^3 \\ c = -15x^4 \\ d = 4x^5 \end{cases} \qquad (6)$$

The bifurcation equation showed that when the control variables satisfy this equation, a mutation occurs in the system and the effect of each control variable upon the mutation would be obtained[13-14].

A normalization equation was used to convert the different qualitative states of the control variables in the system into the same state and calculate different x values for each control variable of the same target. Normalization equation is the basic computing formula that using catastrophe theory to comprehensive analysis and evaluation system, It carries out quantized recursive operation for system, Therefore, the total catastrophe subordinate function, of the system characterized is obtained by the state characteristics of the system. Thus:

The swallowtail catastrophe normalization equation was:

$$\begin{cases} x_a = a^{\frac{1}{2}} \\ x_b = b^{\frac{1}{3}} \\ x_c = c^{\frac{1}{4}} \end{cases} \quad (7)$$

The butterfly catastrophe normalization equation was:

$$\begin{cases} x_a = a^{\frac{1}{2}} \\ x_b = b^{\frac{1}{3}} \\ x_c = c^{\frac{1}{4}} \\ x_d = d^{\frac{1}{5}} \end{cases} \quad (8)$$

According to the fuzzy decision theory, the complementary and non-complementary principles should be adopted during evaluation, which depend on the relationship between variables. The complementary principle is utilized when there is a certain relationship between the variables in the system where the state variable x takes the average value of the catastrophe level of each variable $(x_a, \dots x_n)(n \leq 4)$, then $x = (x_a + \cdots + x_n)/n$. In contrast, the non-complementary principle is for all the variables irreplaceable where the state variable x takes the minimum value of the catastrophe level of each variable$(x_a, \dots x_n)(n \leq 4)$. As such, the minimax criterion was applied.

3. CONSTRUCTING THE EVALUATION INDICATOR SYSTEM

The aim of the CDIO engineering education model is to nurture students in a modern, team-based environment, enabling them to become engineers who are proficient in applying CDIO in the context of complex and value-added engineering products, processes, and systems. The evaluation of implementation effectiveness was determined by all the relevant stakeholders in students' learning. In this study, we invite graduates, the direct recipients of education, to be participants. Thereby, their achievements of the expected learning are assessed in relation to the CDIO engineering education model by examining their personal development and professional abilities[15-18]. The main influencing factors determining the ability to achieve the expected effectiveness were confirmed by applying the evaluation standards for engineering personnel as well as elements of the CDIO curriculum. The main factors were broken down, one by one, into a number of indicators to build a hierarchical structure for the evaluation indicator system.

Based on the CDIO outline and on the relevant requirements of educational evaluation, the authors of this study divided the evaluation criteria into 4 two-level indexes from the four dimensions of "subject knowledge" "personal skills and attitudes" "non-technical skills""career competence and development " , then16 three-level evaluation indicators again.To ensure their validity, experts were consulted to assess the indicators in terms of substance and scope. In the first round, seven domestic experts who promoted the CDIO engineering education model were employed to evaluate the 16 indicators. After repeated consultation and deliberation, they finalized 14 evaluation indicators, which were included in the first draft of the questionnaire design, as shown below:

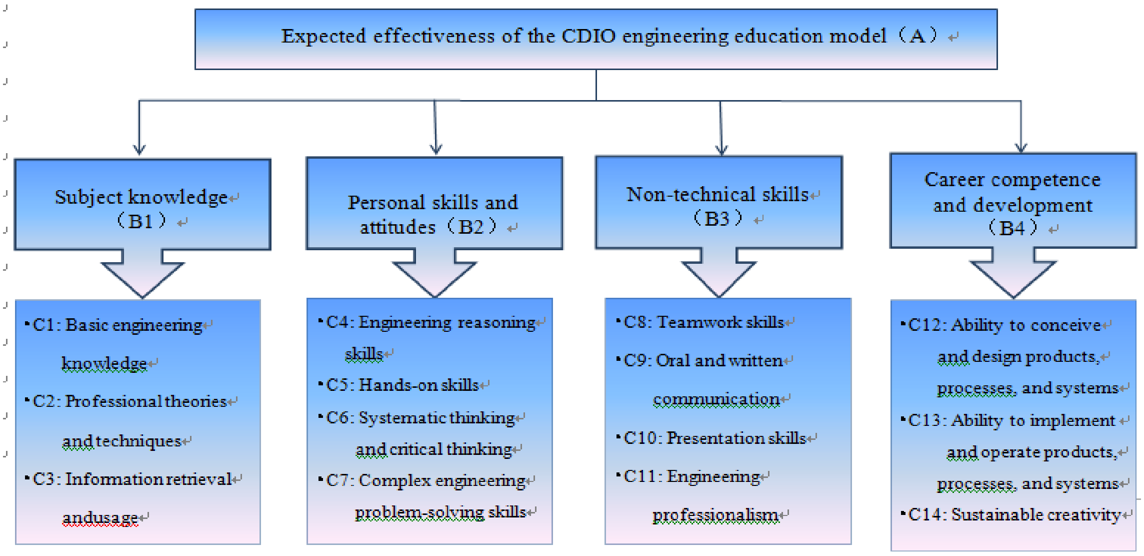

Figure1: Evaluation index system of the CDIO Education Model.

In the second round, 14 domestic experts with experience of implementing the CDIO engineering education model were invited to test the validity of the questionnaire and measure its representativeness using the content validity ratio.

Table1：Test of the content validity ratio.

	V-A	M-A	A	N-V-A	I	Average
content validity	6	4	3	1	0	8.14

Notes:

- V-A: Very Appropriate, A=10 points
- M-A: More Appropriate, B=8 points
- A: Appropriate,C= 6points
- N-A: Not Very Appropriate, D=4 points
- I: Inappropriate,F=0 points

The content validity of the indicators shown above ranged between 8.0 and 8.5, which demonstrates high content validity; the indicators selected for evaluating the effectiveness of the CDIO engineering education model, therefore, were appropriate. The state variable x represented the expected level of achievement when implementing the CDIO model. The evaluation range of the 14 indicators included five levels: very satisfied, satisfied, average, dissatisfied and very dissatisfied; whose respective values were 5, 4, 3, 2, and 1.

According to CEM, the overall evaluation indicator (A) is at the top of the evaluation system for the achievement of expected learning in the CDIO engineering education model. The middle layer presents a butterfly catastrophe, with indicators (B1), (B2), (B3), and (B4) corresponding to the control variables x_{B1}, x_{B2}, x_{B3}, x_{B4}; of the catastrophe system. The catastrophe systems displayed from left to right are as follows: swallowtail, butterfly, swallowtail, and butterfly. Evaluation indicators 1, 2 and 3 are related to “subject knowledge” and correspond to the control variables x_{C1}, x_{C2}, x_{C3} of the catastrophe system. Evaluation indicators 4, 5, 6 and 7 are related to “personal skills and attitudes” and correspond to the control variables x_{C4}, x_{C5}, x_{C6}, x_{C7} of the catastrophe system. Evaluation indicators 8, 9 and 10 are related to “non-technical skills” and correspond to the control variables x_{C8}, x_{C9}, x_{C10} of the catastrophe system. Evaluation indicators 11, 12, 13 and 14 are related to “career competence and development” and correspond to the control variables x_{C11}, x_{C12}, x_{C13}, x_{C14} of the catastrophe system. As the study evaluated the achievement of the expected effectiveness of the CDIO model, the complementary principle applied to each catastrophe model.

4. DATA SOURCES AND SAMPLE DESCRIPTIONS

The participants in this study graduated from YS University between 2011 and 2017. During their studies, they were taught using a “project-based” model based on the concept of CDIO. For the survey, a total of 328 questionnaires were sent out, of which 250 were returned, and valid questionnaires 248.The data is composed as follows:

Table2: Questionnaire statistics.

year	2011	2012	2013	2014	2015	2016	2017	total
number	36	36	37	38	36	34	31	248

4.1 Data Reliability Test

This study adopted the Cronbach's α reliability coefficient for evaluation, using this formula[19]:

$$\alpha = \left(\frac{\mathrm{n}}{\mathrm{n}-1}\right) \times \left[1 - \frac{\sum \mathrm{S}_\mathrm{i}^2}{\mathrm{S}_0^2}\right] \tag{9}$$

where n is the total number of items in the scale, S_i^2 is the intra-item variance of the score of the ith item, and S_0^2 is the variance of the total score of all the items. The survey data into the formula (9), by calculation, this questionnaire's Cronbach's α=0.726, the "Subject knowledge" Cronbach's α=0.257, the "Personal skills and attitudes" Cronbach' s α=0.951, the "Non-technical skills" Cronbach's α=0.454, the "Career competence and development" Cronbach's α=0.342. The internal consistencies of the four dimensions of the questionnaire and the questionnaire as a whole were above 0.70, so meet the requirements of exploratory research.

4.2 Normalized Transformation

To obtain a better distribution of research data, a normalized transformation was performed on the original data by subtracting the minimum value from the original data of each variable and dividing by the range (the difference between the maximum and minimum value of each variable), using this formula[20-21]:

$$\tilde{x}_{i,j} = \frac{x_{i,j} - \min\limits_{1\le j\le n}(x_{i,j})}{\max\limits_{1\le j\le n}(x_{i,j}) - \min\limits_{1\le j\le n}(x_{i,j})} \tag{10}$$

where i is the number of indicators , i=1,2, ……, and j is the number of units, j=1,2, …….

In this paper, the normalization transformation is used to normalize the index system step by step. Because of the complexity of the calculation process, this paper only takes the evaluation data of the 2011 graduates as an example to show the deducing process of the implementation effectiveness CDIO education model evaluation. First, the original values of each indicator at the lowest level were processed using equation(10), the results are shown as table3:

Table3: The data of the 2011 graduates' evaluation of normalization transformation.

2011 graduates	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
	0.1736	0.2153	0.2222	0.0764	0.0694	0.0833	0.0625
	C8	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
	0.3264	0.0694	0.4028	0.1806	0.2292	0.5000	0.1875

After processing, the values were between 0 and 1. Next, the values were converted using formulas 2-7 and 2-8:

$$x_{\mathrm{B}1}:\ x_{C1} = \sqrt{0.1736} = 0.4167$$

$$x_{C2} = \sqrt[3]{0.2153} = 0.5594$$

$$x_{C3} = \sqrt[4]{0.2222} = 0.6866$$

$$x_{\mathrm{B}1} = \sqrt[4]{\frac{(x_{c1} + x_{c2} + x_{c3})}{3}} = \sqrt[4]{0.5675}$$
$$= 0.8680$$

According to the principle of complementarity:

$$x_A = \frac{(x_{B1} + x_{B2} + x_{B3} + x_{B4})}{4} = 0.8412$$

According to the same method, the evaluation data of the 2012-2017 graduates can also be calculated, as shown in table 4:

Table4:Evaluation index value and result.

Variable	x_{ij}	2011	2012	2013	2014	2015	2016	2017	Average
(B1)	x_{C1}	0.4167	0.5188	0.4905	0.5362	0.5570	0.5825	0.4859	0.5125
	x_{C2}	0.5994	0.5835	0.6095	0.6120	0.6300	0.6850	0.5504	0.6100
	x_{C3}	0.6866	0.7025	0.6969	0.6756	0.6277	0.7071	0.6756	0.6817
	x_{B1}	0.8680	0.8807	0.8797	0.8830	0.8819	0.9007	0.8691	0.8804
(B2)	x_{C4}	0.5257	0.5372	0.5400	0.5946	0.6094	0.5721	0.6105	0.5699
	x_{C5}	0.5865	0.5987	0.6108	0.6411	0.6243	0.6168	0.5611	0.6056
	x_{C6}	0.2886	0.2655	0.2915	0.3162	0.3474	0.3273	0.3118	0.3069
	x_{C7}	0.3969	0.4252	0.4481	0.4943	0.4694	0.5228	0.4367	0.4562
	x_{B2}	0.8522	0.8549	0.8608	0.8745	0.8749	0.8739	0.8635	0.8650
(B3)	x_{C8}	0.5713	0.5250	0.5408	0.5323	0.5334	0.5976	0.5271	0.5468
	x_{C9}	0.4109	0.4252	0.4395	0.5055	0.4694	0.4149	0.4807	0.4495
	x_{C10}	0.7967	0.7809	0.7981	0.7847	0.7615	0.8174	0.7967	0.7908
	x_{B3}	0.7700	0.7596	0.7699	0.7794	0.7669	0.7810	0.7756	0.7718
(B4)	x_{C11}	0.6519	0.7329	0.7201	0.7101	0.7190	0.7632	0.6971	0.7135
	x_{C12}	0.7448	0.7539	0.7367	0.7307	0.7235	0.7684	0.7207	0.7398
	x_{C13}	0.7071	0.6797	0.7007	0.6834	0.7134	0.6124	0.7635	0.6943
	x_{C14}	0.5724	0.6300	0.6339	0.6369	0.6371	0.7324	0.6057	0.6355
	x_{B4}	0.8746	0.8875	0.8870	0.8838	0.8872	0.8959	0.8865	0.8861
Result(A)	x_A	**0.8412**	**0.8457**	**0.8494**	**0.8552**	**0.8527**	**0.8629**	**0.8487**	**0.8508**

5. EVALUATION RESULTS VERIFY AND ANALYSIS

5.1 The Evaluation Result of Principal Component Analysis

CEM is used to evaluate the implementation effectiveness of the CDIO education model, whether this method is reliable or practical? Therefore, this paper uses the evaluation index system as shown in figure 1 and the evaluation data collected, using the method of principal components analysis(PCA) to verify this example. If the evaluation results of the two methods are consistent, then there is a reason to believe that the evaluation result of CME is true and effective, so it can avoids the chance of consistency of the evaluation results. PCA is a common method in multivariate statistical analysis, the calculation procedure is as follows:

First, suppose there are m evaluation objects and n evaluation indexes, and the scores of each principal component are calculated)：

$$F_{tk} = \sum_{i=1}^{n} \frac{y_{ti} x_{ik}}{\sqrt{\lambda_k}} \tag{11}$$

F_{tk} isthe value of the kth principal component about item the valuated object, y_{ti} isthe normalized value of the ith evaluating index about item the valuated object, x_{ik} is the load value of the k th principal component about item I th of evaluation, λ_k is the characteristic value of the kth principal component.

Second the proportion of the variance contribution of each principal component is the weight, the score of composite principal component of each evaluated object was calculated.

$$E_t = \sum_{k=1}^{s} R_k F_{tk} \tag{12}$$

E_t is the comprehensive score of the tth evaluated object, R_k is the weight of the score about the kth principal component, s is the number of principal components extracted(the number of principal components extracted is determined by the accumulated variance contribution rate of over 85%)[22-23].According to the above steps, evaluation of the implementation effect of education mode of CDIO project of 2011-2017 graduates, The results are shown in table5.

Table5:Evaluation result of PCA.

	2011	2012	2013	2014	2015	2016	2017
E_t	0.0764	0.0283	0.00099	0.01829	0.02811	0.11630	0.01450

5.2 Consistency Check of Two Evaluation Results

The consistency of the evaluation results of the mutation evaluation method and the principal component analysis method was tested by the Kendall cofactor test. The results are shown in table6.

Table6: Test result of Kendall.

	2011	2012	2013	2014	2015	2016	2017
Kendall Synergistic coefficient	0.408	0.367	0.361	0.217	0.255	0.335	0.332
Chi square value	190.96	186.29	249.06	172.24	96.15	61.03	77.64
Probability p value	0	0	0	0	0	0	0

It can be seen that the coefficients of Kendall's collaborative test for the evaluation results of the 7th graduates are all between 0-1, and the probability p all the 0.00. The evaluation results of the two methods are verified by the Kendall's, so the evaluation results of the two methods are statistically signify cant consistent.

The core of the CEM is to establish a recursive algorithm for the multi-objective and multi-level comprehensive evaluation problem by using the normalized formula deduce the bifurcation equation of the catastrophe theory. Its main advantage is that it avoids the concept of direct use of "weights" which are difficult to be determined and they are subjective. At the same time, because the normalized formula reflects the mechanism of the evaluation index to a certain extent, the catastrophe evaluation model can consider the importance of each evaluation index reasonably and quantitatively.

5.3 Evaluation Results Analysis

The learning process of the traditional teaching mode has been arranged by the predecessors according to the optimal structure, and the students only need to absorb and understand quickly. But the CDIO engineering education mode with "project" for the driver, around the "project" is completed, will be this major should master the fragmentation of knowledge and ability construction, it and the emphasis of the traditional teaching mode has great differences.

As the learning experience, knowledge base, reading exposure, cognitive level, academic skills, and practical abilities of each student are different, inconsistent effectiveness was achieved in the implementation of the CDIO engineering education model. The model emphasizes student-centered learning, requiring students to abandon the traditional model of passive reception and to embrace active participation in the learning process. The results showed that the overall evaluation of the students' achievement in relation to "subject knowledge" was high. Through implementing the CDIO model, students better understood or remembered abstract theories and concepts, and were able to apply their theoretical knowledge in practical engineering situations. They also formed new cognitive frameworks relating to professional learning in order to help strengthen their grasp of fundamental knowledge.

The evaluation of "personal skills and attitudes" focused on a comparison with traditional teaching methods, and addressed the limitations of the students' knowledge of engineering technology and methods in the context of multi-level, multi-area, and large-scale complex systems. The implementation of the CDIO education model made students realize that there are unpredictable challenges in learning and enhanced their individual capabilities and attitudes by repeatedly strengthening their skills of engineering reasoning, systematic thinking and critical thinking, practical hands-on training, and solving complex engineering problems. According to the graduates' feedback, the CDIO model achieved relatively good levels of effectiveness here.

The development of "non-technical skills" among students mainly depended on the "projects" offered during the implementation of the CDIO model. A "project" is a broad concept and an important factor worthy of further study. The specific content of a project can effectively stimulate enthusiasm for learning. During projects, factors such as team composition and the nature of the collaborative atmosphere among team members directly influenced the frequency and intensity of communication during the learning process, thereby directly affecting the students' development of non-technical skills. The graduates rated this area as average. This result will encourage schools to focus more on the selection of project content, team composition, and evaluation methods in order to achieve higher teaching effectiveness when the CDIO education model is implemented in the future.

"Career competence and development" focused on the training of the ideal qualities necessary for engineers. Limited teaching hours in institutions are a huge constraint on the facilitation of career development. The CDIO education model guides students to form product-oriented values that enable them to recognize the professional abilities of engineers in visual thinking, effective communication, social responsibility, and accountability during their autonomous practice of the CDIO model. This ensures that the students demonstrate greater creativity in their future engineering careers. The graduates rated this area as relatively good.

Based on the standards of classroom teaching effectiveness and on the characteristics of the CDIO education model, the overall evaluation was classified using five levels: excellent（$Result \geqslant 0.90$）, good（$0.80 \leqslant Result < 0.90$）, average（$0.70 \leqslant Result < 0.80$）, pass（$0.60 \leqslant Result < 0.70$） and fail（$Result < 0.60$）.So it can be seen that the evaluation of the graduates is good, indicating that the graduates have a higher recognition of the effect of the CDIO teaching model.

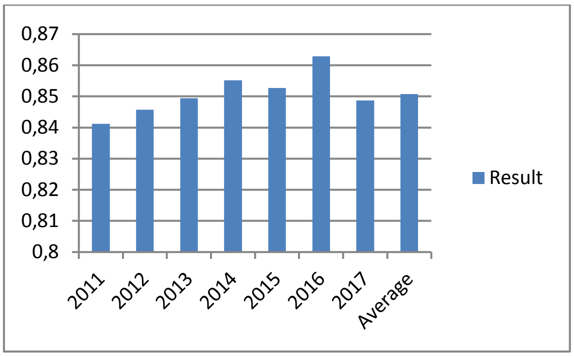

Figure2: 2011-2017 Bar graph of evaluation results.

Students can learn in the same major, and the group will not have the extreme ability difference. Compared with the results of the seven graduates, we can see that the overall trend of scores is getting higher and higher. As for the reasons for the low score of the 2017 graduates, the author once again communicated with the graduates and learned that the number of students in this class is more than that of the previous grade. As a local university with traditional engineering advantages, YS university is limited by practical difficulties such as shortage of resources for running schools.

Evaluation feedback from graduates has always been an effective means for higher education institutions to strengthen their relationships with corporations and society, to obtain external information, to reform personnel training models, and to improve the quality of the teaching they offer. By comparing the evaluation feedback of students who graduated in different years, we found that students who graduated earlier reflected more on their experiences and achievements under the CDIO model after their graduation. This shows that the CDIO education model has indeed established a solid professional foundation among students, allowing them to accumulate qualities and abilities that offer them more opportunities to perform well as engineers in their working lives.

There is no fixed standard for the implementation of the CDIO education model. Higher education institutions adopt their own appropriate methods of implementing the model to ensure that students continuously accumulate and practice innovation and teamwork, to ensure that they develop practical and analytical abilities, and to ensure that, during their participation, they gradually build up a scientist's pragmatic sense of judgment. The evaluation results from several cohorts of YS University graduates show that the CDIO model achieved results that were good or excellent. The students' awareness of, and satisfaction with, the CDIO engineering education philosophy were also high. In future, higher institutions should continue to review and improve the implementation of the CDIO education model and strive to achieve better expected results, ultimately promoting the model.

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