Engineering design process in STEM education: an illustration with the topic “wind energy engineers”

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Abstract. As STEM education has many strengths, it has been studied applied by numerous educational institutions around the world. Recently, STEM education has been paid more attention in Vietnam, but the design and organization of teaching STEM topics are still inconsistent, causing difficulties for teachers while teaching. The engineering design process (EDP) is a decision-making process, often repetitive, in which basic scientific, mathematical and technical concepts are applied to develop optimal solutions to meet the goals targeted. Among the basic elements of EDP are the development of objectives and criteria, synthesis, analysis, formulation, testing and evaluation. Teachers can easily apply EDP in classroom projects or activities, and it can also provide a way to develop new curricula. Applying EDP helps teachers improve their students’ problem-solving ability as well as introduce students to technical fields. With these characteristics, EDP can be applied in STEM education. Therefore, this study proposes the use of EDP in teaching STEM topics in Vietnam. The experiment was conducted at the Viet Bac High School - Thai Nguyen Province with the subject "Wind Energy Engineers" in teaching Physics for Grade 10th. By evaluating the performance of students’ tasks, consulting experts’ opinions on the teaching process that had been designed, and the initial results show that it is possible to use the engineering design process in STEM education in high schools.

I. Introduction

1.1. STEM education

STEM education has been interested in many countries, which can be considered as an important highlight in the innovation of teaching methods in recent years in many countries around the world [10]. STEM is a curriculum that is based on the idea that education should equip learners with the knowledge and skills related to science, technology, engineering and math - in an interdisciplinary approach so that the learners can apply them into solving daily problems. Instead of teaching four subjects separately and discretely, STEM education combines them into a coherent learning model based on practical applications [9]. STEM education brings many practical benefits not only for learners but also for their future society. Many studies have pointed out the benefits of STEM education such as: Increasing ability to solve practical problems, increasing creativeness for learners [18]; STEM education helps learners develop critical and creative thinking skills [12]; STEM education helps to connect theory with practice, increasing students' interest in learning [2]; STEM education helps learners increase their learning motivation as well as improve their learning outcomes [11]; STEM education helps learners be career-oriented, in which the interest in careers in STEM industry is higher [5]. STEM education has strengths such as: (1) STEM education is an integrated educational method based on interdisciplinary approach and through practice and application.
Thereby, students will both learn scientific knowledge and learn how to apply that knowledge into practice; (2) STEM education emphasizes the formation and development of problem solving ability for learners. In each STEM-themed lesson, students are given a situation with practical problems that need to be addressed with respect to scientific knowledge. To solve that problem, students must explore and study the knowledge of relevant subject areas and use them to solve the problem; (3) STEM education promotes a new learning style for learners, which is an innovative learning style. Given the role of an inventor, the learners will have to understand the nature of the equipped knowledge; know how to expand knowledge; know how to adjust and reprocess them to solve the problematic situation [3], [12], [22], [23].

1.2. STEM education in Vietnam

STEM education was paid attention and put into teaching quite late in Vietnam compared to in other countries in the world. In 2013, the Ministry of Education and Training of Vietnam organized the contests “Applying interdisciplinary knowledge to solve practical situations for high school students” and “Integrated Teaching for high school teachers”. Especially, the contest "Creative Science and Technology" organized by the Ministry of Education and Training for high school students has become an annual activity [14]. In January 2016, the project “Applying the UK's STEM education method into Vietnam's context in the 2016-2017 school year” was implemented at 15 secondary and high schools in Hanoi, Hai Duong, Hai Phong, Nam Dinh and Quang Ninh and achieved many positive results [6].

Especially, since the 2021-2022 school year, a new general education program is proposed to be implemented in Vietnam. Compared to the old one, this program will have a lot of changes, one of which is the inclusion of STEM education in the subjects. In the general education program, STEM education can be said to have drawn more attention as: (1) The new general education program has all STEM subjects: Mathematics; Natural Sciences; Technology; Computing, Physics, Chemistry, Biology; (2) The position and role of informatics and technology education are significantly improved; (3) Most STEM subjects have STEM topics; (4) The role of STEM education is clearly stated in the general program “Implementation of integrated education, especially integrated education of science, technology, engineering and math (STEM education); integrated education on environmental protection, economical and efficient use of energy, natural disaster prevention, climate change adaptation and meeting the requirements of sustainable social development” [15]; (5) The role of STEM education is clearly stated in the curriculum of subjects, for example, in the Natural Science curriculum, it is stated “It is necessary to include STEM education in teaching to develop students' ability to combine the knowledge and skills of the fields of natural sciences, technology, engineering, and math into solving practical situations” and “Along with Mathematics, Technology and Informatics, Natural Science contributes to the promotion of STEM education - one of the educational directions that are being developed in the world as well as in Vietnam, contributing to meeting the requirements of providing young human resources for the industrialization and modernization of the country” [16].

Thus, it can be seen that the implementation of STEM teaching in Vietnam is a matter that needs to be researched. In fact, there have been many studies on assessing the reasonable process of applying STEM education in Vietnam’s teaching conditions, including proposals to design STEM topics in the form of project-based teaching [8], design STEM teaching topics for use in experiential activities [12], [19] or design STEM teaching topics in scientific club activities [19]. However, little research has been done on EDP-based teaching of STEM. Meanwhile, EDP has many advantages to promote the strengths of STEM education, so this study proposes the use of EDP in the process of teaching STEM topics. An example cited to illustrate is the topic “Wind Energy Engineers” in teaching Physics of Grade 10th.
1.3. Engineering Design Process

The engineering design process (EDP) is one of the strategies available to implement STEM education. Nur Rosliana Mohd Hafiz and Shahrud Kadri Ayop, who have studied 37 articles on EDP and STEM education, have shown that in recent years, the EDP has been shown to be closely related to STEM education; it is possible to use EDP as a means to implement STEM. There has been a series of studies examining the effectiveness of EDP in STEM education and the results of those studies have proven its importance [1]. In EDP, there are some important points such as: (1) repetition, (2) open ending, in which a problem may have many feasible solutions, (3) meaningful context to study science, math, and technology concepts and (4) stimulate thinking. After students choose a potential solution, they analyze and evaluate the solution to determine if it is the optimal solution. This step not only helps students find the right solution, but also helps them realize that there may be more than one correct answer [13].

The interests of the instructors were in developing a curriculum that [13]:
- focused on learner-centered, open-ended, and constructivist activities,
- introduced pre-engineering skills that are not typically addressed in K-12 education,
- exposed students to an authentic engineering working environment, included team oriented projects, and
- guided students towards adaptive critical thinking, to engage them in developing meta-cognitive skills.

The steps in the EDP process are also understood in different ways. According to Mangold, this process consists of 8 steps (Table 1); According to Buddies, this process consists of 9 steps: Define the Problem; Do Background Research: Specify Requirements; Brainstorm Solutions; Choose the Best Solution; Develop the Solution; Build a Prototype; Test and Redesign; Communicate Results [4]. According to English, L. D., & King, D. T., this process consists of 5 steps: Problem Scoping; Idea Generation; Design and Construct; Design Evaluation; Redesign [7]. A number of other authors divide the EDP into 12 steps: Define the problem, Brainstorm possible solutions, Research Ideas/Explore Possibilities, Establish criteria & constraints, Consider alternative solutions, Select an approach, Develop a design proposal, Make a model or prototype, Test and evaluate, Refine the design, Create the solution, Communicate results [21].

Table 1. Guiding questions for applying the Engineering Design Process [13]

| Step in the Engineering Design Process | Guiding Questions used as prompts |
|----------------------------------------|----------------------------------|
| Step 1: Define the problem             | Who? What? When? Where?          |
| Step 2: Research the problem           | Where and how would you find more information about the problem? |
| Step 3: Brainstorm possible solutions  | Try thinking of as many solutions as you can, no matter how crazy. |
| Step 4: Analyze and evaluate solutions | Now that you have a number of ideas, what features are most important in the design you choose? Ex. – Cost, time, weight, etc. |
| Step 5: Choose best solution           | Based on your ideas and analysis, choose the best solution. |
| Step 6: Create prototype               | How would you create a prototype? What materials would you need? |
| Step 7: Test prototype                 | How would you test our prototype? |
| Step 8: Redesign if needed             | How will you know if you need to redesign? |
|                                        | What are some reasons you might? |
Although the terms are different, the procedure is basically the same. In particular, there is an emphasis on testing, evaluating and modifying the design so that the final product meets the set goal. In our study, we chose the 5-step EDP process (Figure 1) [7] because it not only fully expresses the meaning of EDP but also is easy to for students to implement, and for teachers to control and collect information.

Figure 1. The EDP

2. Methodology

2.1. Target group

The purpose of this study is to find out if the EDP can be used in STEM education-oriented teaching, if so, what are the possible steps? Therefrom, the study has made recommendations for teachers when using the EDP model in STEM education in Vietnam.

2.2. Methods of Inquiry

To achieve the goals targeted, the research team designed the teaching process according to the problem-solving teaching method. Combining the Sternberg’s problem-solving teaching which describes seven steps of problem-solving cycle, including (1) problem identification, (2) problem definition, (3) strategy emerging, (4) organization of information, (5) allocation of resources, (6) monitoring, and (7) evaluation [20] with the EDP, the researcher proposes a 5-step STEM teaching process (Figure 2). Therefrom, a specific teaching process with the topic “Physics with environmental protection” – Physics of Grade 10th was proposed.

Figure 2. STEM-themed teaching process based on EDP

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The topic “Physics with environmental protection” has the objectives as follows [17]: Students are able to discuss, propose, select options and implement:
- The need to protect the environment in national development strategies.
- The role of individuals and communities in environmental protection.
- The impact of current energy use on the environment, economy and climate of Vietnam.
- Summary of pollutants in fossil fuels, acid rain, nuclear energy, ozone depletion, climate change.
- Classification of fossil energy and renewable energy.
- The role of renewable energy.
- Some basic technologies for obtaining renewable energy.
- Designing and manufacturing a number of models of generators using renewable energy.

These goals would be implemented by students in 15 periods. After dividing the duration according to the goals above, the research team chose the goal of “Designing and manufacturing some models of generators using renewable energy” and implemented within 2 lessons. In these 2 lessons, students implemented the topic “Wind energy engineer”.

**Step 1. Assigning tasks.** After conducting the warm-up activity which helps students envision the need to increase the use of renewable energy, the teacher gives them the task: Using the turbine supplied (Figure 3) to design and manufacture a system of wind turbines to create wind power generators with the highest capacity. In this step, the teacher divides the students into groups, unifying the goals of the assigned task, unifying the student (or group) evaluation plan.

**Step 2. Planning.** After receiving the task, every group meets and proceeds to make an implementation plan. (The teacher should suggest students what content should be presented in the plan, for example, to whom a task is assigned? What is the product to be achieved? What is the deadline for completing the product? etc.)

**Step 3. Building, Testing and evaluating, Redesigning.** After having the blueprints, necessary materials, manufacturing tools, students proceed to build products. The products will then be tested and evaluated. Building → testing → evaluating → redesigning → rebuilding ... will be carried out repeatedly to find the product which achieves the goal targeted.

**Step 4. Reporting and discussing.** The whole working process will be recorded, through which students select the form of report, design of the report and practice presenting the report. Finally, the teacher organizes for groups’ reporting (Teacher should also suggest students some forms of reporting such as: plays, paper (A0) reports; reports via videos; reports through PowerPoint presentations; etc.) The location of the report is not necessarily in the classroom, it can be in the lab, on the school yard, etc. At the end of each report, students can make questions and debate about the process or the products.

**Step 5. Assessing and concluding.** After all groups present their reports, the teacher assesses the working process and products of each group according to the contents agreed in step 1. The final conclusions should also be made for results of each group and the overall results of the task assigned in step 1. Especially, the comments which are still unclear or controversial in the reporting and discussing step should be concluded.

After designing the teaching process as described above, the research team conducted a pedagogical experiment to answer the question given in section 2.1 of this paper. During the experiment, the class was divided into 4 groups of students; each group has 01 volunteer to monitor the whole process of student work to give the most accurate assessment of the proposed teaching process. Finally, the research team took teacher’ opinions about the teaching process designed through the questionnaire and through the discussions.
3. Research Findings

3.1. The experiment procedure

The research team conducted an experiment at class 11A15 of Viet Bac High School in Thai Nguyen province from July 25, 2019 to August 8, 2019. This is the time when students had just finished the 10th grade and were about to enter the 11th grade (started on September 5, 2019). Annually, a certain number of students (usually ethnic minority students, who have just finished the 9th grade) from northern mountainous provinces of Vietnam are selected to study at Viet Bac High school. These students have average academic performance compared to students in Thai Nguyen province as well as in Vietnam but they have good academic performance at their schools and are inclined to study natural sciences. There are 50 students (22 boys, 28 girls) in class 11A15 with 44 students from ethnic minorities. The experimental plan is presented in Table 2.

| No. | Time                  | Activities                                      |
|-----|-----------------------|-------------------------------------------------|
| 1   | 25/7/2019 (45 minutes)| - The teacher assigned the task                |
|     |                       | - The students received the task and planned    |
|     |                       | - The students got the approval of the teacher on the plan |
|     |                       | - The teacher and the students agreed on criteria |
| 2   | 26/7-07/8/2019        | - Groups of students performed the task as planned|
|     |                       | - The teacher and the volunteers monitored the working process planned and conducted by students |
| 3   | 08/8/2019 (45 minutes)| - The students reported and discussed the products. |
|     |                       | - The teacher concluded and assessed the products and the working process of groups of students. |

3.2. The results of the experiment

* Assessment of the products

After receiving the task, the groups immediately conducted a group meeting, proposing a plan to perform the task. The ideas were then discussed in the classroom. There were two final alternatives: Building generators with (1) vertical axis wind turbines and (2) horizontal axis wind turbine. Therefrom, the research team assigned to groups 1 and 3 to proceed under plan (1); Groups 2 and 4 proceed to plan (2).

The plan was set up by students right in the classroom. This plan was approved by the teacher. Finally, the teacher and students agreed on the criteria to evaluate students’ performance. The assessments included: product assessment (judged by judges), peer assessment and self-assessment.

In step 3, the groups of students repeated the process of designing, building, testing, evaluating, redesigning, etc. to offer the most optimal plan. Here, the practicality and STEM factors were clearly revealed when students had to answer some basic questions such as:

- Is it necessary to install a switch during the finishing step? If yes, which would be suitable? Where to buy it? What is the price? etc. Therefore, students had to apply their practical knowledge to find the most suitable switch.

- Does the material affect generating capacity? How to know that? etc. Therefore, students selected some easy-to-find objects such as plastic bottles, cardboard, cans, etc. to conduct the tests.

- How to know if a test is available for maximum power? Here, students could not use measuring instruments because of their relatively small capacity. Based on the suggestion of supplied led bulbs (3
pcs), students could buy more similar led bulbs to try the maximum number of light bulbs to have a conclusion about the capacity for each test.

- Does the number of blades affect the power? How to know that? Here, students conducted experiments with different numbers of blades to get the answer.
- What are the problems encountered in designing? For example, the shape of the blades, the area of each blade, what is the most convenient process of replacing blades? ...

![Figure 4. Several forms of blades designed and tested by students](image)

During the implementation process, the level of work completion as well as the proposed plan is different among groups; however, in general, they completed quite well the goals targeted. Three groups selected the switch sold in stores and installed the switch into the wind turbine system, the remaining group connected wires directly (The wires can be disconnected); Students knew to choose many different materials to make wind turbines such as plastic (from plastic bottles), paper (from covers), aluminum (from Coca-Cola cans, beer cans); Students tested the capacity of wind turbines by observing the number of lighted LEDs (in the report, the groups also offered many other options such as using ammeter and voltmeter to measure or use incandescent lights but these options are not feasible because the electric current generated from wind turbines is too small; students had different options to easily replace different types of blades when testing/assessing the power of the turbine such as using the blades attached to the toy wheels, using the blades attached to the shuttlecock. This helps to remove the blades from the turbine shaft easily. The research team especially appreciated the practical knowledge and creativeness of students in step 3.

In step 5, to evaluate students’ ability to solve problems during the implementation of the topic “Wind Energy Engineers”, the team evaluated on an average of 3 scores: (a) through teacher assessment form (Table 3), (b) through peer assessment sheets and (c) through self-assessment questionnaire (Table 4).
Table 3. Teacher’s assessment form

| No. | Criteria                                                                 | Maximum score | Real score |
|-----|--------------------------------------------------------------------------|---------------|------------|
| 1   | The rationality in setting the bracket for the generator                 | 1             |            |
| 2   | The rationality in setting the replacement of blades in each version     | 1             |            |
| 3   | The rationality in setting bulbs to test the power                       | 1             |            |
| 4   | The scientific level in testing shapes of blades                          | 2             |            |
| 5   | The reliability of the results                                           | 2             |            |
| 6   | The reasonability of the report and presentation of the products.        | 1             |            |
| 7   | The creativeness revealed by the products                                | 2             |            |
|     | **Total**                                                               | **10**        |            |

Table 4. Self-assessment and peer assessment form

Name of student: ……………………………..
Group: ………………………………………..

| No. | Criteria                  | Completing the task on time | Creative-ness | Supporting other classmates | Total |
|-----|----------------------------|----------------------------|---------------|-----------------------------|-------|
|     | **Maximum score**         | 4                          | 3             | 3                           | 10    |
| 1   | Nguyen Van A              |                            |               |                             |       |
| 2   | Nguyen Van B              |                            |               |                             |       |
| 3   | ……………                  |                            |               |                             |       |

In Table 4, if the assessment form is scored by Student A, the first line of the questionnaire is the self-assessment score, and the 2nd, 3rd lines, etc. are peer assessment scores. Students only conducted peer assessments in their groups.

The final result of each student is calculated by the formula \( x = \frac{a+b+c}{3} \). Accordingly, the assessment results are shown in Table 5. The study also compared the results of the assessment of problem-solving competence that students achieved with their academic performance in the STEM subjects in grade 10th (Table 5).
### Table 5. Students’ academic performance and ability assessment (Class 11A15)

| Level          | Math | Physics | Chemistry | Biology | Technology | STEM (*) | Ability assessment |
|---------------|------|---------|-----------|---------|------------|----------|-------------------|
| Excellent (%) | 36   | 30      | 42        | 60      | 50         | 42       | 40                |
| Good (%)      | 36   | 36      | 44        | 32      | 30         | 36       | 30                |
| Medium (%)    | 20   | 34      | 10        | 6       | 16         | 18       | 30                |
| Fairly weak (%) | 8   | 0       | 4         | 2       | 4          | 4        | 0                 |
| Weak (%)      | 0    | 0       | 0         | 0       | 0          | 0        | 0                 |

(*) Students’ STEM competence is ranked by their average score of STEM subjects (Math, Physics, Chemistry, Biology, and Technology)

Looking at table 5, we can see that the academic performance in the subjects of STEM are not similar. This is completely normal because each student has their own abilities and forte. Average scores of STEM subjects are not close to the results of students’ competency assessment through the topic “Wind Energy Engineer”. With regard to this difference, by interviewing the teacher, we found that most of the tests of students in the class are assessing knowledge, not taking into account the competence assessment. This, initially, allowed the research team to claim that: A student with good academic performance is uncertainly to have good competence (especially problem solving competence) and vice versa. However, more research is needed to confirm this statement.

**Figure 5. Students building, testing products and reporting**

* Assessment of the teaching procedure

To evaluate the feasibility of the teaching procedure, the research team collected the opinions of 45 teachers of Natural Science subjects (Math, Physics, Chemistry, Biology, and Technology) of Viet Bac High school after being invited to participate in the student product report on August 8, 2019. First, the groups presented the whole experimental process and experimental goals. Then the groups distributed questionnaires to the teachers present. Finally, the research team discussed with teachers and recorded the opinions of teachers about the effectiveness of applying the EDP into STEM education. The questions for teachers’ questionnaire are shown in Table 6.
**Table 6. Questionnaire for teachers**

| Questions                                                                 | Levels |
|---------------------------------------------------------------------------|--------|
| Q1. If the EDP is applied in STEM education in the procedure (presented in figure 3), which level of teaching goal can be achieved? | (1)    |
|                                                                            | (2)    |
|                                                                            | (3)    |
|                                                                            | (4)    |
|                                                                            | (5)    |
| Q2. If the EDP is widely implemented in STEM education in Vietnam, which level is the feasibility? | (1)    |
|                                                                            | (2)    |
|                                                                            | (3)    |
|                                                                            | (4)    |
|                                                                            | (5)    |

The results of the questionnaire is illustrated in figures 6 and 7.

![Figure 6. The result of question 1](image1)

![Figure 7. The result of question 2](image2)

It can be seen that most teachers thought that they could use the EDP model in teaching in the orientation towards STEM education. The probability to achieve goals was at high levels (levels 4, 5) and feasibility when applied in practical teaching was also at high levels (levels 4, 5), together accounting for 93%. The research team was also interested in assessing students in STEM teaching. Discussing the method of assessing that the groups performed, most teachers thought that the criteria given were reasonable and could be applied in practical teaching. However, there were some concerns such as: If there is only one teacher in the class, the process of monitoring and assessing groups is quite difficult due to the large number of students, or students who do not know how to assess their peers and self-assess may cause the inaccuracy of the results.

In addition, the research team also talked with teachers at Viet Bac high school to get better understanding about the problems that may be encountered when implementing this model. Some comments were recorded as follows:

- Setting up a fan page or chat group to monitor and support students in the process of producing the products;
- Increasing support for students on equipment such as machines, camcorders, computers (in fact 100% of students here do not have personal computers, the PowerPoint report was entirely made on mobile phones);
- Taking the scores that the students got as one of testing scores to encourage students in the process of working (currently this is considered a new study under the general program which will be...
implemented in Vietnam in 2021, so it is independent of official learning program, hence these scores were not allowed to be recorded in students' school reports).

Besides, there were also comments on the difficulties that the teacher faced when applying the EDP in practice, such as: the teacher had not been trained, there was no guidance documents to apply the EDP in STEM teaching, there were financial problems, there were management issues outside the classroom and exam issues (currently in Vietnam, exams focus on assessing knowledge, not attaching importance to assessment the capacity), the number of students per class is still large, time limitation (using the process the team recommended, the teacher had to spend more time in the classroom and outside the classroom than traditional teaching), etc.

4. Discussion

While using the EDP in STEM education to achieve the goals targeted, teachers should pay attention to the following points:

- At steps 1 and 2, it is necessary to assign specific and clear tasks; to agree on criteria to assess students and control the implementation plans;
- At step 3, teachers should not interfere with the conducting process of students; they should only urge and supervise this process. Teachers can also use social networks / software to manage and monitor, from which there is an accurate assessment of the working process of groups; However, teachers should remind students how to collect data, images, etc. to have the best report in step 5.
- At step 4, most of Vietnamese students are at the suitable age for conducting pedagogical experiments, so they can complete this stage quite well
- At step 5, teachers should create a comfortable atmosphere when discussing, but they also need to control the discussion, avoiding the situation when some of the ideas are off topic or there is not stop for a controversial issue. Especially, there must be conclusions about each plan, each scientific knowledge in each debate or problems encountered.
- Assessing criteria need to be clear and quantifiable. In terms of peer assessment and self-assessment, the criteria should be simple and few. Teachers should show students who are not familiar to peer assessment and self-assessment forms how to use those forms.

The current implementation of STEM education in Vietnam is still spontaneous and not systematic; however, regarding the benefits that it brings, STEM education will soon develop strongly in Vietnam.

5. Conclusion

Through the research process, the conclusions can be drawn as follows:

- Using the EDP in STEM education can help to meet the educational goals targeted;
- The EDP in STEM education that consists of 5 steps: Assigning tasks; Planning; Building, Testing and evaluating the products; Reporting and discussing; Assessing and concluding (Figure 3) is reasonable and can be widely implemented in teaching practice in high schools in Vietnam;
- It is possible to assess students' ability, especially the ability to solve problems by combining the forms of teacher assessment, self-assessment and peer assessment.
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