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PAPER

# Implementation of New-Product Creativity through an Engineering Design Process to Foster Engineering Students' Higher-Order Thinking Skills

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## ABSTRACT

Many studies in engineering education believe that higher-order thinking skills (HOTs) are a fundamental competency for engineering students. Polymer engineering students study and analyze the character and structure of polymer materials and use that knowledge to design innovative new products. However, students might need more applied contexts to creativity and learning motivation in polymer material instruction. This paper is a study to present new-product creativity (NPC) through the engineering design process (EDP) for polymer engineering students. The quasi-experimental design was implemented in the learning activity of the polymer-processing laboratory course. A total of 21 participants were recruited from two groups of students (10 were in the experimental group, and 11 were in the control group) at a university in Thailand. The experimental results showed that the students who learned with NPC-EDP had better HOTs in the polymer-processing laboratory course than those who learned with conventional learning. In addition, the students also showed that they were motivated to learn meaningfully in engineering education.

## KEYWORDS

higher-order thinking skills, engineering design process, engineering education

## 1 INTRODUCTION

The engineering discipline is one of the essential parts of STEM (Science, Technology, Engineering, and Mathematics) education [1]. Therefore, many engineering education institutions focus on effective teaching and learning [2]–[5]. Numerous studies have addressed the effectiveness of various classes that aim to cultivate higher-order thinking skills (HOTs) to improve the academic achievement of students [6]–[8]. Developing HOTs is essential to engineering education, so active learning activities are implemented to prepare students' thinking skills to enter the

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labor market [9]. Activating students' higher-order thinking skills, which emphasize the influence of students' scientific knowledge, design process, and critical thinking, can be challenging [10]. To promote HOTs in engineering education, the engineering design process (EDP) is also essential to designing learning activities. Putra et al. [11] proposed a learning activity through EDP to engage critical thinking skills in a physics classroom. It facilitated students' group collaboration, where they could share and explore their ideas and engage in argumentation, planning, trying, and testing. After students decided on their design to solve the problem, they examined their structure and saw if the results matched other groups'. This situation demonstrated the thinking process, which is the learning goal.

Polymer engineering students analyze the character and structure of materials and use that knowledge to design innovative new products. However, students might need more applied contexts to promote creativity and learning motivation in polymer materials instruction. Usually, they take courses in chemistry and materials science to learn and specialize in areas such as polymer synthesis or polymer processing. However, a difficulty of learning polymer processing is that it requires a combination of theoretical knowledge and practical skills to generate innovative products.

This study aimed to develop a new-product creativity (NPC) learning activity through the engineering design process in the polymer-processing laboratory course. This course would make students understand the use of sound insulation made from natural rubber, its properties, and applications in today's world. Accordingly, the students' conceptual, higher-order thinking skills and learning motivations were examined to investigate the learning activity. The following research questions were investigated.

1. Do the students who learned with NPC-EDP have a significantly better conceptual understanding than those who learned with conventional learning?
2. Do the students who learned with NPC-EDP show significantly better higher-order thinking skills than those who learned with conventional learning?
3. How were the students who learned with the NPC-EDP learning motivated?

## 2 RELATED WORK

### 2.1 Higher-order thinking skills

HOTs are essential skills that refer to the cognitive process of solving complex problems and making decisions to generate new ideas. The revised Bloom's taxonomy proposed by Krathwohl [12] is a framework for classifying statements of what teachers expect or intend students to learn in the learning process. The cognitive domain of Bloom's taxonomy consists of lower-order thinking skills (LOTs) (remembering, understanding, applying) and HOTs (analyzing, evaluating, and creating), as shown in Figure 1. Of course, HOTs are globally emphasized essential thinking skills that have become a core focus of instruction in many classrooms. Three domains of HOTs consisted of *analysis*, where the student can separate into parts and determine how the parts relate to one another; *evaluating*, where the student can make judgments based on criteria and standards by checking material attributes; and *creating*, where the student can combine elements to form a coherent or functional whole into a new product.

HOTs can promote problem-solving and critical thinking skills that employers highly value in any career and are necessary for future success [13], [14]. Many learning approaches have been used to encourage HOTs with instructional design interventions that engage students. One study found that collaboration was the only learning factor that had indirect and direct effects on HOT [15]. In addition, an inductive reasoning strategy can enhance students' HOTs when students facing application, analysis, and evaluation problems have to make or create a solution with the highest cognitive level [16].

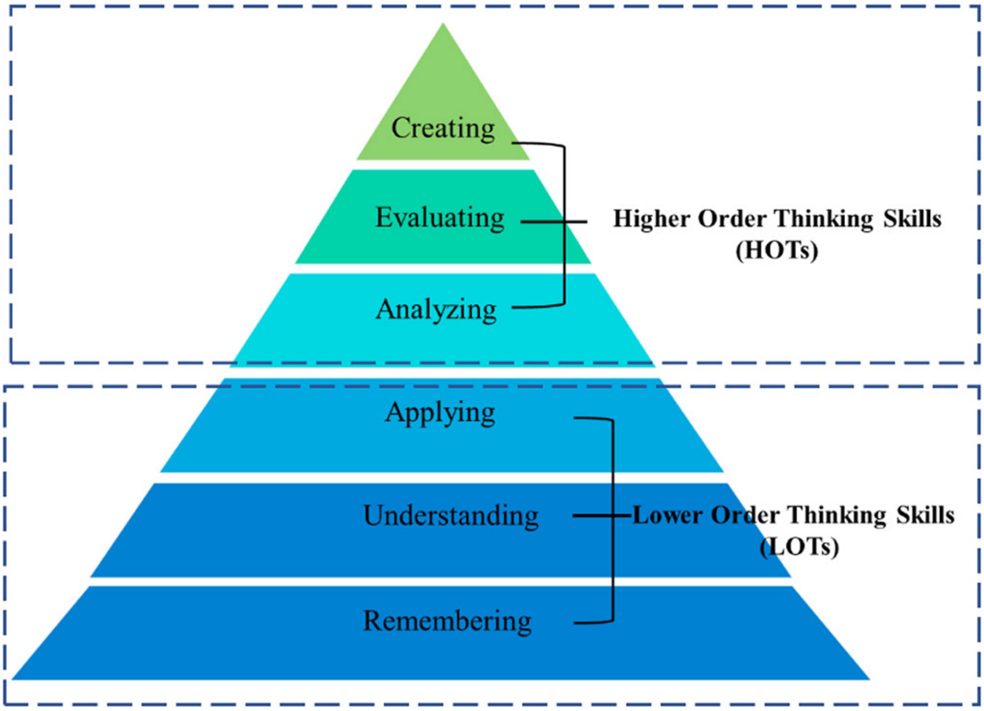



**Fig. 1.** The revised Bloom's taxonomy of cognitive domain

HOTs are essential for engineering students because they enable the students to think critically, analyze complex problems, and develop innovative solutions. They also allows students to deepen their understanding of engineering concepts, apply knowledge. and connect new information to think creatively and generate new ideas that are important in science and engineering fields.

## 2.2 Engineering design process

Many studies have conceptualized the EDP as an important context for integrating engineering education [17], [18]. The EDP focuses on engineers following a systematic approach to develop a solution to a problem or create a new product. It also allows engineering students to systematically generate, evaluate, and specify the engineering concepts of systems or processes based on function, objectives, and needs. It encourages students to adopt a curious mindset and to approach problems from multiple perspectives based on questioning existing norms [19].

Researchers in the engineering education area have proposed a variety of EDPs. Most studies employ problem scenarios, present a design brief, and use brainstorming, laboratory activities, and writing activities while utilizing the EDP to drive learning activities [20].

The EDP is important for students because it can help them solve problems, generate solutions, and develop innovative products. Thus, the EDP is a systematic approach that encourages engineering students to think creatively and explore new ideas. In addition, it provides hands-on learning opportunities involving building and testing prototypes, which can enhance their understanding of engineering concepts and connect classroom learning to real-world problems.

In this study, we are interested in the EDP proposed by Hill et al. [21] and how it is employed to drive new-product creativity through learning activities. It applies creative solutions to help teachers understand how to apply learning methods to promote students' engagement in solving real-world problems with the engineering concepts they learn about while integrating science and engineering. The core step of this EDP for driving new-product creativity learning activities consists of five phases: the *asking phase,* where the student identifies an engineering type of problem; the *imagining phase*, where the student brainstorms ideas; the *planning phase*, where the student chooses the best idea and sketches it out; the *creating phase*, where the student makes a prototype idea; and the *improving phase*, where the student tests a material aspect, as shown in Table 1. Figure 2 show the conceptual framework of the study.

**Table 1.** The steps of the EDP

| EDP Phase | Student Activities |
|---|---|
| Asking | The students can define an engineering problem related to improving the problems with sound insulation made from natural rubber. In this step, they identify and clearly define the problem or need that requires a solution. They can understand user requirements and factors that impact the design. |
| Imagining | The students can develop ideas, solve problems, and find solutions through brainstorming activities. In this step, they form the conceptual design after research and gather information on existing solutions, materials, and design principles. |
| Planning | The students choose the best idea and sketch materials with sound insulation from natural rubber. They plan to create detailed prototypes via drawing and writing in this step. |
| Creating | The students test the material and make a prototype in the polymer laboratory. Prototypes are built and tested to evaluate the functional performance of the design. Then, the students gain feedback from testing. |
| Improving | The students present their product, explain how it is a solution to the original problem, and propose applications for future work. In this step, they can refine the final design created and prepare for presenting the production process. |

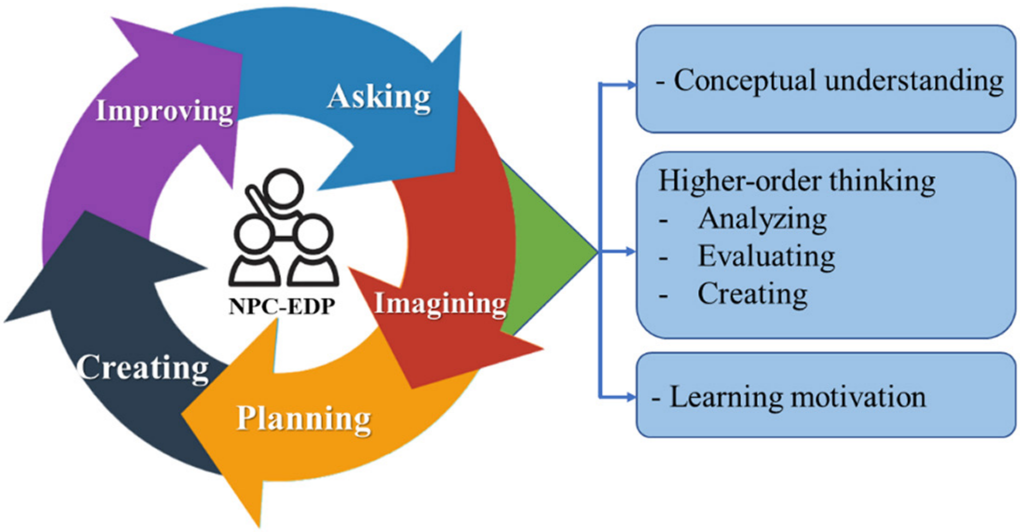



**Fig. 2.** A conceptual framework of NPC-EDP learning model

# 3 METHODOLOGY

## 3.1 Participants

A total of 21 students were divided into two groups. The control group consisted of 11 students (9 male and 2 female), and the experimental group consisted of 10 students (9 males and 1 female) at a university specializing in engineering and technology education in Thailand. All participants were enrolled in the polymer-processing laboratory course integrated into the curriculum, and the students were graded based on participation in the course.

## 3.2 Research instruments

The research tools used in this study consisted of conceptual understanding tests, higher-order thinking scoring rubrics, and motivation questionnaires. The conceptual understanding used for the pre-tests and post-test were related to understanding sound insulation made from natural rubber; each test contained five items (total of ten scores).

The scoring rubrics for evaluating higher-order thinking skills used to assess the development of students' abilities have three domains of learning outcomes (analysis, evaluating, and creating). They were employed to assess the students' presentation section. Three experienced teachers verified the validity of the conceptual understanding tests and scoring rubrics tests.

The student motivation questionnaire was adapted from Srisawasdi and Panjaburee [22] to explore students' motivation to participate in learning activities. It consists of twenty-five items using a five-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree). Five dimensions were measured: *intrinsic motivation*, *career motivation*, *self-determination*, *self-efficacy*, and *grade motivation*.

## 3.3 Experimental procedure

This study is quasi-experimental design research. We used the pre-test and post-test nonequivalent groups design. The participants were split into two groups. All groups were taught by the same teacher to ensure the same primary content was delivered to all participants. The study was conducted over six weeks (120 minutes per week). Before the learning activity, the participants in both groups had an introduction to the concept of sound insulation from natural rubber. Afterwards, they were assigned to take the pre-test in the first week (120 minutes). They participated in the learning activities in the second and third weeks (240 minutes).

During the learning process, the participants in the experimental group learned with the NPC-EDP–based learning approach. At the same time, the participants in the control group learned with the traditional practices–based learning approach. In the final week of the experiment, the participants in both groups took the post-test and completed their presentations in week 4 (120 minutes). The participants in the experimental group took the learning motivation questionnaire, as shown in Figure 3.

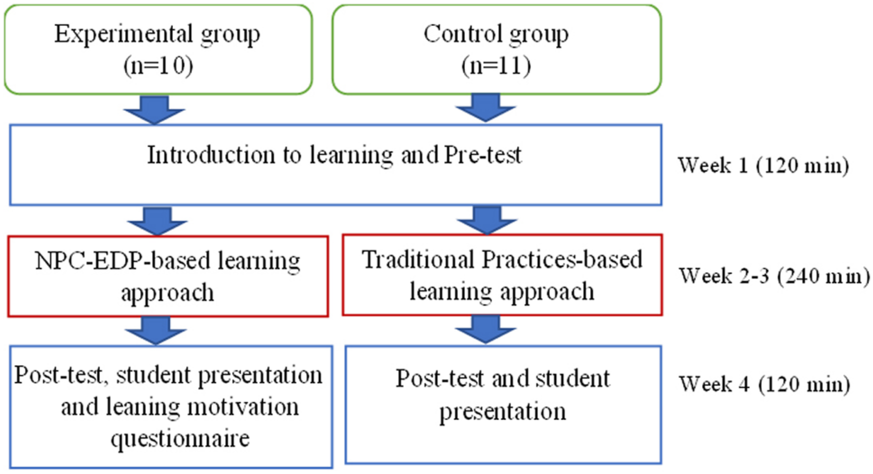



**Fig. 3.** Experimental procedure

In the learning process (Figure 4a), the students use the instrument for natural rubber testing with a compression-molding machine to mold rubber. Figure 4b shows the students using a moving-die rheometer to test and analyze the cure characteristics of the rubber compound and monitor the processing characteristics.

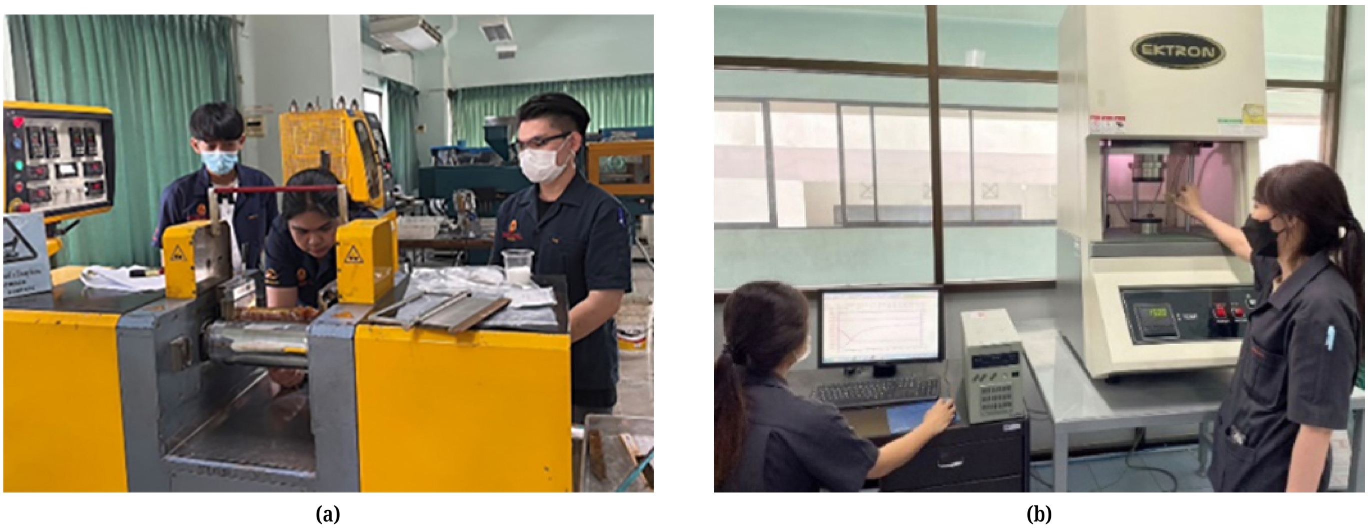
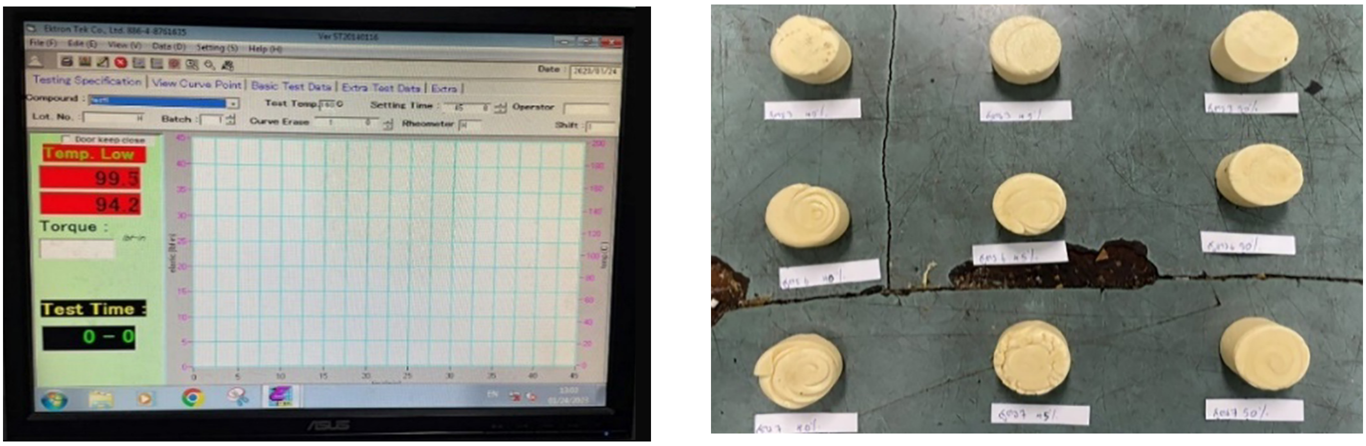


**Fig. 4.** (a) Compression-molding machine and (b) moving-die rheometer

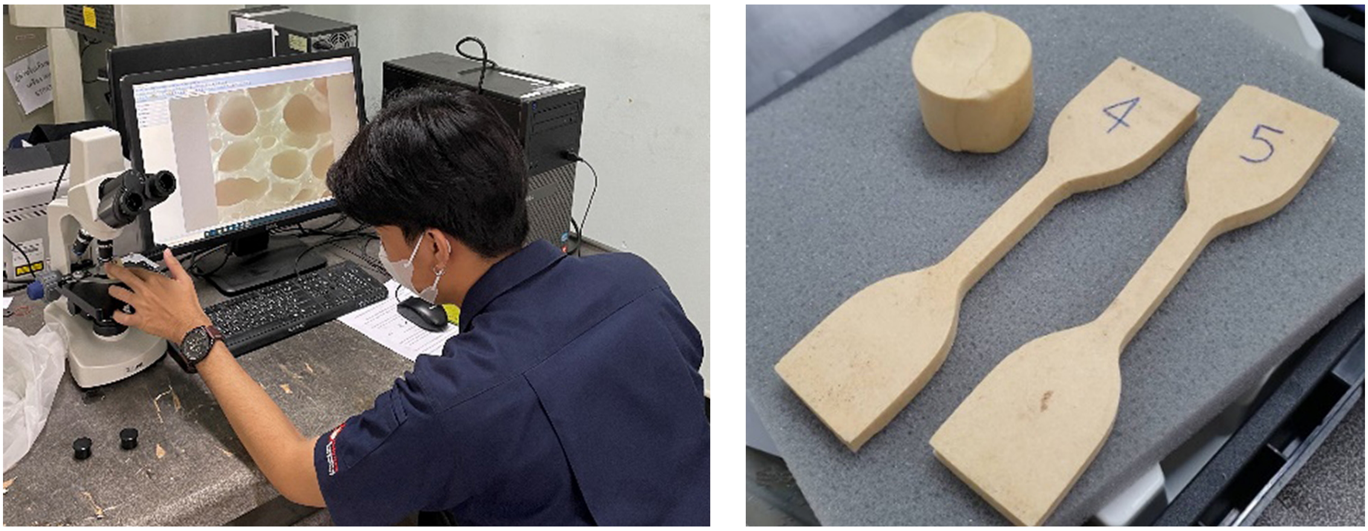
Figure 5a shows software for testing natural rubber, and Figure 5b shows an example of a natural rubber compound produced by adding specific chemicals to raw rubber to improve and alter the characteristics of the rubber for the desired use.




(a) (b)

**Fig. 5.** (a) Testing software and (b) natural rubber compounds

Figure 6a shows the students testing rubber using an optical microscope during learning activities, and Figure 6b shows an example of natural rubber prototypes designed and produced by the students.




(a) (b)

**Fig. 6.** (a) Testing with an optical microscope and (b) the natural rubber prototypes designed and produced by the students

## 4 RESULTS

### 4.1 Students' conceptual understanding

To compare the conceptual understanding of the sound insulation from natural rubber, pre- and post-test scores were analyzed with independent sample t-tests. Table 2 shows that the t-tests revealed no significant difference between the conceptual pre-test of the experimental group (EG) and control group (CG) (EG: M = 3.40, SD = 1.38; CG: M = 3.27, SD = 2.02, t = 0.22).

The students' conceptual understanding was significantly different on the post-test than on the conceptual pre-test (EG: M = 9.11, SD = 7.51; CG: M = 6.18, SD = 7.36,

$t = 2.53$, $p < 0.05$). This significant difference indicates that the students in both groups increased their conceptual understanding of sound insulation from natural rubber.

**Table 2.** The t-test result of students' conceptual understanding

| Test | Group | N | Mean | SD | t | Sig. |
|---|---|---|---|---|---|---|
| Pre-test | EG | 10 | 3.40 | 1.38 | 0.22 | .82 |
| | CG | 11 | 3.27 | 2.02 | | |
| Post-test | EG | 10 | 9.11 | 7.51 | 2.53 | .02* |
| | CG | 11 | 6.18 | 7.36 | | |

*Note:* *p < .05.

## 4.2 Students' higher-order thinking skills

Regarding the students' higher-order thinking skills, differences between the experimental group (EG) and control group (CG) were significantly different in all dimensions: analysis dimension (EG: M = 4.63, SD = 0.26, CG: M = 2.36, SD = 0.81) with ($t = 7.20$, $p < 0.05$); evaluating dimension (EG: M = 4.63, SD = 0.09, CG: M = 2.82, SD = 0.21) with ($t = 10.96$, $p < 0.05$); and creating dimension (EG: M = 4.73, SD = 0.02, CG: M = 2.55, SD = 0.29) with ($t = 10.96$, $p < 0.05$), as shown in Table 3. This significant difference indicates that the students in both groups increased their higher-order thinking skills.

**Table 3.** The t-test result of students' higher-order thinking skills

| HOTs Dimension | Group | Mean | SD | t | Sig. |
|---|---|---|---|---|---|
| Analysis | EG | 4.63 | 0.26 | 7.20 | .00* |
| | CG | 2.36 | 0.81 | | |
| Evaluating | EG | 4.63 | 0.09 | 10.96 | .00* |
| | CG | 2.82 | 0.21 | | |
| Creating | EG | 4.73 | 0.02 | 12.89 | .00* |
| | CG | 2.55 | 0.29 | | |

*Note:* *p < .05.

## 4.3 Students' learning motivation

Descriptive statistics describe the mean scores from the students' motivation questionnaires. The five dimensions show that students' intrinsic motivation relates to engaging, curious, and enjoyable learning activities (M = 3.72, SD = 0.94). The students' career motivation can help them get a good job, a career promotion, or a career advantage, using the knowledge acquired about designing sound insulation from natural rubber one's career, and related career topics (M = 3.94, SD = 0.79). As for students' self-determination, they always prepared well for learning about designing sound insulation from natural rubber, expending enough effort, learning, and using strategies (M = 3.34, SD = 0.91). While for students' self-efficacy, they earned good scores, felt confident on tests, gained knowledge and understanding, and felt sure about the tasks associated with designing sound insulation from natural rubber ($M = 3.50$, $SD = 0.75$). Likewise, the students' Grade motivation focused on scoring high grades and the importance of gaining better grades in the tasks associated with designing sound insulation from natural rubber learning ($M = 3.76$, $SD = 1.01$), as shown in Table 4.

**Table 4.** The result of students' learning motivation

| Students' Motivation Dimension | Mean | SD | Interpretation |
|---|---|---|---|
| Intrinsic motivation | 3.72 | 0.94 | Agree |
| Career motivation | 3.94 | 0.79 | Agree |
| Self-determination | 3.34 | 0.91 | Neutral |
| Self-efficacy | 3.50 | 0.75 | Agree |
| Grade motivation | 3.76 | 1.01 | Agree |

*Note:* 1–1.5 = "strongly disagree," 1.51–2.50 = "disagree," 2.51–3.50 = "neutral," 3.51–4.00 = "agree," and 4.01–5.00 = "strongly agree."

There was a statistically significant positive correlation ($p < 0.05$) between Intrinsic motivation (IM) and Career motivation (CM), Self-determination (SD) and Self-efficacy (SE), and Self-efficacy (SE) and Grade motivation (GM). The correlation between Career motivation (CM) and Self-determination (SD) was not statistically significant ($p > 0.05$), as can be seen in Table 5.

**Table 5.** The Pearson correlation coefficients results among students' learning motivation

| Dimension | IM | CM | SD | SE | GM |
|---|---|---|---|---|---|
| Intrinsic motivation (IM) | 1.000 | | | | |
| Career motivation (CM) | 0.669* | 1.000 | | | |
| Self-determination (SD) | 0.636 | 0.365 | 1.000 | | |
| Self-efficacy (SE) | 0.533 | 0.510 | 0.763* | 1.000 | |
| Grade motivation (GM) | 0.666 | 0.575 | 0.714 | 0.654* | 1.000 |

*Note:* *$p < 0.05$.

## 5 CONCLUSIONS

We studied implementing a new product creativity model for polymer engineering students through the engineering design process (NPC-EDP). Twenty-one students participated in the polymer-processing laboratory course. The finding found that the NPC-EDP was helpful to the students in terms of improving their conceptual understanding and promoting higher-order thinking in designing sound insulation from natural rubber. Additionally, it motivated the students to learn essential content about engineering polymers. Motivating students to enjoy learning activities can be challenging. Our study used active learning and interactive strategies that systematically incorporate hands-on activities into the learning experience. This can help and motivate students to stay engaged. The findings were aligned with the cognitive task involved in forming design learning activities and placement along an engineering design process to create guiding steps to guide students' thinking while solving the problem [23], [24]. An EDP is critical for student engineering courses to help students develop successful solutions to complex problems.

This study acknowledges the limitation of the small sample size for comparison. Further qualitative approaches may support our research finding. We hope that our study contributes to the polymer engineering field and better prepares engineering students for achieving success in transdisciplinary engineering education.

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