



## Effectiveness of the Teaching Factory Model in Vocational Education to Improve Design Thinking among Students in the Electronics Engineering Expertise Program

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### Abstract

This study aimed to examine the effectiveness of the Teaching Factory (TEFA) model in vocational education in improving the design thinking of students in the Electronics Engineering Expertise Program and to identify the supporting and inhibiting factors in its development. The study employed mixed methods with an explanatory sequential design. The quantitative phase applied a quasi-experimental pretest-posttest control group design involving 39 eleventh-grade students at SMK Negeri 1 Pringgabaya, consisting of 19 students in the experimental group who participated in TEFA-based learning and 20 students in the control group who participated in expository instruction. The quantitative instrument was a 30-item Likert-scale design thinking questionnaire based on six dimensions of design thinking. The data were analyzed using descriptive statistics, N-gain, paired-samples t-test, independent-samples t-test, ANOVA, ANCOVA, and effect size analysis. The qualitative phase was conducted through semi-structured interviews with seven students from the experimental group and one Electronics Engineering teacher, and the data were analyzed thematically. The results showed that the experimental group experienced a greater improvement in design thinking than the control group. The mean N-gain of the experimental group was 0.63, while that of the control group was 0.39. The tests of gain, N-gain, posttest scores, ANOVA, and ANCOVA showed significant differences with large effect sizes. Improvement also occurred across all dimensions of design thinking, particularly mindfulness to the process and impacts on others, human-centeredness, and collaboratively working with diversity. The qualitative findings showed that the development of design thinking was supported by authentic learning contexts, orientation toward user needs, collaboration, prototyping, testing, product revision, teacher guidance, and practical facilities. The main obstacles included limited time, uneven coding ability, technical constraints related to sensors and circuits, and the tendency to choose safe solutions. Therefore, TEFA was effective in improving the design thinking of Electronics Engineering students in the vocational school context.

**Keywords:** Teaching factory; Vocational education; Design thinking; Electronics engineering; Mixed methods

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## INTRODUCTION

Vocational education plays a strategic role in preparing students to enter the workforce and build long-term careers. Unlike academic pathways, which place greater emphasis on conceptual mastery, vocational education is designed to bridge the gap between classroom learning and the real needs of industry. The complexity of the labor market, the acceleration of technological development, and shifts in economic structures require graduates who not only possess technical knowledge but are also able to adapt quickly to changing industrial needs and global demands. In this context, vocational education becomes an important route

for students to acquire competencies that are relevant to the contemporary labor market and to reduce the risk of educated unemployment.

Various studies have shown that the main strength of vocational education lies in the integration of theoretical knowledge with practical training, including through dual training models that combine school-based learning with direct experience in the workplace. This model helps students develop skills that are genuinely needed in the workplace and improves their work readiness (Nazarova et al., 2021). Partnerships between educational institutions and industry have also been shown to enrich the learning process through the use of modern equipment and practitioner mentoring, allowing the quality of student learning outcomes to become closer to actual industry standards (Okhawere, 2025). In addition to technical aspects, vocational education contributes to the development of soft skills such as adaptability, resilience in facing change, and willingness to engage in lifelong learning, which are considered important for sustaining long-term careers (Makwa et al., 2025). It is therefore not surprising that various reports indicate that vocational graduates tend to be absorbed into the labor market more quickly than graduates from non-vocational pathways, as long as the competencies they acquire are aligned with labor market needs (Paramole & Adeoye, 2024; George, 2025; Kinyondo & Shija, 2023; Appiah-Kubi et al., 2025).

Among the various fields of vocational education, the Electronics Engineering Expertise Program holds an important position because it is directly related to the development of technology-based industries. Students in this program are required to master concepts of electricity, analog and digital electronics, control systems, and the ability to use and develop modern technology-based devices. A competency-based electronics engineering curriculum requires not only mastery of knowledge but also skills in working with devices, instruments, and systems that are relevant to industrial practice (Budiastuti et al., 2023). Various studies emphasize that student involvement in authentic and project-based practical activities is crucial to ensuring that the competencies developed do not remain only at the theoretical level (Korkmaz, 2018; Dahiya & Nehra, 2015).

At the same time, technological development and the demands of the electronics industry require graduates who are not merely skilled in carrying out routine procedures, but are also able to solve complex problems, innovate, and orient themselves toward sustainable solutions. This is where design thinking skills become highly relevant for students in the Electronics Engineering Expertise Program. Design thinking, with its emphasis on understanding user needs, exploring creative ideas, and testing solutions iteratively, is aligned with the characteristics of modern electronic system and device design, including in the context of environmentally friendly practices and energy efficiency (Nikoloudakis & Rangoussi, 2024). Thus, the Electronics Engineering Expertise Program logically becomes one of the key contexts in which design thinking is not only relevant, but should also become an integral part of the learning process.

Nevertheless, various empirical findings show that the design thinking abilities of vocational education students, including those in engineering fields, remain far from expectations. Several studies report that vocational students are often not yet able to apply design thinking processes systematically when dealing with complex technical problems. Nordin et al. (2022), for example, showed that many students tend to rely on conventional and linear problem-solving patterns and do not sufficiently develop the exploration of alternative ideas. Aflatoony et al. (2017) added that many vocational students and university students lack confidence in practicing design thinking because of limited learning experiences that explicitly train this way of thinking. Syah and Nasri (2023) also indicated that vocational programs more often emphasize routine technical skills, while the creative and reflective aspects that form the core of design thinking are less adequately facilitated.

Design thinking itself is generally understood as a human-centered, iterative thinking process that combines empathy, problem definition, idea development, prototyping, and

testing (Liu & Leong, 2022). In the context of vocational education, design thinking is not merely a creative approach, but a framework for connecting technical knowledge with real contexts and user needs. The integration of design thinking into learning has been shown to improve students' creative confidence, innovation ability, and entrepreneurial orientation (Novak & Mulvey, 2020; Liu & Leong, 2022; Lin et al., 2024). In electronics engineering, this means that students do not only understand how to assemble or repair circuits, but are also able to design new solutions that are responsive to user needs while considering safety, efficiency, and sustainability.

However, recognition of the importance of design thinking has not been fully reflected in teaching practices in many vocational education institutions. A number of studies show that students' low level of design thinking is closely related to the dominance of traditional and teacher-centered teaching practices. Kustini (2023) argued that lecture-based approaches that position students as passive recipients of information tend to hinder the development of creativity, collaboration, and critical reflection. McLaughlin et al. (2019) also highlighted that traditional teaching patterns often do not provide space for students to engage in iterative processes of formulating and testing solutions, although these processes are central to design thinking. Huang et al. (2023) emphasized that design thinking promotes deeper learning compared with conventional teaching, but its implementation in many vocational programs remains limited.

Other findings that strengthen this argument come from research on the effectiveness of active learning. Yadav et al. (2014) showed that immersive and project-based learning experiences result in better conceptual understanding and problem-solving ability than traditional lectures. Freeman et al. (2014) reported that one-way lecture formats consistently perform below active learning in developing critical thinking skills. Mo et al. (2024) underlined that weaknesses in vocational education competencies are related to the slow renewal of teaching approaches that integrate innovative methods such as design thinking. In other words, when opportunities for project-based learning, collaboration, and idea exploration are limited, students' opportunities to develop design thinking are also reduced.

In the context of the Electronics Engineering Expertise Program, this condition may widen the gap between industrial demands and graduate profiles. Learning practices that focus too much on completing procedural tasks or routine exercises without real problem contexts can make students proficient at the operational level, but less prepared when asked to design new solutions or respond to challenges they have never encountered before. In fact, many problems in electronics, such as the design of embedded systems, IoT devices, or automation solutions, require the ability to identify user needs, explore several design alternatives, and iterate based on feedback. This condition indicates the need to adopt a more authentic and contextual vocational learning model so that students' design thinking can develop more systematically.

One model that has developed in modern vocational education and offers potential to address this issue is Teaching Factory (TEFA). Teaching Factory is understood as a learning approach that integrates school-based learning with production or service practices resembling those found in real industry. In TEFA, schools collaborate with business and industry partners to create a learning ecosystem in which students work on real product- or service-based projects, rather than merely simple simulations (Ismayati et al., 2020; Bikas et al., 2021). Through this model, the boundary between "learning" and "working" becomes thinner because students face quality standards, deadlines, and communication demands that are relatively close to industrial conditions.

Various studies show that the implementation of TEFA contributes to improving work readiness, technical skills, and even entrepreneurial interest. Nugroho et al. (2024) and Iliani et al. (2022) reported that student involvement in Teaching Factory projects strengthens entrepreneurial orientation and students' understanding of business processes, ranging from

product design and production to marketing. Bikas et al. (2021) emphasized that TEFA increases curriculum relevance to industry needs and reduces the competency gap between schools and the workplace. When students are involved in solving real problems proposed by industry partners, they are encouraged to integrate theoretical knowledge with practical and commercial considerations, which provides an ideal context for the development of design thinking.

More specifically, the characteristics of TEFA are closely aligned with the principles of design thinking. Wahjusaputri and Bunyamin (2022) showed that TEFA encourages students to follow systematic problem-solving steps, beginning with understanding needs and problem contexts, formulating problems, developing ideas, and testing solutions. Muslim et al. (2020) and Patria et al. (2024) emphasized that student involvement in activities that simulate real business operations fosters critical thinking, creativity, collaboration, and communication. In this process, students are naturally encouraged to carry out design iterations, improve products or services based on feedback, and develop solutions that are more feasible and valuable. Maksun et al. (2022) also found that involvement in Teaching Factory contributes to the improvement of metacognitive skills, such as reflection and self-regulation, which are important foundations for developing design thinking.

Although this body of evidence shows that TEFA has strong potential to develop higher-order thinking skills, including design thinking, studies that specifically examine the effectiveness of Teaching Factory in improving students' design thinking in the Electronics Engineering Expertise Program remain relatively limited. Many previous studies have focused on work readiness, technical competence, or entrepreneurial interest, while the design thinking dimension has not been explored in depth in the context of electronics engineering vocational education. Based on this background, this study aims to explore the effectiveness of the Teaching Factory (TEFA) model in vocational education in improving students' design thinking in the Electronics Engineering Expertise Program. Specifically, this study addresses the following two research questions.

1. How effective is the Teaching Factory (TEFA) model in vocational education in improving students' design thinking in the Electronics Engineering Expertise Program?
2. What are the supporting and inhibiting factors in the development of design thinking among students in the Electronics Engineering Expertise Program during the implementation of the Teaching Factory (TEFA) model?

## LITERATURE REVIEW

### Electronics Engineering Learning in Vocational Education

Vocational education is generally positioned as a bridge between academic learning and the mastery of practical skills needed in the workplace. In the context of an increasingly complex and digitalized labor market, vocational education systems are required not only to produce graduates who are able to operate technology, but also to prepare individuals who are sufficiently adaptive to changes in industrial needs and the global economy. The integration of theoretical knowledge with practical training, for example through dual systems and partnerships with industry, is often regarded as one of the main strengths of vocational education because it enables students to learn directly in work-based environments while also participating in formal learning (Nazarova et al., 2021; Okhawere, 2025). Within this framework, electronics engineering learning, as one of the technical fields, holds a significant position because it is closely related to the needs of technology-based industries.

In the Electronics Engineering Expertise Program, the demand for a balance between conceptual mastery and practical experience is particularly strong. Competency-oriented programs are required to ensure that students not only understand the theory of circuits, digital systems, and measuring instruments, but are also able to apply this knowledge to real problems in workshops, laboratories, and industrial environments (Budiastuti et al., 2023).

Therefore, various studies have highlighted the importance of active student involvement through practical activities and project-based learning, so that students do not merely become recipients of information, but become actors who construct knowledge through direct experience (Korkmaz, 2018; Dahiya & Nehra, 2015). This focus on concrete competence is consistent with the view that effective vocational education contributes to improving work readiness and workplace well-being, including for more vulnerable groups such as students with disabilities (Zainun et al., 2020).

However, current industrial needs do not stop at operational skills. In electronics engineering, industry requires graduates who are able to design, adapt, and integrate technology into broader systems. This is where approaches that emphasize complex problem solving and systems thinking become crucial. The integration of interdisciplinary learning, for example in topics such as analog electronics or embedded systems, is considered capable of strengthening students' ability to understand the relationships among components and the impact of design decisions on the whole system (Mao, 2021). At the same time, teamwork and social competence are no longer considered additional skills, but part of the minimum competency profile required in project-based work environments (Dahiya & Nehra, 2015; Bodrug & Leyfa, 2020). Students are expected to collaborate, communicate effectively, and participate in multidisciplinary teams, which are characteristic of modern engineering projects.

Changes in the technological landscape have also encouraged various curriculum reforms in vocational engineering education, including electronics engineering. The development of remote laboratories, the use of interactive technologies, and learning models that simulate real industrial situations are among the strategies used to maintain the relevance of learning (Ak et al., 2018; Wahyudianto et al., 2025). Nevertheless, the presence of technology and modern facilities does not automatically guarantee the development of higher-order thinking capacities such as creativity and design thinking, because these capacities depend greatly on how pedagogical strategies are designed. In other words, electronics engineering learning in vocational education currently has strong potential to respond to industrial demands, but at the same time faces a serious challenge: how to design learning experiences that not only strengthen technical skills, but also develop students' ability to design solutions, adapt, and innovate.

### **Design Thinking**

Design thinking in vocational education is understood as a human-centered, iterative framework oriented toward solving real problems through the stages of empathy, problem definition, idea development, prototyping, and testing. This approach emphasizes creativity, exploration, and the willingness to iterate based on feedback. A number of studies position design thinking as an approach that is relevant to the demands of contemporary work, particularly in engineering and technology fields, because it helps connect technical knowledge with user needs and socio-economic contexts (Liu & Leong, 2022). In vocational education, design thinking is often associated with the development of entrepreneurial and innovation capacities, but such claims still need to be examined critically at the level of learning practice, not merely in curriculum documents.

For the purposes of this study, design thinking is operationally formulated into six dimensions as proposed by Ladachart et al. (2022): first, being comfortable with uncertainty and risks; second, human-centeredness; third, mindfulness to the process and impacts on others; fourth, collaboratively working with diversity; fifth, orientation to learning by making and testing; and sixth, being confident and optimistic to use creativity. These six dimensions position design thinking not merely as a sequence of procedural steps, but as a set of dispositions and ways of interacting with problems, other people, and the learning process.

In the context of students in the Electronics Engineering Expertise Program, these six dimensions are relevant when they are required to design technical solutions under conditions

of incomplete information, work in heterogeneous teams, and still consider the needs of end users. The dimension of being comfortable with uncertainty and risks is important because electronics engineering practice often requires decision making under conditions where data are not fully certain, for example when designing or modifying circuits that have not yet been tested in a particular environment. Human-centeredness encourages students not to focus solely on technical accuracy, but also on user experience and needs, such as safety, ease of use, and sustainability. Mindfulness to the process and impacts on others requires awareness that design decisions can affect colleagues, users, and the environment. Collaboratively working with diversity is consistent with the reality that electronics engineering projects almost always involve teamwork with different role distributions. Orientation to learning by making and testing emphasizes that mastery of concepts and procedures needs to be complemented by prototyping activities and repeated experimentation. Finally, being confident and optimistic to use creativity becomes a prerequisite for students' courage to propose alternative solutions, rather than merely imitating existing examples.

Although the framework of Ladachart et al. (2022) provides a fairly detailed definition of design thinking, empirical literature shows that the design thinking ability of vocational students, including those in electronics engineering, has not developed in accordance with this ideal. Nordin et al. (2022) found that many students still rely on linear and conventional problem-solving patterns when dealing with complex technical challenges. Aflatoony et al. (2017) reported that students and university students have difficulty shifting from traditional learning patterns to practices that provide space for exploration and iteration, so dimensions such as comfort with uncertainty and the courage to use creativity have not appeared strongly. Syah and Nasri (2023) highlighted that vocational programs still emphasize routine technical skills, while human-centeredness, collaboration in diversity, and reflection on social impact have not become explicit areas of focus.

On the other hand, when design thinking is genuinely integrated into learning design, several studies show positive impacts. Novak and Mulvey (2020) found that the integration of design thinking into instructional technology can improve students' creative confidence, which is aligned with the dimension of being confident and optimistic to use creativity. Lin et al. (2024) reported that the implementation of design thinking can improve learning motivation, especially when students are involved in repeated processes of making and testing solutions, which relates to the dimension of orientation to learning by making and testing. However, there remains a considerable gap between such practices and the dominant reality of teaching in many vocational institutions, which still depends on lectures and routine exercises. Kustini (2023), McLaughlin et al. (2019), and Huang et al. (2023) consistently show that traditional teaching practices tend not to provide sufficient space for empathy, risk exploration, meaningful collaboration, or process reflection, making it difficult for most dimensions of design thinking to develop optimally.

In synthesis, the literature indicates two important points. First, design thinking, particularly through the six dimensions proposed by Ladachart et al. (2022), offers a rich framework for explaining the types of abilities needed by vocational students in an innovation-based industrial era. Second, empirical evidence indicates that the achievement of these dimensions among vocational students remains low, especially in learning environments dominated by traditional methods. This condition opens space for more specific research, for example by examining whether a more authentic and contextual learning model, such as Teaching Factory, can truly contribute to strengthening the six dimensions of design thinking among students in the Electronics Engineering Expertise Program.

### **Teaching Factory (TEFA)**

Teaching Factory (TEFA) was introduced as a model that seeks to reduce the gap between vocational education and real industrial practice. The core of TEFA is the creation of a learning environment that resembles or is integrated with production and service

processes in the business sector, enabling students to learn while being involved in activities that have value and standards relevant to the labor market (Ismayati et al., 2020; Bikas et al., 2021). Within this framework, learning is no longer understood merely as the transfer of knowledge from teacher to student, but as a process of participation in professional practice, including dealing with demands related to quality, time, cost, and team coordination. This approach is offered as a response to the criticism that vocational education is too theoretical and insufficiently connected to workplace realities, especially in technical fields such as electronics engineering.

TEFA implementation usually takes place through direct collaboration between schools and industry, in which the projects, products, or services completed by students are designed based on real needs. Several studies have shown that this approach can improve curriculum relevance, student engagement, and the alignment of graduates' competencies with industry needs (Ismayati et al., 2020; Bikas et al., 2021). In addition, TEFA is often associated with strengthening entrepreneurial orientation because students engage with the processes of product design, production, and possible commercialization. Nugroho et al. (2024) and Iliani et al. (2022) reported that involvement in Teaching Factory projects contributes to the growth of entrepreneurial interest and readiness to face industrial challenges. These findings should certainly be interpreted carefully, but they at least indicate that TEFA is not only intended to improve technical skills, but also students' attitudes and career orientation.

In this study, the TEFA framework refers to the phases formulated by Hulyadi et al. (2025). The model begins with the identification of unmet market needs, namely the mapping of industrial or user needs for products and systems that are not yet adequately available. In the context of the Electronics Engineering Expertise Program, this phase may involve identifying the need for electronic devices, systems, or solutions in industrial, household, or service-sector environments, such as automation needs, monitoring systems, or energy-efficient devices. The next phase is orientation, which prepares students for the project through the introduction of industrial contexts, initial specifications of electronic products, and role distribution within teams. After that, the problem statement phase focuses on formulating the problem in a more structured manner, for example by defining circuit design challenges, technical constraints, safety standards, and performance criteria that must be achieved.

The next stage is concept design, which directs students to develop electronic solution concepts based on the formulated problem. At this stage, students explore several design alternatives, select components, prepare system block diagrams, and consider ergonomic aspects and ease of maintenance. The up-skilling phase includes training to develop the production and testing skills needed, such as advanced soldering techniques, microcontroller programming, the use of PCB design software, or measuring instruments. After basic production competencies are strengthened, implementation is carried out by executing the production or prototype assembly process according to industrial standards, including work scheduling, quality control, and technical documentation.

The cycle continues to evaluation, namely testing the performance of electronic products in the field or under conditions that simulate real use. At this stage, students analyze whether the prototype meets technical specifications, safety standards, and user needs. Based on the evaluation results, iteration and scale-up are carried out by revising the design, improving the production process, and preparing scenarios for increasing production scale if the solution is considered technically and economically feasible. In the framework of Hulyadi et al. (2025), this series of phases is directed toward effective solutions, which in this study are interpreted as electronic product or system solutions that are functional, meet market needs, and can be replicated on a broader scale.

From a pedagogical perspective, the TEFA phase structure proposed by Hulyadi et al. (2025) has strong potential to support the development of higher-order thinking skills,

including design thinking. Each phase contains explicit opportunities for students to empathize with users through unmet market needs and problem statement activities, develop ideas and create prototypes through concept design and implementation, learn through making and testing during implementation and evaluation, and consciously carry out iteration through the iteration and scale-up phase. This is consistent with the findings of Wahjusaputri and Bunyamin (2022), who stated that TEFA encourages a systematic problem-solving approach in the context of authentic industrial challenges, as well as with the findings of Muslim et al. (2020), Patria et al. (2024), and Maksum et al. (2022), which showed improvements in critical thinking, creativity, collaboration, and metacognition through involvement in TEFA. The question, which then becomes the focus of this study, is the extent to which the implementation of these TEFA phases can actually strengthen the dimensions of design thinking among students in the Electronics Engineering Expertise Program.

## METHOD

### Research Design

This study employed a mixed-methods approach with an explanatory sequential design (Creswell, 2009). In this design, quantitative data collection and analysis were conducted first, followed by qualitative data collection and analysis. The quantitative phase was used to examine the effectiveness of the Teaching Factory (TEFA) model in improving the design thinking of students in the Electronics Engineering Expertise Program, while the qualitative phase was used to obtain contextual explanations of the factors that supported or inhibited the development of design thinking during the implementation of TEFA.

The quantitative phase used a quasi-experimental design with a pretest-posttest control group design. This design was used because the experimental and control groups were drawn from existing classes at the school; therefore, student placement was not conducted through individual randomization. The experimental group received instruction using the Teaching Factory model, whereas the control group received expository instruction. Both groups were given a pretest before instruction and a posttest after instruction to determine changes in students' design thinking.

**Table 1.** Research design

Group	Pretest	Treatment	Posttest
Experimental	O <sub>1</sub>	Teaching Factory model	O <sub>2</sub>
Control	O <sub>1</sub>	Expository instruction	O <sub>2</sub>

Note: O<sub>1</sub> = initial measurement of design thinking; O<sub>2</sub> = final measurement of design thinking.

The qualitative phase was conducted after the implementation of instruction and the collection of quantitative data. Qualitative data were collected through semi-structured interviews with students from the experimental group and the teacher involved in the learning process. The interviews were directed at exploring students' and teacher's experiences during the implementation of TEFA, particularly those related to understanding user needs, group work, technical problem solving, product development and testing, design revision, and the development of students' confidence in proposing creative ideas. The integration of quantitative and qualitative data was conducted at the interpretation stage by connecting patterns of change in design thinking scores with empirical experiences obtained from the interviews.

### Participants

The participants in the quantitative phase were eleventh-grade students in the Electronics Engineering Expertise Program at SMK Negeri 1 Pringgabaya. The profile of the research participants is presented in Table 2. The number of participants analyzed was 39 students, consisting of 19 students in the experimental group and 20 students in the control group. All participants were at the vocational secondary education level and enrolled in the

same expertise program. The age range of participants was 16 to 18 years. The experimental group consisted of 9 male students and 10 female students, while the control group consisted of 16 male students and 4 female students.

**Table 2.** Profile of research participants

Participant	N	Age	Program/Role	Gender Composition
- Experimental group students	19	16–18 years	Eleventh-grade students in Electronics Engineering.	9 male students, 10 female students
- Control group students	20	16–17 years	Eleventh-grade students in Electronics Engineering.	16 male students, 4 female students
- Student informants	7	16–18 years	Students from the experimental group.	Selected purposively
- Teacher informant	1	-	Electronics Engineering teacher.	Key informant

In the qualitative phase, student informants were selected purposively from the experimental group. The selection of informants considered students' involvement in the TEFA learning process and their ability to provide information about learning experiences, technical constraints, group work, product testing processes, and the development of creative ideas. The student informants consisted of seven students, namely S-01, S-05, S-07, S-10, S-14, S-15, and S-19. One Electronics Engineering teacher who was directly involved in the implementation of TEFA was interviewed as a key informant to obtain a pedagogical perspective on the implementation of instruction, classroom dynamics, and student activities during the learning process.

### Implementation Procedure of the Teaching Factory Model

The implementation of TEFA in the experimental group was carried out through vocational learning that placed students in a sequence of activities resembling industrial work practices. In this study, the learning context used was an Automatic Plant Watering System project. This project functioned as a medium for implementing TEFA in Electronics Engineering learning, not as the title or main focus of the study. Through this context, students followed learning stages that included identifying user needs, formulating problems, designing solutions, developing prototypes, testing, revising, and reflecting.

The implementation of TEFA was conducted in six meetings. The first meeting focused on problem orientation. The teacher presented the context of the need for automatic plant watering in the school environment, after which students conducted observations, asked questions, and identified user needs. This activity produced a list of problems and project needs that served as the basis for the next stage.

The second meeting focused on idea exploration and solution design. The teacher facilitated students in discussing alternative solutions, while students developed initial ideas, compared several design alternatives, and determined the design to be developed. Activities at this stage resulted in an initial product design, including the proposed functions, main components, and system workflow.

The third meeting was directed toward work planning and role distribution. Students prepared a work schedule, divided tasks within groups, and determined the tools and materials needed. Role distribution included circuit assembly, programming, sensor installation, casing development, testing, and process documentation.

The fourth meeting was the production or prototyping stage. Students began to realize their designs into prototypes through circuit assembly, programming, sensor installation, component integration, and initial functional testing. The teacher acted as a facilitator who provided technical guidance and ensured that the work process followed safety procedures and learning objectives.

The fifth meeting focused on product testing, evaluation, and revision. Students tested the prototype functions, recorded technical problems, evaluated design weaknesses, and made improvements based on the test results. The teacher provided feedback on system functionality, circuit safety, work neatness, and product suitability to user needs.

The sixth meeting consisted of presentation and reflection. Students presented the products they had developed, explained the work process, described the challenges they faced, and reflected on their experiences during TEFA-based learning. Reflection focused on experiences in understanding user needs, working in groups, dealing with technical failures, testing products, improving designs, and proposing creative ideas.

In the control group, instruction was conducted using an expository approach. The teacher delivered the material through explanation, demonstration, and structured exercises. The material, learning outcomes, and time allocation were adjusted to match those of the experimental group. However, the control group instruction did not explicitly use the TEFA stages and did not systematically emphasize the cycle of identifying user needs, prototyping, testing, revising, and reflecting.

### **Instruments and Data Collection**

Quantitative data were collected using a design thinking questionnaire administered before and after instruction. The questionnaire used a 1-to-5 Likert scale, ranging from strongly disagree to strongly agree. The instrument was developed based on six dimensions of design thinking, namely being comfortable with uncertainty and risks, human-centeredness, mindfulness to the process and impacts on others, collaboratively working with diversity, orientation to learning by making and testing, and being confident and optimistic to use creativity. The questionnaire consisted of 30 statement items. The minimum total score was 30 and the maximum score was 150. Higher scores indicated stronger levels of design thinking.

The questionnaire items were developed by adapting design thinking indicators to the context of Electronics Engineering learning. The dimension of being comfortable with uncertainty and risks measured students' comfort in dealing with uncertainty and the risk of technical failure. The dimension of human-centeredness measured students' orientation toward user needs. The dimension of mindfulness to the process and impacts on others measured students' attention to work processes, safety, and the impact of solutions. The dimension of collaboratively working with diversity measured students' ability to work in teams with role distribution and differences of opinion. The dimension of orientation to learning by making and testing measured students' tendency to learn through making, testing, and revising. The dimension of being confident and optimistic to use creativity measured students' confidence in using creativity to solve technical problems.

Qualitative data were collected through semi-structured interviews. The student interview guide focused on students' experiences in participating in TEFA-based learning, their understanding of user needs, technical constraints encountered during tool design and testing, group collaboration, the process of creating and improving products, confidence in proposing creative ideas, and the supporting and inhibiting factors in learning. The teacher interview guide focused on the implementation of TEFA, observations of student activities, students' responses to technical problems, the quality of group work, learning phases considered important, and the supporting and inhibiting factors in TEFA implementation. In addition to questionnaires and interviews, learning documents and activity notes were used as supporting data.

### **Data Analysis**

Quantitative data were analyzed using descriptive and inferential statistics. Descriptive statistics included mean, standard deviation, minimum score, maximum score, gain, and N-

gain. Gain was calculated as the difference between posttest and pretest scores. N-gain was calculated using the following formula:

$$N\text{-gain} = (\text{posttest score} - \text{pretest score}) / (\text{maximum score} - \text{pretest score})$$

The N-gain category was determined based on the following criteria: high if N-gain  $\geq 0.70$ ; moderate if  $0.30 \leq \text{N-gain} < 0.70$ ; and low if N-gain  $< 0.30$ . N-gain calculations were conducted for the total design thinking score and for each dimension of design thinking.

Before difference testing was conducted, the data were examined through assumption tests. The normality test was conducted using the Shapiro-Wilk test, while the homogeneity of variance test was conducted using Levene's test. The decision to use parametric tests was based on whether the assumptions of normality and homogeneity were met. The increase in scores from pretest to posttest within each group was analyzed using the paired-samples t-test. Differences in pretest, posttest, gain, and N-gain scores between the experimental and control groups were analyzed using the independent-samples t-test. One-way ANOVA was used to examine differences in posttest, gain, and N-gain scores based on the learning group.

ANCOVA was used as an additional analysis, with the design thinking posttest score as the dependent variable, learning group as the independent variable, and pretest score as the covariate. Before ANCOVA was applied, relevant assumptions were examined, including the linearity of the relationship between the covariate and the dependent variable and the homogeneity of regression slopes. Effect sizes were reported to complement the inferential test results, namely Cohen's *d* for between-group difference tests, *dz* for within-group pretest-posttest tests, eta squared ( $\eta^2$ ) for ANOVA, and partial eta squared ( $\eta_p^2$ ) for ANCOVA.

Qualitative data were analyzed using thematic analysis. The analysis was conducted through several stages: repeatedly reading the interview transcripts, identifying units of meaning, coding important statements, grouping codes into themes, and interpreting the themes based on the research focus. Coding was directed toward themes related to TEFA implementation and the six dimensions of design thinking. Student and teacher data were compared to identify similarities, differences, and relationships among themes. The results of the qualitative analysis were then used to provide contextual explanations for the patterns of change in design thinking scores and the dynamics of TEFA implementation.

### Research Ethics

This study was conducted by observing the ethical principles of educational research. Before data collection, the researcher obtained permission from the school and coordinated with the teacher involved in the learning process. Students were informed about the purpose of the study, the form of their involvement, and the use of data for academic purposes. Participant identities were kept confidential by using codes, such as E for the experimental group, C for the control group, S for student informants, and T for the teacher informant. Students' participation in completing the questionnaire and interviews was voluntary. The collected data were used for analysis and scientific reporting.

### RESULTS

The measurement results showed that the Teaching Factory (TEFA) model in vocational education contributed positively to improving the design thinking of students in the Electronics Engineering Expertise Program. In the implementation of the study, TEFA was operationalized through vocational learning activities that placed students in the process of identifying user needs, designing solutions, developing prototypes, testing, revising, and reflecting on products. The project context used in the learning implementation was an Automatic Plant Watering System, so students did not merely complete technical tasks but also dealt with user needs, field constraints, product function standards, and iterative improvement processes.

### Effectiveness of the Teaching Factory Model on Students' Design Thinking

The descriptive analysis showed that the experimental group experienced a greater increase in design thinking scores than the control group. The descriptive statistics of students' total design thinking scores are presented in Table 3 and visualized in Figure 1.

**Table 3.** Descriptive statistics of students' total design thinking scores

Group	N	Pretest M ± SD	Posttest M ± SD	Gain M ± SD	N-gain M ± SD	Min-Max	Mean N-gain Category
Experimental	19	93.63 ± 8.06	129.05 ± 6.62	35.42 ± 6.99	0.63 ± 0.10	0.46-0.76	Moderate
Control	20	91.05 ± 5.63	114.35 ± 5.73	23.30 ± 8.51	0.39 ± 0.12	0.18-0.60	Moderate

In the experimental group, the mean pretest score of 93.63 increased to 129.05 in the posttest. The mean gain of the experimental group was 35.42, with a mean N-gain of 0.63. In the control group, the mean pretest score of 91.05 increased to 114.35 in the posttest. The mean gain of the control group was 23.30, with a mean N-gain of 0.39. Both groups were in the moderate N-gain category, but the mean N-gain value of the experimental group was higher than that of the control group.



**Figure 1.** Comparison of mean pretest and posttest design thinking scores in the experimental and control groups

Figure 1 shows that the initial design thinking scores of the two groups were relatively close, namely 93.63 in the experimental group and 91.05 in the control group. After instruction, both groups showed improvement, but the increase in the experimental group was more pronounced. The posttest score of the experimental group reached 129.05, while that of the control group reached 114.35. This pattern indicates that the implementation of TEFA produced a stronger increase in design thinking scores than expository instruction.

The distribution of N-gain categories showed different improvement patterns between the two groups, as presented in Table 4. In the experimental group, 7 students were in the high category and 12 students were in the moderate category. No students in the experimental group were in the low category. In the control group, no students reached the high category; 15 students were in the moderate category and 5 students were in the low category.

**Table 4.** Distribution of N-gain categories for design thinking

Group	N	High	Moderate	Low
Experimental	19	7	12	0
Control	20	0	15	5

Before difference testing was conducted, the data were examined for normality and homogeneity. The Shapiro-Wilk (W) test results showed that the pretest, posttest, gain, and N-gain data in both the experimental and control groups were normally distributed because all p-values were greater than 0.05. The homogeneity of variance test using Levene's test also

showed that the variances of the two groups were homogeneous for all tested variables. Therefore, parametric analysis could be used to examine differences in design thinking scores. The results of the normality and homogeneity tests for total design thinking scores are presented in Table 5.

**Table 5.** Results of normality and homogeneity tests for total design thinking scores

Variable	W Exp.	p	W Con.	p	Levene F	p	Decision
Pretest	0.953	0.436	0.935	0.191	1.761	0.193	Normal & homogeneous
Posttest	0.946	0.340	0.957	0.484	0.382	0.540	Normal & homogeneous
Gain	0.979	0.935	0.962	0.575	0.386	0.538	Normal & homogeneous
N-gain	0.915	0.090	0.982	0.962	0.074	0.787	Normal & homogeneous

Next, the paired-samples t-test was used to examine the increase in design thinking scores from pretest to posttest within each group. The results of the paired-samples t-test for pretest-posttest design thinking scores in each group are presented in Table 6. The results in Table 6 show that both the experimental and control groups experienced significant improvement. In the experimental group, the increase from pretest to posttest was significant,  $t(18) = 22.099$ ,  $p < 0.001$ , with an effect size of  $dz = 5.07$ . In the control group, the increase from pretest to posttest was also significant,  $t(19) = 12.244$ ,  $p < 0.001$ , with an effect size, or Cohen's d-sub-z ( $dz$ ), of 2.74. This means that both groups improved after instruction, but the improvement in the experimental group was greater.

**Table 6.** Results of the pretest-posttest design thinking test within each group

Group	Pretest M ± SD	Posttest M ± SD	Difference M ± SD	t	df	p	dz	Decision
Experimental	93.63 ± 8.06	129.05 ± 6.62	35.42 ± 6.99	22.099	18	<0.001	5.07	Significant
Control	91.05 ± 5.63	114.35 ± 5.73	23.30 ± 8.51	12.244	19	<0.001	2.74	Significant

Between-group difference tests were conducted to determine whether there were differences in initial scores, final scores, gain, and N-gain between the experimental and control groups. The results of the difference tests for design thinking scores between the experimental and control groups are presented in Table 7.

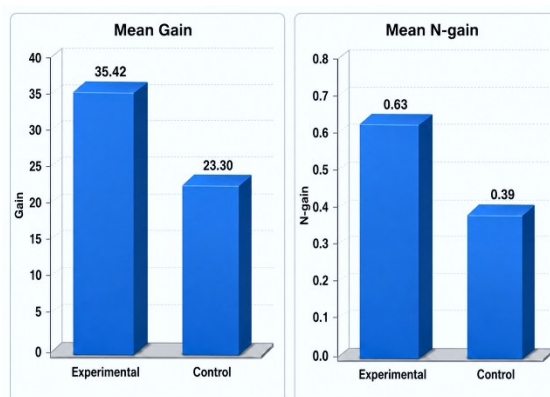
**Table 7.** Results of difference tests for design thinking scores

Tested Data	Exp. M ± SD	Control M ± SD	Mean Diff.	t	df	p	Cohen's d	Decision
Pretest	93.63 ± 8.06	91.05 ± 5.63	2.58	1.165	37	0.252	0.37	Not significant
Posttest	129.05 ± 6.62	114.35 ± 5.73	14.70	7.425	37	<0.001	2.38	Significant
Gain	35.42 ± 6.99	23.30 ± 8.51	12.12	4.847	37	<0.001	1.55	Significant
N-gain	0.63 ± 0.10	0.39 ± 0.12	0.24	7.009	37	<0.001	2.25	Significant

The pretest difference test showed no significant difference between the experimental and control groups,  $t(37) = 1.165$ ,  $p = 0.252$ . This indicates that the initial design thinking abilities of the two groups were relatively comparable before the instructional treatment was given.

For the posttest scores, there was a significant difference between the experimental and control groups,  $t(37) = 7.425$ ,  $p < 0.001$ , with Cohen's  $d = 2.38$ . The experimental group obtained a higher mean posttest score than the control group. The gain difference test also showed a significant difference,  $t(37) = 4.847$ ,  $p < 0.001$ , with Cohen's  $d = 1.55$ . Similarly,

the N-gain difference test showed a significant difference,  $t(37) = 7.009$ ,  $p < 0.001$ , with Cohen's  $d = 2.25$ . These results indicate that the improvement in students' design thinking in the TEFA group was higher than that in the expository instruction group. Figure 2 further emphasizes the difference in design thinking improvement between the two groups.



**Figure 2.** Comparison of mean gain and N-gain between the experimental and control groups

The mean gain of the experimental group was 35.42, which was higher than that of the control group at 23.30. A similar difference was also observed in N-gain, namely 0.63 in the experimental group and 0.39 in the control group. Thus, the difference in effectiveness was not only reflected in the final scores, but also in the magnitude of improvement achieved by students after instruction.

One-way ANOVA was conducted as an additional test to examine the effect of learning group on posttest, gain, and N-gain scores, as presented in Table 8.

**Table 8.** Results of one-way ANOVA for posttest, gain, and N-gain scores based on learning group

Dependent Variable	df	F	p	$\eta^2$	Decision
Posttest	1, 37	55.134	<0.001	0.598	Significant
Gain	1, 37	23.490	<0.001	0.388	Significant
N-gain	1, 37	49.128	<0.001	0.570	Significant

The ANOVA results showed that the learning group had a significant effect on posttest scores,  $F(1,37) = 55.134$ ,  $p < 0.001$ , with eta squared ( $\eta^2$ ) = 0.598. This means that approximately 59.8% of the variation in posttest scores could be associated with differences in learning groups. For gain scores, the ANOVA result was also significant,  $F(1,37) = 23.490$ ,  $p < 0.001$ , with  $\eta^2 = 0.388$ . For N-gain, the ANOVA result showed a significant difference,  $F(1,37) = 49.128$ ,  $p < 0.001$ , with  $\eta^2 = 0.570$ . Thus, differences in learning models made a strong contribution to improving students' design thinking.

ANCOVA was conducted with posttest score as the dependent variable, learning group as the independent variable, and pretest score as the covariate. The results of ANCOVA for design thinking posttest scores with pretest as a covariate are presented in Table 9.

**Table 9.** Results of ANCOVA for design thinking posttest scores with pretest as a covariate

Analysis Component	df	F	p	$\eta p^2$	Adjusted Mean	Decision
Homogeneity of regression slopes test: pretest $\times$ group	1, 35	4.122	0.050	0.105	-	Marginal
Covariate: pretest	1, 36	3.403	0.073	0.086	-	Not significant
Learning group	1, 36	51.537	<0.001	0.589	Exp. = 128.71; Control = 114.68	Significant

The ANCOVA results showed that after controlling for pretest scores, the learning group still had a significant effect on posttest scores,  $F(1,36) = 51.537$ ,  $p < 0.001$ , with partial eta squared ( $\eta p^2$ ) = 0.589. The adjusted posttest mean in the experimental group was 128.71,

while that in the control group was 114.68. However, the homogeneity of regression slopes test showed a p-value of 0.050. Because this value was at the threshold of significance, the ANCOVA results were positioned as a supporting analysis. The main conclusion remains stronger when based on the gain and N-gain difference tests.

Based on this series of analyses, the TEFA model was effective in improving the design thinking of students in the Electronics Engineering Expertise Program. This effectiveness was evident from the increase from pretest to posttest in the experimental group, the significant posttest difference between the experimental and control groups, and the significant differences in gain and N-gain with large effect sizes.

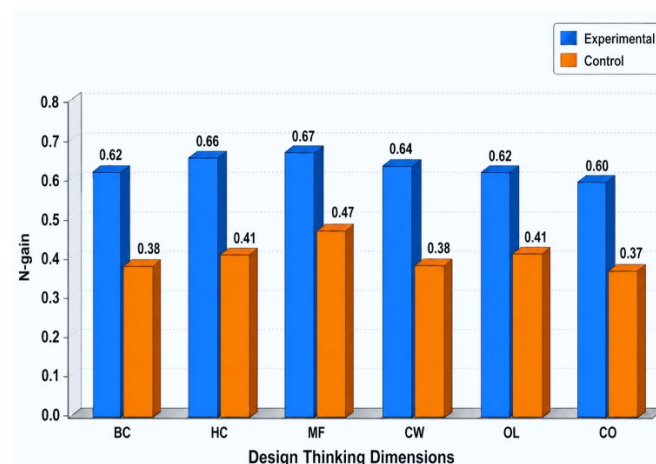
### Improvement in Design Thinking Based on Dimensions

Dimension-based analysis was conducted to identify which aspects of design thinking improved after the implementation of TEFA. The six dimensions analyzed were being comfortable with uncertainty and risks (BC), human-centeredness (HC), mindfulness to the process and impacts on others (MF), collaboratively working with diversity (CW), orientation to learning by making and testing (OL), and being confident and optimistic to use creativity (CO). The results are presented in Table 10 and visualized in Figure 3.

**Table 10.** Descriptive statistics based on dimensions of design thinking

Dimension	Group	Pretest M $\pm$ SD	Posttest M $\pm$ SD	Gain M $\pm$ SD	N-gain M $\pm$ SD	Category
BC	Exp.	16.95 $\pm$ 2.93	25.00 $\pm$ 2.24	8.05 $\pm$ 2.57	0.62 $\pm$ 0.12	Moderate
	Control	17.05 $\pm$ 2.28	21.95 $\pm$ 2.11	4.90 $\pm$ 2.13	0.38 $\pm$ 0.14	Moderate
HC	Exp.	12.47 $\pm$ 1.35	17.47 $\pm$ 1.12	5.00 $\pm$ 1.67	0.66 $\pm$ 0.15	Moderate
	Control	11.95 $\pm$ 1.43	15.30 $\pm$ 1.42	3.35 $\pm$ 1.60	0.41 $\pm$ 0.17	Moderate
MF	Exp.	9.63 $\pm$ 0.68	13.21 $\pm$ 0.85	3.58 $\pm$ 0.90	0.67 $\pm$ 0.15	Moderate
	Control	9.40 $\pm$ 1.39	12.00 $\pm$ 1.17	2.60 $\pm$ 1.10	0.47 $\pm$ 0.17	Moderate
CW	Exp.	16.32 $\pm$ 1.57	21.79 $\pm$ 1.58	5.47 $\pm$ 1.47	0.64 $\pm$ 0.16	Moderate
	Control	15.85 $\pm$ 1.39	19.30 $\pm$ 1.78	3.45 $\pm$ 1.70	0.38 $\pm$ 0.18	Moderate
OL	Exp.	13.42 $\pm$ 1.57	17.53 $\pm$ 1.35	4.11 $\pm$ 1.63	0.62 $\pm$ 0.19	Moderate
	Control	13.05 $\pm$ 1.19	15.90 $\pm$ 1.65	2.85 $\pm$ 1.53	0.41 $\pm$ 0.20	Moderate
CO	Exp.	24.84 $\pm$ 2.71	34.05 $\pm$ 2.25	9.21 $\pm$ 3.15	0.60 $\pm$ 0.15	Moderate
	Control	23.75 $\pm$ 2.22	29.90 $\pm$ 2.67	6.15 $\pm$ 3.22	0.37 $\pm$ 0.17	Moderate

In the experimental group, all dimensions improved. The highest mean N-gain was found in the dimension of mindfulness to the process and impacts on others at 0.67, followed by human-centeredness at 0.66, collaboratively working with diversity at 0.64, being comfortable with uncertainty and risks at 0.62, orientation to learning by making and testing at 0.62, and being confident and optimistic to use creativity at 0.60. In the control group, all dimensions also increased, but the N-gain values were lower than those in the experimental.



**Figure 3.** Mean N-gain for each dimension of design thinking

Figure 3 shows that the experimental group obtained higher mean N-gain scores across all design thinking dimensions than the control group. The dimension with the highest improvement in the experimental group was mindfulness to the process and impacts on others at 0.67, followed by human-centeredness at 0.66 and collaboratively working with diversity at 0.64. Meanwhile, the control group showed lower improvement across all dimensions, with the highest value in mindfulness to the process and impacts on others at 0.47. This pattern indicates that TEFA did not only affect total scores, but also strengthened various aspects of design thinking more evenly.

Next, difference testing of N-gain based on design thinking dimensions between the experimental and control groups was conducted, and the results are presented in Table 11.

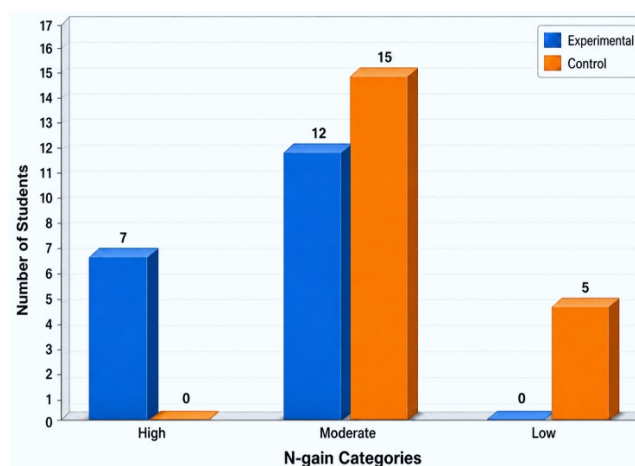
**Table 11.** Results of N-gain difference tests based on design thinking dimensions

Dimension	Exp. M	Con. M	t	df	p	Cohen's d	F	$\eta^2$	Decision
BC	0.62	0.38	5.679	37	<0.001	1.82	32.252	0.466	Significant
HC	0.66	0.41	4.868	37	<0.001	1.56	23.693	0.390	Significant
MF	0.67	0.47	4.022	37	<0.001	1.29	16.178	0.304	Significant
CW	0.64	0.38	4.902	37	<0.001	1.57	24.031	0.394	Significant
OL	0.62	0.41	3.291	37	0.002	1.05	10.828	0.226	Significant
CO	0.60	0.37	4.569	37	<0.001	1.46	20.877	0.361	Significant

The N-gain difference tests for each dimension showed that the experimental group had significantly higher improvement than the control group across all dimensions of design thinking. The largest difference was found in the BC dimension, with  $t(37) = 5.679$ ,  $p < 0.001$ , Cohen's  $d = 1.82$ , and eta squared ( $\eta^2$ ) = 0.466. Other dimensions also showed significant differences with large effect sizes, namely HC, MF, CW, OL, and CO. Thus, TEFA did not only improve the total design thinking score, but also improved all dimensions that constitute design thinking.

The improvement in the BC dimension indicates that students in the experimental group developed a stronger ability to deal with uncertainty and risk during the completion of vocational tasks. The improvement in HC indicates that students began to consider user needs, such as water-use efficiency, ease of operation, and tool safety. The improvement in MF shows that students paid more attention to work processes and product impacts. The improvement in CW indicates the development of group work based on role distribution and the resolution of differences of opinion. The improvement in OL was reflected in the activities of making, testing, calibrating, and revising products. The improvement in CO indicates that students became more confident in proposing creative ideas, although this dimension still leaves room for further strengthening.

The distribution of N-gain categories for design thinking in the experimental and control groups is visualized in Figure 4.



**Figure 4.** Distribution of N-gain categories for design thinking

Figure 4 shows a different distribution of N-gain categories between the experimental and control groups. In the experimental group, 7 students reached the high category and 12 students were in the moderate category, with no students in the low category. In contrast, in the control group, no students were in the high category, 15 students were in the moderate category, and 5 students were in the low category. This finding indicates that TEFA not only improved the mean score, but also encouraged more students to reach a better level of improvement.

### Supporting and Inhibiting Factors in the Development of Design Thinking through TEFA

The qualitative findings were used to explain the factors that supported and inhibited the development of design thinking during TEFA-based learning. The student interview findings on the development of design thinking through TEFA are presented in Table 12.

**Table 12.** Student interview findings on the development of design thinking through TEFA

Informant Code	Interview Focus	Summary of Empirical Findings	Related Design Thinking
S-01	Experience participating in TEFA	The student considered the project interesting but challenging because they had to work quickly and neatly, similar to an industrial setting. The most interesting part was when the pump could turn on automatically when the soil was dry, while the most difficult part was Arduino debugging and soil moisture sensor calibration.	Orientation to learning by making and testing; mindfulness to the process
S-05	Understanding user needs	The student identified the needs of the school gardener, such as fatigue caused by manual watering, the need to save water, ease of use, and tool safety from rain or short circuits.	Human-centeredness
S-07	Problems in designing, assembling, programming, and testing	The student faced problems with unstable sensors, voltage noise, and Arduino coding errors. Solutions were carried out through troubleshooting, checking paths with a multimeter, reading the serial monitor, searching for references, and consulting the teacher.	Being comfortable with uncertainty and risks; mindfulness to the process
S-10	Group collaboration	Task distribution was carried out based on members' expertise, such as hardware, coding, and casing. Differences of opinion regarding sensor position were resolved through direct field testing.	Collaboratively working with diversity
S-14	Making, testing, and improving products	The processes of assembling and disassembling, sensor calibration, and debugging helped the student understand the relationship between component theory and the overall working system of the tool.	Orientation to learning by making and testing; problem solving
S-15	Confidence in proposing creative ideas	The student felt more courageous in proposing ideas, such as adding a three-color LED as a soil condition indicator and a fuse for circuit safety.	Being confident and optimistic to use creativity

Informant Code	Interview Focus	Summary of Empirical Findings	Related Design Thinking
S-19	Supporting and inhibiting factors	Supporting factors included teacher guidance, workshop facilities, complete tools, and freedom to try solutions. Inhibiting factors included limited project time, less-than-optimal quality control, and uneven initial ability in C/C++ programming.	All dimensions, especially prototyping, testing, and creative confidence

The student interview data showed that learning through a real project engaged students in the process of understanding user needs, solving technical problems, dividing roles within groups, testing products, improving designs, and proposing creative ideas.

The teacher interview data strengthened the student findings. The teacher interview findings on TEFA implementation and students' design thinking are presented in Table 13.

**Table 13.** Teacher interview findings on TEFA implementation and students' design thinking

Teacher Code	Interview Focus	Summary of Empirical Findings	Implications for Design Thinking
T-01	Implementation of TEFA in learning	TEFA ran systematically and placed students in an industrial work atmosphere. The stages of identifying customer needs, production, testing, and product handover were implemented as planned.	TEFA provided an authentic context for developing design thinking
T-01	Changes in understanding problems and user needs	Students shifted from merely focusing on making circuits work to paying attention to end users, ergonomics, ease of operation, and tool safety protection.	Strengthened human-centeredness
T-01	Students' attitudes in facing technical problems	When sensors were unstable, coding errors occurred, or the system did not work, students began to discuss, map potential failures, and conduct partial testing of components.	Strengthened resilience in facing uncertainty and reflection on process
T-01	Group collaboration	Task distribution was based on competence, such as programming, hardware, and casing finishing. Design conflicts were resolved through technical compromises that prioritized tool function.	Strengthened collaboration in diversity
T-01	The most influential TEFA activities	The customer identification phase and product revision after testing were considered the most influential in encouraging students' empathy, critical thinking, and creativity.	Strengthened human-centeredness, prototyping, testing, and iteration
T-01	Supporting and inhibiting factors	Supporting factors included project worksheets, electronic components, the TAV laboratory, and motivation because the product was used in real situations. Inhibiting factors included limited time and uneven C programming ability.	TEFA success depended on facilities, time, and students' technical readiness
T-01	Dimensions that developed most and	The most visible dimensions developed were interdisciplinary collaboration and user orientation. The	TEFA was effective, but additional strategies were

Teacher Code	Interview Focus	Summary of Empirical Findings	Implications for Design Thinking
	still needed strengthening	dimension that still needed strengthening was creative confidence, especially the courage to choose innovative solutions.	needed to strengthen innovation courage

The teacher stated that TEFA created an industrial work atmosphere, encouraged discipline in following SOPs, and made students focus not only on the technical success of the tool, but also on user needs, safety, product quality, and ease of use. The teacher also observed that students were more able to conduct troubleshooting when facing technical problems.

A synthesis of interview data was conducted to identify the supporting and inhibiting factors in the development of design thinking through TEFA. The synthesis results are presented in Table 14.

**Table 14.** Synthesis of supporting and inhibiting factors in the development of design thinking through TEFA

Type of Factor	Specific Factor	Empirical Evidence	Impact on Design Thinking
Supporting	Real project in TEFA-based learning	The product was developed to address the need for plant watering in the school environment	Made learning more authentic and meaningful
Supporting	User involvement	Students identified the needs of the school gardener, water efficiency, tool safety, and ease of use	Strengthened human-centeredness
Supporting	Prototyping and testing	Students assembled, tested, calibrated, debugged, and revised the product	Strengthened orientation to learning by making and testing
Supporting	Role-based collaboration	Tasks were divided based on hardware, coding, casing, and testing abilities	Strengthened collaboratively working with diversity
Supporting	Teacher guidance and project worksheets	The teacher provided guidance, worksheets helped organize the project workflow, and students received guidance on work stages	Kept the TEFA process structured
Supporting	Workshop facilities and electronic components	The availability of tools and materials supported production and testing processes	Supported experimentation, evaluation, and product revision
Supporting	Product used in a real context	Students were motivated because their work was not only a classroom assignment, but was used in the school environment	Increased responsibility and work quality
Inhibiting	Limited time	Project time was considered insufficient, especially for prototyping, quality control, and revision stages	Limited the depth of design iteration
Inhibiting	Uneven coding ability	Some students were not yet proficient in Arduino or C/C++, causing the debugging process to run slowly	Hindered smooth implementation and testing

Type of Factor	Specific Factor	Empirical Evidence	Impact on Design Thinking
Inhibiting	Technical problems with sensors and circuits	Unstable sensors, voltage noise, wiring problems, and program errors often occurred	Required troubleshooting skills that were not evenly developed
Inhibiting	Tendency to choose safe solutions	Some students still chose conventional technical solutions instead of exploring new features	Limited creative confidence and the courage to take innovation risks

Based on the synthesis of interview data, the main supporting factors for the development of design thinking through TEFA were project authenticity, user involvement, prototyping and testing processes, role-based group work, teacher guidance, project worksheets, workshop facilities, and students' motivation because the product was used in a real context. The inhibiting factors were limited time, uneven initial programming ability, technical difficulties with sensors and coding, and the tendency of some students to choose safe and conventional solutions.

The quantitative and qualitative results showed a mutually reinforcing pattern. Quantitatively, the experimental group experienced greater improvement in design thinking than the control group, both in total scores, gain, N-gain, posttest scores, and all dimensions of design thinking. Qualitatively, this improvement was reflected in students' experiences in understanding user needs, facing technical constraints, working collaboratively, conducting prototyping and testing, and proposing creative solutions. Therefore, the TEFA model in vocational education can be considered effective in improving the design thinking of students in the Electronics Engineering Expertise Program, although its effectiveness remains influenced by sufficient time, students' technical readiness, the quality of teacher guidance, and support for practical facilities.

## DISCUSSION

The findings of this study indicate that the Teaching Factory (TEFA) model in vocational education was effective in improving the design thinking of students in the Electronics Engineering Expertise Program. This effectiveness was evident from the increase in pretest-to-posttest scores in the experimental group, the significant difference in posttest scores between the experimental and control groups, and the differences in gain and N-gain that demonstrated the advantage of the experimental group. The mean N-gain of the experimental group was in the moderate category, but its value was higher than that of the control group. In addition, the proportion of students who reached the high N-gain category appeared only in the experimental group, whereas the control group still included students in the low category. This pattern indicates that TEFA did not merely produce an increase in mean scores, but also encouraged more students to reach a better level of design thinking development.

The statistical test results strengthen this interpretation. The pretest difference test showed that the initial design thinking abilities of the two groups were relatively comparable, so the differences in final outcomes can be more reasonably attributed to the different learning models implemented. The posttest, gain, N-gain, and ANOVA tests showed significant differences with large effect sizes, meaning that the improvement was not only statistically significant but also practically meaningful in the context of vocational learning. The ANCOVA results also showed a significant effect of learning group on posttest scores after controlling for pretest scores. However, because the homogeneity of regression slopes test was at the threshold of significance, the ANCOVA results should be interpreted with caution. Therefore, the conclusion regarding the effectiveness of TEFA is stronger when based on the

consistency of the gain, N-gain, posttest, and ANOVA results, rather than on ANCOVA alone.

The effectiveness of TEFA can be explained through its authentic, productive, and work-oriented learning characteristics. In TEFA, students do not merely receive information or follow predetermined technical procedures, but are involved in a sequence of activities resembling vocational work practices. They are required to understand user needs, design solutions, distribute work roles, develop prototypes, test product functions, improve weaknesses, and reflect on the processes they have carried out. This kind of structure shifts learning from mere technical practice toward a more complex problem-solving experience. This is consistent with the idea that strong vocational education should not only prepare students to master operational skills, but also develop adaptive, collaborative, and innovative abilities relevant to industrial needs.

This finding supports the view that TEFA can bridge the gap between school-based learning and industrial practice needs. Ismayati et al. (2020) and Bikas et al. (2021) emphasized that TEFA creates a learning environment that brings students closer to real production or service processes, allowing them not only to understand concepts but also to experience demands related to quality, time, responsibility, and work coordination. In the context of this study, TEFA-based learning provided students with opportunities to face real electronics engineering problems, such as sensor instability, wiring errors, coding constraints, calibration, and product function testing. These situations required students to think more systematically and not stop at procedural completion. They needed to identify the source of problems, discuss alternative solutions, test hypotheses, and improve designs based on test results. This process is what makes TEFA relevant for strengthening design thinking.

The improvement in design thinking in the experimental group can also be understood because TEFA is closely aligned with the principles of design thinking. Design thinking emphasizes understanding human needs, the courage to face uncertainty, collaboration, prototyping, testing, iteration, and the use of creativity to solve problems. These principles were evident in the TEFA learning process implemented in this study. Students did not only create products to make them function, but also considered user needs, ease of use, water efficiency, circuit safety, and tool durability under environmental conditions. This shows that learning did not stop at a technical orientation, but began to move toward a user-oriented perspective. This finding is consistent with Liu and Leong (2022), who positioned design thinking as an approach for connecting technical ability with user needs and socio-economic contexts.

In the dimension of being comfortable with uncertainty and risks, the experimental group showed greater improvement than the control group. This can be explained by the nature of TEFA, which exposes students to work situations that are not entirely predictable. In expository instruction, students usually follow examples, teacher instructions, or exercises whose answers are relatively predictable. In contrast, in TEFA, students face more open conditions: sensors may be unstable, programs may produce errors, circuits may fail to work, and test results may differ from expectations. When students had to check pathways using a multimeter, read the serial monitor, find the causes of program errors, and discuss with group members, they were learning that failure is not the end of the process but part of the problem-solving cycle. Thus, TEFA helped students become more comfortable with uncertainty and technical risks.

The improvement in the human-centeredness dimension indicates that students began to develop a more user-centered way of thinking. The interview findings showed that students identified user needs, such as the fatigue experienced by school gardeners in manual watering, the need to save water, ease of operation, and tool safety from rain or short circuits. This is important because in engineering education, students can easily become trapped in technical success alone, such as whether a circuit turns on or a tool functions. Through TEFA, this

orientation shifted toward broader questions: whether the product meets user needs, is easy to use, is safe, and is beneficial in a real context. This shift supports the argument that design thinking can broaden the way engineering students understand problems, from merely component or circuit problems to human, use, and contextual problems.

The dimension of mindfulness to the process and impacts on others also showed the highest improvement in the experimental group. This result indicates that students became more aware of work processes and the impacts of the solutions they designed. In TEFA, students were assessed not only based on the final product, but also on how they worked, followed stages, conducted testing, documented processes, and improved products based on field findings. Such process awareness is important in vocational education because technical work is always related to safety standards, product quality, responsibility toward users, and the impact of design decisions. The teacher's observation that students began to pay attention to SOPs, tool safety, and product quality strengthens the evidence that TEFA can build better process awareness than learning that only emphasizes task completion.

In the dimension of collaboratively working with diversity, the results showed that TEFA encouraged more meaningful group work. Students divided tasks based on competence, such as hardware, coding, casing, and testing. Differences of opinion were not only resolved through verbal compromise, but also through technical trials. For example, when different views emerged regarding sensor position, students tried several alternative positions and compared the data readings. This pattern shows that collaboration in TEFA does not merely mean working in groups, but working based on argumentation, evidence, and role responsibility. This finding is consistent with the views of Muslim et al. (2020) and Patria et al. (2024), who emphasized that TEFA can strengthen collaboration, communication, creativity, and student engagement in solving real problems.

The improvement in the dimension of orientation to learning by making and testing shows that the experience of making, testing, and improving products was one of the main strengths of TEFA. Students learned through assembling and disassembling, sensor calibration, debugging, circuit testing, and design revision. These activities provided a learning experience different from expository instruction because students developed understanding through direct interaction with products, tools, data, and failure. When students found that a tool did not work as expected, they needed to connect component theory, program logic, measurement results, and field conditions. This process made electronics engineering learning more integrative. This finding is in line with Yadav et al. (2014) and Freeman et al. (2014), who showed that active and problem-based learning is stronger in promoting understanding and problem-solving ability than one-way instruction.

The dimension of being confident and optimistic to use creativity also increased significantly, although the qualitative findings still indicated that this aspect needs further strengthening. Students began to show more courage in proposing creative ideas, such as adding a three-color LED indicator for soil conditions and a fuse for circuit safety. However, the teacher noted that some students still tended to choose safe and conventional technical solutions. This shows that TEFA had already provided space for creativity, but the courage to take innovation risks had not fully developed in all students. This finding is reasonable because creative confidence is influenced not only by learning design, but also by students' prior experience, technical mastery, time availability, classroom culture, and tolerance for failure. Therefore, the development of creative confidence in TEFA requires further support, such as providing space for exploring alternative designs, formative feedback, and more adequate time for iteration.

The qualitative findings clarify the mechanisms through which TEFA can improve design thinking. The supporting factors that emerged included teacher guidance, project-based worksheets, workshop facilities, complete components, freedom to try solutions, and motivation because the product was used in a real context. These factors created learning

conditions that made students feel that the tasks they completed had practical consequences and value. The product was not treated merely as an exercise, but as a solution that would be used by others. This condition is important because design thinking develops more strongly when students face real problems, real users, and the need to produce solutions that can be tested.

On the other hand, this study also shows that the effectiveness of TEFA does not occur automatically. Several obstacles limited the depth of design thinking development, particularly limited time, uneven initial programming ability, technical problems with sensors and circuits, and the tendency of some students to choose safe solutions. Limited time made the quality control, revision, and iteration processes less than optimal. In fact, iteration is an important part of design thinking. Uneven coding ability also caused some groups to need more time to solve technical problems, so learning energy could be absorbed by resolving basic errors. These obstacles indicate that the implementation of TEFA requires pedagogical and technical readiness, not merely a change in learning model.

In the context of Electronics Engineering vocational education, the findings of this study have important meaning. Electronics engineering students should not only be trained to assemble, measure, or repair circuits based on procedures. They also need to be trained to understand user needs, identify problems, develop several alternative solutions, test designs, and improve products based on data. TEFA provides space for developing these abilities because students work in contexts that are closer to vocational practice. Thus, TEFA can serve as a relevant approach to strengthening the relationship between technical competence and design thinking in vocational education.

This finding also expands empirical evidence regarding TEFA. Most previous studies have positioned TEFA as a model that affects work readiness, technical competence, productivity, or entrepreneurial interest. This study shows that TEFA also has the potential to strengthen design thinking, especially when learning is designed with stages that allow students to understand user needs, develop prototypes, test products, revise designs, and reflect on processes. In other words, the contribution of TEFA lies not only in its resemblance to the world of work, but also in its ability to shape a more adaptive, collaborative, and reflective design thinking pattern.

Nevertheless, the interpretation of these findings should remain proportional. The effectiveness of TEFA found in this study applies to the context of students in the Electronics Engineering Expertise Program within a particular research setting, with a limited number of participants and a limited implementation duration. Therefore, these findings should not be generalized too broadly without further studies in different school contexts, expertise programs, and student characteristics. However, the consistency between the quantitative and qualitative findings provides a sufficiently strong basis for stating that TEFA is a model worth considering in vocational learning to improve students' design thinking.

The findings affirm that the improvement in students' design thinking was not caused merely by practical activities, but by the quality of the learning experience provided by TEFA. When vocational practice is connected to user needs, collaboration, testing, revision, and reflection, students gain space to develop a way of thinking that is more open, empathetic, creative, and evidence-based. This serves as an important foundation for developing Electronics Engineering learning that is not only oriented toward technical skills, but also toward the ability to design solutions that are relevant, safe, and valuable for users.

## CONCLUSION

This study shows that the Teaching Factory (TEFA) model in vocational education is effective in improving the design thinking of students in the Electronics Engineering Expertise Program. This effectiveness is evident from the increase in pretest-to-posttest scores in the experimental group, the significant difference in posttest scores between the

experimental and control groups, and the differences in gain and N-gain that indicate the superiority of the experimental group. The statistical test results show that the improvement in the TEFA group was not only statistically significant but also had a large effect size, indicating that TEFA made a practical contribution to strengthening students' design thinking.

The improvement in design thinking occurred not only in the total score, but also across all measured dimensions, namely comfort in facing uncertainty and risks, human-centeredness, mindfulness to the process and impacts on others, collaboration in diversity, orientation to learning through making and testing, and confidence in using creativity. The experimental group showed higher mean N-gain scores than the control group across all dimensions. These findings indicate that TEFA is able to create a vocational learning experience that not only trains technical skills but also develops a design mindset that is more empathetic, reflective, collaborative, experimental, and creative.

The qualitative data strengthened the quantitative results by showing that the improvement in students' design thinking was supported by authentic learning experiences, involvement in solving real problems, interaction with user needs, role-based group work, prototyping and testing activities, and teacher guidance. However, the findings also show that the success of TEFA was influenced by students' technical readiness, sufficient time, facility availability, the quality of project worksheets, and the intensity of teacher mentoring. Therefore, TEFA can be regarded as a relevant learning model for improving the design thinking of Electronics Engineering students, but its implementation needs to be systematically designed so that all stages of learning can run optimally.

## LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, the study was conducted in one school and one expertise program, so the generalization of the findings to other vocational education contexts should be made with caution. Second, the number of participants was relatively limited, namely 39 students, with an experimental and control group composition that was not fully balanced. Third, group assignment was based on existing classes, so this study is more appropriately understood as a quasi-experiment rather than a true experiment with strict individual randomization.

Fourth, the duration of TEFA implementation was still limited, so the processes of iteration, quality control, product revision, and strengthening creative confidence could not yet be developed in greater depth. Fifth, design thinking was measured using a Likert-scale questionnaire, meaning that the quantitative data still depended on students' self-reported responses, although they were complemented by student and teacher interviews. Sixth, the qualitative data mainly described students' and teacher's experiences in the context of a particular project, so other TEFA project variations may produce different dynamics. Therefore, the findings of this study are better positioned as contextual empirical evidence of the effectiveness of TEFA in improving the design thinking of Electronics Engineering students, rather than as a universal claim for all vocational education contexts.

## RECOMMENDATIONS

Based on the findings, vocational education teachers are encouraged to implement TEFA more systematically by emphasizing the stages of identifying user needs, formulating problems, designing solutions, prototyping, testing, revising, and reflecting. Schools need to support TEFA implementation by providing workshop facilities, practical components, adequate learning time, and clear, operational project-based worksheets. Strengthening students' basic competencies, particularly in programming, schematic reading, troubleshooting, and the use of measuring instruments, also needs to be carried out before or during TEFA implementation so that the learning process is not hindered by gaps in technical ability. Future research is recommended to involve larger samples, more diverse schools,

longer implementation periods, and different vocational project variations so that the effectiveness of TEFA on design thinking can be examined more broadly and deeply.

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#### AUTHOR CONTRIBUTIONS STATEMENT

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Muhammad Roil Bilad		✓		✓			✓	✓		✓		✓	✓	

#### CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

#### ETHICAL APPROVAL

The researchers meticulously followed ethical protocols throughout the research process, adhering to the principles outlined in the Declaration of Helsinki.

#### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy considerations of research participants.

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