From Classroom to Industry: Enhancing Student Competencies through STEAM-Based Project-Based Learning in Fabrication and Manufacturing Technology

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***Abstract*—The modern industry requires graduates who are not only theoretically competent but also possess technical skills, problem-solving talents, and job preparedness. However, a large gap still exists between classroom learning and industry requirements. This study examines the practicality and effectiveness of the Science, Technology, Engineering, Arts, and Mathematics (STEAM)-based Project-Based Learning (PjBL) approach for helping students improve their skills in fabrication and manufacturing technology and prepare for jobs in the industry. The study involved 64 students, 10 lecturers, and 10 industry practitioners in the Diploma III Mechanical Engineering Program at Universitas Negeri Padang, Indonesia. The research was conducted using the Research and Development (R&D) method based on the Borg and Gall model, which Puslitjaknov simplified into six stages: data collection, planning, initial product development, preliminary field testing, product revision, and main field testing. The data analysis prioritized practicality, efficacy, and industry preparedness. The STEAM-PjBL approach dramatically improved students' technical competencies, capacity for problem solving, design innovation, communication, teamwork, and project management skills—all of which are important in the manufacturing industry. The pretest findings revealed no significant difference between the control and experimental groups (*p*-value = 0.91), indicating equivalent starting positions. However, the posttest results showed a substantial improvement in the experimental group (*p*-value = 0.00), indicating that the model successfully enhanced learning outcomes. Thus, including STEAM-PjBL in the curriculum is a viable method for closing the gap between higher education and industry demands.**

***Keywords*—Science, Technology, Engineering, Arts, and Mathematics (STEAM), Project-Based Learning (PjBL), competencies, fabrication and manufacturing technology, technical education**

I. Introduction

The rapid advancement of technology in the era of the Fourth Industrial Revolution has significantly transformed industrial demands, particularly in the field of Fabrication and Manufacturing Technology. Today's industries require a workforce that possesses strong theoretical knowledge and demonstrates technical skills, innovation, and high levels of professionalism. Therefore, higher education plays a crucial role in preparing students to face the increasingly complex and dynamic challenges of the professional world in the future. However, a considerable gap still exists between classroom learning and industry practices. Many engineering graduates struggle to apply the theories they have learned to real-world contexts, negatively impacting their job readiness [1].

Fabrication and Manufacturing Technology is a field that requires multidisciplinary competencies, including product design, technical analysis, production cost estimation, and implementation of fabrication and manufacturing processes. In the industrial world, professionals in this field must not only understand theoretical concepts but also master practical skills related to production operations and problem solving in manufacturing processes [2]. Unfortunately, the current higher education system still relies heavily on conventional theory-based learning methods, leaving students with limited hands-on experience in tackling industrial challenges.

The commonly used teaching methods in engineering education are still centered around lecture-based learning, where instructors serve as the primary source of information, while students predominantly receive material passively [3]. Learning success is typically evaluated through written exams, which place greater emphasis on memorizing theoretical concepts rather than applied understanding and practical skills [4]. Consequently, students have minimal engagement in practice-based learning experiences, making it difficult for them to connect theory with real-world applications [5]. Additionally, this method does not sufficiently promote the development of other essential industry skills such as collaboration, communication, leadership, and problem-solving [6]. Consequently, many graduates struggle to adapt to work environments that demand innovative solutions and effective teamwork [7].

To address these challenges, the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach has been recognized as an innovative learning strategy capable of bridging the gap between theory and practice in engineering education [8, 9]. STEAM is an interdisciplinary approach that integrates science, technology, engineering, arts, and mathematics to create more applicable and contextual learning experiences [10–12]. Through this approach, students not only gain a deeper understanding of engineering concepts but are also encouraged to develop creativity and innovative thinking in problem solving [13]. One of the most effective methods for implementing STEAM is Project-Based Learning (PjBL), which enables students to learn through real-world projects that reflect the challenges present in the industry [14–16]

The integration of STEAM into PjBL provides a dynamic

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approach to bridging the gap between academic learning and industrial demands, especially in the fabrication and manufacturing technology sector [17, 18]. As industries increasingly demand graduates with not only technical competence but also creativity, teamwork, and problem-solving abilities, educational institutions must create learning models that nurture these talents [19].

This study aimed to develop a STEAM-PjBL learning model that can be implemented in Fabrication and Manufacturing Technology courses. This model is expected to enhance students' technical competencies while encouraging their creativity in designing innovative solutions to challenges in the manufacturing industry. Additionally, this study focuses on analyzing the effectiveness of this learning model in improving students' preparedness for industrial challenges, both in terms of technical skills and teamwork capabilities.

II. Literature Review

The STEAM-based Project-Based Learning (PjBL) approach offers a more active and challenge-based learning experience [20–22] In this model, students not only learn theoretical concepts but also apply them in real-world projects that require teamwork, analysis, problem-solving, and effective decision-making [23, 24]. By engaging directly in industry-based projects, students gain a deeper understanding of how theoretical knowledge is applied in practical settings, thereby enhancing their readiness to enter the workforce [25, 26]. Furthermore, this method provides opportunities for students to develop collaboration, communication, and leadership skills that are essential in modern work environments [27–29].

Recent studies have highlighted the effectiveness of the STEAM-based Project-Based Learning (PjBL) approach in enhancing students' competencies in engineering and manufacturing. One relevant study found that implementing STEAM-based PjBL in metal welding technology education significantly improved students' technical skills, including their understanding of manufacturing processes, welding techniques, and design analysis. Additionally, the study revealed that students who engaged in this approach showed improvements in critical thinking, problem-solving, and teamwork skills—key elements in the manufacturing industry [1, 30–33].

However, Rahim *et al.* [1] has several limitations that should be considered. One of the main drawbacks is the use of 11 syntaxes in the learning process, making the sequence of activities excessively long and complex. Syntax refers to a series of systematic phases or steps in learning designed to achieve key ideas and objectives according to the chosen strategy and method of teaching. While a structured syntax can provide clear guidance in the learning process, an excessive number of syntaxes may lead to a high cognitive load for students, thereby hindering the effectiveness of learning.

Additionally, overly lengthy syntax has the potential to reduce student engagement in the learning process. The more steps students must follow, the higher the risk of fatigue, especially if the syntax used is inflexible and does not consider the dynamics of student involvement in the learning process. This can lead to decreased motivation and an increased likelihood of students merely following procedures without a deep understanding of the concepts. In STEAM-PjBL-based projects, the success of learning heavily depends on active student participation at each stage. If too many syntaxes must be followed, students may focus more on completing tasks mechanically rather than exploring and developing their conceptual understanding and innovative abilities.

As a solution, this study developed a more concise and structured syntax model consisting of eight stages designed to enhance the effectiveness of STEAM-PjBL-based learning in Fabrication and Manufacturing Technology. By implementing this eight-stage syntax, the learning process is expected to become more effective, efficient, and engaging for students. This structure enables students to focus more on both technical and non-technical skills in a balanced manner, reducing learning fatigue while improving their readiness to face real-world industrial challenges.

Although numerous studies have demonstrated the effectiveness of the STEAM-PjBL approach in engineering and manufacturing fields, most of these studies remain general and have not specifically addressed its implementation in Fabrication and Manufacturing Technology. Previous research has primarily focused on students' cognitive and academic aspects, whereas this study emphasizes the holistic development of competencies, including technical skills, innovation, problem-solving abilities, and industry readiness. Therefore, this study contributes to understanding how the STEAM-PjBL approach can be effectively applied in the context of fabrication and manufacturing technology and how it enhances students' preparedness for industrial careers.

III. Materials and Methods

A. Research Methodology

This study falls under the category of Research and Development (R&D) [34]. The objective of the research is to analyze the practicality and effectiveness of the STEAM-based (Science, Technology, Engineering, Arts, and Mathematics) Project-Based Learning (PjBL) model in enhancing students' competencies in the Fabrication and Manufacturing Technology course. The developed learning model is expected to bridge the gap between theory and practice while helping students become better prepared for the increasingly complex industrial environment, which demands technical skills, problem-solving abilities, and innovation in design and manufacturing processes.

Prior to execution, this study received ethical permission from Universitas Negeri Padang Research Ethics Committee (UNP). All research participants, including students and lecturers, received a clear and comprehensive description of the study's aims, procedures, rewards, and potential hazards. Participation is entirely optional, with no compulsion in any manner. All respondents provided written informed permission prior to data collection. Throughout the research procedure, participants' identities and personal data were kept totally secret, and the data generated was solely utilized for scientific purposes.

B. Development Model

This research adopts the Borg and Gall development model, which has been simplified by the Center for Policy Research and Innovation [35] into six main stages, as shown in Fig. 1:

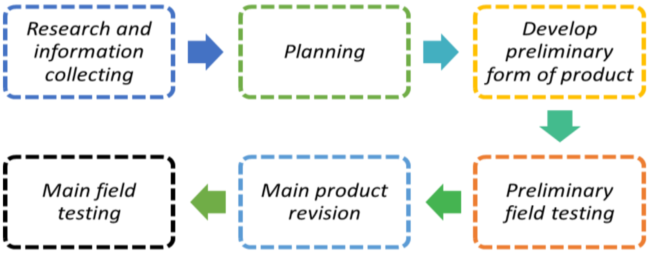

Fig. 1. Steps of the borg and gall development model.

The research and development process follows six main stages.

1) The first stage, research and information gathering, entails performing a literature study, interviewing lecturers and industry practitioners, and polling students to determine their learning requirements. The first stage, research and information gathering, entails performing a literature study, interviewing lecturers and industry practitioners, and polling students to determine learning requirements. To assess the readiness of the PjBL model development using the STEAM approach of the Fabrication and Manufacturing Technology course, the researcher distributed a needs analysis questionnaire to 32 students and 10 lecturers who had taught the course. The questionnaire was structured based on the respondents' level of accomplishment.
2) The second stage, Planning, focuses on designing the PjBL-STEAM learning syntax to align with industry requirements and develop research instruments. The researcher explored the PjBL model using the STEAM method and developed its processes in line with the Fabrication and Manufacturing Technology curriculum at Universitas Negeri Padang, Department of Mechanical Engineering, Faculty of Engineering.
3) In the third stage, the preliminary form of the product is developed, and the learning model framework is created, including the development of modules and assessment rubrics. In the development stage, construct validation was carried out on the STEAM approach PjBL model product for the Fabrication and Manufacturing Technology Course. The products include model books, modules, lecturer and student guides, RPS, SAP, job sheets and projects. Validity and practicality instruments were also prepared and validated before being used in FGD
4) The fourth step, preliminary field testing, is a small-scale experiment with students to obtain input on the basic model, which includes two lecturers and 16 students.
5) The fifth stage, Main Product Revision, is carried out to refine and improve the learning model.
6) Finally, the sixth stage, Main Field Testing, involves implementing the revised model on a larger scale to evaluate its overall effectiveness in enhancing student learning and industry readiness. The trial involved two classes, each consisting of 32 students selected purposively. The model was applied using a quasi-experimental approach with a classical experimental design.

C. Experimental Design

This study employs a quasi-experimental design using a pretest-posttest control group design. The students were divided into two groups: the Experimental Class, which applied the PjBL-STEAM model by integrating project-based learning with artistic aspects in product design, and the Control Class, which followed a lecture-based learning method. To assess the impact of the intervention, both groups underwent a pretest before the learning process and a posttest afterward. The evaluation focuses on measuring improvements in students' competencies across the cognitive, affective, psychomotor, and artistic (Art) aspects.

D. Research Subjects

This study was conducted in the Diploma III Mechanical Engineering Program at a University in Indonesia. The research sample was selected using a purposive sampling technique and consisted of 64 students enrolled in the Fabrication and Manufacturing Technology course. The sample was divided into two groups: the Experimental Class, which consisted of 32 students, and the Control Class, which also consisted of 32 students. Additionally, this study involved 10 lecturers and 10 industry practitioners as evaluators to assess the effectiveness of the developed model.

E. Instruments and Data Collection Techniques

The instruments used in this study covered several evaluation aspects. Cognitive tests (pretest-posttest) were used to measure students' improvement in theoretical understanding before and after the learning intervention. Questionnaires and observations were conducted to assess the practicality of the learning model from the perspectives of the students and lecturers. Additionally, a rubric for Assessing Psychomotor and Artistic (ART) skills was applied to evaluate students' technical skills and innovation in product design.

F. Data Analysis

The data in this study were analyzed using both quantitative and qualitative approaches with several statistical tests. Normality testing was conducted using the Kolmogorov-Smirnov test to ensure that the pre- and post-test data followed a normal distribution. Next, homogeneity testing was performed using Levene's test to examine the equality of variances between the experimental and control groups. Finally, a t-test was used to compare the post-test results of both groups to identify significant differences in learning achievement.

G. Model Effectiveness Evaluation

The effectiveness of the PjBL-STEAM model was measured based on four key aspects. The cognitive aspect was assessed through pre- and post-test results to evaluate improvements in students' conceptual understanding. The affective aspect was evaluated using student motivation questionnaires, project engagement, and interviews with lecturers. The psychomotor aspect was measured based on students' project execution skills and the quality of the final product. The Artistic (ART) aspect is assessed through product design innovation, aesthetics, ergonomics, and the integration of technology, such as Computer-Aided Design (CAD), in the design process.

IV. Result and Discussion

A. Learning Design Results of the Project-Based Learning Model with the STEAM Approach in the Fabrication and Manufacturing Technology Course

The analysis stage is the initial step in data collection, which aims to identify issues in the learning process. This analysis was conducted through interviews and observations to identify the challenges faced in the Fabrication and Manufacturing Technology course. Based on the interview results, several key issues were identified, one of which was the continued implementation of lecture-based learning, which does not sufficiently encourage active student engagement. Additionally, the teaching materials and media used have not fully supported the achievement of learning objectives, making them less effective in enhancing students' understanding and skills in designing, analyzing, and fabricating products according to industry needs.

Based on these findings, a learning model that can support an interactive, creative, and communicative learning process is needed. The instructional media used must also be designed in such a way as to increase student engagement in understanding concepts, designing, and analyzing fabrication production using a more engaging approach that aligns with industry requirements.

In response to the identified challenges, a STEAM-based Project-Based Learning (PjBL) model was developed for the Fabrication and Manufacturing Technology course. In its development, the various identified issues were the main considerations in designing the course materials and implementing the learning model. Developing a learning flowchart was crucial to ensure that the designed model and learning products were systematic. At this stage, the learning flowchart design was developed as a foundation for implementing the STEAM-based PjBL model in the Fabrication and Manufacturing Technology course, as illustrated in Fig. 2.

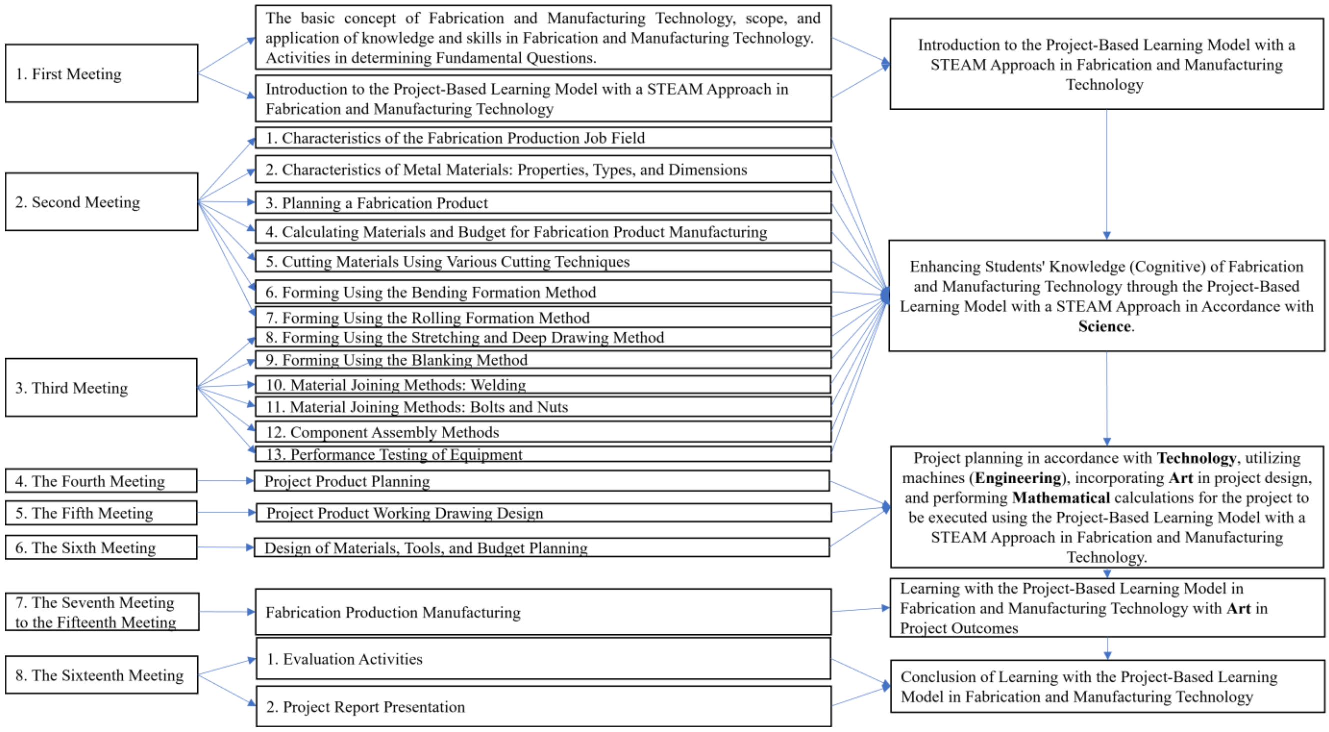

Fig. 2. Learning design flowchart of the project-based learning model with a STEAM approach in the fabrication and manufacturing technology course.

The implementation of the STEAM-based Project-Based Learning (PjBL) model in the Technology of Fabrication and Manufacturing course yielded positive outcomes, closely associated with the execution of its eight instructional phases, as shown in Fig. 3 with 8 phases.

In the first phase, Formulating Learning Outcomes and Defining Essential Questions, students were directed to understand the intended learning goals and were presented with essential questions that encouraged real-world problem solving. This approach strengthened students' conceptual understanding and analytical thinking, as reflected in their improved pre- and post-test scores.

During the second phase, Understanding the Concept of Teaching Materials, lecturers facilitated students' in-depth study of learning modules and group discussions to explore the scientific foundations of the subject matter. This activity enhanced students' cognitive engagement and conceptual mastery, as evidenced by the cognitive assessment results.

The third phase, Project Planning, required students to design a project that integrated elements of science, technology, engineering, art, and mathematics in a cohesive manner. Thoughtful planning at this stage enabled students to simultaneously develop technical competencies and aesthetic creativity, with the application of mathematics, such as material calculations and welding positions, further reinforcing their numerical skills.

In the fourth phase, Scheduling, students and lecturers collaborated to manage timelines and organize project execution. This fostered students' time management and discipline, contributing to the timely completion of high-quality projects.

The fifth phase, Executing the Project Tasks, provided students with the opportunity to apply theoretical knowledge and technical skills in practice, while also incorporating artistic elements. This hands-on experience improved students' psychomotor abilities, as shown in the evaluations that recorded enhancements in both technical execution and the aesthetic quality of the final products.

In the sixth phase, Monitoring, lecturers actively supervised the project process, ensuring that students stayed on track and received the necessary guidance. This ongoing support improved the effectiveness of the learning process and minimized errors, with the lecturers reporting that the model was practical and reliable.

The seventh phase, Assessment and Evaluation, enabled students to receive constructive feedback on their projects, which contributed to quality improvements and a deeper conceptual understanding. Objective evaluation also fosters affective growth, including greater responsibility and discipline among students.

Finally, in the eighth phase, Project Presentation, the students delivered formal presentations of their project outcomes to lecturers and peers. This activity not only developed their communication skills but also encouraged critical reflection and peer discussions. As a result, students exhibited stronger subject mastery and social competencies, which are key indicators of success in implementing the STEAM-based PjBL model.

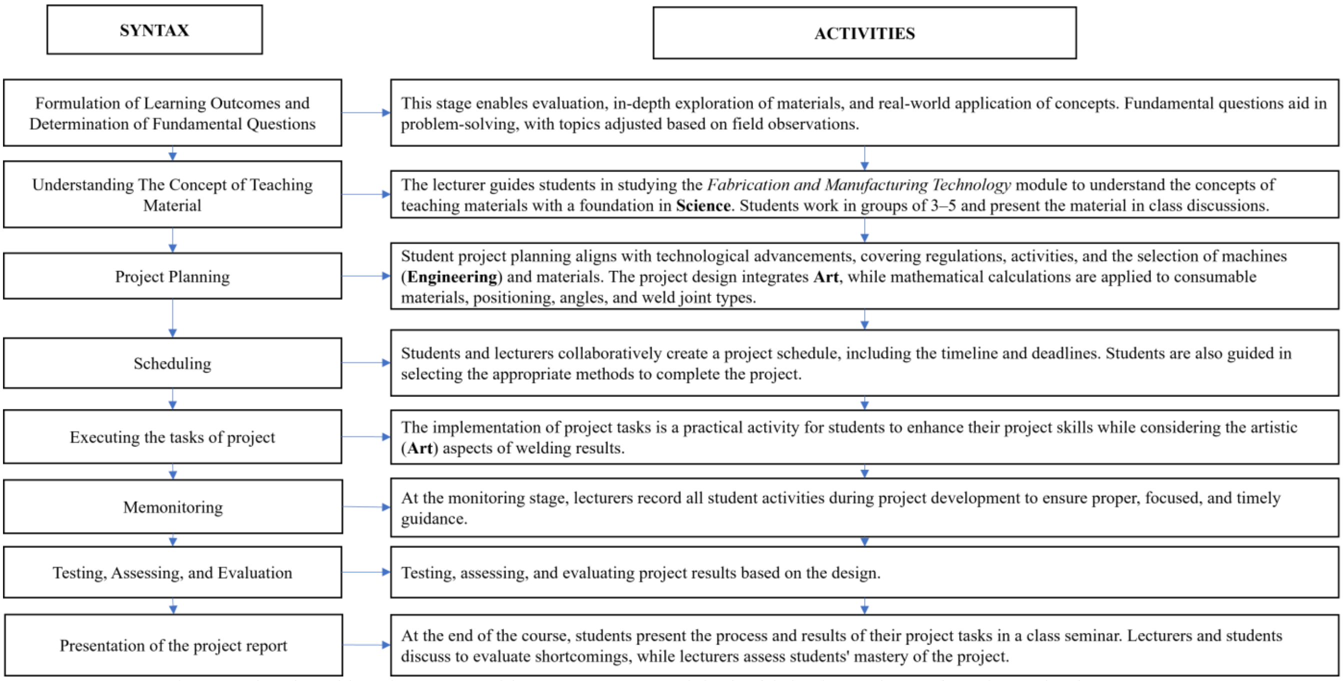

Fig. 3. Project-based learning syntax with a STEAM approach in the fabrication and manufacturing technology course.

The Project-Based Learning (PjBL) model with a STEAM approach in the Fabrication and Manufacturing Technology course is supported by guidebooks for both lecturers and students. The lecturer's guidebook consists of five chapters: Introduction, Supporting Theory of the Project-Based Learning Model with a STEAM Approach in the Fabrication and Manufacturing Technology Course, Implementation of the PjBL Model with a STEAM Approach, Assessment of the PjBL Model with a STEAM Approach, and Conclusion with References. Similarly, the student's guidebook follows the same structure, covering Introduction, Supporting Theory of the PjBL Model with a STEAM Approach, Implementation of the PjBL Model, Assessment of the PjBL Model, and Conclusion with References. These guidebooks were designed to facilitate the learning process and ensure the systematic and effective implementation of the STEAM-based PjBL model.

In addition to the guidebook, this learning model is supported by the Fabrication and Manufacturing Technology Module, which consists of 13 chapters. The first chapter discusses the characteristics of fabrication production work, followed by the second chapter, which discusses the characteristics of metal materials, including their properties, types, and dimensions. The third chapter focuses on fabrication product planning, and the fourth and fifth chapters cover material estimation, budgeting, and various cutting methods. Chapters six–nine explain different forming methods, such as bending, rolling, stretching, deep drawing, and blanking. The tenth and eleventh chapters focus on material-joining techniques, including welding and fastening with bolts and nuts. The twelfth chapter discusses the component assembly methods, and the final chapter covers equipment performance testing. This module is designed to support the implementation of the STEAM-based Project-Based Learning (PjBL) model, enabling students to gain a deeper understanding of the concepts and apply them in fabrication and manufacturing practices.

With the guidebook and module, the STEAM-based Project-Based Learning (PjBL) approach in Fabrication and Manufacturing Technology is expected to be implemented effectively, enhance students' understanding, and equip them with relevant skills that align with industry needs.

B. Practicality Results of the Project-Based Learning Model with a STEAM Approach in the Fabrication and Manufacturing Technology Course

The practicality assessment of the Project-Based Learning (PjBL) model with a STEAM approach in the Fabrication and Manufacturing Technology course involved both lecturers and students (Table 1).

The practicality test by lecturers was conducted using an instrument comprising 15 statements designed to assess various aspects of practicality. Seven lecturers who taught the Fabrication and Manufacturing Technology course participated in the evaluation. The assessment focused on usability (ease of use), information quality, interaction quality, functionality, usefulness, and reliability of the app. The results of the analysis indicate that the average practicality score from the lecturers' evaluation reached 90.29%, signifying that the PjBL model with a STEAM approach is highly practical for implementation in learning.

Table 1. Practicality test results according to lecturers and students

No	Respondents	Sample Size	Average Percentage Score (%)	Practicality Category
1	Lecturers	7	90.29	Highly Practical
2	Students	32	89.46	Highly Practical

Meanwhile, the practicality test based on students' evaluations involved 32 respondents and utilized an instrument comprising 30 statements. The students' assessment yielded an average score of 89.46%, which also fell into the highly practical category. This confirms that the learning model can be effectively implemented in the Fabrication and Manufacturing Technology course.

Based on the evaluation results from both lecturers and students, it can be concluded that the PjBL model with a STEAM approach is not only practical for application but also enhances students' understanding and skills throughout the learning process. Therefore, this model contributes positively to improving students' learning outcomes.

C. Effectiveness of the Project-Based Learning Model with a STEAM Approach in the Fabrication and Manufacturing Technology Course

1) Cognitive aspect learning outcomes

The effectiveness of the Project-Based Learning (PjBL) model with a STEAM approach in improving students' learning outcomes can be analyzed by comparing the average learning scores at the beginning and end of the course for both the control and experimental groups. This study involved 64 students, comprising 32 students in the control group and 32 in the experimental group. This comparison aimed to measure changes in students' learning outcomes before and after implementing the project-based learning model.

At the beginning of the course, the average score of the control class was 42.38, whereas the experimental class had a slightly lower average score of 42.25. However, after course implementation, both groups showed significant improvement. The average score of the control class increased to 80.27, whereas that of the experimental class reached 89.97. These data indicate that both groups had relatively similar academic abilities before the treatment, suggesting that the observed improvement in learning outcomes can be attributed to the implementation of the PjBL model with a STEAM approach in the Fabrication and Manufacturing Technology course. Table 2 presents a comparison of students' learning outcomes before and after the course:

The analysis results show that the control group, which employed a lecture-based learning method, experienced an average score increase of 37.89 points. Meanwhile, the experimental group, which implemented the PjBL model with a STEAM approach in the Fabrication and Manufacturing Technology course, exhibited a higher increase of 47.72 points in the post-test. This finding demonstrates that the application of the PjBL model with a STEAM approach is more effective in enhancing students' learning outcomes than the lecture-based learning method used in the control group.

Table 2. Comparison of students' learning outcomes in the pretest and posttest

No	Test	Control Class	Experimental Class
1	Pretest	42.38	42.25
2	Posttest	80.27	89.97
	Increase	37.89	47.72

The improvement in learning outcomes for both the control and experimental groups can also be visualized through the histogram in Fig. 4.

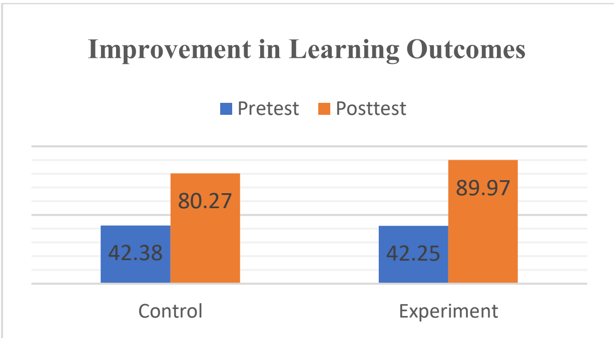

Fig. 4. Histogram of the average learning outcome improvement in the experimental and control classes.

a) Descriptive analysis results of normality and homogeneity tests on cognitive ability

Normality testing is an essential preliminary step in data analysis to determine whether the obtained data follow a normal distribution. One of the methods used for this purpose is the Kolmogorov-Smirnov test, which measures the extent to which the data distribution deviates from a normal one.

Based on the normality test results presented in Table 3, the significance (Sig.) of the value of the Kolmogorov-Smirnov test for the pretest in the control class is 0.051, while for the experiment class, it is 0.081. Both values exceeded the significance level of $\alpha = 0.05$, indicating that the pretest data in both classes followed a normal distribution.

Table 3. Descriptive analysis results of normality and homogeneity tests on cognitive ability

Test	Group	Normality Test			Homogeneity Test			
		Kolmogorov-Smirnov Statistic	df	Sig.	Levene Statistic	df1	df2	Sig.
Pretest	Control	0.155	32	0.051	0.516	1	62	0.475
	Experiment	0.146	32	0.081				
Posttest	Control	0.128	32	0.196	3.162	1	62	0.080
	Experiment	0.151	32	0.063				

For the posttest normality test, the significance value of the Kolmogorov-Smirnov test for the control class was 0.196, while for the experimental class, it was 0.063. Similar to the pretest results, both values exceeded $\alpha = 0.05$, confirming that the posttest data in both the control and experimental classes also followed a normal distribution. Thus, all pretest and posttest data met the normality assumption, making them suitable for parametric statistical analysis in this study.

Homogeneity testing was conducted to determine whether the variances of the two data groups, namely the control and experimental classes, were similar. Homogeneous variance is one of the assumptions in parametric statistical analysis that must be met to ensure valid and reliable results are obtained.

According to the homogeneity test results presented in Table 4, the significance value for the pretest was 0.475, while for the posttest, it was 0.080. Both values exceeded the significance threshold of $\alpha = 0.05$, indicating that the variances of both groups were homogeneous. This indicates that both groups exhibited similar variability before and after the intervention. Therefore, a comparative analysis of the pretest and posttest results between the experimental and control groups can be conducted with high validity, leading to more accurate conclusions.

Table 4. T-test results for pretest and posttest

Test	N	F	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Pretest	32	0.516	0.91	0.13	118.99
Posttest	32	3.162	0.00	9.70	128.41

b) T-test results for pretest and posttest

An independent t-test was conducted to determine whether there was a significant difference in the mean scores between the control and experimental groups before and after the intervention in the Fabrication and Manufacturing Technology course. The t-test for the pretest aimed to ensure that both groups had equivalent initial abilities, while the posttest t-test was used to assess the effectiveness of the STEAM-based Project-Based Learning (PjBL) model in improving students' learning outcomes.

Based on the t-test results presented in Table 4, the *Sig. The (2-tailed)* value for the pretest was 0.91 (> 0.05), indicating that both groups had nearly identical mean scores before the intervention. This suggests that there was no significant difference between the experimental and control groups before treatment administration.

Meanwhile, the t-test results for the post-test showed a significance value of 0.00 (< 0.05), indicating a significant difference in learning outcomes between the control and experimental groups after the intervention. The *Mean Difference* value of 9.70 suggests that the experimental group experienced greater improvement in learning outcomes than the control group.

These results confirm that the STEAM-based PjBL model is more effective than conventional teaching methods in the *Fabrication and Manufacturing Technology* course. This approach not only enhances students' cognitive understanding but also provides hands-on experience in fabrication and manufacturing processes, thereby improving their skills and competencies in the field.

2) Results of affective domain assessment

The affective domain was assessed by observing students' attitudes during the learning process. The evaluated aspects included honesty, discipline, interest, self-concept, responsibility, tolerance, collaboration, and participation in group discussions. Table 5 presents the results of the affective domain assessment for students in the experimental class, which implemented the STEAM-based Project-Based Learning (PjBL) model in the *Fabrication and Manufacturing Technology* course, compared to the control class that applied a lecture-based learning model.

Table 5. Affective domain assessment results for students in the experimental and control classes

No	Class	Number of Students	Attitude	Interest	Self-Concept	Tolerance	Collaboration	Confidence	Group Discussion	Average Score	Criteria
1	Experimental	32	87.71	85.31	85.25	86.50	87.66	85.00	87.38	86.40	Very Good
2	Control	32	83.02	80.21	82.13	79.75	82.66	81.50	78.00	81.04	Good

Based on the analysis results, students who learned using the STEAM-based Project-Based Learning (PjBL) model achieved an average affective score of 86.40**,** which was classified as very good. Meanwhile, students who participated in lecture-based learning obtained an average score of 81.04, which was classified as good.

These findings indicate that the STEAM-based PjBL model is more effective in enhancing student engagement, attitudes, and participation than conventional lecture-based learning methods.

3) Results of psychomotor domain assessment

The psychomotor domain was assessed through observations by the instructor after students completed the assigned project. The evaluated aspects in the psychomotor domain included students' skills throughout the learning process. Observations were carried out in several stages: Project Planning, Fabrication Production, Fabrication Production Results, Project Completion Time, Report, and Presentation.

Table 6 presents the psychomotor assessment results for students in the experimental class, which applied the STEAM-based Project-Based Learning (PjBL) model in the *Fabrication and Manufacturing Technology* course, compared to the control class.

Table 6. Psychomotor domain assessment results for students in the experimental and control classes

No	Class	Number of Students	Project Planning	Fabrication Production	Fabrication Production Results	Project Completion Time	Report and Presentation	Average Score	Criteria
1	Experimental	32	87.88	86.09	88.25	87.50	85.47	87.04	Very Good
2	Control	32	71.50	72.50	73.88	77.34	77.81	74.61	Good

The psychomotor assessment results indicate that students in the experimental class achieved very good scores in all evaluated aspects, including Project Planning, Fabrication Production, Fabrication Production Results, Project Completion Time, Report, and Presentation, with an average score of 87.04.

In contrast, students in the control class attained good scores, with an overall average score of 74.61. These findings suggest that implementing the STEAM-based Project-Based Learning (PjBL) model in the *Fabrication and Manufacturing Technology* course was effective in enhancing students' project planning abilities, production skills, and the quality of the completed projects.

4) Art (Aesthetic) assessment of fabrication production technology

The artistic aspect (art) of the project was evaluated by **10** welding lecturers and 10 industry professionals who used products from Fabrication and Manufacturing Technology. This assessment was based on design indicators and project quality, measured using ten questions. The following Table 7 are the results of the artistic evaluation of the products.

Table 7. Artistic assessment results of fabrication and manufacturing technology project for experimental and control classes

No	Class	Respondents	Average Artistic Assessment of Fabrication Production Technology Project		Average	Criteria
			Design	Project Quality		
1	Experimental	20	85.20	88.80	87.00	Sangat Baik
2	Control	20	79.00	80.40	79.70	Baik

The artistic assessment results of the Fabrication and Manufacturing Technology project were obtained from 10 welding lecturers and 10 industry professionals, both for the experimental and control classes. The results show that the products designed and manufactured in the experimental class exhibited excellent artistic quality, while the products in the control class were categorized as good.

This study successfully designed and developed a STEAM-based Project-Based Learning (PjBL) model tailored to the learning characteristics of the *Fabrication and Manufacturing Technology* course. The model was designed not only to enhance students' technical competencies but also to integrate artistic and aesthetic dimensions into the manufacturing design and production processes. The findings indicate that the implementation of this model positively influenced students' cognitive, affective, and psychomotor domains, including their creative thinking skills, teamwork abilities, and the ability to produce aesthetically pleasing and functional products.

These results reinforce the argument that integrating the STEAM approach into vocational education can address the limitations of conventional teaching methods, which often focus solely on technical and cognitive aspects. Previous studies [1], have rarely explored in depth how artistic and aesthetic dimensions can contribute to the development of 21st-century skills within the context of technological education. Therefore, this model offers a more holistic and transdisciplinary approach to learning in the manufacturing domain.

Structurally, the model consists of eight main syntactic stages: (1) formulation of learning outcomes and essential questions, (2) understanding of course materials, (3) project planning, (4) schedule development, (5) project task execution, (6) process monitoring, (7) outcome evaluation, and (8) final product presentation. This syntax allows students to build interdisciplinary understanding, apply knowledge contextually, and solve problems through a collaborative and reflective project-based learning approach.

From a practical implementation standpoint, the model provides a systematic framework to support lecturers in managing project-based learning effectively. The use of modules and instructional guides developed alongside the model has also been shown to enhance students' understanding of course content and learning processes.

The Project-Based Learning (PjBL) model with a STEAM approach in the Fabrication and Manufacturing Technology course has proven effective in significantly enhancing students' competencies, particularly in theoretical knowledge, technical skills, and creativity. This research aligns with the findings of Irdalisa *et al.* [36], which indicate that an interdisciplinary approach in STEAM-based PjBL can improve students' fabrication and design skills. Students involved in STEAM-based projects not only understand theoretical concepts but also apply them in the development of innovative products. Additionally, Lu *et al.* [16] emphasizes that integrating theory and practice through STEAM-based PjBL can bridge the gap between academia and industry, providing students with more relevant work experience.

The STEAM-PjBL model proves effective due to its integration of project-based learning with the interdisciplinary domains of Science, Technology, Engineering, Art, and Mathematics, thereby enhancing students' competencies in a holistic manner. The project-based approach encourages active student engagement in the learning process, promotes the application of theoretical knowledge in real-world contexts, and cultivates problem-solving and collaboration skills. The interdisciplinary nature of STEAM enables students to understand the interconnections among different fields and fosters creativity and innovation, moving beyond rote memorization of concepts.

For instance, in the *Technology of Fabrication and Manufacturing* course, students do not only learn welding techniques (Engineering) and material calculations (Mathematics), but also explore material properties (Science) and how to incorporate aesthetic considerations into product design (Art). When designing and fabricating a component, for example, students are required to calculate material needs, ensure the strength of welded joints, and consider artistic elements to make the product not only functional but also visually appealing. This process enriches students' cognitive, affective, and psychomotor domains, better preparing them to face the increasingly complex and multidimensional demands of the industrial world.

The advantages of STEAM-based Project-Based Learning (PjBL) over lecture-based learning are evident from the results of pretests and posttests, which show a significant improvement in students' competencies. This improvement occurs due to students' independent exploration during project execution, where they must understand theoretical concepts before applying them to real-world situations. This finding is also supported by Sigit *et al*. [37], who discovered that project-based learning in the STEAM context enhances students' problem-solving skills and technical understanding more deeply than conventional learning methods. The use of modern technology, such as Computer-Aided Design (CAD) and production simulation, in projects also plays a crucial role in developing students' technical skills [38].

From the perspective of creativity and innovation, the STEAM approach in Project-Based Learning (PjBL) enables students to develop more innovative, aesthetically pleasing, and industry-relevant solutions. This aligns with the findings of Ayuningsih and Sutama, which indicate that integrating artistic elements into STEAM encourages students to think creatively and develop visually and functionally appealing designs [39]. Additionally, the research by Haddar *et al*. [40] compared the effectiveness of STEAM-based PjBL with traditional PjBL in fabrication technology education and found that students using the STEAM approach excelled in design innovation and had a broader understanding of the integration of technology and aesthetics.

Student engagement and motivation also increased through the implementation of the STEAM-based Project-Based Learning (PjBL) model. The main factors driving this improvement include real-world-relevant projects, team collaboration that strengthens social interactions, and the integration of technology with artistic elements to create a more engaging and diverse learning process. This finding is supported by Mansyur and Bahar, who stated that STEAM-based PjBL enhances students' collaboration and innovation skills in technology and fabrication projects [41]. Furthermore, Lin and Tsai found that this approach helps students engage more actively in learning, improve their communication skills, and foster more effective teamwork [42].

The relevance of the STEAM-based PjBL approach in the field of Fabrication and Manufacturing Technology is becoming increasingly evident in meeting industry demands for graduates with strong technical skills, high creativity, and good collaboration abilities. Students who learn through this method not only understand the fabrication process but also integrate various aspects such as production efficiency, product design aesthetics, and process optimization to meet industry standards. Fitriyah and Ramadani stated that STEAM-based PjBL significantly contributes to enhancing students' creative and critical thinking skills, which are highly needed in the modern manufacturing industry [43]. Moreover, Mariani and Indriyanti [44] emphasized that this learning model also positively impacts cognitive load reduction and increases self-efficacy, helping students gain confidence in applying academic concepts in industrial settings. In learning, Arsy and Syamsulrizal [45] demonstrated that implementing STEAM-based PjBL enhances creative thinking skills, which are a fundamental foundation for innovation in fabrication and manufacturing. Thus, this approach not only prepares students academically but also equips them with practical skills relevant to industry needs.

Despite its proven effectiveness, implementing this model still faces several challenges, such as faculty readiness in designing appropriate STEAM projects and students' ability to adapt to more independent learning methods. Widana and Septiari noted that the lack of training for faculty in implementing STEAM-based PjBL can be a major obstacle to the success of this model [46]. In addition, several significant challenges were encountered throughout the research process, spanning the planning, development, and implementation stages of the STEAM-based Project-Based Learning (STEAM-PjBL) model in the Fabrication and Manufacturing Technology course. One of the primary challenges was the limited initial understanding of the STEAM-PjBL approach among students. Most were unfamiliar with the interdisciplinary nature of STEAM, which integrates science, technology, engineering, the arts, and mathematics holistically. Consequently, they experienced confusion, particularly when relating artistic and design elements to manufacturing technology.

Another notable issue was the varying levels of readiness among both lecturers and students in adopting project-based learning. Some lecturers, still accustomed to traditional instructional methods, required additional time and training to effectively facilitate a collaborative and integrated learning environment.

Infrastructure and resource limitations also posed critical challenges. The existing laboratory facilities and fabrication equipment were insufficient to support complex, multidisciplinary projects, thereby constraining students' creativity and idea exploration. Moreover, involving industry practitioners as evaluators and learning partners required intensive coordination. Their limited availability often hindered the provision of comprehensive feedback on student project processes and outcomes.

Assessing the model's effectiveness holistically also presented a methodological challenge. Evaluations needed to encompass cognitive, affective, and psychomotor domains, including work skills, communication, and collaboration. Developing valid and reliable instruments to assess all these dimensions was particularly demanding. Additionally, integrating time-intensive project-based learning into a fixed curricular structure posed both administrative and technical difficulties, especially in ensuring alignment with learning outcomes and student workload.

The findings of this study provide several significant practical implications for teaching, particularly in the Technology of Fabrication and Manufacturing course within vocational education. The integration of the STEAM approach into the Project-Based Learning (PjBL) model has been proven to enhance the quality of instruction through an interdisciplinary framework that emphasizes not only technical aspects but also aesthetics and creativity. This approach fosters the development of critical thinking, problem-solving, collaboration, and communication skills—core competencies of the 21st century that are highly relevant to the demands of the modern workforce.

Furthermore, the availability of a structured instructional model accompanied by comprehensive guidance for both instructors and students enables the learning process to be more systematic, focused, and efficient. Students become more active, engaged, and responsible in their learning, as they are directly involved in designing and completing real-world projects that align with industry needs.

Project-based learning has also been shown to support higher learning outcomes across cognitive, affective, and psychomotor domains. However, the successful implementation of this model requires adequate resource support, including tools, materials, and funding. Therefore, careful planning and strong institutional commitment are essential to ensure the sustainability of its application. It is crucial for educational institutions to develop efficient and sustainable implementation strategies, including the establishment of partnerships with industry to support effective, contextualized, and workforce-relevant project-based learning.

V. Conclusion

This study has developed a Project-Based Learning (PjBL) model with a STEAM approach for the Fabrication and Manufacturing Technology course, designed to enhance students' knowledge and skills in designing, analyzing, calculating, and developing aesthetic aspects of projects aligned with industry advancements. The research includes the development of a STEAM-based PjBL model tailored to the characteristics of the Fabrication and Manufacturing Technology course. The study outcomes include various learning outputs, such as a structured learning model, instructor guidebooks, student guidebooks, and learning modules for Fabrication and Manufacturing Technology.

The practicality of this learning model has been evaluated from both faculty and student perspectives. Based on faculty assessments, practicality was measured through usability (ease of use), information quality, interaction quality, functionality, usefulness, and reliability, with results indicating that this model is efficient for learning. Meanwhile, student evaluations also rated the STEAM-based PjBL model as highly practical and effective in supporting the learning process. The study findings further demonstrate that this learning model helps students construct a more comprehensive understanding and skill set, contributing to improved learning outcomes in cognitive, affective, and psychomotor aspects, as well as producing projects with high aesthetic value.

The implementation of the STEAM-based PjBL model in the Fabrication and Manufacturing Technology course has shown a significant improvement in students' learning outcomes, as evidenced by better pretest and posttest scores compared to traditional teaching methods. Based on these findings, STEAM-based PjBL can serve as an effective alternative to enhance student engagement and learning achievement in both knowledge and skill aspects.

However, this study also identifies several challenges, particularly related to the relatively high cost of implementation. Therefore, further research is needed to develop more cost-efficient project designs while maintaining quality in accordance with industry standards.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

B.R. contributed to the conceptualization, research mapping, supervision, and initial draft writing. C.A. was responsible for methodology design and formal data analysis. S.I. provided critical review and editorial refinement of the manuscript. J. curated and organized the dataset. F.E. contributed to the initial drafting and data curation. J.A. conducted the final review and performed language editing and manuscript refinement. All authors have read and approved the final version of the manuscript for publication.

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