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STEM-based CNC learning to empower creative and innovative thinking skills in undergraduate students

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Abstract

The demand for creative and innovative problem-solvers in industry has encouraged educators to integrate STEM (Science, Technology, Engineering, and Mathematics) with practical technological tools such as Computer Numerical Control (CNC) into the learning environment. This article presents a learning-centered CNC-based STEM course designed to enhance students' creative and innovative skills through project-based learning and student-centered pedagogies. The method employed in this study uses a mixed-method approach to comprehensively understand the impact of CNC-integrated STEM learning on students' creativity and innovation. The article provides a nuanced view of how CNC-STEM learning influences student outcomes. The project-based (PBL), student-centered learning model empowers students to design, build, and critically evaluate original CNC projects. Improving creativity and innovative skills with STEM-based CNC education includes: using PBL in CNC education gives students the opportunity to work on real-world projects, which stimulates their critical and creative thinking. Students gain creative thinking and imaginative problem-solving skills by creating and producing their own items. Collaborative learning using STEM-based CNC instruction promotes student cooperation. When students work in groups, they exchange ideas, solve issues together, and gain knowledge from one another, which develops their innovative and creative thinking, and using STEM to support teaching factory.

Keywords: CNC, Engineering education, Creative, Innovative, Marketplace, STEM, Student-centered approach.

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Contents

Contribution of this paper to the literature
This research serves as a practical guide for marketplace-based CNC learning to enhance the creative and innovative abilities of undergraduate students.

1. Introduction

We are currently in the era of Industry 4.0. Industry 4.0 is a major change that covers all aspects of production in industry by combining digital technology and the internet. The use of digital technology in the Industrial Revolution 4.0 has a significant impact on human life around the world. Overall, the production process in Industry 4.0 is carried out automatically by the system. Most research in Industry 4.0 focuses on the manufacturing sector, which contributes the largest percentage, namely 53%. Research is conducted in various types of manufacturing industries, including mass production, metal processing, and furniture. Research related to production processes such as machining, production scheduling, automation, system design, manufacturing layout, and human interaction with the production process is widely carried out (Deepika, Taj, & Bedar, 2024; Madan et al., 2024).

The problem in the manufacturing industry today is that many machines are still manual. The speed of manual machines is still minimal and less than optimal in supporting production. To increase production, an automation system is needed, but it has a high price. When a machine breaks down, technicians must be brought in from abroad. This will also increase production costs in the industry. For this, it requires technological independence and superior human resources that can overcome the problems of machines in the manufacturing industry.

Most nations in the globe now have the ability to produce commodities thanks to the process of globalization. The process of globalization has increased competition among manufacturers, resulting in variations in the quality of goods produced. As a result, the majority of businesses conduct studies on various strategies or tactics that they may use to create high-quality, environmentally friendly products at a lower cost. The newest production methods used in CNC machining processes (Okokpujie, Bolu, Ohunakin, Akinlabi, & Adelekan, 2019).

In general, identical patterns and directions of movement were observed in the estimations of potential and gap output using the production function, BP filter, and HP filter approaches, despite differences in magnitude. These prospective growth rate projections from 2000 to 2021 demonstrate an impressive degree of agreement, as they were derived using three different methods. The statistics presented also show that, from the early 2000s crisis era to the present, Indonesia's manufacturing sector has grown reasonably steadily, as indicated by the growth rates (Permana, Yudoko, & Prasetio, 2023).

The 21st-century education includes complex capabilities, shifts to technology-based learning, and the need for non-cognitive skills. In this context, it is difficult for Indonesian vocational education instructors to apply 21st-century skills (Mutohhari, Sutiman, Nurtanto, Kholifah, & Samsudin, 2021). The idea behind 21st century learning is to prepare students for living and working in increasingly sophisticated environments (Izhar, Ishak, & Baharudin, 2023). Education should provide students with the skills, information, and attitudes necessary to make constructive contributions to society in the twenty-first century.

In order to address globalization and the needs of the Industry 4.0 era, education at VHS must be prioritized. Getting an education can help you live a better life. It is necessary to keep learning in order to pursue an education. Three things about a person change as a result of learning: knowledge, attitudes, and skills. Education at VHS needs to be prioritized in order to meet the demands of the Industry 4.0 age and globalization. To face global challenges and competency needs, learning is needed that can support complex competencies such as creativity and innovation, one of which is STEM-based learning (Science, Engineering, Technology, and Mathematics).

To improve creativity and innovation, STEM (Science, Technology, Engineering, and Mathematics) learning can be used (Corlu, Capraro, & Capraro, 2014; Marzuki et al., 2024; Nugroho, Permanasari, & Firman, 2019; Tasdemir, 2022). Competence is one of the important elements in determining the quality of human resources, especially in facing challenges in the era of the industrial revolution 4.0, which relies heavily on technology and speed. STEM learning will improve competence (Aguilera & Ortiz-Revilla, 2021; Duong, Nguyen, Nguyen, & Thao-Do, 2022; Hanif, Wijaya, & Winarno, 2019). The interdisciplinary approach emphasized in STEM education encourages students to apply knowledge from various professions to address real-world problems. Students gain practical experience in designing, programming, and operating CNC machines through the integration of STEM and CNC instruction. These skills are critical to modern manufacturing and engineering.

CNC machines are computer-controlled automated instruments that can carry out intricate and accurate tasks. Understanding programming languages, mechanical design, and material qualities is necessary to operate CNC machines. This technical understanding, along with the problem-solving aspect of STEM education, provides children with the tools they need to be creative and innovative.

The combination of STEM (Science, Technology, Engineering, and Mathematics) and CNC (Computer Numerical Control) learning has become a potent strategy for encouraging student creativity and innovation in the rapidly changing fields of technology and education. This article explores how STEM-based CNC learning fosters creativity and innovation while providing an overview of its advantages and applications. The aim of this study is to examine how STEM-based CNC learning can enhance creative and innovative skills. This paper describes a CNC-integrated STEM course offered to undergraduate engineering students. The course is inspired by learning-centered approaches and constructivist pedagogy, encouraging students to become designers, creators, and critical evaluators of their own CNC projects.

The challenges identified in using CNC learning to enhance creativity and innovation in STEM education can be summarized into three key problems:

1. Underutilization of CNC as a creative platform.
2. Lack of hands-on, project-based experiences in STEM curricula.
3. Limited support for student-centred innovation and autonomy.

2. Literature Review

As new cutting-edge technologies enter the worldwide market, the business environment on a global scale is becoming more competitive. These industries are inextricably linked to one another, and to stay ahead of the competition, most of them engage in innovative work through cutting-edge technology research. The implementation of this type of industrial behavior in response to market demands resulting from the adoption of current, or not so state-of-the-art, technologies has largely depended on foresight. Businesses in sectors like SMEs should review their manufacturing strategies and processes. They also must design an environment that results from integrating the most recent business procedures and manufacturing strategies. Advanced Manufacturing Technology (AMT) has become a crucial component of process operation and is viewed as a feasible way for manufacturing companies to increase productivity and reduce costs. One of the manufacturing technologies is Computer Numerical Control (Prasetyo et al., 2023).

The basic idea behind all CNC machines is the same: the machine positions a tool of some kind in a series of positions specified by the program. Subsequently, the tool modifies the workpiece by either removing material or introducing new material. The workpiece or the tool can be positioned by rotating them around a rotary axis or by moving them along one or more linear axes. Depending on the kind of motion used, an assembly that permits positioning along a specific axis is referred to as a "rotary stage" or a "linear stage." The machining process (drilling, grinding, cutting, etc.) creates forces between the workpiece and the tool. The tool may deflect from the intended location as a result of these forces (Rastvorova & Klyucherev, 2021).

CNC machines are instruments that complete the process of creating and producing objects. They are nearly always used in conjunction with downstream components such as CAD, CAPP, and CAM. Neutral data communication protocols like SET, VDA, and the basic graphical transmission standard allow knowledge transfer across different CAD and/or CAM systems. Due to the fact that these standards are primarily meant to transmit geographic coordinates and do not entirely satisfy the criteria of the CAD/CAPP/CAM company, this is only partially successful (Tripathi & Kumar, 2021).

CNC (Computer Numerical Control) machining is a technology that has revolutionized the manufacturing industry by enabling automation and precise control of machine tools. CNC allows for efficient and accurate mass production, facilitating the manufacturing of complex products with a high degree of precision. In this article, we will comprehensively discuss what CNC is, how CNC machines operate, and the benefits they provide across various industries.

Complex part CNC machining involves the processing of post-programs and CAD/CAM-based cutting simulation. Among these, NC program inspection primarily utilizes cutting simulation, with tool path processing and modification ranking second in program processing, thereby enhancing the CAD/CAM programming function. The article examined the application of cutting simulation and its subsequent program processing in product NC machining based on its core technology, CAD/CAM, with the goal of improving the quality and processing efficiency of complex surface NC machining (Cao & Guan, 2018).

By fostering the development of 21st-century skills, STEM can help attain the Sustainable Development Goals (SDGs). It has led to significant innovation in STEM education research, involving Indonesia. Realizing the 2030 SDGs requires education on a fundamental and transformative level. This is a result of the need to increase literacy to support all SDG goals, not just the explicit and targeted integration of education in the fourth SDG goal (Quality Education). According to studies, education has a direct impact on reducing poverty and inequality in areas such as human rights, nutrition and health, the environment, economic growth, and labor productivity. If residents possess the necessary 21st-century skills, especially STEM literacy and skills, these goals can be achieved (Ardwiyanti, Prasetyo, & Wilujeng, 2021).

3. Methodology

The method used in this article employs a mixed-method approach (Creswell, 2014). To comprehensively understand the impact of CNC-integrated STEM learning on students' creativity and innovation, this study adopted a mixed methods design as proposed by Creswell (2014). The rationale for using mixed methods lies in the complexity of educational environments, where both qualitative insights and quantitative evidence are required for meaningful evaluation. This mixed methods approach provided a nuanced view of how CNC-STEM learning influenced student outcomes and helped validate the effectiveness of the instructional design. The subjects of the study were 5th semester students in the 2024/2025 odd semester of the Mechanical Engineering Education study program, Faculty of Engineering, Universitas Negeri Semarang. This research was conducted on the CNC II course. Research design shows in Figure 1.

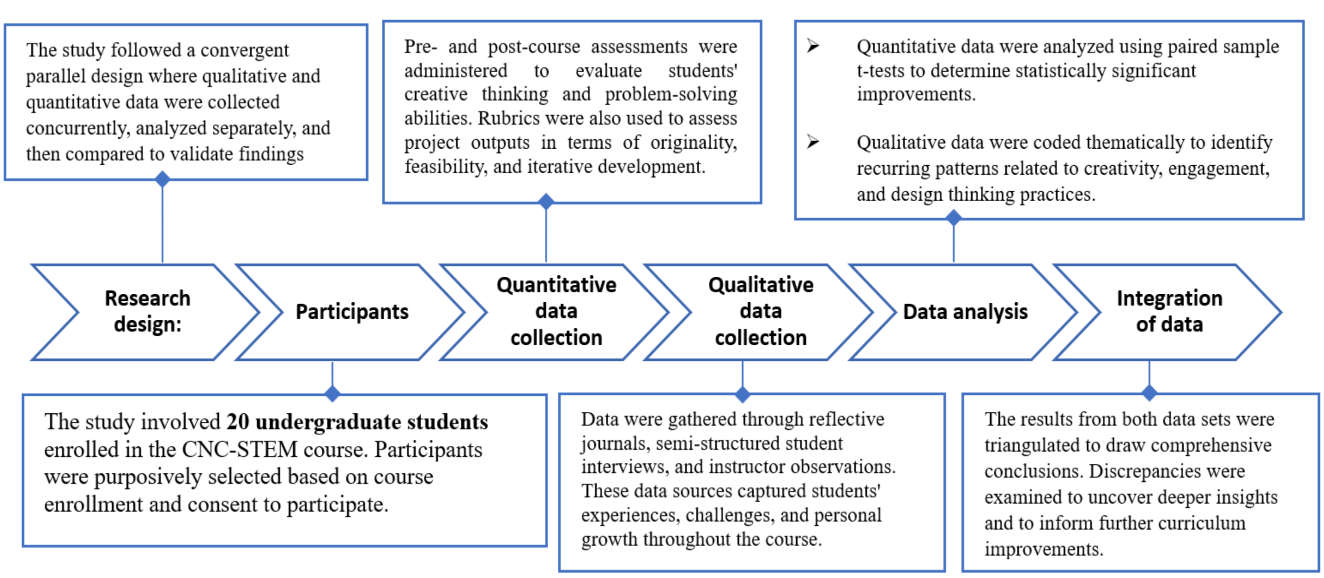

Figure 1. Research design.

4. Result and Discussion

4.1. CNC Learning Design

The framework of the course is based on Ormiston's input–output model, which includes the following elements: pedagogical tactics (process), available resources (environment), intended outcomes (output), and students' prior knowledge (input). Students have limited experience with CNC or digital manufacturing but usually come into the course with a foundational understanding of STEM. Outcomes include students being able to use CNC tools to produce prototypes, solve creative problems, and critically evaluate the design and production processes. The environment encompasses design using CAD/CAM software and access to CNC routers or milling machines. A digital platform using a marketplace is employed to obtain product designs for learning. The course adopts a project-based, student-centered methodology that combines practical experience, direct instruction, and group problem-solving.

Intended Learning Outcomes (ILOs):

1. Describe the principles of CNC operation and its role in manufacturing.
2. Apply STEM concepts to design and simulate CNC-based products.
3. Develop and execute CNC machining projects based on original ideas.
4. Evaluate the effectiveness and creativity of design outcomes.
5. Demonstrate reflective thinking and iterative improvement in design work.

Implementation of the Course:

The course unfolds over 16 weeks and is divided into three main phases:

1. Fundamental Stage (Weeks 1–4):
(a) Introduction to STEM principles and CNC basics;
(b) Learning CAD/CAM tools using Inventor Student version;
(c) Safety and machine operation
2. Development Stage (Weeks 5–12):
(a) Project-based learning with increasing complexity
(b) Collaborative design challenges (based on marketplace)
(c) Peer-to-peer review and iterative improvement
3. Capstone Stage (Weeks 13–16):
(a) Independent final project
(b) Design, CNC fabrication, and presentation.
(c) Evaluation and reflective discussion

The students are guided through scaffolding assignments, group critiques, and digital portfolios. The emphasis is on creating original solutions to open-ended challenges using STEM thinking and CNC manufacturing.

Assessment is aligned with the ILOs and divided into formative (process-based) and summative (product-based) components:

Table 1. ILO Design.

Week	Activities	ILOs	Assessment
1–2	Intro to STEM-CNC, CAD basics	1	Quiz (Pre-test)
3–6	Guided mini-projects	2, 3	Portfolio submission (Post-test)
7–10	Group design challenge	2, 3, 4	Peer review and group report
11–13	Final project development	3, 4, 5	Progress log
14–16	Final fabrication + showcase	3, 4, 5	Product and presentation

Table 1 presents the ILOs designed to enhance the creativity and innovation of undergraduate students through CNC learning activities. The course begins in Weeks 1 to 2 with an introduction to STEM-CNC and basic CAD skills. During this phase, students develop a basic understanding of design and manufacturing principles, and their initial knowledge is assessed through a pre-test quiz. In Weeks 3 to 6, students engage in guided mini-projects that encourage them to apply their CAD and CNC knowledge in creative ways. This stage focuses on developing technical abilities and design thinking, with assessments based on portfolio submissions as a post-test to measure progress.

From Weeks 7 to 10, students participate in a group design challenge, which promotes collaborative problem-solving and innovation. Students work in teams to create unique product designs, receiving feedback through peer reviews and submitting group reports to showcase their teamwork and creative outputs. Weeks 11 to 13 focus on final project development, where students refine their design ideas and translate them into functional prototypes. They document their learning journey and design improvements through progress logs, fostering a reflective approach to innovation. Finally, in Weeks 14 to 16, students carry out the final fabrication of their projects and participate in a showcase event. This stage allows students to demonstrate their creative products and present their design processes, with assessment based on both the product quality and their presentation skills. Overall, this structured approach ensures students experience a complete cycle of ideation, design, development, and presentation, thereby cultivating their creativity, technical competency, and innovative thinking in CNC learning.

STEM is an educational strategy that incorporates mathematics, science, technology, and engineering. The goal of this study is to determine the extent to which science education uses the STEM method and to examine the successful learning process that results from doing so (Suryani, Kun, & Haryanto, 2023). The main goal of STEM education is to provide students with the knowledge and skills they will need to apply what they learn in the lab and classroom to real-world occupations in the twenty-first century. Together, educators, business leaders, and industry should create curricula that will raise this expectation. More importantly, this partnership between educators and business leaders should involve developing curricula as well as internships, mentorships, and practical classroom activities that expose students to professions in a variety of STEM sectors and basic skills (Ejiwale, 2013).
The stages of STEM learning are shown in Figure 2.

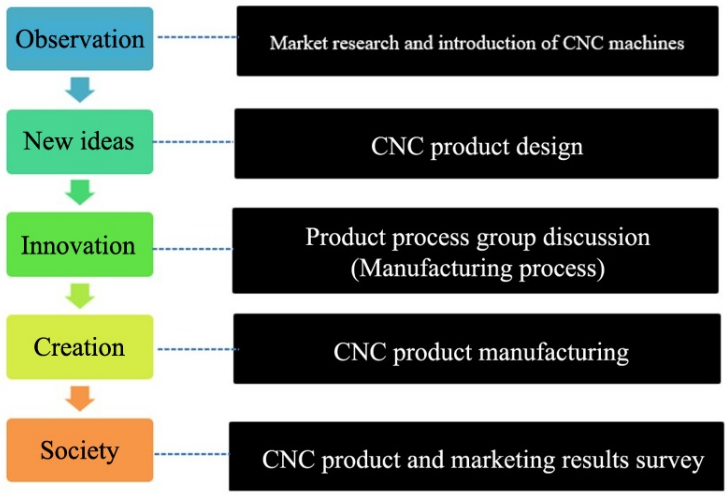

Figure 2. STEM-based CNC learning stages.

Table 2. ILO assessment matrix design.

ILO	Assessment tools	Indicators	Performance criteria
1	Quiz (Pre-test)	Accurate knowledge of CNC processes; correct machine setup (Read And create program)	≥80% quiz score, successful setup and safety compliance
2	CAD design files, design portfolio	Functional and original design using CAD	Submission of 2+ original designs meeting technical specifications
3	CAM simulations, feasibility reports	Simulation success, material/Tool choice, time estimate	90% simulation match between plan and execution.
4	Fabrication logs, final products	Machined product accuracy, tool handling	<2mm deviation from design specs; clean finish
5	Peer reviews, reflection journals	Design iterations, self-assessment, originality	At least 1 improvement cycle and reflective critique.

Table 2 presents the assessment matrix for Intended Learning Outcomes (ILOs), which guides the evaluation of students' creativity and innovation in CNC learning. Each ILO aligns with specific assessment tools, indicators, and performance criteria to ensure students develop comprehensive competencies in CNC processes. ILO 1 focuses on students' knowledge of CNC processes and correct machine setup. This outcome is assessed through a pre-test quiz, where students are expected to achieve at least 80% accuracy, demonstrate successful machine setup, and comply with safety procedures. For ILO 2, students are assessed using CAD design files and design portfolios. The indicator emphasizes the ability to create functional and original designs using CAD software. The performance criterion requires students to submit at least two original designs that meet specified technical requirements, encouraging creativity in product development.

ILO 3 evaluates students' proficiency in CAM simulations and feasibility reporting. The assessment indicators include simulation accuracy, appropriate material and tool selection, and realistic time estimates. Students must achieve a minimum of 90% match between their simulation results and actual execution, fostering innovative problem-solving through accurate planning. ILO 4 assesses the accuracy and quality of final products through fabrication logs and physical prototypes. Students are required to produce machined products with less than 2mm deviation from design specifications and achieve a clean surface finish, demonstrating precision and attention to detail. Finally, ILO 5 develops students' reflective and iterative design skills through peer reviews and reflection journals. The assessment focuses on students' ability to conduct design iterations, engage in self-assessment, and display originality. Students must complete at least one cycle of design improvement and submit reflective critiques, reinforcing their creative thinking and continuous innovation mindset. This structured assessment matrix ensures that undergraduate students not only master CNC technical skills but also enhance their creativity, critical thinking, and innovative abilities throughout the course.

Several scholars approach the typology of separate innovations from different points of view. Regarding the typology of innovation as the good and the typology of the subjects of innovation, institutional science also adopts a novel approach; the relationships between the first and second disclose the advantages of applying specific types of innovation as well as the actor's specific invention. Thus, the theme of the piece is suitably relevant. To develop innovation, a new idea is conceived and then turned into a new process, product, or service. In addition to generating jobs, this procedure boosts the country's economy and generates pure profit for the creative business enterprise (Kogabayev & Maziliauskas, 2017).

Table 3. CNC learning parameter design using STEM.

Indicator	Definition	Parameter
Science	Science is the knowledge or study of nature based on facts learned through experimentation and observation. Physical science.	Product shape changes based on product material, rotation speed analysis.
Technology	In general, technology is defined as a science related to tools or machines that are made to help and make it easier for humans to solve problems.	Use of CAD/CAM software for CNC design and programming.
Engineering	Engineering is the effort to design and create new systems or products using scientific methodology.	Product design and product manufacturing process
Mathematics	Mathematics is the science of numbers and number operations, their relationships, combinations, generalizations, and structures, measurement, and transformations.	Geometric and trigonometric calculations

Improving creativity and innovative skills with STEM-Based CNC Education includes: (a) Project-based learning (PBL): using PBL in CNC education gives students the opportunity to work on real-world projects, which stimulates their critical and creative thinking. Students gain creative thinking and imaginative problem-solving skills by creating and producing their own items. (b) Collaborative learning: STEM-based CNC instruction promotes student cooperation. When students work in groups, they exchange ideas, solve issues together, and gain knowledge from one another, which develops their innovative and creative thinking. (c) Teaching factory: using STEM to support teaching factory.

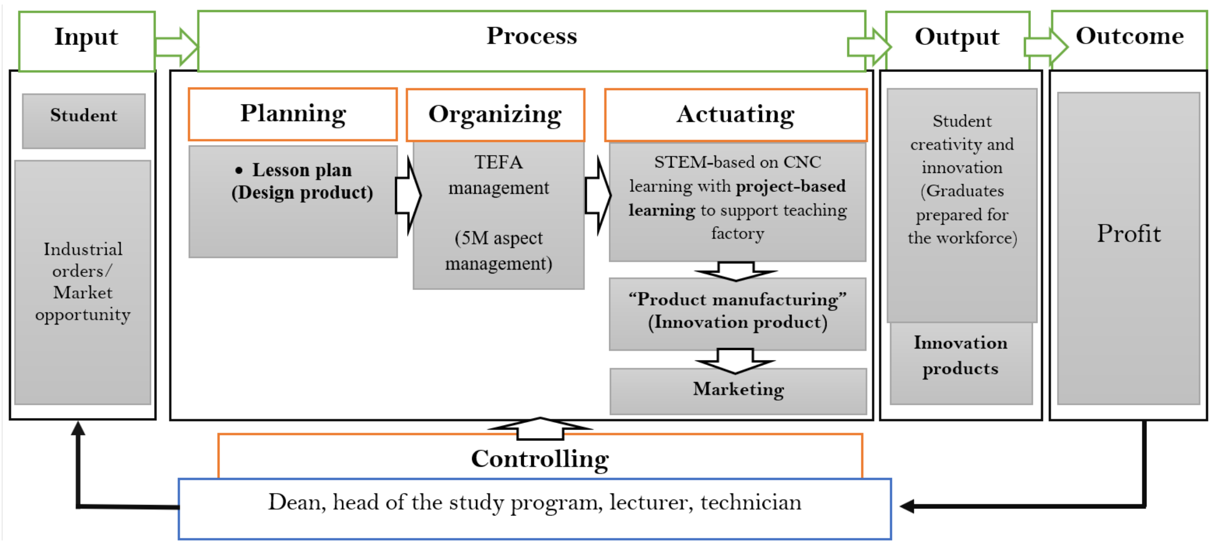

Figure 3. Management model using STEM-based CNC learning.

Figure 3 shows the design of a STEM-based CNC learning management model to support the Teaching Factory. Learning activities begin with CNC learning planning based on marketplace market research results. The search results from the marketplace are then entered into innovative products that will be made by students through CNC learning. In learning activities, students are guided by the Teaching Factory Managing Lecturer. With the research results in the marketplace, then discussed into new products according to the production capacity of existing CNC machines by considering the 5M management aspects (man, material, machine, method, and money). This model develops particularly on the broad applied management sciences, which include disciplines such as HRM and marketing (Jordan, Troth, & Yan, 2025).

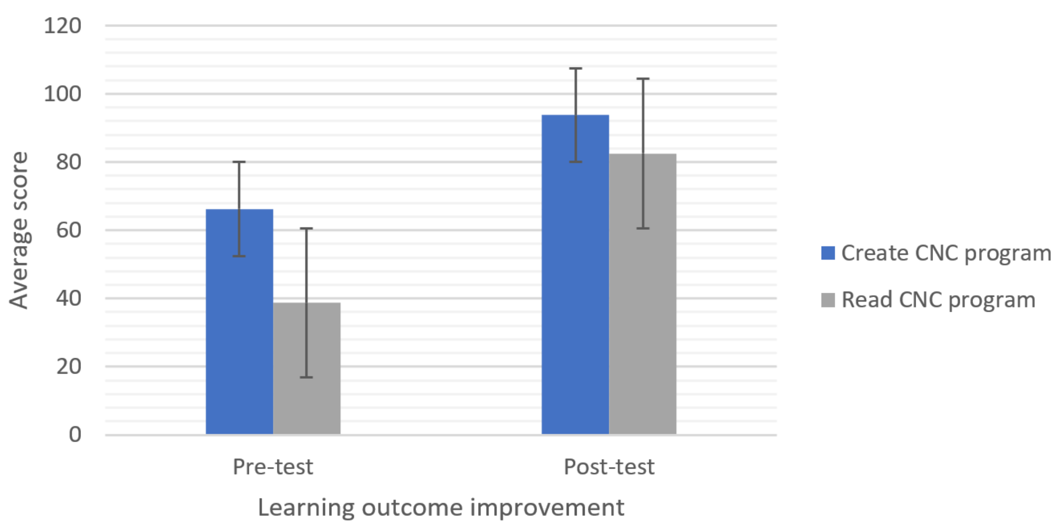

Figure 4. Learning outcome improvement portfolio submission.

Figure 4 shows the measurement results of this guided mini-project. Based on the pre-test data, student errors in making programs at the last cutting point were immediately returned to the starting point. The chisel should have been released from the workpiece first, then positioned to the starting point. Furthermore, STEM-based CNC learning was carried out according to the learning design activities. Based on the assessment results, there was an increase in learning outcomes for the ability to make programs by 29.33%, and the ability to read programs by 53.03%. The results of these measurements are used as guided mini-projects.

Based on surveys, observations, and project evaluations, students report higher confidence in using CNC equipment, increased motivation due to project autonomy, and an enhanced understanding of design and engineering principles. Rubric analysis shows growth in originality, technical execution, and iterative problem-solving. Some students expressed initial difficulty with CAD/CAM software, which improved with access to online resources and peer support. To quantify these improvements, a paired sample t-test was conducted to compare pre-test and post-test performance scores. These findings support the effectiveness of STEM-based CNC learning in enhancing students' creative and technical capacities through project-based experiences.

Table 4. Statistical analysis of CNC learning outcomes.

Learning aspect	Mean pre-test	Mean post-test	Mean increase	t-value	p-value	Interpretation
Create and read program	70.00	90.00	+20.00	8.72	< 0.000001	Significant improvement ($p < 0.05$)

Figure 5, Figure 6, and Figure 7 show the Group Design Challenge. This learning process is carried out to measure the simulation and production capabilities of products from the marketplace. This activity supports STEM activities in CNC learning. In accordance with the STEM learning stages, students observe the products and CNC machines that will be used. In the engineering activity process, the product is then designed using CAD software. Students in groups create basic programs manually to support mathematics activities with geometric calculations, such as making Boston rings and probolt bolts, similar to the simulation in this article. In science activities, students discuss in groups the calculation of cutting speed and CNC parameters based on the material to be made. Furthermore, in technology activities, students conduct simulations using CAM software to ensure the program runs correctly and the appropriate cutting blade is used for the product manufacturing process. Students carefully understand the process of making product designs and production processes using CNC machines. After the product is successfully made, it is then presented and marketed through the marketplace.

Based on the results of searching for CNC-based products on the Indonesian marketplace, two products were obtained. The products searched for are in the simple product category that can be produced during the learning process. The first product is a Boston ring, and the second product is a Probolt bolt. The Boston ring and probolt bolt are shown in Figure 5.

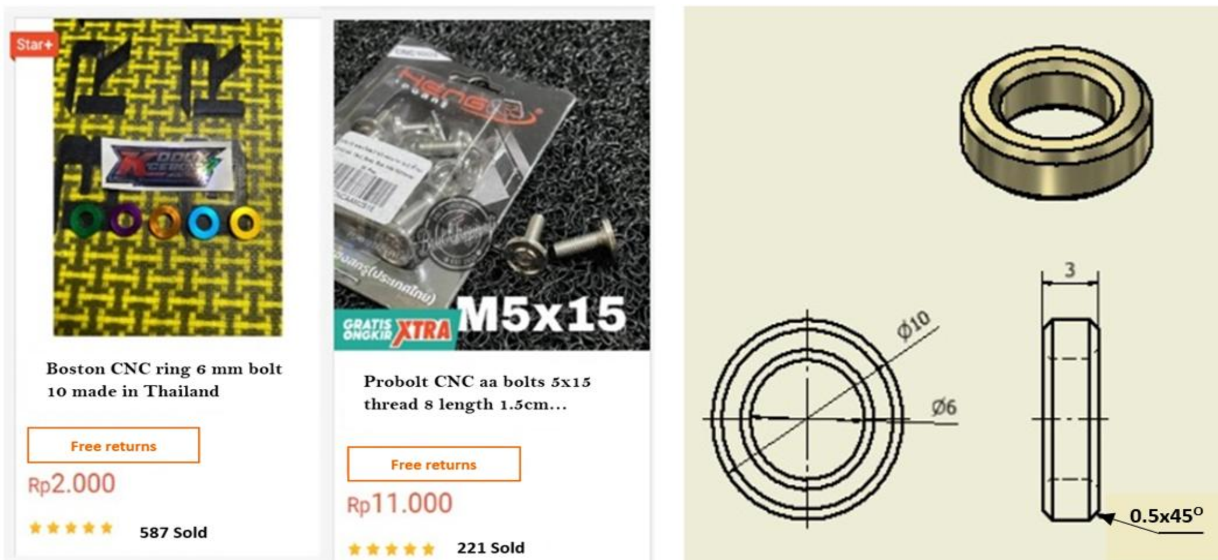

Figure 5. (a) Ring Boston and probolt bolt products using CNC machines on the Indonesian marketplace, (b) ring Boston design using inventor computer aided design (CAD).

Table 5 presents a manual ring program design that guides students through essential CNC machine operations. The program uses basic G-codes and M-codes to introduce students to manual programming, enabling them to understand toolpath planning and machining sequences. This manual programming sequence provides students with hands-on experience in creating basic CNC ring products, enhancing their understanding of manual code structures, spindle control, and linear interpolation. It develops both their technical skills and confidence in operating CNC lathes creatively.

Table 5. Manual ring program design for learning as follows.

G28 U0 W0;	M03 S500 F100;	M05;
T0101;	G01 X9 Z0;	G28 U0 W0;
M04 S500 F100;	G01 X10 Z-5;	T0303;
G00 X10 Z10;	G01 X10 Z-25;	M03 S500 F100;
G01 X0 Z0;	G01 X9 Z-30;	G00 X11 Z12;
G01 X-7 Z0;	G01 X11 Z-30;	G01 X8 Z12;
G01 X-6 Z-5;	G00 X11 Z0;	G00 X10 Z0;
G01 X0 Z5;		M05;
M05;		*G28 U0 W0;*
		M30;

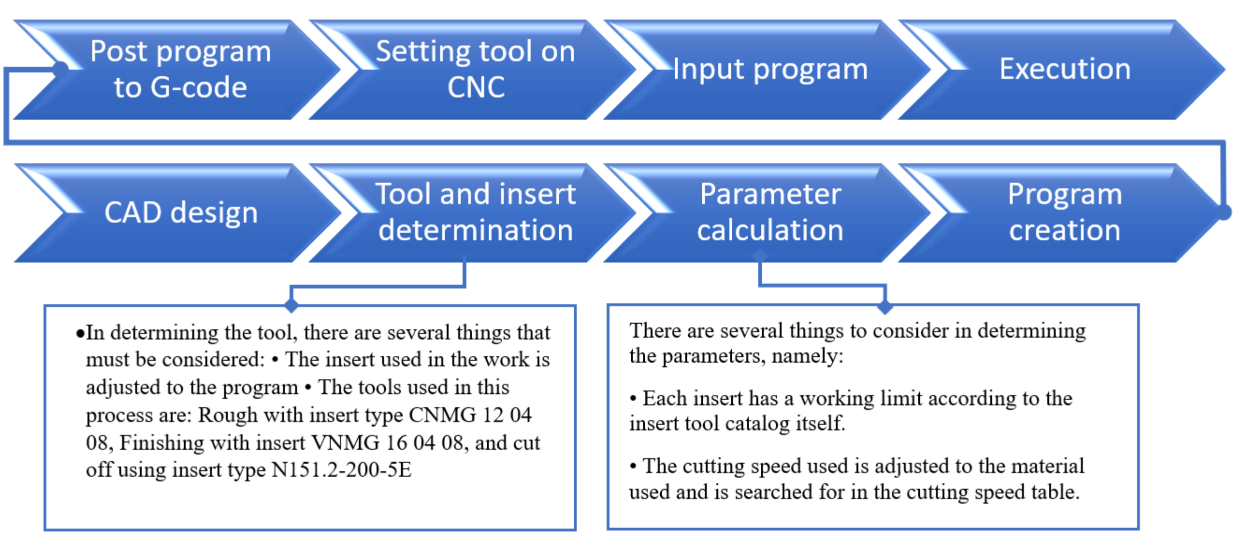

Figure 6. Production process using CNC machines.

After the simulation was carried out, the parameter data obtained were shown in Table 3. Table 6 displays the cutting parameters applied for CNC machining of the Boston Ring using stainless steel material. The table outlines the feed rate, spindle speed, and depth of cut for each toolpath operation to ensure precision and efficiency during production. The total production time is measured at 51 seconds per 4 pieces, reflecting high productivity while maintaining machining quality. These parameters balance material removal rates and surface precision, helping students understand optimal CNC settings for stainless steel workpieces.

Table 6. Parameter.

Materials	Stainless-steel			
Toolpath	**Feedrate (mm/rev)**	**Spindle Speed (CSS)**	**Max. Spindle Speed (Rpm)**	**Depth offcut (mm)**
Rough canned	0.2	60	2000	1
Finish canned	0.1	150	2500	0.2
Drill	0.1	100	1010	3
Cut off	0.05	60	1500	3
Production time	51 s / 4 pcs			

Table 7 presents the complete CNC coding sequence for producing the Boston Ring, utilizing four tools with specific offsets for roughing, finishing, drilling, and cut-off operations. The program begins with rough turning using Tool 1, continues with precision finishing using Tool 2, proceeds to drilling internal features with Tool 4, and completes the process with part cut-off using Tool 3. Each operation applies optimized spindle speeds, feedrates, and cutting paths through G-code commands, ensuring accuracy, efficiency, and high-quality surface finishes. This coding practice helps students develop competence in multi-tool CNC programming and process planning.

Table 7. Coding to Boston Ring.

(PROGRAM NAME - RING)	**(TOOL - 2 OFFSET - 2)**	**(TOOL - 3 OFFSET - 3)**	**G0 X14.**
G21	(OD FINISH RIGHT - 35 DEG. INSERT - VNMG 16 04 08)	(OD CUTOFF RIGHT INSERT - NONE)	G18
(TOOL - 1 OFFSET - 1)	G0 **T0202**	G0 **T0303**	X16.146
(OD ROUGH RIGHT - 80 DEG. INSERT - CNMG 12 04 08)	G18	G18	**Z-12.844**
G0 **T0101**	G97 S2500 M03	G97 S1135 M03	G1 X12.146
G18	G0 G54 X10. Z1.18 M8	G0 G54 X16.828 **Z-2.844**	X10. **Z-14.259**
G97 S1910 M03	G50 S2500	G50 S1500	G18 G3 X9.707 **Z-14.612** I-.5
G0 G54 X10. Z1.25	G96 S150	G96 S60	G1 X9.224 **Z-14.854**
G50 S2000	G70 P100 Q102	G1 X12.828 F.05	G3 X8.517 **Z-15.** I-.354 K.354
G96 S60	G0 Z1.18	X10. **Z-4.259**	G1 X4.99
Z1.18	M9	G18 G3 X9.707 **Z-4.612** I-.5	X8.99
G71 U1. R.2	G28 U0. W0. M05	G1 X9.224 **Z-4.854**	G0 X14.
G71 P100 Q102 U.4 W.2 F.2	**T0200**	G3 X8.517 **Z-5.** I-.354 K.354	G18
N100 G0 X6.103 S150	M01	G1 X4.99	X16.146
G1 X9.531 **Z-.534** F.1	(TOOL - 4 OFFSET - 4)	X8.99	**Z-17.844**
G3 X10. **Z-1.1** I-.566 K-.566	(DRILL 6. DIA.)	G0 X14.	G1 X12.146
N102 G1 **Z-30.**	G0 **T0404**	G18	X10. **Z-19.259**
G0 Z1.18	G18	X16.146	G18 G3 X9.707 **Z-19.612** I-.5
Z1.25	G97 S1010 M03	**Z-7.844**	G1 X9.224 **Z-19.854**
G28 U0. W0. M05	G0 G54 X0. Z5.	G1 X12.146	G3 X8.517 **Z-20.** I-.354 K.354
T0100	Z2.	X10. **Z-9.259**	G1 X4.99
M01	G74 R0.	G18 G3 X9.707 **Z-9.612** I-.5	X8.99
M01	G74 **Z-26.953** Q3. F.125	G1 X9.224 **Z-9.854**	G0 X14.
	G0 Z5.	G3 X8.517 **Z-10.** I-.354 K.354	G28 U0. W0. M05
	G28 U0. W0. M05	G1 X4.99	**T0300**
	T0400	X8.99	M30
			%

Probolt bolt design is shown in Figure 7a. To produce the Probolt bolt product, a jig is required as shown in Figure 7b. After the simulation, the parameter data obtained are shown in Table 4.

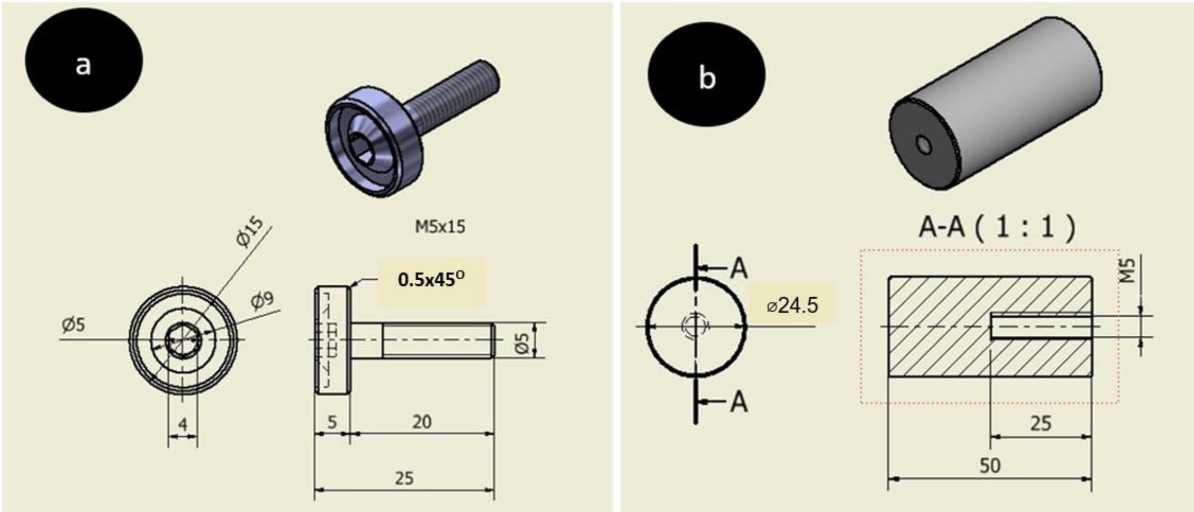

Figure 7. (a) Probolt bolt design, (b) Jig for design of probolt bolt.

Table 8 presents a structured manual CNC coding sequence for manufacturing Probolt bolts as part of STEM-based learning activities. The coding integrates essential machining operations, including rough turning, finishing, and threading, using standard G-code commands such as G71 for roughing cycles and G76 for threading processes. The sequence applies optimized spindle speeds and feedrates while managing precise tool positioning through coordinated X and Z-axis movements. This coding practice enhances students' understanding of CNC programming fundamentals, promotes analytical thinking in toolpath planning, and develops practical skills in producing standardized mechanical components, thereby supporting competency-based learning suitable for engineering education and technical skill development.

Table 8. Manual coding for making probolt bolts with STEM learning.

G28 U0 W0;	G28 U0 W0;
T0101;	T0303;
M03 S500 F80;	MO3 S200 F80;
G00 X15 Z5;	G00 X5 Z5;
G71 U1 R4;	G01 X5 Z0;
G71 P32 Q33 U0.2 W0.2;	G76 P010060 Q200 R100;
N032 G01 X5 Z0;	G76 X4 Z-15 P500 Q200 F1;
G01 X5 Z0;	G01 X10 Z5;
G01 X5 Z-20;	M05;
N033 G01 X15 Z-20;	G28 U0 W0;
G70 P32 Q33;	M30;
G00 X15 Z5;	
MO5;	

Table 9 presents the CNC machining parameters for producing Probolt bolts using stainless steel material. The process applies a feed rate of 0.2 mm/rev with a cutting speed (CSS) of 60 m/min and a maximum spindle speed of 2500 rpm for rough canned cycles, with a depth of cut reaching 1 mm to ensure efficient material removal. For the finish canned operation, the feed rate is reduced to 0.1 mm/rev, the spindle speed increases to 150 m/min, and the maximum spindle speed remains at 2500 rpm with a finer depth of cut of 0.2 mm to achieve higher surface quality. The face groove process utilizes a feed rate of 0.1 mm/rev and a spindle speed of 60 m/min with a maximum limit of 1500 rpm, applying a width of cut at 75% of the tool diameter for consistent groove formation. Overall, the complete production time is approximately 2 minutes per piece, demonstrating an optimized balance between machining efficiency and product quality.

Table 9. CNC parameter for probolt bolt.

Material	**Stainless-steel**				
Toolpath	**Feedrate (mm/rev)**	**Spindle Speed (CSS)**	**Max. Spindle Speed (Rpm)**	**Width of Cut (mm)**	**Depth offcut (mm)**
Rough canned	0.2	60	2500	-	1
Finish canned	0.1	150	2500	-	0.2
Face groove	0.1	60	1500	75%	-
Production time	2 minutes				

Table 10 displays the simulation coding process for manufacturing Probolt bolts using a CNC machine, involving multiple tools and cutting operations to achieve precision machining. The program begins with Tool 1 for rough turning, using a CNMG insert with 90° approach angles. It is followed by Tool 2 for finishing operations, employing a 35° VNMG insert to ensure smooth surface quality. Tool 3 is used for threading, utilizing a small insert with G76 threading cycles. Tool 4 performs face groove cutting with a wide insert to create precise groove features. The simulation incorporates optimized spindle speeds, feed rates, and depth controls, as well as coordinated tool offsets to manage complex toolpaths across roughing, finishing, threading, and grooving stages. The sequence concludes with tool retraction and program termination, providing a complete simulation workflow that trains students on practical CNC programming for accurate and efficient Probolt bolt production.

Table 10. Simulation coding for Probolt bolt manufacturing using CNC machine.

(Program name - Bolt L)	**(TOOL - 2 Offset - 2)**	**(Flip stock)**	**(Tool - 1 OFFSET - 0)**
G21	(OD Finish right - 35 DEG. Insert - VNMG 16 04 08)	(Tool - 4 Offset - 4)	(1. FLAT ENDMILL)
(Tool - 1 offset - 1)	G0 **T0202**	(Face groove right - wide insert - N151.2-600-4E)	G0 **T0100**
(OD rough right - 80 DEG. INSERT - CNMG 12 04 08)	G18	G0 **T0404**	G17
G0 **T0101**	G97 S2500 M03	G18	M23
G18	G0 G54 X15. Z1.18	G97 S3600 M03	G0 G55 X6.683 Z1.697
G97 S1137 M03	G50 S2500	G0 G54 X6.649 Z2.	C0.
G0 G54 X16.8 Z1.25	G96 S150	G50 S3600	G97 S2500 M52
G50 S2500	G70 P100 Q102	G96 S302	G98 G1 F477.4
G96 S60	G0 Z1.18	G1 **Z-.776** F.05	G28 U0. W0. H0. M55
Z1.18	X15.	G0 Z2.	**T0100**
G71 U1. R.2	G28 U0. W0. M05	X8.6	M30
G71 P100 Q102 U.4 W.2 F.2	**T0200**	G1 **Z-1.751** F.1	%
N100 G0 X-.297 S150	M01	G0 Z2.	
G1 X4.531 **Z-1.234** F.1	(TOOL - 3 OFFSET - 3)	G97 S500	
G3 X5. **Z-1.8** I-.565 K-.566	(OD thread right- small insert - R166.0G-16MM01-100)	X1.137	
G1 **Z-20.**	G0 **T0303**	Z1.697	
X13.4	G18	G1 X3.966 Z.283 F.05	
G3 X15. **Z-20.8** K-.8	G97 S750 M03	X6.483 **Z-.976**	
G1 **Z-26.**	G0 G54 X9. Z10.108	X6.683 **Z-.876**	
N102 X16.8	G76 P050030 Q.05 R0.	G0 Z1.414	
G0 Z1.18	G76 X4.134 **Z-17.** P4330 Q3000 R0. E.8	X11.828	
Z1.25	G28 U0. W0. M05	G1 X9. Z0.	
G28 U0. W0. M05	**T0300**	**Z-2.**	
T0100	M01	X8.531	
M01	M00	X6.483 **Z-.976**	
		X6.683 **Z-.876**	
		G0 Z1.697	
		G28 U0. W0. M05	
		T0400	
		M01	

Based on the simulation results for the Boston ring product made of stainless steel material, the estimated processing time is 12.75 seconds per piece, and the Probolt bolt has a production time of 2 minutes per piece. These parameters can be optimized if students succeed in manufacturing products in accordance with safety and health procedures, as well as the operational capabilities of the CNC machine.

Figure 8. CNC learning products.

Based on Figure 8 CNC learning product, ILO 4 and 5 are further supported by observation of CNC items made by students. The capacity to precisely construct components using CNC machines is the main focus of ILO 4. Strong technical execution was evident in one of the student projects, where the machined component showed concentric geometry, smooth outlines, and low dimensional deviation (<2 mm). Students were urged to consider their concepts and suggest improvements for ILO 5. The chosen product's useful yet distinctive shape demonstrated creative thinking, and the students recorded iterative design changes in response to feedback and test results. Their capacity to assess product quality and hone concepts two crucial elements of developing inventive skills is demonstrated by these reflective practices and redesign initiatives.

5. Conclusions

These findings support the effectiveness of STEM-based CNC learning in enhancing students' creative and technical capacities through project-based experiences. This article introduces a STEM-based CNC course aimed at enhancing students' creative and innovative skills. The project-based, student-centered learning model empowers students to design, build, and critically evaluate original CNC projects. Supported by a flexible and inclusive environment, the course helps students develop both technical and soft skills required for future careers in engineering, design, and technology. Preliminary outcomes indicate the approach is successful in engaging learners and cultivating 21st-century skills.

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