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CASE REPORT

Transdisciplinary STEAM and Quality Control Approaches Elevating Vocational Education in Support of SDGs

Enfoques Transdisciplinarios de STEAM y Control de Calidad: Mejorando la Educación Profesional en Apoyo a los ODS

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ABSTRACT

Introduction: the rapid development of modern industries requires vocational education to equip students with both technical expertise and creative, interdisciplinary competencies. To meet these demands, learning models must integrate scientific and technological knowledge with systematic quality assurance. This study examines the relevance and importance of combining STEAM-based learning with Quality Control (QC) to enhance students' readiness for industry-standard production.
Method: this study employed a Pretest-Posttest Control Group Design involving 32 vocational students divided into experimental and control classes. The experimental class received STEAM-QC-based instruction, integrating scientific concepts, technological tools, engineering design, artistic creativity, and mathematical analysis while applying QC at every production stage. Data were collected through tests, observations, and product assessments, and analyzed using Shapiro-Wilk and Levene tests, N-Gain, and Two-Way ANOVA. A total of 42 scholarly sources supported the theoretical and methodological framework.
Results: the STEAM-QC intervention strengthened students' interdisciplinary understanding, improved their systematic work processes, and enhanced the feasibility of their final products. Learning outcomes showed higher improvement in the experimental group, and product evaluations demonstrated better performance in construction quality, aesthetics, and durability. The model also promoted more consistent decision-making and reflective practice during production.
Conclusions: the integration of STEAM and QC provides an effective instructional model for vocational education by aligning academic learning with industrial quality standards. This approach supports the development of competent and innovative graduates and contributes to achieving SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure).

Keywords: STEAM; Quality Control; Vocational Education; Learning Model; SDGs.

RESUMEN

Introducción: el rápido desarrollo de las industrias modernas exige que la educación profesional prepare a los estudiantes con competencias técnicas, creativas y transdisciplinarias. Para responder a estas demandas, los modelos de enseñanza deben integrar conocimientos científicos y tecnológicos con mecanismos sistemáticos de control de calidad. Este estudio examina la relevancia y la importancia de combinar el aprendizaje basado en STEAM con el Control de Calidad (QC) para mejorar la preparación de los estudiantes en la producción conforme a los estándares industriales.

Método: este estudio empleó un diseño Pretest-Posttest con grupo control, involucrando a 32 estudiantes de formación profesional divididos en clases experimental y de control. La clase experimental recibió instrucción basada en STEAM-QC, integrando conceptos científicos, herramientas tecnológicas, diseño de ingeniería, creatividad artística y análisis matemático, aplicando control de calidad en cada etapa del proceso de producción. Los datos se recopilaron mediante pruebas, observaciones y evaluaciones de productos, y se analizaron usando las pruebas de Shapiro-Wilk y Levene, el N-Gain y el ANOVA de dos vías. En total, se utilizaron 42 fuentes académicas para respaldar el marco teórico y metodológico.
Resultados: la intervención STEAM-QC fortaleció la comprensión interdisciplinaria de los estudiantes, mejoró sus procesos de trabajo sistemático y aumentó la viabilidad técnica y estética de los productos finales. Los resultados de aprendizaje mostraron una mejora superior en el grupo experimental, y las evaluaciones de productos reflejaron un mejor desempeño en construcción, estética y durabilidad. Además, el modelo promovió una toma de decisiones más coherente y una práctica reflexiva durante la producción.
Conclusiones: la integración de STEAM y QC constituye un modelo de enseñanza eficaz para la educación profesional, al alinear el aprendizaje académico con los estándares de calidad industrial. Este enfoque contribuye a formar graduados competentes e innovadores y apoya el cumplimiento del ODS 4 (Educación de Calidad) y el ODS 9 (Industria, Innovación e Infraestructura).

Palabras clave: STEAM; Control de Calidad; Educación Profesional; Modelo de Aprendizaje; ODS.

INTRODUCTION

The era of the Industrial Revolution 4.0 has brought about significant changes in the way people work, learn, and interact, driven by rapid advancements in digital technology. This situation demands that every individual continually acquire new skills and adapt to emerging demands. Vocational education plays a crucial role in preparing graduates who are not skilled but also globally competitive. This endeavor aligns with the Sustainable Development Goals (SDGs), particularly quality education (SDG 4) and industry innovation (SDG 9), which emphasize the importance of developing dynamic, productive human resources who are ready to face ongoing changes. To achieve these objectives, vocational education curricula must be designed to be relevant to real-world needs, integrating various disciplines and promoting critical, creative, and collaborative thinking, while understanding the interconnectedness of technology, humanity, and the environment.[1]

The STEAM approach (Science, Technology, Engineering, Art, and Mathematics) is adopted on a broad scale in many including the United States, Europe, and Asia, with a focus on the elementary and secondary education levels, to enhance 21st-century competencies and the relevance of graduates to industrial needs.[2] Product-based vocational education systems that integrate Quality Control (QC) have proven effective in countries with dual TVET systems such as Germany and Switzerland.[3] International studies indicate that strengthening multidisciplinary dimensions and using a structured quality control approace can produce a skilled, adaptive, and innovative workforce. However, research combines the STEAM approach and Quality Control within the vocational education curriculum in Indonesia remains limited. This condition highlights a significant research gap, mainly in preparing vocational graduates who are not only proficient in technical competencies but also innovative and adaptable to global industry demands. STEAM education has emerged as a transformative approach that integrates multiple disciplines to enhance both students' soft and hard skills. Soft skills refer to 21st-century 4C competencies, while hard skills pertain to expertise in the relevant field of study.[4] Although this approach has been implemented at various education levels, from elementary to secondary schools, it is uncommon in vocational education, particularly in the Wood Construction Application course, which is actually highly relevant to the STEAM concept. In this course, students are guided to create wood constructions, either as building components or furniture products. The learning process has indirectly integrated disciplines such as engineering, art, and mathematics, although it has not yet been implemented optimally or in a structured manner.

Based on an initial needs analysis (figure 2) involving 64 students who had completed the Wood Construction Application course, it was found that the Science aspect was mastered well (87,11 %), while the Technology aspect was sufficiently mastered (67,97 %), although this was mostly limited to operating woodworking machinery. Students have not consistently utilized product design software, as manual design activities are still frequently observed. The Engineering aspect was categorized as sufficient (72,27 %). In contrast, the application of Art was relatively low (55,47 %), indicating that students' creativity has not been fully explored, as they tend to prioritize completing assignments quickly while neglecting aesthetics and the artistic value of the product. The Mathematics aspect was adequate (67,58 %), but it was mostly applied to basic dimension calculations, with limited independent work related to cost estimation or material requirement calculations. Overall, these findings suggest that although students possess good foundational knowledge, further enhancement is required in technological mastery, practical skills, and the integration of art and mathematics. Previous studies on this course have attempted to improve product quality, and while they have reported increases in cognitive achievement or knowledge,[5,6] they have not shown corresponding improvements in the quality of furniture products produced as learning outcomes. Analysis of the average scores of Wood Construction Application products in 2022 and 2023 (table 1) shows satisfactory results for construction, function, and product quality indicators. However, the indicators related to design and product innovation remain moderate. These results reinforce the need for improvements in technological mastery, skills, and the creative application of art and mathematics in the learning process.

Table 1. Average Scores of Wood Construction Application Products in 2023

Semester	Mean				
	Construction	Function	Design	Innovation	Quality
Jan-Jun-2022	88,50	89,25	72,50	73,75	80,25
Jan-Jun-2023	88,50	88,00	70,75	71,75	80,00
Category	Good	Good	Enough	Enough	Good

Efforts to enhance the quality of vocational education graduates require innovation in instructional approaches, as well as the systematic integration of multidisciplinary knowledge and compliance with industrial quality standards. The STEAM approach integrates five core domains: Science, Technology, Engineering, Arts, and Mathematics, [7] offering an innovative transdisciplinary learning model. This method provides meaningful learning experiences,[8] equips graduates with practical skills,[9] and enhances the pedagogical dimension of the arts.[10] STEAM also prepares learners to face the challenges of the 21st century,[11] while fostering their motivation and self-efficacy.[12] When implemented consistently, STEAM holds significant potential to transform future learning directions, in line with the increasingly dynamic and interactive demands of the modern era.[13] Project-based assignments in STEAM learning have also been proven to improve students' critical thinking skills.[14] At the elementary level, the implementation of STEAM has proven effective in enhancing students' competencias.[2] including cognitive and affective domains.[15] This approach also introduces innovative learning projects that involve various disciplines.[16] At the secondary level, STEAM has shown positive results in improving academic achievement, learning outcomes, and creativity.[17,18] STEAM education, when combined with Project-Based Learning (PjBL), can improve learning outcomes,[19] although its effect on product quality has not yet been clearly observed. Despite its evident success at the primary and secondary levels, its application in vocational education remains very limited. This limitation is especially notable in the integration of STEAM with frameworks relevant to industrial needs, such as Quality Control (QC).

Modern industries rely on multidisciplinary teams composed of engineers and artists to a greater extent.[20] Supporting this process, QC serves as a crucial element—a systematic mechanism to ensure product quality through maintenance, development, and design that aligns with established standards.[21] An effective QC system not only guarantees economical and satisfactory products but also assures quality from multiple perspectives, such as performance, reliability, aesthetics, and conformity to specifications,[22] ultimately impacting the productivity [23] and quality of industrial products.[24] As consumers become increasingly discerning, manufacturers are required to implement effective quality control to meet market expectations.[25] In vocational education, integrating the STEAM approach with QC is expected to produce graduates with both technical competence and innovative creativity, enabling them to better meet the complex challenges of contemporary professional sectors.

METHOD

This study employed a Pretest–Posttest Control Group Experimental Design, classified as a non-observational interventional experiment because the treatment was directly applied to participants and its effects were measured through learning outcomes and product quality. The sample consisted of 32 students enrolled in the Wood Construction Application course during the January–June 2024 semester. Participants were selected using purposive sampling based on GPA categories (Good, Average, Below Average) and were assigned to the experimental group (n=16) and control group (n=16). Ethical approval and informed consent were obtained.

The independent variable was the learning approach (STEAM integrated with Quality Control versus conventional project-based learning). The dependent variables included students' STEAM learning outcomes, product quality, and QC performance scores. The overall research workflow is presented in figure 1.

The control group received conventional project-based instruction without STEAM or QC integration. Meanwhile, the experimental group received the STEAM-QC approach consisting of five stages: design, material selection, joinery, assembly, and finishing. This instructional design is illustrated in figure 2.

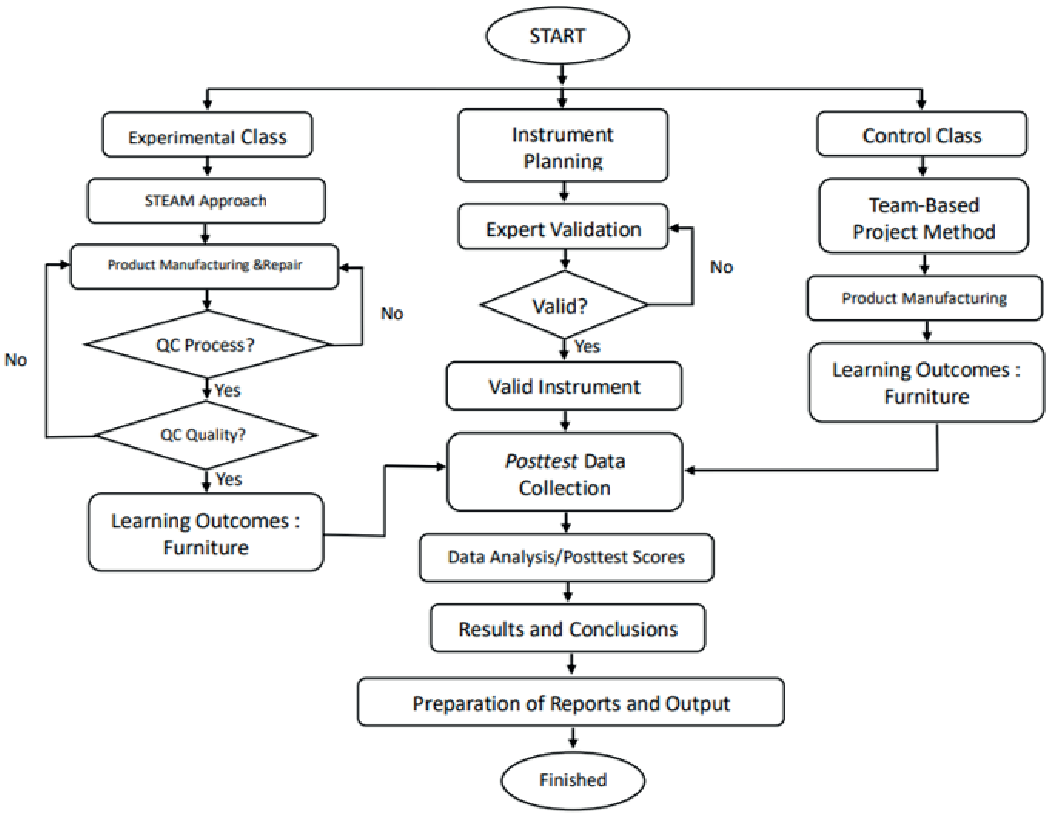

Figure 1. Research Flow

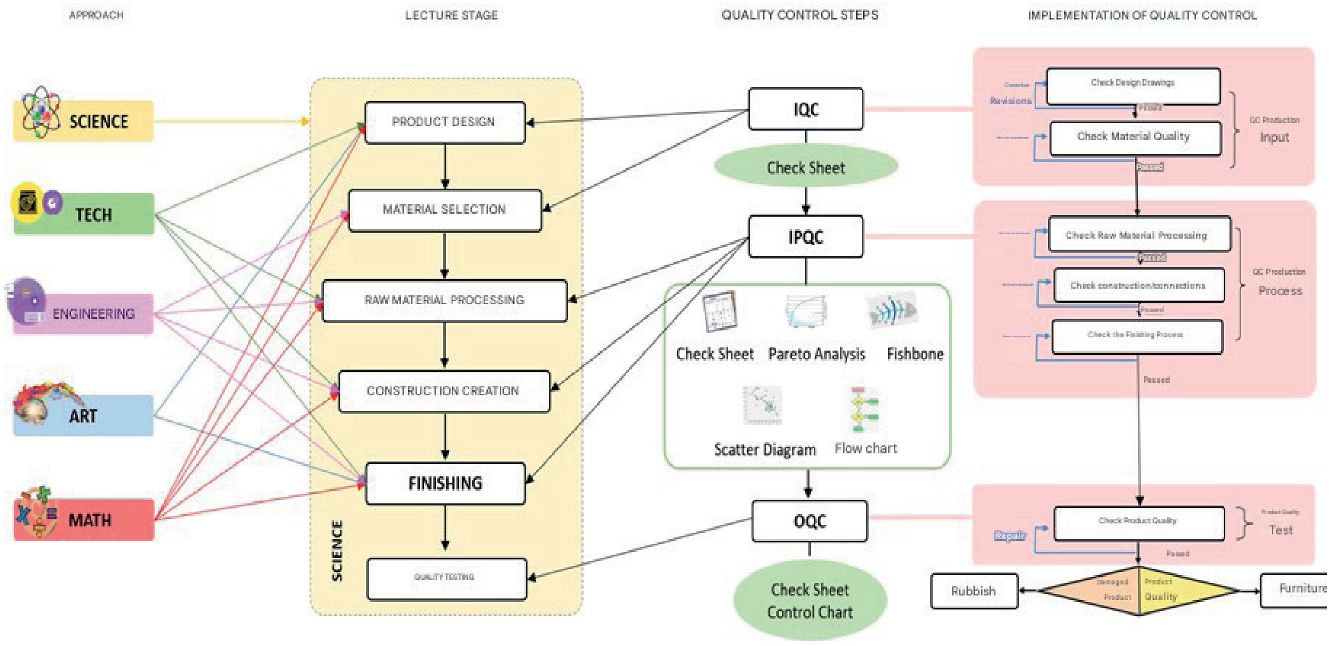

Figure 2. Lecture Design with STEAM Approach based on Quality Control

Each STEAM component was implemented systematically. Science was delivered through theoretical instruction. Technology was introduced through manual tools, portable equipment, stationary machines, and drawing/design software such as AutoCAD and SketchUp. Engineering involved machine operation, woodworking, and application of national competency standards. Art was embedded in creativity, form, color, and aesthetics. Mathematics was applied in budgeting, material estimation, dimensions, scheduling, and business planning.

QC was conducted at three levels: Incoming QC, In-Process QC, and Outgoing QC. Seven QC tools were used: Check Sheets, Graphs, Histograms, Pareto Charts, Cause-and-Effect Diagrams, Scatter Diagrams, and Control Charts. The QC stages are shown in figure 3.

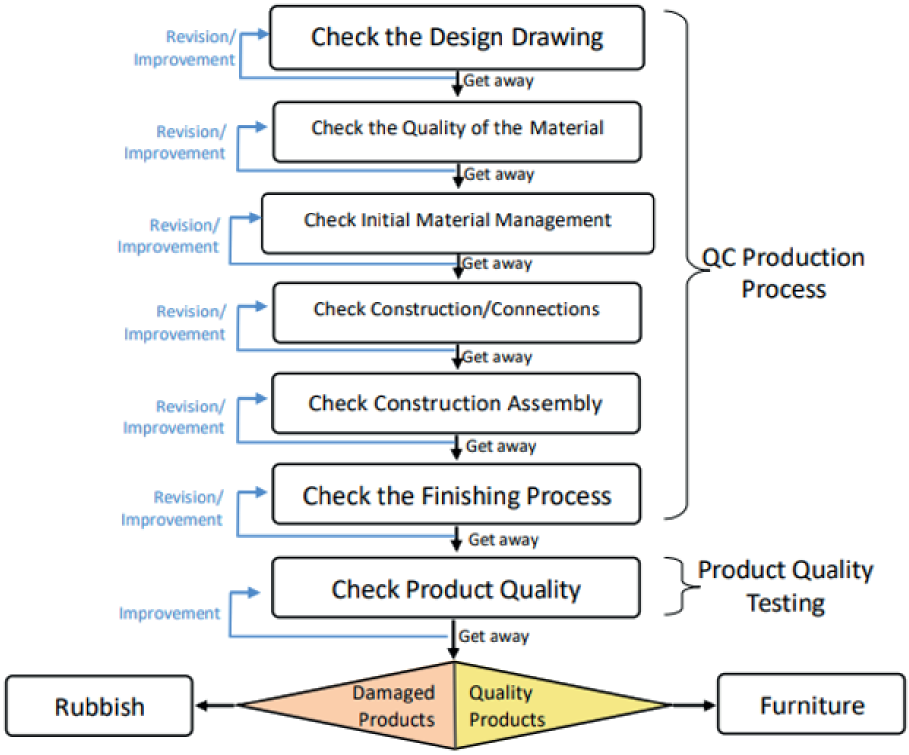

Figure 3. Quality Control Stages

Data were collected through pretests, posttests, QC evaluation sheets, observation rubrics, and documentation. Data analysis employed Two-Way ANOVA, N-Gain calculation, and QC-based product categorization.

RESULTS

Improvement of Learning Outcomes in the Production Process

This study utilized a Two-Way ANOVA to evaluate the influence of class factors, indicators, and their interaction on students' learning outcomes. Prior to analysis, the data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene's Test. The results indicated that the data were distributed in a normal pattern (0,372 > 0,05) and the variances among groups were homogeneous (0,060 > 0,05).

The analysis in table 2 indicates that the class factor had a significant effect on students' learning outcomes (F = 138,609, p < 0,001), demonstrating a clear difference between the experimental and control groups. Conversely, the indicator factor (F = 0,682, p = 0,605) and the interaction between class and indicator (F = 1,560, p = 0,188) were not significant, indicating that the class grouping played the most substantial role in determining learning outcomes, while the other factors had less impact.

Table 2. Mathematics Two-Way ANOVA Test for Production Process: Technology, Engineering, Art, and Mathematics Indicators

Class Tests of Between-Subjects Effects					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	13 135,781[a]	9	1459,531	16,397	0,000
Intercept	954 037,656	1	95 4037,656	10 718,270	0,000
kelas	12 337,656	1	12 337,656	138,609	0,000
indikator	242,813	4	60,703	0,682	0,605
kelas * indikator	555,312	4	138,828	1,560	0,188
Error	13 351,563	150	89,010		
Total	980 525,000	160			
Corrected Total	26 487,344	159			

For the production process, the Science indicator was assessed using a questionnaire consisting of 50 items, administered as both a pre-test and post-test. Thus, the N-Gain score was calculated only for the Science indicator. Table 3 summarizes the assessment results for the Science indicator in both experimental and control classes. In the experimental class, the mean pre-test score was 21,88 (range: 10 to 36, SD = 6,67), which significantly increased to 85,63 in the post-test (range: 70 to 95, SD = 7,72).

Table 3. Science Indicator Assessment in Experimental and Control Classes

	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Experiment	16	1	1	16	1,00	0,000
Preetest	16	10	36	350	21,88	6,672
Posttest	16	70	95	1370	85,63	7,719
Control	16	2	2	32	2,00	0,000
Preetest	16	16	34	356	22,25	4,837
Posttest	16	50	90	1120	70,00	12,383

In the control class, the mean pre-test score was 22,25 (range: 16 to 34, SD = 4,84), showing relatively homogeneous initial abilities. After the intervention, the mean post-test score increased to 70,00 (range: 50 to 90, SD = 12,38), indicating significant improvement though with greater variability. Figure 4 illustrates that both classes had similarly low baseline abilities before the intervention. Following the respective interventions, both classes showed improvement in Science indicator scores, with the experimental class experiencing a more pronounced increase.

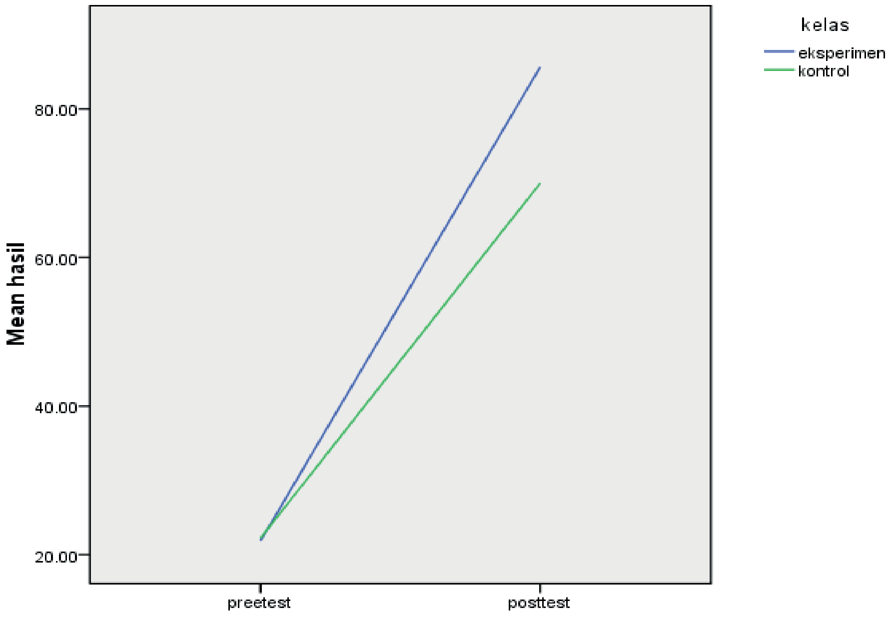

Figure 4. Science Indicator Production Process Assessment

Based on the N-Gain scores in table 4, the experimental class achieved a mean of 81,44 %, while the control class achieved 61,60 %, indicating that the experimental treatment was "effective" and the control "quite effective".

Table 4. N-Gain Scores for Experimental and Control Classes

Class	Mean N-Gain (%)	Std. Error	95 % CI Lower	95 % CI Upper	Min	Max
Experimental	81,44	2,46	76,20	86,68	62,50	94,05
Control	61,60	3,84	53,41	69,80	37,50	87,18

Table 5 presents the production process assessment scores based on the STEAM indicators. For the Science indicator, the experimental class achieved a score of 85,63, while the control class obtained 70,00. The

Technology indicator shows a score of 85,94 for the experimental class and 66,88 for the control class. In the Engineering indicator, the experimental class recorded a score of 86,25, whereas the control class achieved 65,94. For the Arts indicator, the experimental class obtained a score of 87,19 compared to 65,63 in the control class. Lastly, in the Mathematics indicator, the experimental class scored 85,00, while the control class recorded 73,75.

Table 5. Production Process Assessment for STEAM Indicators

Indicator	Experimental	Control
Science	85,63	70,00
Technology	85,94	66,88
Engineering	86,25	65,94
Art	87,19	65,63
Mathematics	85,00	73,75

Quality Of Product

Product quality assessment was conducted on the completed products, focusing on aspects such as appearance, safety, construction, stability, and durability. The prerequisite analysis showed that the data were normally distributed (table 6, Shapiro-Wilk, Sig. 0,127 > 0,05) and that the variance in product quality was homogeneous between the experimental and control classes (table 7, Levene's Test, Sig. 0,446 > 0,05).

Table 6. Test of Normality for Product Quality Indicators

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	Df	Sig.
Standardized Residual for Residual	0,089	40	0,200*	0,957	40	0,127

Table 7. Test of Homogeneity of Product Quality Indicators

F	df1	df2	Sig.
1,021	9	30	0,446

The Two-Way ANOVA table 8 revealed a significant difference in product quality between the experimental and control classes (Sig. 0,000 < 0,05), but no significant difference based on the quality indicators (Sig. 0,100 > 0,05). Furthermore, there was no significant interaction between class and indicator in determining product quality (Sig. 0,734 > 0,05). This shows that product quality was more influenced by the treatment applied in the experimental class rather than by differences between the quality indicators.

Table 8. Two-Way ANOVA for Product Quality Indicators

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2927,798[a]	9	325,311	20,499	0,000
Intercept	24 5478,390	1	245 478,390	15 468,748	0,000
kelas	2759,752	1	2759,752	173,905	0,000
indikator	136,099	4	34,025	2,144	0,100
kelas * indikator	31,948	4	7,987	0,503	0,734
Error	476,079	30	15,869		
Total	248 882,268	40			
Corrected Total	3403,877	39			

Based on the product quality assessment (table 9), the experimental class achieved scores ranging from 80,00 to 90,00, while the control class ranged from 60,00 to 75,25.

Table 9. Product Quality Assessment: Appearance, Safety, Construction, Stability, and Durability

Indicator	Experiment					Control				
	P1	P2	P3	P4	Mean	P1	P2	P3	P4	Mean
Aesthetics	75,00	85,25	89,55	90,00	84,95	60,25	64,75	70,00	65,00	65,00
Safety	85,00	90,00	89,75	84,85	87,40	70,00	75,00	74,50	69,55	72,26
Construsction	89,50	90,00	85,00	89,50	88,50	75,25	71,50	70,00	70,45	71,80
Stability	80,00	89,75	90,00	85,00	86,19	70,00	65,00	69,75	75,00	69,94
Durability	90,00	80,00	89,75	85,00	86,19	69,50	74,55	70,25	70,35	71,16

DISCUSSION

The findings of this study demonstrate that the STEAM-based instructional model integrated with Quality Control (QC) provides a more effective learning experience for vocational students than conventional approaches. The structured combination of STEAM and QC encourages students to work systematically, integrate multidisciplinary knowledge, and apply quality standards throughout the production process. This aligns with previous studies [26] emphasizing that project-based learning rooted in authentic tasks can enhance vocational students' creativity, critical thinking, communication, and collaboration.

The present study reaffirms the role of STEAM in strengthening students' interdisciplinary understanding. Prior literature highlights that STEAM-based learning facilitates the development of conceptual reasoning,[27] linguistic competence,[28] and higher-order cognitive skills.[29] It also supports students' abilities in critical thinking,[30] computational reasoning,[31] collaboration,[32] and creativity.[33] While previous research has predominantly focused on primary and secondary education contexts or specific conceptual topics,[34] this study contributes to the growing body of evidence on STEAM effectiveness at the higher vocational level, particularly in product-based learning environments.

A key contribution of this research lies in demonstrating the pedagogical value of integrating QC within a STEAM framework. QC does not only function as a mechanism to reduce production defects, as noted in traditional industrial contexts,[35,36] but also serves as an instructional tool that cultivates students' ability to evaluate processes, identify errors, and make data-driven decisions. The use of QC tools encourages students to engage in systematic thinking, enhancing their ability to achieve consistent performance and meet industry expectations regarding aesthetics, functionality, and durability. This finding supports the view that QC connects theoretical knowledge with practical execution in industrial settings.[37]

The integration of STEAM and QC in this study also highlights important implications for vocational curriculum development. Although students benefited from the approach, some challenges were observed related to maintaining consistent quality and performing QC independently. These challenges suggest that mastery of QC principles requires more sustained exposure and explicit instruction. This observation is consistent with previous research[38] indicating that competency-based learning alone is insufficient unless accompanied by systematic evaluation and continuous practice. The adoption of performance-based assessments can further strengthen students' analytical and problem-solving skills, which are essential for vocational graduates.[39]

Furthermore, this study offers important theoretical implications by showing how QC enhances the outcomes of STEAM learning beyond cognitive achievement. By embedding QC at each production stage, students develop metacognitive awareness, process-management skills, and the capacity to uphold professional standards. This strengthens the argument that vocational education must increasingly integrate cross-disciplinary competencies to prepare students for the demands of modern industries, particularly in the era of the Fourth Industrial Revolution.

Finally, the STEAM-QC approach implemented in this study contributes to the achievement of Sustainable Development Goals, specifically SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure). By fostering technical competence, creativity, and systemic problem-solving, this integrated model supports the development of competent and innovative future professionals. The alignment between educational practices and industrial standards further ensures that vocational graduates are equipped with the skills necessary to compete in a rapidly evolving global labor market.

CONCLUSIONS

This study indicates that the implementation of the STEAM approach integrated with Quality Control (QC) can serve as an effective learning model in vocational education. This approach supports the achievement of the research objectives, namely improving the quality of the learning process and producing products that meet technical and aesthetic standards. The integration of STEAM and QC encourages students to think transdisciplinarily, work systematically, and understand the importance of quality standards throughout the production process.

Overall, the STEAM-QC learning model provides an important contribution to strengthening vocational graduates' competencies, particularly in creativity, problem-solving, and readiness to face modern work environments. This model is aligned with industry demands and supports the achievement of SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure).

Nevertheless, this study has several limitations, particularly in the QC implementation, which was carried out entirely by lecturers without the involvement of industry practitioners, and in the limited research context involving only one study program. Therefore, future research is recommended to involve more extensive collaboration with industry practitioners and to examine the application of this model across various vocational fields. Such efforts are expected to provide a more comprehensive understanding of the effectiveness of the STEAM-QC approach in supporting the goals of vocational education and sustainable development.

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CONFLICT OF INTEREST

The authors declare no conflict of interest related to the publication of this article. All authors have read and approved the final version of the manuscript.

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