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DEVELOPING SMART BUILDING LEARNING MEDIA (KNX SYSTEM) AND ITS IMPACTS ON STUDENT'S LEARNING OUTCOMES

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Abstract
This study investigated the developments of Smart Building learning media (KNX System) which focuses on control system elements at SMK Negeri 3 Surabaya, assessed through three aspects: (1) media validity, (2) media practicality, and (3) media effectiveness. This research uses the Research & Development (R&D) development method using the Borg & Gall model. Validity assessments included trainer validity tests, module validity tests, validity tests of student response questionnaires, validity tests of pretest and posttest, validity tests of attitude observation sheets and skills observation sheet tests. The results of the validity test showed that this trainer scored 86%, the validity test of the module scored 81%, the validity test of the student response questionnaire scored 77%, the validity test of the pretest and posttest questions got a score of 75%, the validity test of the attitude observation sheet scored 76%, and the validity test of the skill observation sheet scored 74%. Next, a practicality test was carried out which resulted in a score of 69%, in the practice category. For the latter, an effectiveness test was performed to assess how effectively the treatment is applied. The result of the N-Gain score obtained a value of 0.5, which was in the interval of $0.3 \leq n \leq 0.7$. This indicated that the average N-Gain score is categorized as moderate. To differentiate between the average score of the pretest and posttest, the Paired Sample T-Test was performed using SPSS, resulting in a p value of 0.000. This indicated a significant influence on student learning outcomes before and after the implementation of this learning media. It can be concluded that the learning media developed is suitable for use in learning and can be used as a reference for the development of learning media in other learning elements.

Keywords: Control system, KNX system, learning media, smart building, vocational school.

Introduction

The fourth industrial revolution, or Industry 4.0, has fundamentally changed the landscape of education, industry, and society. As countries strive to compete globally, improving the quality of education has become a major focus of national development programs (Schwab, 2017). In Indonesia, the Ministry of Industry (Kemenperin) has responded by introducing evaluation indicators to prepare for the implementation of Industrial Technology 4.0, recognizing the need for an innovative, adaptive, and technology-literate workforce (Kemenperin, 2018). Technological advances have significantly affected educational practices, especially in the achievement of learning objectives. According to Heinich et al. (1996), the integration of appropriate media and learning methods is essential to create an engaging, interactive, and effective learning environment. Well-designed learning media can facilitate the understanding of complex concepts through visualization and simulation, foster student motivation, and improve the delivery and retention of subject matter. In addition, learning media that is aligned with industry needs can increase students' readiness to enter the world of work, especially in vocational education settings (Mayer, 2009).

The development of technology-based learning media that is in line with the needs of the industry is the concept of smart building. This concept refers to the integration of automated systems and intelligent devices within buildings to improve energy efficiency, occupant comfort, and operational effectiveness (Clements-Croome, 2013; Buckman, Mayfield, & Beck, 2014). One of the technologies that supports the implementation of smart building is the KNX system which is controlled by ETS (Engineering Tools Software) software. The system is flexible and scalable, allowing for the addition or modification of devices without the need to change the installation completely. In addition, the KNX system also provides ease in terms of maintenance, efficiency in the use of cables, and improved security systems compared to conventional systems that are still widely used in Indonesia.

KNX technology represents the standard application of modern control systems, enabling the centralized integration and management of various building functions—such as lighting, HVAC, and security—through a flexible and scalable data bus architecture (KNX Association, 2022). Implementing KNX in educational settings not only improves students' understanding of automation and control concepts but also provides practical experience with real-world building automation, which is important for preparing students to meet the demands of a smart and energy-efficient building environment (Clements-Croome, 2013).

Learning involving modern control systems such as KNX, configured through Engineering Tools Software (ETS), can significantly improve student achievement by supporting the development of cognitive, affective, and psychomotor domains. In the cognitive domain, students gain an understanding of the principles of automation and the operation of control systems; in the affective domain, they develop a positive attitude towards energy efficiency and the responsible use of technology; and in the psychomotor domain, they acquire practical skills in designing and operating KNX-based building automation systems. Thus, learning media based on smart building technology and KNX not only function as an innovative educational tool but also provide a comprehensive strategy to improve student competencies in line with the demands of Industry 4.0 (Clements-Croome, 2013; KNX Association, 2022).

The development of technology-based learning media that is in line with the needs of the industry is exemplified by the concept of smart building. A smart building is defined as a structure that integrates automated systems and smart technologies to optimize energy consumption, improve operational efficiency, and improve occupant comfort (Buckman, Mayfield, & Beck, 2014). One of the key technologies supporting the implementation of smart buildings is the KNX system, which is configured through Engineering Tools Software (ETS). KNX systems offer high flexibility and scalability, allowing for the addition or modification of devices without requiring major changes to existing installations. In addition, KNX provides advantages in terms of ease of maintenance, efficient use of cables, and improved safety compared to conventional building systems (Sinopoli, 2010). These features make KNX the solution of choice for modern building automation, supporting current and future demands for intelligent and sustainable building management.

KNX technology exemplifies the application of modern control systems, which are defined as interconnected components designed to regulate and control processes so that they operate according to predetermined parameters (Nise, 2015). As a standard platform for building automation, KNX enables seamless integration and centralized management of various building functions – such as lighting, HVAC, and security – through a flexible and scalable data bus architecture (Sinopoli, 2010).

In an educational context, utilizing a control system such as KNX as a learning medium not only deepens students' understanding of technical concepts in automation and control, but also provides valuable hands-on experience in configuring and operating real-world building automation systems. This practical exposure is essential to prepare students to meet the demands of a smart and energy-efficient building environment.

Learning involving modern control systems such as KNX, configured through Engineering Tool Software (ETS), can significantly improve student achievement by supporting the development of cognitive, affective, and psychomotor domains. In the cognitive domain, students gain an understanding of the principles of automation and the operation of control systems; in the affective domain, they develop a positive attitude towards energy efficiency and the responsible use of technology; and in the psychomotor domain, they acquire practical skills in designing and operating KNX-based building automation systems. Thus, learning media based on smart building technology and KNX not only serve as an innovative educational tool but also provide comprehensive strategies to improve student competencies in line with the demands of Industry 4.0 (Bloom et al., 1956; Sinopoli, 2010). From the facts and main issues above, the writers are interested in investigateing the development of Smart Building learning media (KNX System) which focuses on control system elements at SMK Negeri 3 Surabaya, assessed through three aspects: (1) media validity, (2) media practicality, and (3) media effectiveness.

Literature Review

Learning media development

The development of learning media is the central focus in efforts to improve the quality of education, especially in the context of rapid technological advances in the Industry 4.0 era. According to Heinich et al. (1996), learning media are all physical means that can present messages and stimulate students to learn. The selection and development of appropriate instructional media is essential to facilitate the delivery of complex concepts, increase student motivation, and support the achievement of learning objectives.

Instructional media serve as intermediaries between teachers and students, helping to clarify subject matter, visualize abstract ideas, and make learning more interactive and engaging (Heinich et al., 1996; Mayer, 2009). Mayer (2009) emphasizes that multimedia learning, which combines text, images, and interactive elements, can significantly improve students' understanding and retention of information. The integration of technology-based media, such as simulations and smart building trainers, allows students to experience real-world applications, thus preparing them for the demands of modern industries and workplaces.

In addition, the use of learning media is closely related to the learning outcomes framework introduced by Bloom et al. (1956), which includes cognitive, affective, and psychomotor domains. Effective learning media not only supports the acquisition of knowledge (cognitive), but also fosters positive attitudes (affective) and develops practical skills (psychomotor). By combining relevant technology and authentic context, teachers can create a learning environment that is motivating, interactive, and aligned with the competencies needed in the 21st century (Heinich et al., 1996; Mayer, 2009). In summary, the systematic development and integration of learning media is essential to achieve educational goals, increase student engagement, and equip learners with the skills and attitudes necessary to succeed in the Industry 4.0 era.

Smart building

Smart buildings are defined as structures that integrate advanced technology and automated systems to optimize energy efficiency, operational effectiveness, and occupant comfort, while minimizing environmental impact (Sinopoli, 2010; Wong & Wang, 2017). These buildings use intelligent control systems to automatically manage lighting, HVAC, security, and other infrastructure, enabling real-time monitoring, adaptation to changing conditions, and efficient utilization of resources. The implementation of smart building strategies, such as automatic lighting and climate control, not only reduces energy consumption but also improves safety and comfort for users. As technology evolves, smart buildings increasingly incorporate sensors, actuators, and interconnected devices, allowing buildings to respond dynamically to internal and external stimuli (Wong & Wang, 2017).

By applying the concept of smart environments, smart buildings can innovatively assess and improve their performance by directly engaging their systems to monitor and adapt to changing conditions (Cook & Das, 2005). In these buildings, energy use is managed through an integrated automation network—such as KNX—that is supervised by a central software controller. This system connects sensors, actuators, and other devices to interpret data and execute commands automatically (Sinopoli, 2010). For example, smart building strategies enable automation of lighting, curtains, or garage doors, significantly improving energy performance by maximizing the use of natural sunlight during the day and activating artificial lighting only when needed. This reduces unnecessary electricity consumption, which often occurs when the system is operated manually and the user forgets to turn it off. Thus, smart buildings not only support sustainability and efficiency, but also provide a safer, more comfortable, and adaptive environment for residents (Wong & Wang, 2017; Cook & Das, 2005).

KNX system

KNX is a global building automation standard, set by EN 50090 and ISO/IEC 14543-3, which allows a wide range of devices and systems to operate in a single control and monitoring network (KNX Association, 2022; Sinopoli, 2010). The standard is based on the OSI (Open Systems Interconnection) model, providing a universal communication framework for smart home and building automation applications (Kastner et al., 2005). Instead of producing hardware, the KNX Association publishes standards and offers Engineering Tool Software (ETS) for system configuration, allowing manufacturers such as ABB, Schneider Electric, and Siemens to manufacture KNX-compliant products (KNX Association, 2022; Wong & Wang, 2017).

KNX operates on a data bus architecture, where each device is assigned a unique bus address, allowing it to send and receive commands and information across the network. By connecting all nodes in parallel along a single cable, KNX facilitates seamless communication between sensors, actuators, and controllers, providing centralized monitoring and control for the entire system (Sinopoli, 2010; Wong & Wang, 2017). This unified platform supports a wide range of building automation functions, including lighting management, HVAC, security, and more, with the flexibility to add or modify devices without major changes to installation. The system's scalability and ease of maintenance make it a perfect fit for residential and commercial applications.

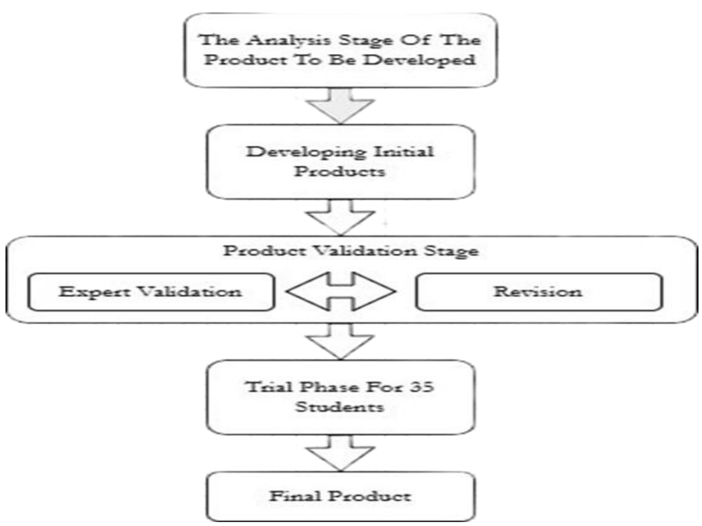
Unlike other smart relay applications such as CX Program or Zelio for PLCs, ETS is a vendor-independent database-based platform that combines product information from multiple manufacturers to simplify the design of building automation systems (KNX Association, 2022). As the official Engineering Tool Software for KNX, ETS allows integrators to connect individual devices into integrated installations and configure multiple communication media and device parameters. The platform also serves as an educational gateway through its demo edition, supporting up to five residential devices such as lighting, HVAC units, and motorized curtains. With comprehensive project planning utilities and a multi-vendor product database, ETS streamlines the process of building automated installations and enables centralized management of all components connected to KNX (Sinopoli, 2010; Wong & Wang, 2017).

Methodology

Research design and approach of the study

This research aims to develop the smart building learning media based on the KNX system to improve student learning outcomes on the control system elements at SMKN 3 Surabaya. This study uses quantitative and qualitative approach, because the data collected is in the form of numbers and analyzed using statistical techniques as well as analyzing the data collection in interview and observation. This approach examines the extent to which the developed learning media is able to influence the improvement of student learning outcomes in cognitive, affective, and psychomotor aspects. And in development using the Borg & Gall model (Borg & Gall, 1983), which is simplified into five main stages: (1) needs analysis, (2) product development, (3) expert validation, (4) field testing for practicality and effectiveness, and (5) data analysis. This model is widely recognized in educational research to systematically guide the development and validation of instructional products (Heinich et al., 1996). The developed products consist of a smart building trainer that utilizes the KNX system, which is automatically controlled through Engineering Tool Software (ETS 6 V.6.2.2), and a teaching module that focuses on smart building control systems, in accordance with the latest technological developments and the Internet of Things (IoT) paradigm (Sinopoli, 2010; KNX Association, 2022). The detailed research procedure is illustrated in Figure 1.

Figure 1. *Borg & gall research procedures* Adapted from Borg & Gall (1983) in Gustiani (2019)



The research process consists of several stages, namely the stages of product analysis, the development of learning media products, product validation by experts, the implementation of media practicality tests on 35 students majoring in TITL class XI with a focus on the application and effectiveness of teaching media, the final product produced by the teaching module and smart building trainer (KNX system) that has been validated. The core data collected included product testing and validation results, which included students' competency levels before and after the use of the developed media, and student responses. The study used a single-group pre-test post-test design, in which one group of subjects was given treatment without a control group. The initial test assesses students' basic abilities, while the final test evaluates the improvement of learning outcomes after using the KNX system-based smart building learning media for control system elements. The research design is presented in Figure 2.

Figure 2.

O1 X O2

Adapted from Sugiyono, (2018).

Information:

O_1 : Pre-test score before treatment

X : Treatment of the use of smart building learning media (KNX system) in control system elements

O_2 : Post-test score after treatment

Research site and participants

In research, the population includes each unit of analysis whose characteristics will be estimated. Unit of analysis refers to a specific entity or object being studied (Abdullah et al., 2022). In this study, the sample consisted of all 35 students enrolled in the Electrical Power Installation Engineering (TITL) Class XI study program of SMK Negeri 3 Surabaya, who were taking the Control System element course. The sampling technique used was saturated sampling, using the entire population of students in grade XI TITL SMK Negeri 3 Surabaya as a research sample. This technique is used because the population is not too large and the entire population is considered to represent the needs of the developed learning media trial (Kumara, 2018).

Data collection and analysis

The data collection instrument is prepared in accordance with the research approach and is used as a reference for experts' assessment of the developed product. This instrument serves to collect data on the validity, practicality of media, and the effectiveness of learning outcomes through the use of learning media (Medica et al., 2020). The data collection techniques in the research used to obtain the right research results can be explained in Table 1.

Table 1. *Data collection techniques used in research*

No.	Aspects	Data Collection Techniques
1.	Media validity	Expert validation
2.	Media practicality	Student Response Questionnaire
3.	Media effectiveness	Pre-test *and* post-test questions for students' cognitive domains
4.	Learning outcomes	Student Attitude Assessment Student Skills Assessment Observation Sheet

Adapted from Djanuarfianti et al., (2023).

The study combines expert validation by subject matter and media experts, evaluates practicality through student feedback, and measures effectiveness through improved student learning outcomes achieved with learning media. The assessment of learning media is carried out by two validators, by material and media experts. The validation data was measured using a Likert scale with a weight of 5.4.3.2.1 which represents very good to bad. This scale is used to convert ordinal data into quantitative data that can be analyzed statistically. To assess the level of validity of the learning medium, the final score is presented in percentages, as shown in Table 2.

Table 2. *Range percentage validator*

Achievement Presentation	Value Scale	Interpretation
81% ≤ score ≤ 100%	5	Highly Valid
61% ≤ score ≤ 80%	4	Legitimate
41% ≤ score ≤ 60%	3	Quite Valid
21% ≤ score ≤ 40%	2	Less Valid
Score ≤ 0% ≤ 20%	1	Cancel

To calculate the response percentage, use the following formula:

$$\text{Total Score (\%)} = \frac{Sum\ of\ score\ obtained}{Max\ score\ x\ Number\ of\ validators} \times 100\% \quad (1)$$

The results of the presentation that have been obtained are then reformatted into a table to make it easier to interpret the research. The student response questionnaire was analyzed to evaluate the practicality of the learning media, with the assessment criteria detailed in Table 3.

Table 3. *Range of student response questionnaire percentage*

Achievement Presentation	Value Scale	Interpretation
81% ≤ score ≤ 100%	5	Very Practical
61% ≤ score ≤ 80%	4	Practical
41% ≤ score ≤ 60%	3	Quite Practical
21% ≤ score ≤ 40%	2	Less Practical
Score ≤ 0% ≤ 20%	1	Practical

To calculate the response percentage, use the following formula:

$$\text{Total Score (\%)} = \frac{\textit{Sum of score obtained}}{\textit{Max score x Number of validators}} \text{ x } 100\% \quad (2)$$

f respondents

Student response data is arranged in tables to simplify the analysis and interpretation of research findings, learning outcomes in three affective, cognitive, and psychomotor domains. The evaluation was carried out after participating in learning using smart building learning media (KNX system), and compared with the criteria for completeness of learning objectives (KKTP) of 78. Affective assessment is carried out through observation sheets, while cognitive assessment uses pretest and posttest tests based on the number of correct answers. For the psychomotor realm, the assessment is taken from the results of the practicum sheet. Djarir & Achmad (2024) stated that final learning outcomes were a combination of three domains with weight, affective 30%, cognitive 30%, and psychomotor 40%.

This procedure assesses effectiveness by examining significant data discrepancies. Before the t-test was performed, normality tests were performed using Shapiro-Wilk in SPSS 27 to determine whether the data were distributed normally, with the criteria hiding the normally distributed data and assuming that the data was not distributed normally, with the criteria accepted if the significance value was more than Then the data met the normality criteria, Then followed by the paired sample t-test to determine the effect after using smart building learning media (KNX) system). The hypothesis tested was that there was no significant influence and there was a significant influence on the value of learning outcomes;

H0H1H0 ≥ 0,05. H0H1

In addition, according to Coletta & Steinert, (2020), an N-gain analysis was conducted to assess the effectiveness of learning media by comparing pretest and posttest scores. The n-gain value was categorized as high (n ≥0.7), medium (0.3≤ n <0.7), and low (n ≤0.3).

Findings

Developing product in learning media and smart building teaching module (KNX System)

This research resulted in a product developed in the form of learning media and a smart building teaching module (KNX system) which discusses a series of control systems about the competence of control system expertise at SMK Negeri 3 Surabaya, smart building learning media (KNX system) is shown in Figure 3.

Figure 3. *Smart building learning media (KNX system)*

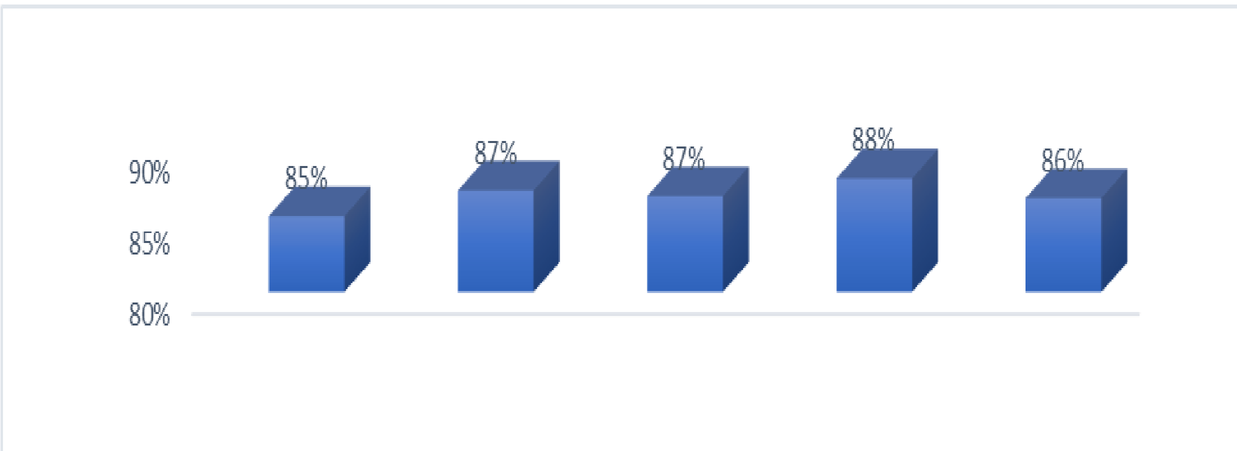
This learning media has features such as where to connect banana plugs, main components, and the application of the KNX system control system. The teaching module contains material related to the KNX system control system which consists of five materials equipped with formative questions and LKPD from each material. For the teaching module using the smart building trainer (KNX system) shown in Figure 4.

Figure 4. *Smart building teaching module cover (KNX system)*

Content validty analysis

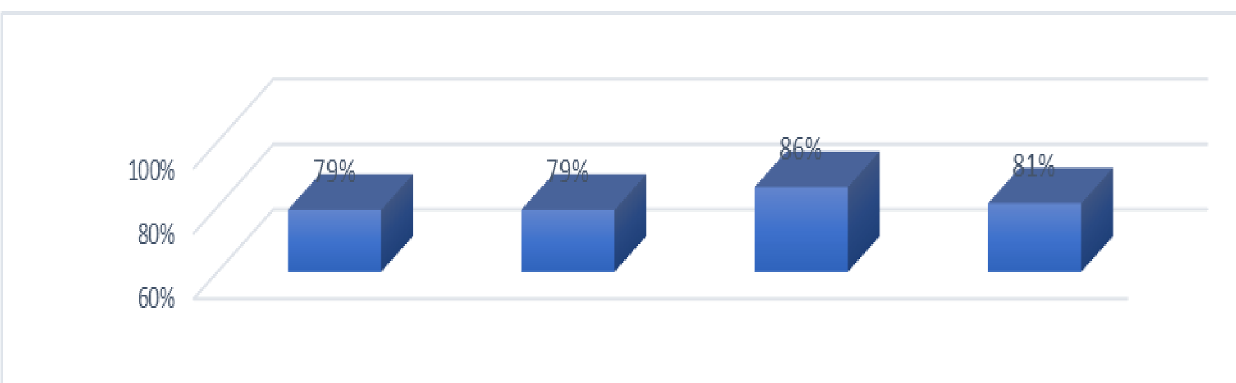
The validator fills out the validation sheet created by the researcher. Some of the elements that were validated included learning media, teaching modules, questions, student response questionnaires, attitude observation sheets, and skill observation sheets. The media feasibility validation sheet instrument has its aspects. For the recapitulation of the media feasibility instrument validation score by the three validators obtained a score of 86%, which means that it is very valid for use in learning can be seen in Figure 5.

Figure 5. *Media validator assessment results bar chart*



Instrument module feasibility validation sheet, there are aspects. For the recapitulation of the module feasibility instrument validation score by the three validators, a score of 81% which means it is very valid for use in learning can be seen in Figure 6.

Figure 6. *Module validator assessment results bar chart*



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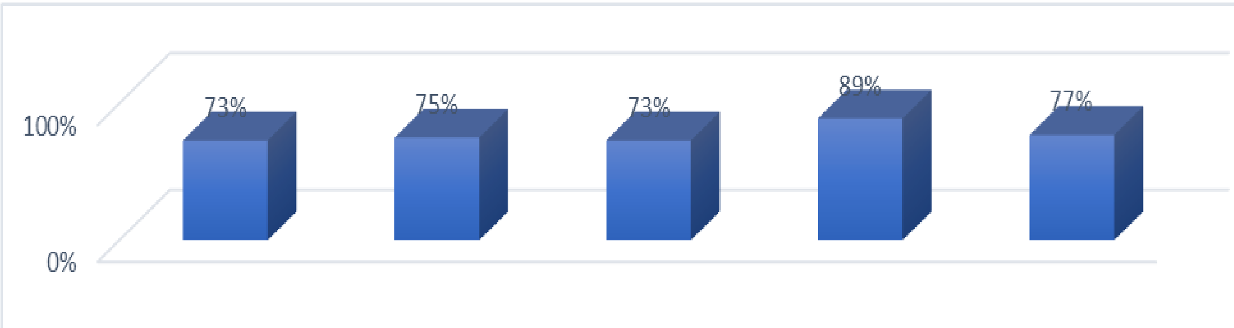
The feasibility of student feedback is assessed through several aspects using a validation sheet. The three validators gave a score of 77%, which shows that the questionnaire is valid for learning use can be seen in Figure 7.

Figure 7. *Bar chart of validator assessment results on response questionnaire*

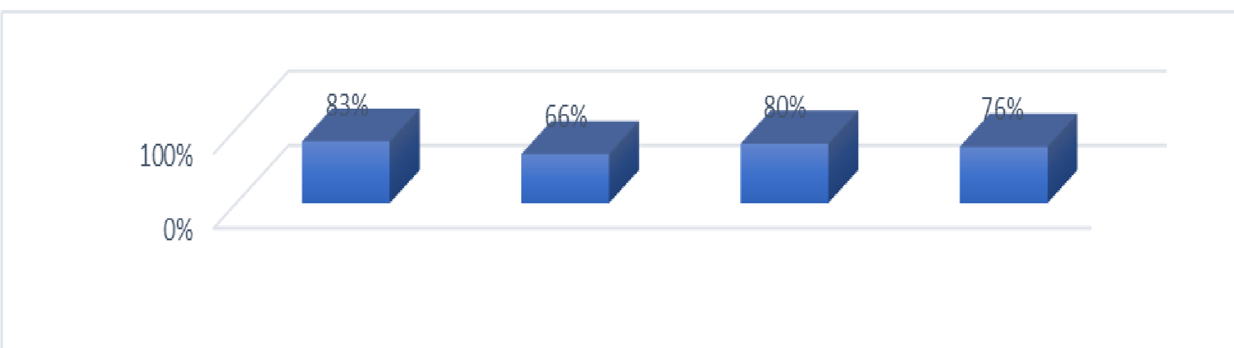


The feasibility of pretest and posttest questions was assessed using a validation sheet with a combined score of 75% for the three validators which means that they are valid for use in learning can be seen in Figure 8.

Figure 8. *Validator assessment result bar chart for pretest and posttest questions*

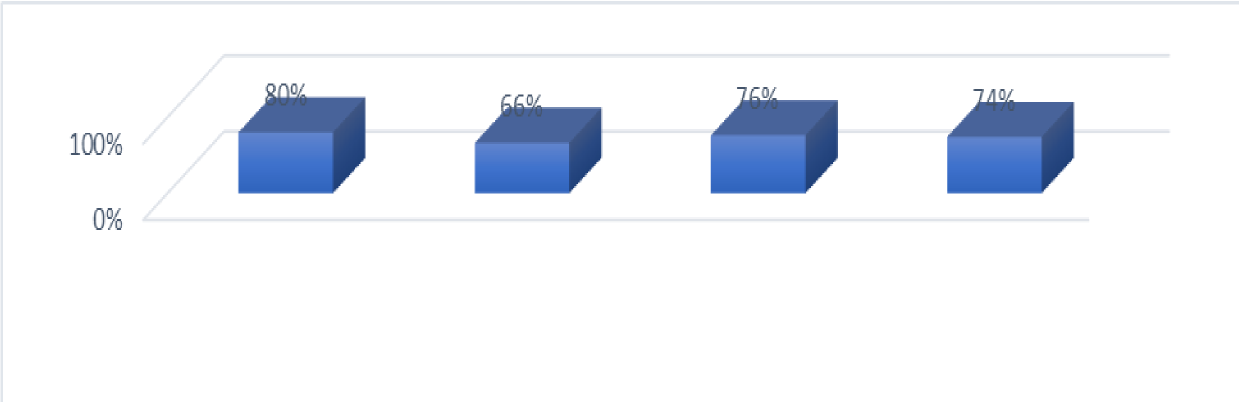
Instrument validation feasibility observation sheet, there are aspects. For the recapitulation of the instrument validation score, the feasibility of the observation sheet, attitude observation sheet, by the three validators obtained a score of 76%, which means it is valid for use in learning, can be seen in Figure 9.

Figure 9. *Bar chart of validator assessment results from the attitude observation sheet*



The feasibility of instrument validation sheets skill observation sheets, there are aspects. For the recapitulation of the validation scores, instrument eligibility, skill observation sheets by the three validators, a score of 74% was obtained, which means it is valid for use in learning, can be seen in Figure 10.

Figure 10. *Validator assessment result bar chart for skill observation sheet*



Practicality analysis

Response validation sheets are used to ensure the suitability of learning media by analyzing student responses. The results of student response data can be displayed on the following bar chart:

Figure 11. *Bar diagram of media practicality assessment results*

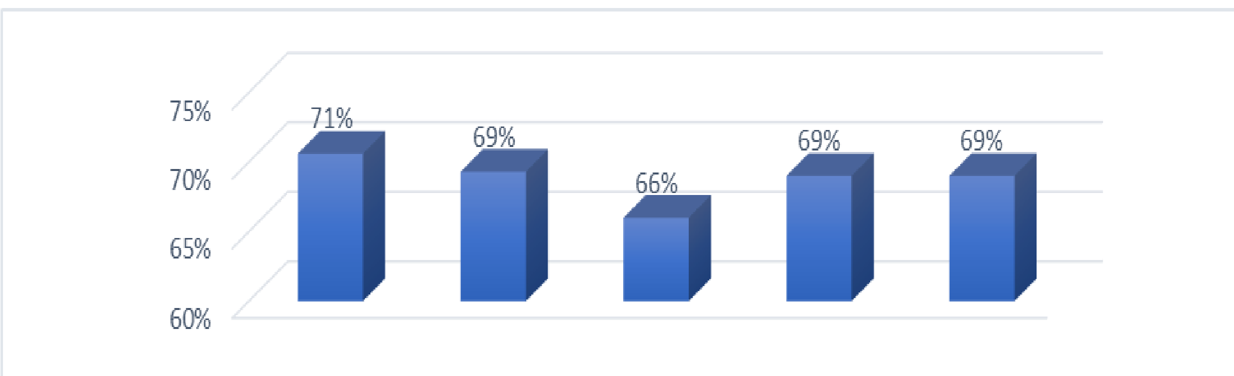


Figure 11 explains the calculation of the validation instrument used to evaluate the practicality of the media applied to students at SMK Negeri 3 Surabaya, obtaining a score of 69% which means it is valid to be used for learning.

Effectiveness analysis

The effectiveness of the KNX smart building system learning media was tested through three approaches, namely the normality test, the T-test, and the N-gain test. This test aims to assess how effective the learning media developed is on the value of learning outcomes. The normality test is a prerequisite to ensure whether the data on student learning outcomes is distributed normally before the difference test is carried out by parametric statistical methods. This test was performed using the

Shapiro-Wilk method with the help of SPSS Statistics 27. The statistical hypothesis applied in this study is stated as follows:
H0 : Normal distributed data
H1 : Data is not distributed normally

In the normality test, the hypothesis is accepted if the significance value is ≥ 0.05 and rejected if the ≤ is 0.05. Table 4 of the test results shows that all significance values of affective, cognitive, and psychomotor aspects are above 0.05 of the normal distributed learning outcome data.

Table 4. *Normality test*

	Statistics	*Df*	*Sig.*
Affective	.968	35	.396
Cognitive	.950	35	.111
Psychomotor	.975	35	.579

Paired samples were T-tested to evaluate whether the use of learning media resulted in significant differences from pre-test and post-test scores in affective, cognitive, and psychomotor aspects. The results of the analysis obtained a significance value of 0.000. T-test results below 0.05 indicate that all three domains show significant influence before and after media applications, as shown in Table 5.

Table 5. *T-test*

	Mean	Std. Deviation	t	Df	Sig.(2-tailed)
Pretest-Postest Affective	-17.629	7.535	-13.842	34	.000
Pretest-Postest Cognitive.	-13.229	4.250	-18.414	34	.000
Psychomotor Pretest-Postest	-13.257	5.101	-15.375	34	.000

Furthermore, the effectiveness test was also performed by calculating the normalized gain value, which measures how much the learning outcome improved to the maximum value obtained. The N-gain values calculated based on 35 students are as follows:

Table 6. *N-Gain test*

Learning Outcomes	N-Gain Value	Player
Affective	0,5	Keep
Cognitive	0,5	Keep
Psychomotor	0,5	Keep

From the results of the N-gain test, the use of smart building trainer learning media (KNX system) shows that it is in the medium category. This media is quite effective in supporting students' understanding and mastery of the material elements of the control system.

Discussons

From the findings and analysis, it was found that developing KNX-based Smart Building teaching materials by examining its validity, practicality, and impact on student achievement in the topic of control system at SMK Negeri 3 Surabaya with expert evaluations resulted in high validity scores—86% for instructor guides, 81% for module content, 77% for student feedback surveys, 75% for pre- and post-test items, 76% for attitude observation rubrics, and 74% for skills assessment rubrics that demonstrate that the material meets quality standards for classroom use. From a student's point of view, the medium scored 69% on practicality, placing it in the "practical" range and demonstrating its acceptance and ease of use. Effectiveness was confirmed through paired sample t-assays, which revealed statistically significant improvements in the cognitive, affective, and psychomotor domains ($p = 0.000$). In addition, an N-gain of 0.5 reflects a moderate level of learning gain. Overall, KNX-based Smart Building media has proven to be valid and effective, in line with the requirements of 21st century pedagogy and the competencies demanded by Industry 4.0. Those findings showed that developing KNX based smart building teaching material is effective for teaching materials since it helps students to understand learning materials better. These findings were in line with a research study conducted by Djanuarfianti, Zuhrie, Rusimamto & Achmad, (2023) that the development of an invention-based Programmable Logic Controller (PLC) teaching module using CX-Programmer for Electrical Power Engineering may improve significantly as learning media to be achieved by students of SMK Negeri 2 Surabaya.

Conclusion and Recommendations/Implications

This research was conducted to create and assess KNX-based Smart Building teaching materials by examining its validity, practicality, and impact on student achievement in the topic of control system at SMK Negeri 3 Surabaya. Expert evaluations resulted in high validity scores—86% for instructor guides, 81% for module content, 77% for student feedback surveys, 75% for pre- and post-test items, 76% for attitude observation rubrics, and 74% for skills assessment rubrics that demonstrate that the material meets quality standards for classroom use. From a student's point of view, the medium scored 69% on practicality, placing it in the "practical" range and demonstrating its acceptance and ease of use. Effectiveness was confirmed through paired sample t-assays, which revealed statistically significant improvements in the cognitive, affective, and psychomotor domains ($p = 0.000$). In addition, an N-gain of 0.5 reflects a moderate level of learning gain. Overall, KNX-based Smart Building media has proven to be valid and effective, in line with the requirements of 21st century pedagogy and the competencies demanded by Industry 4.0.

As a next step, it is recommended to expand the development of learning materials by incorporating more advanced topics, such as Internet of Things (IoT) integration and app-based remote control features. Subsequent studies should adopt an actual experimental design with a control group to evaluate the impact of the media more rigorously. In addition, field tests in some schools with varied student populations are recommended to examine the feasibility and application of the material in the long term. Finally, future investigations should also investigate non-cognitive outcomes, such as learning motivation, attitudes toward technology, and career readiness, to ensure the media aligns with educational goals and evolving industry requirements.

Disclosure statement

No potential conflict of interest was reported by the authors.

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