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Development of Physics Teaching Materials Based on Concept Elaboration to Enhance Students' Critical Thinking Skills

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Abstract: This study aims to develop concept elaboration-based physics teaching materials to enhance students' critical thinking skills. The development utilized a 4D (define, design, develop, disseminate) model, which involved validation by experts, practicality assessment by teachers, and field testing with thirty-two Grade XI students. The teaching materials were evaluated for validity, practicality, and effectiveness. The content validity analysis using Aiken's V produced values ranging from 0.77 to 0.82, conveying that the teaching materials were in the valid category. Teachers' assessments showed high practicality, with an average score of 81.5%, while students provided good responses to the teaching materials, with an average of 81%. The effectiveness test, using the Mann–Whitney U test, showed a significant difference between the experimental and control classes ($Z = 3.6 > 1.96$), with average critical thinking scores of 21 and 17 in the post-test, respectively. These results demonstrate that the concept elaboration-based teaching materials are valid, practical, and effective in improving students' critical thinking skills. The implementation of this approach is expected to enhance students' critical thinking skills within the physics learning experience.

Keywords: 4D Model; Concept elaboration; Critical thinking skills; Physics education; Teaching materials development

Introduction

The Merdeka curriculum is a recent educational change aimed at enhancing the quality of learning in Indonesia (Ledia & Bustam, 2024). The Merdeka curriculum differs from the previous curricula, where the contents are designed optimally so that students have enough time to deepen their understanding of concepts and strengthen their capacities (Kemdikbudristek, 2022). Essentially, the government does not specify specific learning strategies and assessment methods to be implemented, yet learning is expected to make students more creative, critical, and innovative (Anggraena et al., 2022). In order to foster students with global competitiveness and attitudes based on Pancasila, civic character education was applied to cultivate Pancasila students with six main characteristics, including critical reasoning, creativity, independence, faithfulness, devotion to God Almighty, noble character, mutual cooperation, and global diversity (Juliani & Bastian, 2021). For that reason, ideally, effective teaching materials need to be compiled to support Merdeka Curriculum learning (Maulida, 2022).

Teaching materials in the learning context are units consisting of a series of learning activities that are structured clearly and in detail to achieve several planned objectives. Teaching materials consist of a process of learning activities, through which students can master existing competencies and evaluate the effectiveness of learning. Teaching materials that are compiled holistically and systematically can motivate

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and attract the attention of students (Elisa et al., 2022). Proper teaching materials are able to enhance the quality of the learning process (Camellia et al., 2022).

As an institution implementing the Merdeka Curriculum, teachers at SMAN 11 Makassar are encouraged to design creative and innovative learning experiences that address students' diverse needs. However, classroom teaching materials still rely heavily on theoretical contents. Although teachers recognize the importance of developing more relevant teaching resources, limited time and workload constrain their efforts, leading them to depend primarily on textbooks issued by the Ministry of Education and Culture. These textbooks are often dense and contain excessive information, making it difficult for students to absorb the content effectively. Moreover, they lack clear connections between physical concepts and real-life applications, preventing students from linking classroom learning to everyday experiences.

Students often experience difficulties in processing and analysing data or evaluating their calculations because they lack a full understanding of the underlying concepts and their interrelationships. They also struggle to identify variable relationships, which frequently leads to incorrect conclusions when solving physics problems. However, these abilities to process, analyse, and evaluate information are core process skills outlined in the Learning Outcomes for Phase F of the Merdeka Curriculum. Strengthening students' critical thinking skills can effectively develop these process skills. Critical thinking enables students to interpret problems, analyse data, extract essential information, evaluate results, and communicate findings that supports higher-order thinking and scientific inquiry (Heinrich et al., 2015; Jagodzinski & Wolski, 2015; Tiruneh et al., 2017).

Developing teaching materials combined with an elaboration approach can be implemented to facilitate the learning process and to enhance students' critical thinking. The elaboration approach enables learners to understand concepts in depth, analyse the relationships between physics concepts, and relate them to real-life phenomena (Degeng, 1989). Through the elaboration approach, students are not only able to summarize and connect existing physical concepts, but also to improve their learning outcomes (Destini, 2022). This addresses the difficulties students experience in relating physics concepts to one another during problem-solving (Nurul, 2022). Additionally, according to Widya (2023), the elaboration strategy component integrated into teaching materials is considered effective for learning, because the concepts in the teaching materials are described from general to specific and linked to each other.

Critical thinking skills play a major role in contemporary social life, especially in the 21st century. In this century, critical thinking skills are needed to face the challenges of rapid change (Jagodzinski & Wolski, 2015). Critical thinking helps with better decision-making regarding complex real-life issues, and encourages individuals to become more active and informed citizens (Tiruneh et al., 2017). According to Hayes (2015), critical thinking is a fundamental prerequisite for analysing texts, art objects and other people's ideas, as well as for communicating with other individuals. Critical thinking is the foundation for understanding an issue comprehensively, so that complex issues can be understood (Heinrich et al., 2015). In physics learning, critical thinking is an essential skill to comprehend natural phenomena and solve everyday problems (Priscilia & Haryani, 2025). Therefore, improvements in students' critical thinking skills need to be made, as demonstrated in several previous studies (Ahmadiah et al., 2023; Cynthia et al., 2023; Doyan et al., 2025; Matsun et al., 2022; Yersi et al., 2025).

Based on this description, the development of physics teaching materials based on concept elaboration is proposed as a solution to improve learning effectiveness. These materials are designed to serve as essential resources that strengthen students' critical thinking. Through the integration of concept elaboration, students are guided to identify the relevance of physics concepts to real-life situations, including problem-solving and technological applications. Currently, the teaching materials used at SMAN 11 Makassar do not incorporate this approach. Although several studies have explored elaboration-based teaching materials (Destini, 2022; Sumardi & Kusumawati, 2019; Widya et al., 2023), research that explicitly integrates concept elaboration to enhance students' critical thinking skills remains limited. Therefore, this study addresses that gap by developing and validating concept elaboration-based physics teaching materials aimed at improving students' critical thinking abilities. For that reason, the objective of this study is to develop concept elaboration-based physics teaching materials to improve students' critical thinking skills that the meet criteria of validity, practicality and effectiveness.

Method

Type of Research

This type of research is research and development (R&D). According to Sugiyono (2013), research and development is a research method used to produce a product that is tested for its effectiveness. In producing a product, the research is conducted by analysing needs and testing the effectiveness of the product to ensure it can be widely beneficial. Development involves transforming a design concept into a physical form, which is written or produced so that it can be widely used (Rayanto & Sugianti, 2020).

The research design used in this study is the 4D development model by Thiagarajan (1974). This development design consists of four main stages: define, design, develop, and disseminate. Figure 1 describes the flow process of development.

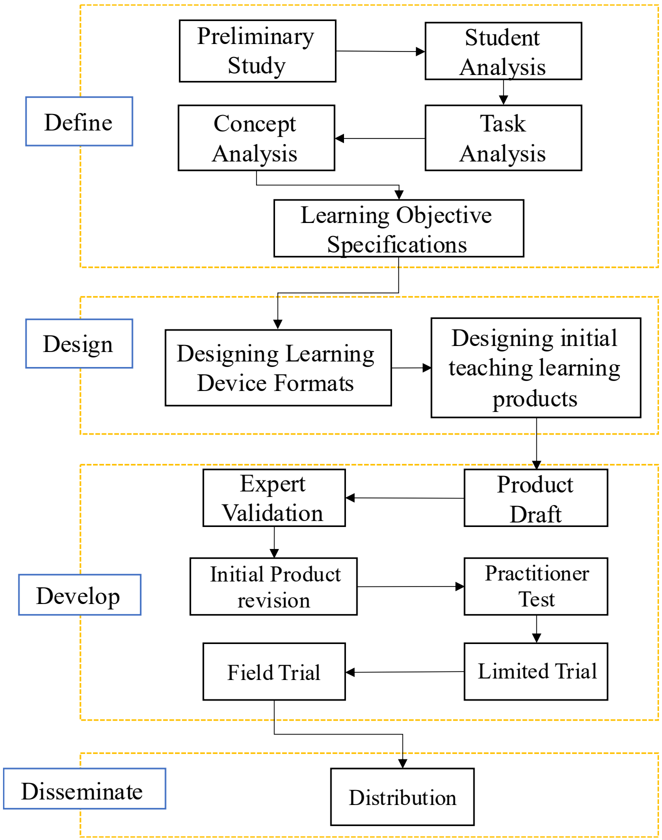

Figure 1. Process flow of the development using 4D model

Define Stage

The define stage is the initial stage carried out in this study to determine what products will be developed and their specifications. Define stage aims to define the learning requirements in the form of learning objectives. The stage consists of front-end analysis, students' analysis, concept/material analysis, task analysis and learning objectives analysis. In this stage, several findings are obtained through observations and interviews with one of the physics teachers at SMA Negeri 11 Makassar regarding the learning process, learning facilities and problems in physics learning. The results indicate the need for teaching materials based on concept elaboration to improve students' critical thinking skills.

Design Stage

After identifying the problems and determining what products would be developed along with the specifications, the next stage to be conducted is the design stage. At this stage, the design of concept elaboration-based physics teaching materials was carried out. The teaching materials developed were adapted to the problems identified in the definition stage. In addition, the design of the development instruments was carried out at this stage. The activities during the design phase include the selection of instructional materials and content, the determination of the format for these materials, and the development of a preliminary draft. The format of teaching materials generally consists of an introduction, content, and references. The contents in the teaching materials are designed to accommodate concept elaboration learning steps to improve critical thinking skills.

The critical thinking skill indicators used are based on Facione (2011), namely interpretation, analysis, evaluation, explanation and inference. Interpretation involves understanding and expressing the essential meaning of data or situations, such as interpreting experimental graphs and explaining relationships between physical variables. Analysis refers to identifying relationships among concepts or arguments, exemplified by analysing connections between physics principles and their real-world implications. Evaluation entails assessing the accuracy and logical soundness of information, for instance, comparing experimental results with theoretical predictions. Explanation is the ability to clearly communicate reasoning and justify procedures, such as describing how physical concepts are applied in technology. Inference involves drawing reasonable conclusions from evidence, including predicting outcomes and applying physics concepts to new situations. Finally, self-regulation requires monitoring and correcting one's reasoning, as seen when students reflect on experimental errors and propose procedural improvements. Together, these indicators guide students to think systematically, critically, and reflectively in learning physics.

Develop Stage

The development stage involves turning the previously created design into a tangible product. The aim at this stage is to develop teaching materials for physics based on the concept elaboration, along with other research instruments that have been validated and reviewed by three experts. The activities carried out at this stage were the validation of teaching materials, the validation of research instruments, and conducting limited tests for teaching materials and test instruments to assess students' critical thinking skills. The validity criteria for these items were using the Aiken's V equation which later discussed in Data Analysis Technique.

The teaching materials and other research instruments were then revised for field testing with 32 students in class XI-B. In addition, student response sheets were also distributed to determine student responses to the teaching materials developed. The revised results of the elaboration-based physics teaching materials were depicted in Figure 2.

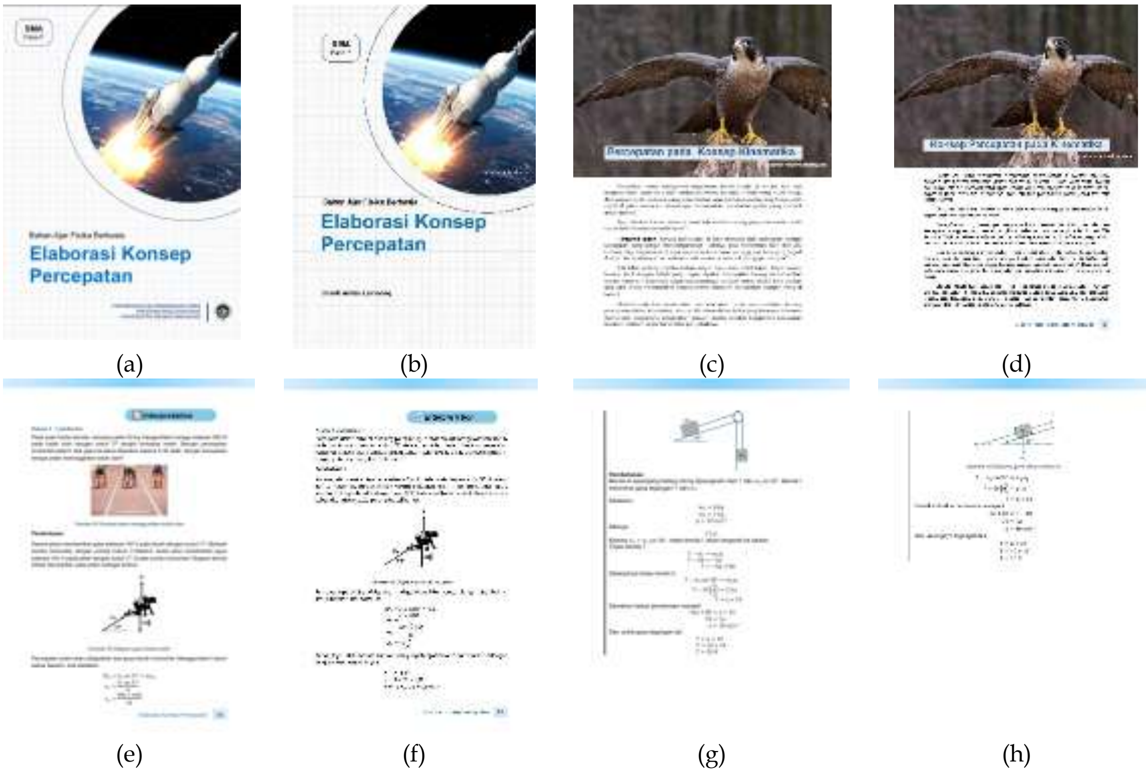

Figure 2. Revised results of concept elaboration-based physics teaching material (2nd draft). The figure shows the changes made during the revision process, including improvements to the cover and subject title design, the removal of unnecessary images, and the addition of relevant visuals in the problem discussion section to enhance clarity and engagement.

Dissemination Stage

After field testing and instrument revision, the next stage is the dissemination. This stage aims to distribute the developed physics teaching materials. The developed teaching materials were distributed in PDF format to physics teachers at SMAS YP PGRI 3 Makassar, SMAN 23 Makassar, and SMA Negeri 11 Makassar. Along with the distribution, practitioners (teachers) were requested to evaluate and provide feedback on the practicality and quality of the materials.

Research Subject

The research was conducted at SMA Negeri 11 Makassar in the first semester of the 2025/2026 academic year. There are two classes that are the subjects of the experiment, namely XI-A as the control class and XI-B as the experimental class, with 32 students in each class. A post-test only design was used, where the test was only conducted once after the treatment. The model design is depicted in Figure 3.

$$\begin{array}{ccc} R_1 & X & O_1 \\ R_2 & - & O_2 \end{array}$$

Figure 3. Model post-test only control design

Where:

X : Treatment using physics teaching materials based on the concept elaboration

O1 : Post-test results in classes that used physics teaching materials based on concept elaboration

O2 : Post-test results in classes that did not use physics teaching materials based on concept elaboration

- : Did not use physics teaching materials based on concept elaboration

R : Study group

Data Analysis Techniques

Validation Index

The data obtained from the validation of teaching materials, practitioner assessment questionnaires, student response questionnaires, and critical thinking tests were analysed by reviewing the input and important notes from the expert team. The results of the analysis were used as a reference for revising the teaching materials and instruments to be used in the study. In addition, the assessment criteria for teaching materials and research instruments to have an adequate degree of validity were that the average validity of each aspect was in the valid category. If this was not met, the revision process had to be carried out based on the experts' suggestions regarding the aspects that were deemed inadequate.

The analysis used to obtain information about the level of relevance of the product being tested for validity uses the content validity coefficient (Aiken's V) (Hasanah et al., 2025; Ibrahim et al., 2024; Nilyani & Ratnawulan, 2023; Nurwina et al., 2025; Saputri et al., 2021; Yadiannur & Rahmah, 2025). In addition, before being applied in learning, the instruments for testing students' critical thinking skills were first subjected to a limited trial analysis consisting of item analysis and reliability testing with students outside the research subjects.

Expert validity testing was used to determine the level of relevance assessed by three experts using the validation sheet for physics teaching materials based on concept elaboration, the practitioner assessment questionnaire sheet, the student response questionnaire sheet, and the student critical thinking ability test. Aiken's V equation was used to calculate the content validity coefficient based on the results of each expert's assessment of an element through equation (1).

$$V = \frac{\sum s}{n(c-1)} \quad (1)$$

Note:
V = Expert agreement index regarding item validators
s = Difference between each expert's score and the lowest score ($r-I_0$)
r = Rater's fixed score
I_0 = Lowest assessment score
N = Number of experts
C = Highest validity assessment score
In terms of the Aiken test requirement, if V ≥0.4, then the expert agreement index is considered valid.

Analysis of Practitioner and Students Response

The practitioner assessment and student response questionnaire on physics teaching materials based on concept elaboration aim to assess the practicality and determine students' responses to the teaching materials that have been developed. The questionnaire assessment uses a Likert scale consisting of four score levels, namely not relevant with a value of 1, less relevant with a value of 2, relevant with a value of 3, and very relevant with a value of 4 (Saefan et al., 2024; Sukarelawan et al., 2024). The assessment of student response questionnaires also uses a Likert scale consisting of four score levels, namely disagree with a value of 1, somewhat disagree with a value of 2, agree with a value of 3, and strongly agree with a value of 4. An analysis was conducted using the following equation (2) (Trianto, 2010).

$$PRS = \frac{\sum A}{\sum B} \times 100\% \quad (2)$$

Where
PRS = Percentage of practitioners/students responding to the categories specified in the instrument
∑A = The total score obtained for each category stated in the questionnaire
∑B = Maximum score for each category by practitioners/students on the questionnaire

Category Critical Thinking Skills Score

Data on critical thinking skills were obtained from data collection instruments in the form of post-tests from both the control and experimental classes. The scoring rules were that the maximum ideal score = 26 and the minimum ideal score = 0, so r = 26, k = 5 and p = 6, resulting the category in Table 1.

Table 1. Critical Thinking Skills Score Category for Students

Interval Class	Category
24-29	Very High
18-23	High
12-17	Medium
6-11	Low
0-5	Very Low

Prerequisite Tests

The prerequisite tests were conducted to ensure that the data met the assumptions required for selecting the appropriate statistical analysis, thereby supporting the validity of the research findings. The normality and homogeneity tests served as prerequisite analyses to verify the distribution characteristics and variance equivalence of the data before applying the Mann–Whitney U test (Asrizal et al., 2023).

The normality test was conducted to determine whether the data were derived from a normally distributed population. This analysis employed the Lilliefors test using Microsoft Excel. The data were considered normally distributed if the calculated L value was smaller than the L table value at a significance level of α = 0.05.

The homogeneity test was applied to determine whether the two data groups possessed equal variances. This analysis was carried out using the F-test in Microsoft Excel, where the data were considered homogeneous if the calculated F value was less than or equal to the F table value.

The Mann Whitney U Test

After conducting prerequisite tests, namely normality and homogeneity tests, the Mann Whitney U test was carried out. The Mann Whitney test is a nonparametric test used in independent sample comparison tests (Asrizal et al., 2022; Bektiarso et al., 2021; Permana et al., 2021; Yennita et al., 2024). The criteria for deciding on the research hypothesis are as follows: the null hypothesis (H_0) states that the average critical thinking test results of the experimental class are lower than or equal to those of the control class, indicating no significant difference between students who used physics teaching materials based on concept elaboration and those who did not. Conversely, the alternative hypothesis (H_1) states that the average critical thinking test results of the experimental class are higher than those of the control class, meaning that there is a significant difference between the critical thinking test results of students who use physics teaching materials based on concept elaboration and those who did not. The decision regarding hypothesis acceptance or rejection was based on Z-score analysis, where H_0 is rejected if the absolute value of the Z-score exceeds the Z-table value, and H_0 is accepted if the absolute value of the Z-score is less than or equal to the Z-table value.

Result and Discussion

Validity of Physics Teaching Materials Based on Concept Elaboration

The initial design in the form of Draft I was compiled and then validated by experts to determine the feasibility of physics teaching materials based on concept elaboration before conducting limited trials. The aspects of content validation for expert assessment were content suitability, presentation, language and graphics. The average expert validity test scores for the four assessment aspects using content validity coefficient analysis (Aiken's V) are presented in Table 2.

Table 2. Results of Content Validity Analysis of Teaching Materials

Aspects	Total Valid Item Score	V	Criteria
Content Suitability	14.0	0.82	Valid
Presentation	12.1	0.81	Valid
Language	13.8	0.77	Valid
Graphics	12.0	0.80	Valid

Based on Table 2, it is known that in terms of content suitability, the average expert agreement index (V) was 0.82 and was within the valid criteria, while in terms of presentation, the average expert agreement index (V) was 0.81 and was within the valid criteria. In terms of language, the average expert agreement index (V) was 0.77, which is within the valid criteria, while in terms of graphics, the average expert agreement index (V) was 0.8, which is also within the valid criteria.

The content validity of the physics teaching materials based on concept elaboration was analysed using the Aiken's V expert agreement index test from the assessments of three validators. An instrument is considered valid if the Aiken's V coefficient is greater than 0.4. Based on the validity analysis results presented in Table 2, the physics teaching materials based on concept elaboration are considered valid and suitable to proceed to the trial stage with minor revisions. In addition, validity assessments were also conducted on the practitioner assessment questionnaire, the student response questionnaire, and the student critical thinking ability test. Based on the assessment of three validators, the practitioner assessment questionnaire and student response questionnaire were declared feasible and valid for use in the field without the need for revision, while the critical thinking skills test was declared feasible and valid for use in the field with minor revisions.

The results of this study are in line with the results of previous studies. The research on the development of physics teaching materials conducted by Ahmadiah (2023) to improve students' critical thinking skills using the 4D model demonstrated valid results. The assessment aspects meet the requirements of the Aiken formula, where V ≥ 0.4, including the content aspect with a value of 0.77, the language aspect with a value of 0.78, the presentation aspect with a value of 0.78, and the graphic aspect with a value of 0.76. Similar results were shown in the development carried out by Cynthia et al. (2023) for the development of interactive physics teaching modules to improve students' critical thinking skills. The teaching module development was in the valid category and was feasible for testing. The teaching module product was considered valid based on the components of the learning product being interrelated.

Practitioners' Assessment of Physics Teaching Materials Based on Concept Elaboration

Practitioners' assessments of physics teaching materials based on concept elaboration were obtained from a questionnaire given to practitioners. The questionnaire was completed by six physics teachers at SMA Negeri 11 Makassar. Every component of the practitioner assessment questionnaire had 40 items evaluated on a Likert scale, with scores ranging from 1 to 4 based on established criteria. Practitioners' assessments of physics teaching materials based on concept elaboration covered the aspects of content suitability, presentation, language and graphics. The results of the analysis of the practitioners' assessment of the physics teaching materials based on the elaboration of concepts can be seen in Table 3.

Table 3. Results of Practitioners' Assessment of Teaching Materials

Aspects	Total Score	Percentage %	Criteria
Content Suitability	175	88	Very Practical
Presentation	170	85	Very Practical
Language	165	83	Very Practical
Graphics	159	80	Practical

Based on the practitioner assessment analysis in Table 3, the practitioner assessment of physics teaching materials based on concept elaboration for the aspects of content suitability and presentation was in the very practical criteria, while the aspects of language and graphics were in the practical criteria. For the content suitability aspect, a total score of 175 was obtained with a percentage of 88%, for the presentation aspect a total score of 170 was obtained with a percentage of 85%, for the language aspect a total score of 165 was obtained with a percentage of 83%, and for the graphics aspect a total score of 159 was obtained with a percentage of 80%. It is known that practitioners/teachers assigned scores above 61% for all aspects, indicating a highly favourable response to the concept elaboration-based physics teaching materials that had been developed, hence affirming their practicality in classroom utilisation.

The results of the practitioner assessment questionnaire analysis in Table 3 show that six teachers gave assessments for all aspects with an average percentage of 81.5%, which is above 61%, indicating that practitioners responded very well or positively to the physics teaching materials based on concept elaboration that had been developed. The teaching materials have been declared practical and can be used in physics lessons at school. Identifying learners' needs prior to product development not only received positive responses from teachers but was also regarded as a practical approach for classroom implementation (Ayani et al., 2025; Nursyahitna et al., 2024; Rahmawati et al., 2021; Rasmi et al., 2023).

These analysis results are supported by previous research by Yosa (2025) in developing physics teaching materials using the 4D model. Practitioners' responses to the physics teaching module were in the very practical category for all assessment aspects, including content, presentation, graphics, and language. The criteria of highly practical were also achieved by the physics teaching material development product carried out by Mapau et al. (2025) through several assessment categories, such as the coverage of the teaching module content, the suitability of the teaching module, the advantages of the teaching module, and the practicality of the teaching module.

Students' Responses of Physics Teaching Materials Based on Concept Elaboration

The responses of students to physics teaching materials were obtained from a questionnaire given to class XI.11 at SMAN 11 Makassar. The questionnaire used had undergone validation by experts and was agreed to be a valid instrument. The student response questionnaire was completed by 32 students. The questionnaire consisted of 20 statements assessed using a Likert scale with a score range of 1 to 4 according to the specified categories. The results of the analysis of student responses to physics teaching materials based on concept elaboration can be seen in Table 4.

Table 4. Results of Practitioners' Assessment of Teaching Materials

Aspects	Total Score	Percentage %	Criteria
Content Suitability	524	82	Very Good
Language	300	78	Good
Presentation	410	80	Very Good
Engagement and Interactivity	423	83	Very Good
Practicality	416	81	Very Good

According to Table 4, students' responses to physics teaching materials based on concept elaboration for the aspect of content suitability were in the very good category, the language aspect was in the good category, while the aspects of involvement and interactivity and practicality were in the very good category. For the aspect of content suitability, a total score of 524 was obtained with a percentage of 82%, the language aspect obtained a total score of 300 with a percentage of 78%, the presentation aspect obtained a total score of 410 with a percentage of 80%, the engagement and interactivity aspect obtained a total score of 423 with a percentage of 83%, and the practicality aspect obtained a total score of 416 with a percentage of 81%. The students' responses to the physics teaching materials for all aspects were above 61%, indicating an enthusiastic reception of the provided teaching materials.

The questionnaire on students' responses to physics teaching materials consists of 20 statements related to physics teaching materials based on the concept elaboration. The results of the analysis of the student response questionnaire in Table 4 show that 32 students responded with an average percentage of 81% in the very good category. The results revealed that students comprehended the linguistic features and conceptual content of the developed teaching materials. The developed teaching materials addressed problems in which students often took a long time to understand physics concepts, indicating the need for accessible and easy-to-understand teaching materials (Ayani et al., 2025; Hidayati et al., 2023). This finding is in line with the development of teaching modules conducted by Ulfa et al. (2025), where the responses given by students to the physics learning modules were in the very practical category with a percentage of 89%.

The use of the 4D development model facilitates the identification of learning needs, analysis of curriculum requirements, and understanding of student characteristics, ensuring that the resulting teaching materials address real classroom challenges and align with specific learning objectives.

Effectiveness of Physics Teaching Materials Based on Concept Elaboration

The effectiveness of using physics teaching materials based on the concept elaboration can be measured using a critical thinking ability test instrument given to students in grades XI.9 and XI.11 at SMA Negeri 11 Makassar. The critical thinking ability test was given to students after (post-test) the learning process was carried out. There were 26 multiple-choice questions in the critical thinking ability test, which had been declared valid and reliable. The critical thinking ability test was compiled based on Facione's critical thinking ability indicators, namely interpretation, analysis, evaluation, inference, and explanation. The critical thinking test is a dichotomous test, meaning that if the item is correct, it is given a score of 1, and if it is incorrect, it is given a score of 0. The scoring rules are that the ideal maximum score is 26 and the ideal minimum score is 0.

The results of the critical thinking ability tests for the control class and the experimental class were then analysed descriptively. The results of the descriptive analysis of the critical thinking ability test scores of the participants are presented in Table 5.

Descriptive data on students' critical thinking scores in Table 5 suggest that the average score obtained by students in the experimental class was 21, which is in the 18-23 interval class, meaning it is in the high category with a highest score of 26, lowest score of 10, standard deviation of 3.85 and variance of 14.80. Meanwhile, the average score obtained by students in the control class was 17, which falls within the 12-17 interval class, meaning it is in the moderate category with the highest score of 23, the lowest score of 8, a standard deviation of 3.79, and a variance of 14.38.

Table 5. Descriptive Data on Students' Critical Thinking Skills Scores

Pharameters	Experiment	Control
Sample Size	32	32
Ideal Highest Score	26	26
Ideal Lowest Score	0	0
Highest Score	26	23
Lowest Score	10	8
Score Range	16	15
Average Score	21	17
Standard Deviation	3.85	3.79
Variance	14.80	14.39

Figure 4 illustrates the distribution of students' critical thinking skills score in the control and experimental classes as represented by a box plot.

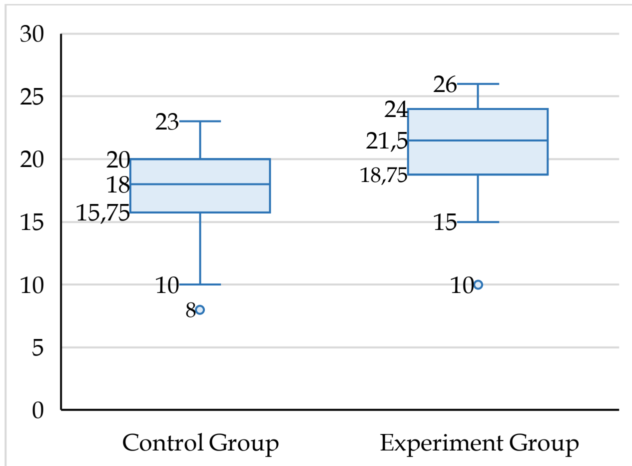

Figure 4. Box Plot of Students' Critical Thinking Skills Score in Control and Experimental Class

The median score of the experimental class (21.5) is higher than that of the control class (18.0), indicating a generally better performance among students who used the teaching materials. The interquartile range (IQR) of the experimental class is also slightly wider, suggesting greater variability in student achievement within that group. The presence of a few outliers in each group indicates individual differences in performance; however, the overall distribution demonstrates that the use of the teaching material based on concept elaboration positively influenced students' critical thinking skills compared to students who did not use the teaching material.

The data obtained from the study were also used in inferential analysis to test hypotheses. However, prior to this, prerequisite tests were conducted, namely normality and homogeneity tests.

The normality test is used to determine whether the data come from a normally distributed population or not. The results of the normality test calculations in this study are presented in Table 6.

Table 6. Descriptive Data on Students' Critical Thinking Skills Scores

Data	Experiment Class	Control Class
N	32	32
L_{count}	0.91	0.09
L_{table}	0.15	0.15
α	0.05	0.05
Decision	Not Normally Distributed	Normally Distributed

From the analysis results, the L_{count} in the experimental class was 0.91 and the L_{table} value was 0.15 with α=0.05. Meanwhile, the L_{count} value in the control class was 0.09 and the L_{table} value was 0.15. This means that in the experimental class, $L_{count}>L_{table}$, meaning that the data were not normally distributed, while in the control class, $L_{count}<L_{table}$, meaning that the data were normally distributed.

The homogeneity test is used to determine whether two groups of data have the same variance (homogeneous) or not. The results of the homogeneity test analysis yielded an experimental class variance of 14.358 and a control class variance of 14.803. The F_{count} value was 1.031 and the F_{table} value was 1.822, meaning that $F_{count}<F_{table}$. Therefore, the conclusion is that the data from both groups is homogeneous.

The results of the Mann Whitney test analysis of the critical thinking ability scores of students using Microsoft Excel obtained a calculated Z value of 3.6 and a table Z value for α=0.05 of 1.96. Based on the analysis results |Z count|>Z table, H_0 is rejected, meaning that there is a difference between the critical thinking ability test results of students who used physics teaching materials and those who did not. Thus, the results of the Mann Whitney U test prove that the use of teaching materials based on the concept elaboration has a significant effect and can be declared effective in improving students' critical thinking skills.

The physics teaching materials based on the concept elaboration emphasise sequencing, synthesis and developing lesson content from general to specific or from simple to more complex. This structure helps students organise knowledge hierarchically, which promotes analysis and interpretation as they connect initial general concepts with more detailed sub-concepts. The inclusion of tables and graphs, such as acceleration over time with descriptions helps students to interpret and evaluate data by identifying trends, patterns, and causal relationships among physical quantities. An introduction at the beginning of each section provides an overview that guides students to recognise concepts and predict their interconnections, thus fostering interpretation and inference.

Furthermore, the detailed comparison of related sub-concepts requires students to analyse similarities and differences, strengthening their analytical reasoning. Contextual problems embedded within each section challenge students to apply the concepts to real-life phenomena, thereby developing their ability to draw inferences and make evidence-based explanations. Simplifying complex ideas into relatable examples supports explanation, as students are prompted to articulate their reasoning in familiar contexts. Finally, practical problems and reflection questions require students to evaluate outcomes and regulate their thought processes, engaging evaluation skills from students. Through these integrated features, the teaching materials enhance the indicators of critical thinking skills. The integration of these features facilitates the systematic enhancement of students' critical thinking abilities across all indicators (Erlangga et al., 2024).

The physics teaching materials based on the elaboration of the concept of acceleration emphasise sequencing, synthesis, and developing lesson content from general to specific or from simple to complex. The teaching materials are structured in such a way as to emphasise each critical thinking indicator in each section of the material. The presentation of tables and graphs of events such as acceleration over time with descriptions helps students to interpret data better. The introduction at the beginning of each section provides essential meaning for students to interpret the material holistically. Students' analytical skills are trained by presenting one concept in relation to another in more detail. The ability of students to draw conclusions from questions or events is developed through teaching materials by involving several events that enable students to draw statements that are the essence of these events. In addition, complex ideas are discussed in a simpler way that is closer to the students' daily lives, enabling them to explain an event. Students' evaluation skills are trained by presenting contextual problems in the teaching materials.

These results confirm previous findings from several researchers in applying the elaboration model to physics learning. Development research conducted by Widya et al. (2023) produced elaboration-based teaching materials that were confirmed to help students understand thermodynamics subject. There was an increase in the average results achieved by students after elaboration-based teaching materials were used in the classroom. This was because students were encouraged to think structurally and analyse information, both data and graphs, in detail. The same results were also obtained by Sumardi (2019). Applying elaboration learning in physics teaching materials increased students' understanding of concepts in the experimental class with an average N-gain value of 0.44, which was higher than the average N-gain value of the control class at 0.33. Destini (2022) found the same results when applying the elaboration learning model to electromagnetic wave material, where student learning outcomes were significantly influenced by the elaboration learning model.

Conclusion

The findings of this study demonstrate that the physics teaching materials based on concept elaboration are valid, practical, and effective for enhancing students' critical thinking skills. Content validation using Aiken's V confirmed that all assessed aspects met the valid criteria, while practitioner evaluations from six physics teachers and responses from 32 students consistently indicated high levels of practicality and positive user experience. Effectiveness testing further showed that students who used the materials achieved higher critical thinking scores than those in the control group, with the Mann–Whitney U analysis confirming a significant difference between the two groups. This effectiveness is supported by the structured organisation of content from general to specific, the integration of visual representations, contextual problems, and clear conceptual explanations that explicitly reinforce key indicators of critical thinking. Overall, the teaching materials developed through the 4D model successfully address classroom needs and contribute to supporting physics learning in the classroom.

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U.A.L: Conceptualization, methodology, writing original draft preparation, formal analysis, visualisation, writing-review and editing; M.A.: validation, supervision and resources; H.: conceptualization, supervision

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The authors declare no conflict of interest.

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