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Enhancing Trigonometric Critical Thinking Through Innovative Learning: A Design Thinking Approach

Dhidik Joko Purnomo[1], Ida Dwijayanti[2], Aryo Andri Nugroho[3]

[1] Universitas PGRI Semarang, Indonesia, dhidikpurnomo39@guru.sma.belajar.id
[2] Universitas PGRI Semarang, Indonesia, idadwijayanti@upgris.ac.id
[3] Universitas PGRI Semarang, Indonesia, aryoandri@upgris.ac.id

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ABSTRACT

This study aims to identify alternative solutions for enhancing students' critical thinking skills in mathematics, taking into account the needs of students and teachers, as well as developments in science, technology, and future educational demands. A design thinking approach was adopted, following five key stages: empathize, define, ideate (including meta-analysis), prototype, and test. The research involved 90 tenth-grade students and 8 mathematics teachers from three schools: SMAN 1 Semarang, SMAN 5 Semarang, and SMAN 14 Semarang. Data were collected through observations, questionnaires, and interviews. The findings reveal three innovative learning strategies that can effectively foster critical thinking in mathematics education: the development of differentiated project-based learning (PBL) grounded in TPACK and supported by Articulate Storyline; the use of Jejak Timur Media, assisted by the Math City Map; and the implementation of differentiated PBL activities that integrate the Jejak Timur Math City Map. These innovations, developed through the design thinking process, demonstrate the potential of integrating technology and student-centered learning models to improve critical thinking outcomes. The study concludes that applying the design thinking framework to the development of mathematics instruction offers effective and adaptable strategies to meet the evolving challenges of education and promote essential 21st-century skills.

Corresponding Author:
Ida Dwijayanti
Universitas PGRI Semarang, Indonesia, idadwijayanti@upgris.ac.id

1. INTRODUCTION

Education plays a crucial role in human life. It is the primary factor that determines the progress of a nation. One of the key objectives of education is related to mathematics, as it must be taught to all students to equip them with the ability to think logically, analytically, systematically, critically, and creatively, as well as the ability to collaborate. According to PermendikbudRistek Number 5 of 2022 on Graduation Competency Standards in Mathematics, one of the objectives of mathematics education is to develop numeracy skills and apply critical mathematical thinking in reasoning and problem-solving.

Septiani and Pujiastuti (2020) stated that mastery of mathematical concepts can help students apply and implement these concepts effectively. Therefore, students must develop strong critical thinking skills in each lesson to master the subject matter more easily. When solving problems, certain rules are required, and these rules are based on the concepts students have learned. According to Wardani (2020), conceptual understanding is formed independently by students and is not merely acquired through knowledge transfer. Critical thinking is an essential skill that students must develop to understand and communicate mathematical concepts in accordance with established rules. In mathematics learning activities, teachers should place greater emphasis on concept mastery, ensuring that students build a solid foundation to achieve satisfactory results.

Based on the PISA 2022 results, Indonesia ranked 69th out of 81 countries in terms of average reading and mathematics scores, highlighting a lack of analytical and critical thinking skills among students. Moreover, Indonesia's mathematics score declined by 13 points compared to previous assessments (OECD, 2023), further indicating that critical thinking skills remain at a low level. Additionally, a survey conducted by the Center for Education and Culture Policy Research (Puslitjakdikbud) revealed that only around 30% of teachers implement critical thinking-based learning methods in their classrooms. This finding suggests that critical thinking has not yet become a priority in many schools.

These findings are consistent with the results of questionnaires and interviews conducted in three different schools: SMAN 1 Semarang, SMAN 5 Semarang, and SMAN 14 Semarang. Several concerns and difficulties were identified among Class X students during the mathematics learning process. Of the total 90 students, 75.6% reported difficulties in problem-solving, while 75.5% experienced challenges in critical thinking skills. Additionally, teacher responses indicated that a significant proportion of students 58.9% still relied on lecture-based learning and conventional media tools. Furthermore, 75% of teachers agreed that students struggle with critical thinking in mathematics and emphasized the need for learning innovation to enhance students' understanding and engagement.

The rapid advancement of science and technology has driven efforts to integrate technological innovations into the mathematics learning process (Fonda, 2018). The use of technology in mathematics education provides significant benefits, particularly through effective learning media that help students grasp abstract concepts in a more concrete and engaging way. For instance, teaching aids, digital technology, and interactive applications can make mathematics learning more enjoyable and easier to understand. Moreover, the role of technology in education extends beyond merely providing information; it also facilitates the learning process and serves as a valuable learning resource (Fricticarani et al., 2023). Therefore, the integration of appropriate learning media is essential to achieving the desired educational outcomes effectively.

A journal study conducted by the researchers on difficulties in critical thinking in mathematics learning highlights several relevant findings. Ardiansyah & Nugraha (2022) state that the use of learning media makes learning more engaging and enhances students' critical thinking skills in mathematics. Similarly, Nurwahid & Ashar (2023) emphasize that teachers must innovate learning media to motivate students, ultimately enabling them to better understand mathematical concepts. Moreover, Riti et al. (2021) argue that, in addition to implementing appropriate learning media and instructional processes, continuous innovation is necessary to develop learning models that effectively maximize students' critical thinking skills.

Based on the concerns and difficulties faced by students in learning, as explained earlier, researchers are interested in exploring solutions to enhance critical thinking in mathematics while minimizing challenges for both students and teachers. These solutions should introduce new ideas that align with the needs and characteristics of students and teachers as users. One approach that can be applied is the Design Thinking method. Design Thinking is a process for generating new and innovative ideas to solve problems and is considered an effective tool in teaching and learning to develop twenty-first-century skills (Luka, 2014; 2019). Research by Riti et al. (2021) also supports this approach, stating that the application of the Design Thinking method in developing an effective learning model can significantly enhance students' critical thinking skills.

Thus, based on the explanation above, this study aims to explore various alternative solutions to enhance critical thinking in mathematics using the design thinking approach. Existing studies on Design Thinking in mathematics focus on general problem-solving but lack specific applications in trigonometry learning. These solutions are developed in accordance with students' needs, teachers' needs, advancements in science and technology, and future educational demands.

2. METHODS

The research method used in this study follows a qualitative research approach incorporating design thinking and meta-analysis. Design thinking is a widely used method in application design, emphasizing a collaborative approach that gathers insights from various disciplines to develop problem-solving solutions. According to Regita & Rani (2023), design thinking aims to enhance the teaching and learning process by making it more interactive, ensuring that the material is effectively absorbed by students. This method consists of five stages, beginning with the empathize phase and concluding with the test phase. Figure 1 presents a flow diagram of the research process, illustrating the stages of the design thinking methodology applied in this study.

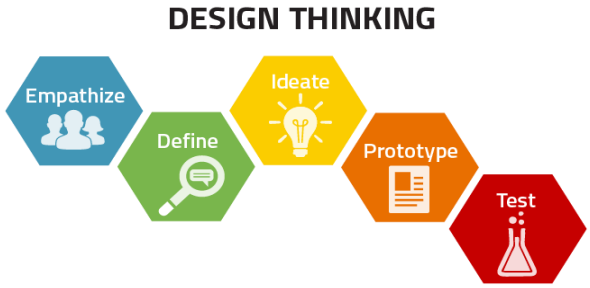

Figure 1. Design Thinking Process

According to Budiraharjo (2022), the Design Thinking method consists of five stages: (1) Empathize, which is a stage to identify user needs for a product by increasing sensitivity to the environment, forming insights, and fostering open-minded thinking in product developers or innovators; (2) Define, where innovators determine the main problem or primary user need that the product aims to address; (3) Ideate, a stage of exploring various alternative ideas to develop product designs that align with user needs; (4) Prototype, where the product design idea is realized in the form of a trial product, known as a prototype; and (5) Testing, where the developed product undergoes testing through experiments involving users.

The population in this study consisted of grade X students and mathematics teachers from three different schools: SMAN 1 Semarang, SMAN 5 Semarang, and SMAN 14 Semarang, with 90 student respondents and 8 Mathematics teacher respondents. Population selection by region in urban and suburban areas. Data collection was conducted using observations, questionnaires, interviews validated by experts, and research references. The research procedure began with the development of a questionnaire and interview sheet, which were validated by expert lecturers, followed by observations to assess students' needs at SMAN 1 Semarang. Subsequently, questionnaires were distributed to the three schools, and data collection was carried out accordingly.

The research method using design thinking consists of the following stages: (1) the empathize phase, (2) the define phase, which includes user persona and "how might we" analysis, and (3) the ideate phase, which involves brainstorming and mind mapping. The ideas generated in the ideate phase are then further supported by meta-analysis. The selection of research subjects for the meta-analysis was customized to the ideas from the ideate phase that emerged.

Data analysis techniques in this study were conducted interactively through the process of data reduction, data display, and verification. The validity of the data was checked using triangulation techniques by testing the consistency of the data obtained from questionnaire and interview responses, as well as using the meta-analysis method to calculate the effect size value in supporting the research ideate. The meta-analysis of effect size data was analyzed using JASP 0.19.2 software, with a significance criterion of p-value < 0.05, indicating that the estimation model could be used to calculate the effect size.

3. FINDINGS AND DISCUSSION

Exploration of learning innovations to improve critical thinking is conducted following the design thinking framework. The stages of the design thinking phase in this exploration of learning innovations are as follows.

3.1 Empathize

Empathize is the first stage of the design thinking method, which requires researchers to have empathy in understanding the desires and needs of users. This stage aims to identify users' needs regarding the product to be developed. Additionally, it serves to enhance sensitivity to the environment, shape and develop insights, and enable developers or innovators to think openly.

At this stage, data collection was conducted using questionnaires and interviews. Researchers designed questionnaires and interview questions to gather initial data from class X students and mathematics teachers. After being validated by experts, the questionnaires were distributed, and in-depth interviews were conducted with students and teachers. The study population consisted of respondents from three different schools: SMAN 1 Semarang, SMAN 5 Semarang, and SMAN 14 Semarang.

Table 1. Students Respondents

School	Number of students	%
SMAN 1 Semarang	35	38.9 %
SMAN 5 Semarang	35	38.9 %
SMAN14 Semarang	20	22.2 %
Amount	90	100 %

The results of data from 90 students showed that only 33.3% of students genuinely liked or enjoyed mathematics, while 66.7% felt neutral, did not particularly like, or even disliked the subject. Additionally, many students experienced concerns and difficulties during mathematics learning in class, with 75.6% struggling to understand concepts and 65.5% finding it difficult to think critically. The most challenging topics identified were logarithms (54.4%), trigonometry (52.2%), and exponents (52.2%).

In addition, 87.8% of students expect interesting learning, while 78.9% prefer learning that aligns with their needs. The low level of students' critical thinking in mathematics is influenced by several factors, one of which is the learning model used by teachers. An inappropriate selection of learning models can significantly impact the learning process and students' ability to think critically.

Table 2. Mathematics Teacher Respondents

School	Number of Teachers	%
SMAN 1 Semarang	4	50 %
SMAN 5 Semarang	2	25 %
SMAN 14 Semarang	2	25 %
Amount	8	100 %

The results of data from 8 mathematics teachers indicated that the most challenging materials for students to understand were trigonometry (75%), logarithms (50%), and exponents (37.5%). Additionally, teachers experienced difficulties in preparing learning media. In fact, according to Ardiansyah & Nugraha (2022), the use of learning media makes lessons more engaging and enhances students' critical mathematical thinking. Facilitating critical thinking through digital media helps students visualize abstract mathematical concepts, as animations and images can illustrate complex ideas that are difficult to grasp verbally (Batubara, 2020).

Furthermore, to better understand the problems and needs of students and teachers, an empathy map is used. Empathy maps provide an overview of students' and teachers' perspectives by organizing their thoughts collaboratively. The results of creating empathy maps are useful for decision-making, allowing for more targeted and effective solutions.

Figure 1. Student Empathy Map

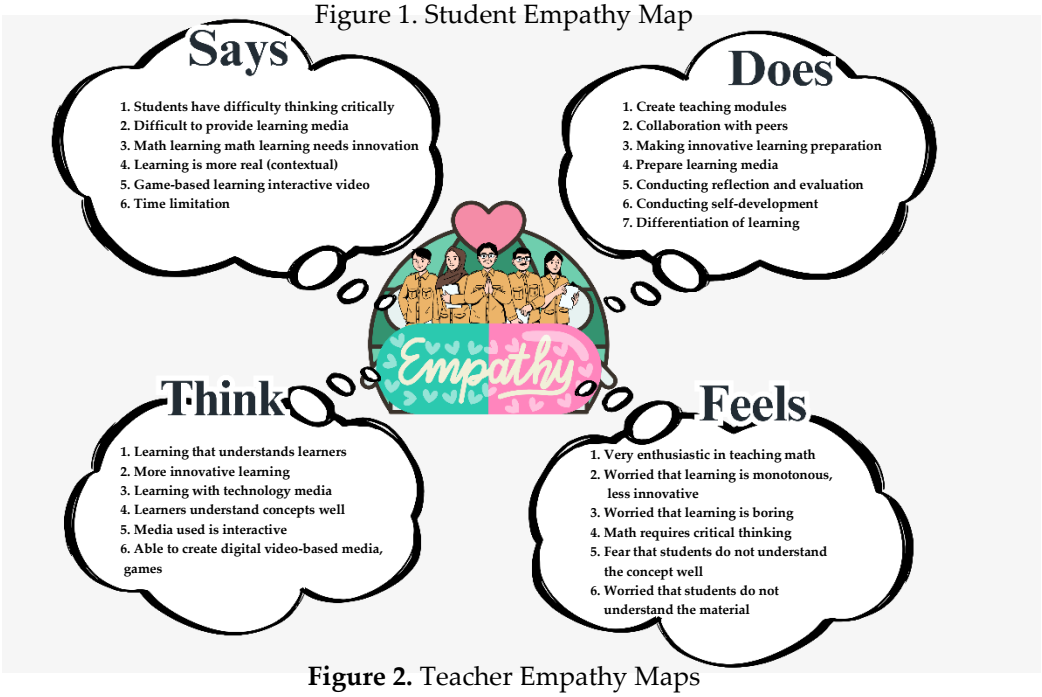

Figure 2. Teacher Empathy Maps

From the results of the empathy map of students and teachers, several key findings were identified: (1) Students experience anxiety and difficulty in critical thinking, often due to their dislike of mathematics. This aligns with research by Sapitri et al. (2023), which states that students' difficulties in understanding mathematics stem from a lack of interest, as it is perceived as a difficult subject; (2) Students find learning monotonous due to a lack of variation in learning media, making them less interested in the subject; (3) Students need innovative learning approaches, such as student-centered learning, outdoor learning, and technology-based learning; (4) Teachers require learning innovations that cater to student needs and enhance critical thinking. This is supported by research from Utomo et al. (2024), which highlights the necessity of a cooperative learning model with internet-accessible tools to create engaging learning experiences for both teachers and students; (5) Trigonometry is considered a difficult topic by both students and teachers. Research by Ardila et al. (2022) found that the average ability to comprehend trigonometry concepts was 49.35, categorized as sufficient, indicating the need for better instructional strategies. Furthermore, Gusmania and Agustyaningrum (2020) emphasized that trigonometry is one of the most challenging mathematical topics, with common difficulties including applying general trigonometric formulas, understanding relationships between trigonometric comparisons, and performing algebraic calculations, leading to frequent errors in solving analytical trigonometry problems.

3.2 Define

The define stage is the process of identifying and clarifying problems obtained in the empathize stage. At this stage, the collected data and information are analyzed to understand the core issues, which are then narrowed down to key problem statements. According to Dam & Siang (2020), formulating a design challenge correctly using the point of view technique involves integrating an understanding of users, their needs, and insights from the empathize phase into a single actionable statement. Thus, each problem identified in the empathize stage will be addressed through a well-defined approach. The point of view techniques used in this process include user charm and the "How Might We" framework.

3.2.1 User Persona

User personas are created based on the results of questionnaires and interviews conducted previously. They help designers understand user needs, behaviors, experiences, and goals (Regita & Rani, 2023).

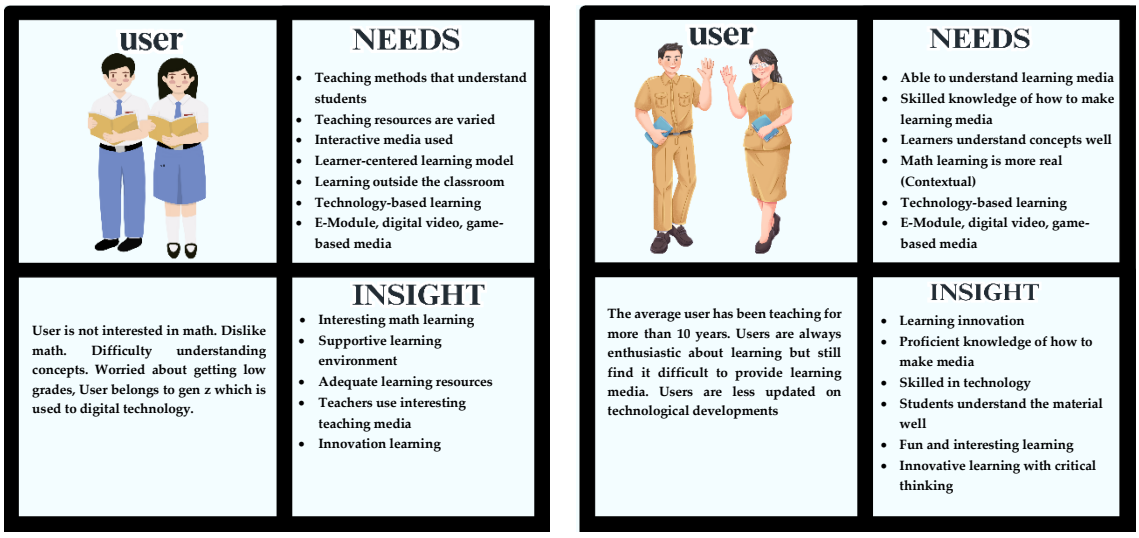

Figure 3. User Persona of Students and Teachers

User personas are used to identify users' needs and problems, helping researchers understand the desired features that provide solutions to these problems.

3.2.2 How Might We (HMW)

How Might We (HMW) is a method for transforming statements into questions. It aims to broaden the author's problem-solving perspective. 'How' represents the question derived from a user's problem, while 'might' suggests possible answers to that question. The results are as follows:

1) How can we make learning mathematics fun? By designing learning that aligns with students' needs.
2) How can we make mathematics learning more enjoyable for students? By using learning media that suit students' needs and interests.
3) How can students' critical thinking skills be improved in learning? By using innovative learning media, engaging teaching methods, and problem-based contextual learning.
4) How can students become more interested in the material? Learning is designed using media that students enjoy, such as interactive digital video-based media, Android games, and outdoor learning experiences.
5) How do math teachers deliver material in class? By using a student-centered learning model.
6) How can we ensure that students do not get bored with mathematics learning? By using Android game-based media and digital videos to make learning more engaging.
7) How can teachers prepare engaging lessons? By creating learning media that align with students' needs.

3.3 Ideate

The Ideate phase in design thinking is the stage of exploring various radical alternative ideas that can serve as solutions to a problem or need (Doorley et al., 2018). At this stage, brainstorming is conducted to generate ideas that address user needs identified in the previous phase. After the brainstorming process, selected ideas are organized into a mind map, which will later serve as candidate features for the application being developed.

Figure 4. Brainstorming Results

The brainstorming results are then visualized in a mind map, illustrating all user ideas as follows:

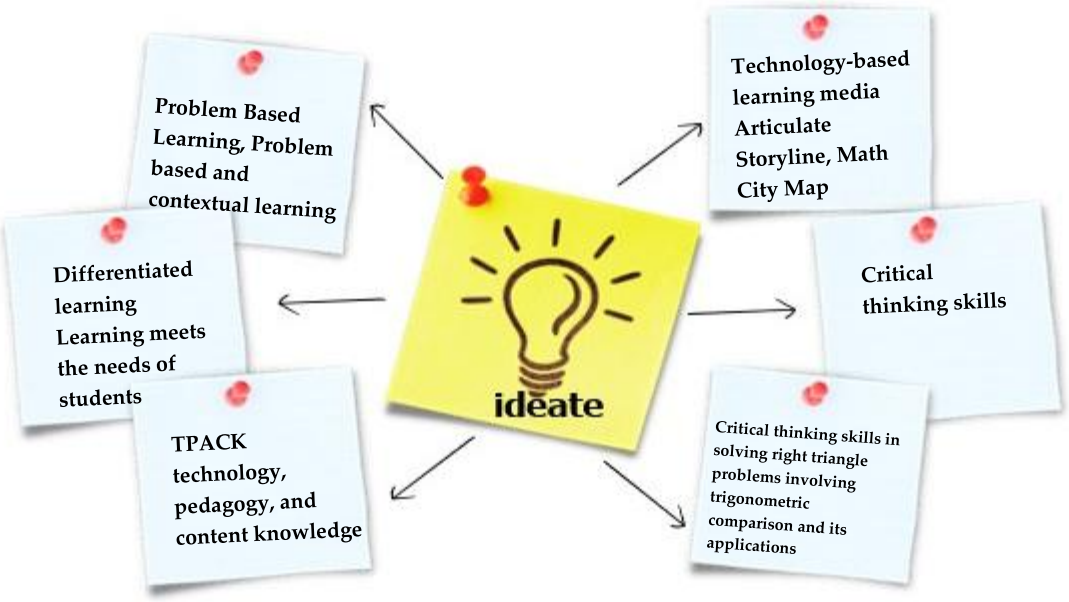

Figure 5. Ideate Phase Mind Mapping

The results of mind mapping revealed various alternative solutions for exploring learning innovations that align with user needs and the current curriculum through the design thinking framework, as follows:

1) Trigonometry Material: Trigonometry is considered a difficult topic to understand by both students and teachers.
2) Critical Thinking Skills: Based on the empathize stage, students feel anxious and struggle with critical thinking. Therefore, the goal is to enhance students' critical thinking skills.
3) Differentiated learning approaches meet the needs of students. In line with the research results of Minangkabu et al. (2024), differentiated learning has been shown to be effective in improving students' critical thinking skills. This approach accommodates differences in learning styles, ability levels, and student interests. However, challenges in implementing differentiated learning include complex classroom management and the preparation of diverse materials. Therefore, differentiated learning is essential, as its varied strategies foster high levels of critical thinking.
4) Problem-Based Learning Model: A learning approach that challenges students to find solutions to real-world problems individually or in groups. In line with Hartanti & Purnomo's (2023) research, the application of the PBL model can enhance critical mathematical thinking skills.
5) Framework: Implementing engaging and innovative learning in trigonometry through technological knowledge, pedagogy, and content (TPACK) framework.
6) Media :
   a) Media Articulate Storyline

   Articulate Storyline is a software application used to create presentations and interactive learning media. Its functionality is similar to Microsoft PowerPoint, but it offers additional features such as animated movements, background music, images, and interactive videos. Articulate Storyline seamlessly integrates text, animation, video, images, and sound, creating an engaging and visually appealing learning format. According to Nurhasannah et al. (2024), learning with interactive Articulate Storyline media is a problem-solving model for critical thinking, requiring students to solve problems using the scientific method stages with the assistance of this interactive media. Thus, this approach aligns with user expectations, which emphasize digital video-based

learning, video games, and Android applications as tools for enhancing critical thinking and problem-solving skills.

b) Math City Map

The Math City Map application is a GPS-based Android application that can be accessed anytime and anywhere. According to Cahyani et al. (2024), the Math City Map application enables students to solve strategic problems related to mathematics within the app and enhances their critical thinking skills.

In line with the user's desire for more varied and engaging learning experiences, monotonous learning should be supplemented with outdoor learning activities. One approach is to design learning by placing GPS coordinates at various locations within the school environment, such as flagpoles, school buildings, Sipeas trees, mosques, football fields, and basketball courts, according to learning needs. Students will be encouraged to think critically to solve problems at each GPS coordinate position. According to Dwijayanti & Nugroho (2023), the success of an environment-based learning model is largely influenced by the use of appropriate media in its implementation. Therefore, researchers hope that Math City Map media can serve as an effective learning aid.

Thus, researchers have identified various alternative solutions to improve critical thinking in mathematics using the design thinking approach, which is based on the needs of students, the needs of teachers, the development of science and technology, and future demands, as follows.

1) Designing Differentiated PBL Learning Based on TPACK with Articulate Storyline;
2) Developing Jejak Timur Media Assisted by the Math City Map; Jejak Timur is an innovative media for Critical Trigonometry Measurement Exploration.
3) Creating Differentiated PBL Learning Activities Based on the Jejak Timur Math City Map.

3.4 Meta-Analysis

The purpose of this meta-analysis research is to examine the ideate solution regarding the influence of the differentiated Problem-Based Learning (PBL) model with Math City Map media and Articulate Storyline media on improving critical thinking. The calculation of effect size is necessary to determine whether the use of the PBL model and media supports the ideate solution. By analyzing six selected articles coded for research, the effect size is calculated using the appropriate formula. The results of these calculations are then analyzed using the meta-analysis method, and the obtained data are as follows.

Table 3. Article data with effect size and standard error

Researcher	Treatment	N	I	ES	SE
(Halawa, 2024)	PBL 1	32	28	0.8750	0.0585
(Muliatmik et al., 2024)	PBL 2	43	37	0.8605	0.0528
(Sutisnawati et al, 2024)	Differentiation 1	30	28	0.9333	0.0455
(Deswita et al., 2024)	Differentiation 2	23	20	0.8696	0.0702
(Mayoza et al., 2024)	Articulate storyline	28	24	0.8571	0.0661
(Ramdani, 2024)	Math City Map	20	19	0.9500	0.0487

Based on the collected data, the research was continued with a meta-analysis using the JASP 0.19.2 analysis software program.

Table 4. Pooled Effect Size Test

Estimate	Standard Error	Z	P
0.900	0.022	40.094	< .001

Table 5. Meta-Analytic Estimates

		95% CI		95% PI	
	Estimate	Lower	Upper	Lower	Upper
Effect Size	0.900	0.856	0.944		

Based on Table 4, the obtained p-value is <0.001, which is less than the alpha value (0.05), indicating a significant influence of the Differentiated PBL model, along with the use of Math City Map media and Articulate Storyline, on critical mathematical thinking. Furthermore, in Table 4 and Table 5, the average effect size (summary effect size estimate) for the Differentiated PBL model and the use of Math City Map media on critical mathematical thinking is 0.900, categorized as a large effect according to Cohen's classification, with a standard error of 0.022. These findings suggest that the proposed solution is well-supported by previous research, demonstrating a significant impact on students' critical thinking skills.

3.5 Prototype Phase

With the process of data collection, idea generation, and solution exploration completed, the next step is to create a prototype design. Prototype development is a crucial stage in design thinking and follows a user-centered approach, as it allows designers to test ideas and refine them within a short period (Dam & Yu, 2020). When planning to test ideas, several factors must be considered, including curriculum, infrastructure, funding, school environment, human resources, energy, and time constraints. The identified design challenge is to develop a differentiated PBL learning design assisted by the Math City Map through focus group discussions (FGDs) involving 16 participants, consisting of six expert lecturers in mathematics education and ten postgraduate students. The differentiated PBL learning design assisted by the math city map then led to the development of the following prototype models: (1) differentiated PBL activity steps; (2) math city map media adapted to school conditions; (3) a critical exploration design for trigonometric measurement; and (4) critical thinking test questions. The differentiated PBL activity steps aim to foster critical thinking-based learning tailored to students' needs. Meanwhile, the design of the math city map takes place within the school environment, incorporating critical thinking questions that utilize real-world objects such as school buildings, surrounding trees, soccer fields, flagpoles, and basketball courts at SMA Negeri 1 Semarang. This approach encourages students to think critically and analyze real-world contexts directly within their surroundings. This approach can be adapted for schools with limited resources.

3.6 Testing

The prototype testing plan was carried out using four methods: (1) a critical thinking test based on the Understanding by Design (UbD) framework, (2) learning observation, (3) a media expert validation sheet for the Math City Map, and (4) a student response questionnaire. This prototype trial was conducted in two phases and evaluated based on its strengths, effectiveness in promoting student engagement, and potential to improve conceptual understanding. Observational data helped capture student interactions and behavioral responses, while expert feedback ensured the media design aligned with pedagogical goals. The questionnaire results offered direct insights into students' learning

experiences and perceived benefits of the prototype. Together, these instruments provided a comprehensive picture of the prototype's instructional quality and areas for improvement.

4. CONCLUSION

Based on the results of the exploration of learning innovations aimed at improving critical thinking through the design thinking framework, the following innovation solutions were identified from the empathize, define, and ideate phases: (1) Designing Differentiated PBL Learning Based on TPACK with Articulate Storyline; (2) Developing Jejak Timur Media Assisted by the Math City Map; (3) Developing Differentiated PBL Learning Activities Based on the Jejak Timur Math City Map. Furthermore, the affirmation in the ideate meta-analysis yielded a p-value < 0.001, which is less than the alpha value (0.05). This indicates a significant and substantial effect (0.900) of the Differentiated PBL model, the use of the Math City Map, and Articulate Storyline media on improving critical thinking skills. Application of the Design Thinking method in developing an effective learning model can significantly enhance students' critical thinking skills.

Based on the research findings, the following suggestions can serve as a guide for the next phases of design thinking, namely the prototype and test stages: (1) For researchers interested in developing interactive learning media, Jejak Timur media assisted by the Math City Map can be used as a reference to enhance both content and methodology; (2) The development of a design for Differentiated PBL Learning activities based on the Jejak Timur Math City Map should be carried out by considering user needs and future curriculum requirements; (3)This study was limited the population in this study consisted of grade X at Semarang City and did not measure long-term retention. Thus, there is a need to testing this model on a larger and more diverse sample. By implementing these recommendations, future research can build upon the findings of this study and make significant contributions to improving interactive learning media or incorporating learning media based on Articulate Storyline or Jejak Timur Math City Map into teaching practices.

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