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Development of STEM Based Mathematics Learning Instruments to Improve Students' Critical Thinking Skills in PBL Model

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Abstract

The research aim was to develop STEM-based learning instruments to improve students' critical thinking skills used in the PBL model that was valid, practical, and readable by students. The research used a simplified 4-D development model in the research and development research method, which consisted of three stages; define, design, and develop. It was because of the Covid-19 pandemic that the learning process was held online, and the effectiveness testing or dissemination stage couldn't be held. The learning instruments consisted of a syllabus, lesson plan, learning material, and student worksheet. Learning instruments' validation testing stated that the learning instruments were valid with the average scores for syllabus was 3.82 out of 4.00, for lesson plan was 3.79 out of 4.00, for learning material was 3.85 out of 4.00, and for student' worksheet was 3.80 out of 4.00. Learning instruments' practicality testing stated that the learning instruments were practical to be used during the learning process, with scores of it were 97.50% for syllabus, 96.43% for the lesson plan, 95.83% for learning material, and 93.06% for student worksheets. Learning instruments' readability testing stated that the learning instruments were readable by students, with scores of it were 82.78% for learning material and 80.83% for students' worksheets.

1. Introduction

Ministerial Regulation of Minister of Education and Culture Number 37 Year 2018 states that there are four objective competencies in curriculum 2013, consists of spirituality competence, social attitude competence, knowledge competence, and skills competence. Based on the four competencies, one of the learning objectives is to process knowledge to solve problems. To solve problems, critical thinking skills are needed. But, based on PISA 2018 result, students' mathematics skills in Indonesia is low. The study stated that Indonesia is still on level 1, where OECD (2019) states that in level 1, students can answer questions involving familiar contexts where all relevant information is present and he questions are clearly defined, are able to identify information and to carry out routine procedures according to direct instructions in explicit situations, and can perform actions that are almost always obvious and follow immediately from the given stimuli. It means, students in Indonesia can only solve daily problems just if all of the related information has been showed directly. Only 1% of Indonesia students who reach level 5 which is students can develop and work with models for complex situations, identifying constraints and specifying assumptions, can select, compare and evaluate appropriate problem solving strategies for dealing with complex problems related to these models, can work strategically using broad, well-developed thinking and reasoning skills, and begin to reflect on their work and can formulate and communicate their interpretations and reasoning. The result shows that students' critical thinking skills is low, because PISA problems are started by daily problems that allow students to use any strategies and formulas to solve it and make them using their critical thinking skills.

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One of strategies to improve students' critical thinking skills is using problem based learning model. Arviana et al. (2018) concluded that problem based learning model can improve students' critical thinking skills because they don't only answer "yes" or "no" but also explain their reason why they answer it. Nafiah (2014) also stated that problem based learning model can create learning environment that can support improvement of critical thinking because it refers to problematic situation. Widyatiningtyas et al. (2015) also claimed that students who use problem based learning model have higher critical thinking skills than student who use conventional learning model, because students in problem based learning model are more active to find out new information.

Another factor that can support improvement of students' critical thinking skills is learning approach. Hafni et al. (2020) claimed that STEM learning approach can improve students' critical thinking skills because it combines two or more topics in one lesson, two or more lesson, or lesson and daily problems. Utami et al. (2018) also stated that the use of STEM in learning process make students get their critical thinking, innovative, creative, communication, and collaboration skills.

Appropriate learning material also maters to improve students' critical thinking skills. Sari et al. (2019) concluded that learning process in school is still teacher centered and learning objective is still concept memorization. Sari & Wutsqa (2019) also stated that mostly teachers don't develop their learning instruments independently. They either download it online or buy it on the publishers. It is because teacher thinks that right learning instruments are not important in learning process. Tanjung & Nababan (2018) also stated that learning instruments have never been tested its validity, practicality during the learning process, and effectiveness so that the learning instruments can't be claimed valid, practical, and effective to help students learn the material.

Based on the description above, it is important to develop science, technology, engineering, and mathematics based learning instruments to improve students' critical thinking skills in problem based learning model. The research aims were (1) to develop science, technology, engineering, and mathematics based learning instruments to improve students' critical thinking skills in problem based learning model, (2) to test science, technology, engineering, and mathematics based learning instruments to improve students' critical thinking skills in problem based learning model' validation, (3) to test science, technology, engineering, and mathematics based learning instruments to improve students' critical thinking skills in problem based learning model' practicality, and (4) to test science, technology, engineering, and mathematics based learning instruments to improve students' critical thinking skills in problem based learning model' readability by students.

2. Methods

The research used simplified 4-D development model by S. Thiagarajan et al. (1976) in research and development research method. 4-D development model consisted of four development stages; define, design, develop, and disseminate. But, due to Covid-19 pandemic impact that made learning process conducted online, the disseminate stage couldn't be conducted. Then, simplified 4-D development model in this research consisted of three development stages; define, design, and develop. There were five steps in define stage, consisted of front-end analysis, learner analysis, task analysis, concept analysis, and specifying instructional objectives. Design stage consisted of four steps; construction of criterion-referenced tests, media selection, format selection, and initial design. In develop stage, there were learning instruments validation testing, learning instruments practicality testing, learning instruments readability testing, and final product.

The aim of front-end analysis was to decide problems in mathematics learning process and curriculum at the school. Learner analysis had been intended to find out students' characteristics during mathematics learning process. Task analysis had been intended to find out basic competencies that were suitable with students' initial ability in mathematics lesson. Concept analysis had been intended based on the task analysis result to decide the material development that were suitable with students. Specifying instructional objectives was intended to decide indicators of competence achievements related to the basic competencies that had been decided in task analysis.

Design stage was started by constructing criterion-referenced tests to check whether learning instruments that were developed suitable in improving students' critical thinking skills based on critical thinking skills' indicators or not. The validation, practicality, and readability of the learning instruments were tested using validation testing, practicality testing, and readability testing. Media and format selection were intended to decide suitable learning instruments that could be used to improve students' critical thinking skills based on students' needs and initial ability. The result of media and format selection conduced initial design of the learning instruments.

The initial design was tested its validation, practicality to be used in learning process, and readability by students as a user of the learning instruments. Suggestions that had been given by validators were used to revise the learning instruments so that the final products were suitable and could improve students' critical thinking skills.

The data of the research were collected by interviewing mathematic teachers of SMA N 1 Banjarnegara, and disseminating questionnaires for learning instruments' validation testing, learning instruments' practicality testing, and learning instruments' readability testing.

Collected data that formed as qualitative scores were converted into quantitative scores based on Likert scale by Sugiyono (2015). Validation of the learning instruments was tested by following formula:

$$Sr = \frac{\sum x}{n}$$

$Sr =$ average score
$\sum x =$ total score from validator
$n =$ maximum total score for each of the learning instruments
(Ni'mah et al., 2018)

The average score was defined based on learning instruments' validation categories, shown in **Table 1.**

Table 1. Learning instruments' validation categories

Average score (Sr)	**Category**
$3.25 \leq Sr < 4.00$	Very good
$2.50 \leq Sr < 3.25$	Good
$1.75 \leq Sr < 2.50$	Not good
$1.00 \leq Sr < 1.75$	Very not good

The learning instruments were defined valid if the average score was classified as very good or good.

Practicality of the learning instruments was tested by following formula:

$$Practicality(\%) = \frac{n}{N} \times 100\%$$

$n =$ score by validator
$N =$ maximum total score
(Hidayat & Irawan, 2017)

The percentage score was defined based on learning instruments' practicality categories, shown in **Table 2.**

Table 2. Learning instruments' practicality categories

Percentage (%)	**Category**
$80 \leq score < 100$	Very good
$60 \leq score < 80$	Good
$40 \leq score < 60$	Good enough
$20 \leq score < 40$	Not good
$0 \leq score < 20$	Very not good

The learning instruments were defined practical to be used in learning process if the practicality percentage was classified as good or very good.

Readability of the learning instruments was tested by following formula:

$$P = \frac{f}{N} \times 100\%$$

$P =$ readability score of the learning instruments
$f =$ score by students
$N =$ maximum total score
(Sudijono, 2014)

The percentage score was defined based on learning instruments' readability categories, shown in **Table 3.**

Table 3. Text' readability categories

Percentage (%)	Category
$P > 66.66$	intelligibly easily
$33.33 \leq P \leq 66.66$	intelligibly
$P < 33.33$	intelligibly difficult

The learning instruments were defined readable by students if the readability percentage was classified as intelligibly easily.

3. Results & Discussions

3.1. Define Stage

3.1.1. Front-end analysis

Result of literature review showed that students' critical thinking skills was low, teacher had not developed learning instruments independently, teacher had just downloaded learning instruments in the internet and publishers, and used learning material was conducted procedurally. Based on interview result, students' critical thinking skills in the school was low, and learning material that was developed by teachers had been procedural and had not used daily problems.

The interview results support PISA 2018 result that shows students in Indonesia critical thinking skills, Sari & Wutsqa (2019) research that claimed learning process in school is using conventional model and teacher has not developed learning instruments, and Tanjung & Nababan (2018) research that concluded learning instruments that are used by teacher in school can't be stated its validity, practicality, and readability.

3.1.2. Learner analysis

Based on interview with SMA N 1 Banjarnegara' mathematics teachers, students' initial ability in mathematics learning, students' motivation to learn, and students' experience in mathematics learning were diverse, generally, students were more familiar with conventional learning model where they listen to their teacher during learning process, some students were excited to learn, students had been given some materials to be read before lesson starts, then the materials were discussed during the learning process although not all students joined the discussions, students preferred to ask their friends instead of asking their teacher if they find some difficulties during the learning process, students focus was to solve mathematics problems instantly, some students didn't like to solve daily problems, while the other liked to solve daily problems that didn't need deep analysis to solve it.

The interview results support Akdeniz et al. (2016) claim that says students need other people help in order to develop their knowledge, Ormrod (2016) claim that says learning process start when students interact with other, Slavin (2018) claim that says environment has an influence of someone character.

3.1.3. Task analysis

Basic competencies that were developed in the research were 3.6. and 4.6. basic competencies. The basic competencies were:

Table 4. Basic Competencies

3.6. Explaining composite function and inverse function and its properties and determining its existence.
4.6. Solving problems related to composite function and inverse function.

3.1.4. Concept analysis

Based on interview with SMA N 1 Banjarnegara' mathematics teachers, most students had understood function materials, such as function definition, function presentation form, and functions types. But, students had been struggling to understand composite function operation, both composite function operation definition and composite function operation notation.

The result supports Abdurrakhman & Rusli (2015) statement that learning process starts when students can combine their knowledge with new knowledge, Gazali, (2016) statement that says learning process will be done if students can use their knowledge to understand new concept, by combining their concept and fact with the new concept and fact and Rohaendi & Laelasari (2020) claim about Vygotsky learning theory that says the new knowledge must be too hard to be understood by students if they learn it alone, but can be understood if they get some helps by other. In this context, composite function operation can be understood by them using some helps from their friends and teacher.

3.1.5. Specifying instructional objectives

Indicators of competence achievements that were developed in the research were:

Table 5. Indicators of Competence Achievements

Basic Competencies		Indicators of competence achievements	
3.6.	Explaining composite function and inverse function and its properties and determining its existence	3.6.1.	Describe composite function operation concept.
		3.6.2.	Describe composite function operation notation.
		3.6.3.	Describe domain and range determination of composite function operation.
		3.6.4.	Describe composite function operation properties.
4.6.	Solving problems related to composite function and inverse function	4.6.1.	Apply function concept to find composite function operation concept based on daily problems.
		4.6.2.	Design composite function operation based on daily problems.
		4.6.3.	Apply composite function operation notation to solve composite function operation related problems.
		4.6.4.	Apply composite function operation concept to find out domain and range of the composite function operation.
		4.6.5.	Apply composite function operation notation concept to analyse composite function operation properties in daily problems.

3.2. Design Stage

3.2.1. Construction of criterion-referenced tests

Criterion-referenced test were using learning instruments' validation questionnaire, learning instruments' practicality questionnaire, and learning instruments' readability questionnaire to check whether science, technology, engineering, and mathematics based learning instruments were right or not to improve students' critical thinking skills in problem based learning model.

Developed learning instruments were adjusted Ministerial Regulation of Minister of Education and Culture Number 22 Year 2016, learning material development principals and components by National Educational Department (2008), syllabus development principals and components by Minister of Education and Culture (2016), lesson plan development principals and components by Ministerial Regulation of Minister of Education and Culture Number 103 Year 2014, school curriculum, core competencies, basic competencies, indicators of competence achievements, learning objectives, learning resources, time allocation, evaluations, students' initial ability, daily problems, PBL syntax model, STEM principals by Moore & Smith (2014) and Bybee (2011), scientific approach, and critical thinking indicators to improve students' critical thinking skills by Zakiah & Lestari (2019) and Facione & Gittens (2016), material concept understanding, ease of use by students, and suitability of helping students learning the material independently.

3.2.2. Media selection

Media selection in the research was the development of learning instruments consisted of syllabus, lesson plan, learning material, and students' worksheet in composite function operation material in problem based learning model.

3.2.3. Format selection

Learning instruments were used various fonts, font sizes, spaces, letter sizes, and margins to make it clear and attractive to read. Material developed in the syllabus were composite function operation concept and composite function operation properties, divided into six learning processes and eight lesson time allocation. Meeting 1 lesson plan consisted of one meeting lesson plan with learning objective to find out and describe composite function operation concept based on students' initial ability in function concept. Meeting 2 lesson plan consisted of one meeting lesson plan with learning objective to explain composite function operation notation based on composite function operation concept. Meeting 3 lesson plan consisted of one meeting lesson plan with learning objective to find out and describe domain and range determination in composite function operation based on composite function operation concept. Meeting 4 lesson plan consisted of one meeting lesson plan with learning objective to analyse composite function operation properties based on composite function operation notation. Various colour represented each STEM aspect, illustration in order to giving the clearer material explanation, rubrics and features that support the improvement of critical thinking skills, STEM trivia in some parts of the learning material, and exercises to check whether students had understood the material or not at the end of the learning material were also used in the learning material. Meeting 1 students' worksheet consisted of two STEM daily problem illustrations with ten questions in order to make students find out and describe composite function operation concept. Meeting 2 students' worksheet consisted of two STEM daily problem illustrations with nine questions in order to make students explain composite function operation notation. Meeting 3 students' worksheet consisted of two STEM daily problem illustrations with ten questions in order to make students find out and describe domain and range of composite function operation. Meeting 4 students' worksheet consisted of two STEM daily problem illustrations with ten questions in order to make students analyse composite function operation properties.

3.2.4. Initial design

Initial design of syllabus consisted of title, identity (school' name, subject, grade, and semester), core competencies, basic competencies that were 3.6 and 4.6 basic competencies, materials that were composite function concept and composite function properties, lesson activities for four meetings, assessments that consisted of spiritual, social, knowledge, and skills assessments, time allocation that were eight lesson hours or four meetings, and learning resources. In the end of the syllabus, there were researchers' name and sign, and mathematics teacher's name and sign.

Initial design of each lesson plan consisted of title, identity (school' name, subject, grade, semester, topic that was composite function, and time allocation that was 2 x 45 minutes or one meeting), core competencies, basic competencies that were 3.6 and 4.6 basic competencies, indicator of competence achievements for each meeting/lesson plan, learning objectives for each meeting based on audience, behavior, condition, and degree learning objectives, learning materials for each meeting, consisted of regular learning material, remedy learning material, and enhancement, learning model that was PBL, learning approach that was STEM, learning media that was student' worksheet, learning resources, learning activities that consisted of introduction, main activities, and closing, assessment that consisted of assessment technic for spiritual, social, knowledge, and skills, remedy learning, and enhancement learning. Appendices for each lesson plan consisted of spiritual and social assessment journal, self-assessment by students, friend assessment by students, performance journal, student's assignment that consisted of assignments' blueprint, assignment, answer key, and scoring guideline.

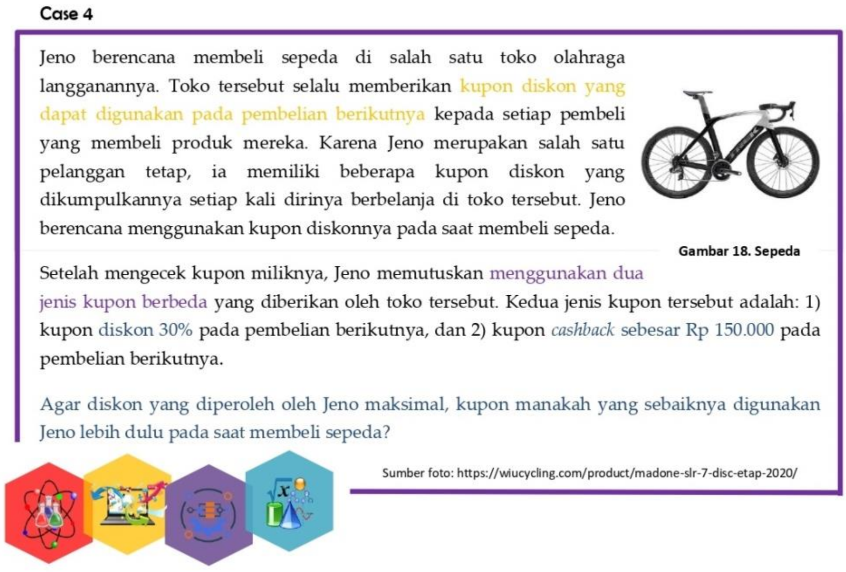

Figure 1. Example of problem related to technology, engineering, and mathematics

Learning material consisted of cover, definition of STEM, contents, manuals, objectives, review of the related material, application of composite function, materials divided into composite function concept, composite function notation, composite function domain and range, and composite function properties, exercises, and resources. In the materials, there were some information related science, engineering, and technology, information related to material using technology, illustrations to help students understand the material easier, and some questions to improve students' critical thinking skills. The problems in the learning material also related to science, technology, engineering, and mathematics.

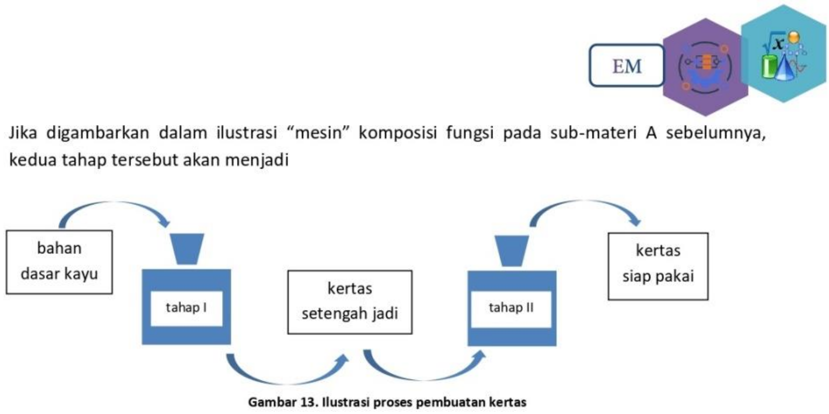

Figure 2. Example of illustration to help students understand the material easier

Figure 3. Example of information related to science

Figure 4. Example of information related to material using technology

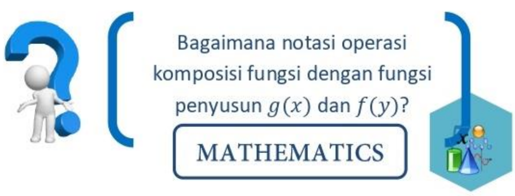

Figure 5. Example of question to improve students' critical thinking skills

Each of students' worksheet consisted of title as header and footer, identity (school' name, grade, semester, topic, time allocation to solve the worksheet, and meeting note), group' identity, learning objectives, instruction, and problems as well as questions.

3.3. Develop Stage

3.3.1. Learning instruments' validation testing

Learning instruments' validation testing result was shown in following **Table 6.**

Table 6. Learning instruments' validation testing result

Validator	Score of Learning Instruments			
	Syllabus	Lesson Plan	Learning Material	Student' Worksheet
Validator 1	56	76	57	53
Validator 2	57	78	56	58
Validator 3	57	73	60	58
Validator 4	59	76	58	59
Average Score	3.82	3.79	3.85	3.80
Categories	Very good	Very good	Very good	Very good

3.3.2. Learning instruments' practicality testing

Learning instruments' practicality testing result was shown in **Table 7.**

Table 7. Learning instruments' practicality testing result

Respondent	Score of Learning Instruments			
	Syllabus	Lesson Plan	Learning Material	Student' Worksheet
Teacher 1	19	27	36	36
Teacher 2	20	27	33	31
Percentage	97.50	96.43	95.83	93.06
Categories	Very good	Very good	Very good	Very good

Suggestions by teacher in the practicality test were to add sub-material in apperception part of meeting 1 lesson plan that were function presentation forms and function types, to give various example problems in learning material to improve students' critical thinking skills, to focus on constant function, linear function, and quadratic function during exercise problems in learning material, and to add some sentences in learning material problems to convince that the problems were easily understandable by students. Thus, meeting 1 lesson plan and learning material were revised based on the suggestions.

3.3.3. Learning instruments' readability testing

Learning instruments' readability testing result was shown in **Table 8.**

Table 8. Learning instruments' readability testing result

Respondent	Score of Learning Instruments	
	Learning Material	Student' Worksheet
Student 1	35	36
Student 2	37	37
Student 3	31	29
Student 4	28	28
Student 5	32	33
Student 6	31	30
Student 7	33	29
Student 8	35	34
Student 9	36	35
Percentage	82.78	80.83
Categories	intelligibly easily	intelligibly easily

Based on the learning instruments' readability testing result, learning material and student' worksheet layout were revised to make sure that it can easily understandable by students. The revision had been done because the learning instruments' readability testing was held online using google form where learning material and students' worksheet format had to be converted from .docx to .pdf so that some fonts that had been used in .docx didn't available in .pdf. It affected students' comfort in reading the learning material and students' worksheet.

3.3.4. Final product

The learning instruments refer to critical thinking skills consists of interpret problem intention, analyse and predict what someone should do to solve the problem, give evidence, make conclusion, state the solution, and evaluate the solution.

In syllabus and lesson plan, learning process and exercise problems starts with determining students' initial ability. When students try to construct their new knowledge, students have chance to identify related information as interpret problem intention indicator. When student try to develop their new knowledge, they will analyse what they will do based on their knowledge, find out some related fact and information, and make conclusion as in analyse and predict what someone should do to solve the problem, give evidence, make conclusion indicators. Then, they write their solution down as state the solution indicator. When students present their solution, other students give their opinion so that they can evaluate their solution together as evaluate the solution indicator.

In learning material and students' worksheet, after each daily problem illustration, it is given a statement related to the material, then a question that asks students to explain their answer. When they try to explain their answer, they will try to understand the question' intention as interpret problem intention. Their interpretation will become a starting point to analyse what will they do next and try to find out fact and information related to the question and material as in analyse and predict what someone should do to solve the problem, give evidence indicators. The fact and information that have been collected then be concluded as in make conclusion, and state the solution indicators. When they discuss it with their friends, they will evaluate their solution to get better and right solutions as in evaluate the solution indicator.

4. Conclusion

Based on the results and discussions of the research, it can be concluded that development of STEM based learning instruments to improve grade X Senior High School students' critical thinking skills in PBL Model used Research and Development research method and simplified *4-D* development model without testing the effectiveness of the learning instruments, focusing on composite function material. It was stated valid based on learning instruments' validation testing, practical to be used in learning process based on learning instruments' practicality testing, readable by students based on learning instruments' readability testing.

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