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Enhancing High School Students' Problem-Solving Skills in Rotational Dynamics through SPARK Model

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Abstract: The purpose of this study was to enhance high school students' problem-solving skills in rotational dynamics through the STEM-Project Approach for Real-World Knowledge (SPARK) model. The study employed a quasi-experimental design with a one-group pre-test and post-test approach to measure the progress of 30 first-year students (15 males and 15 females) from a high school in Bandung, Indonesia. Validated twenty-four essay questions was used to assess students' problem-solving abilities before and after the intervention. The results demonstrated moderate improvements in problem-solving skills, with significant advancements in problem identification (N-Gain: 0.59) and the application of scientific concepts (N-Gain: 0.53), while less improvement was observed in suggesting alternative solutions (N-Gain: 0.23) and designing tools (N-Gain: 0.16). The study, analyzed through portfolios and normalized gain values, indicated medium-category increases in some aspects of problem-solving skills. It can be concluded that the SPARK model is effective in enhancing high school students' problem-solving skills in rotational dynamics, particularly in improving the identification of problems and their relation to physics concepts. However, the model was less effective in improving the design aspect, indicating the need for further development in this area. Future research should focus on creating worksheets that better align with these problem-solving indicators.

Keywords: Problem-solving skills; Poject-based Learning; STEM, SPARK model.

Introduction

Problem-solving is unavoidable in human life and essential for human survival. It involves a cyclical process of recognizing, defining, and addressing problems through strategic thinking and resource allocation (Sternberg & Kibelsbeck, 2022). In today's rapidly changing world, developing 21st-century skills, particularly problem-solving abilities, is critical for students to navigate complex challenges and succeed in a variety of areas. Problem-solving abilities are complex cognitive abilities that use processes like imagery, analysis, synthesis, reasoning, and reflection to understand and overcome problems that do not have an obvious answer. This process entails identifying issues, devising solutions, putting them into action, and assessing the results, with an emphasis on logical reasoning, critical thinking, and reflection to properly digest information. OECD (2013) defines problem-solving competence as an individual's ability to engage in cognitive processes to understand and address challenging circumstances, especially when the solution technique is not immediately clear. These skills are subjective and impacted by prior knowledge, thus an issue may be difficult for one individual but not for another who already knows how to solve it.

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Problem-solving skills are also critical in preparing them for the future (Bybee, 2013; Firman, 2015). As the workforce faces complex challenges, students must have strong problem-solving skills to navigate uncertain situations. Modern education focuses on active problem-solving, applying knowledge to new situations, and building understanding, preparing students to face today's challenges (Funke et al., 2018; Özyurt, 2015; Rausch & Wuttke, 2016; van Laar et al., 2020). Given the importance of these skills, there is an urgent need to implement educational strategies that immerse students in real-world situations, helping them develop effective problem-solving capabilities (Bell, 2010; Kelley & Knowles, 2016; Prasad et al., 2017).

Despite its importance, research shows that students struggle to develop problem-solving skills, revealing a gap in education that fails to meet 21st-century demands. This is especially evident in physics, where Indonesian high school students struggle to apply problem-solving strategies, particularly in rotational dynamics (Parno et al., 2020). Problem-solving skills are essential in this field, as concepts such as torque, angular momentum, and rotational motion require students to apply theoretical knowledge to real-world situations. However, many students struggle to grasp and apply these concepts, resulting in poor problem-solving performance (Frey et al., 2020). This gap underscores the need for educational approaches that go beyond traditional methods, encouraging students to engage with complex concepts in a more practical and hands-on manner (Chistyakov et al., 2023; Kelley & Knowles, 2016).

A major reason for these struggles is that current teaching methods often fail to connect theoretical knowledge with real-world applications. As a result, many students rely on memorized steps instead of truly understanding the concepts, limiting their ability to solve complex problems (Feltovich & Coulson, 1993). This issue is prominent in topics like rotational dynamics, where students struggle to apply abstract concepts and math to real-world problems. Educational approaches should go beyond teaching concepts, providing students opportunities to apply physics principles in tangible, hands-on ways (Frey et al., 2020).

Over the years, various approaches to improving problem-solving education have been investigated, with the STEM (Science, Technology, Engineering, and Mathematics) approach gaining popularity. STEM emphasizes interdisciplinary, real-world learning experiences that promote problem-solving abilities (Bell, 2010; Bybee, 2013). STEM education in physics integrates science, technology, engineering, and mathematics to enhance student understanding and engagement. Teachers' readiness to implement STEM is crucial, with alignment, capabilities, and engagement being key factors (Sulaeman et al., 2022). Practical examples, such as using electron microscopes to teach physics and biology, demonstrate effective STEM integration. These instruments measure structures similar to visible light wavelengths, connecting theoretical concepts to real-world applications (Hughes et al., 2020).

On the other side, STEM-based Project-Based Learning (PjBL) improves students' problem-solving and critical thinking skills in physics, especially in topics such as impulse and momentum, outperforming discovery learning (Purwaningsih et al., 2020). Studies have demonstrated that STEM education through PjBL can develop students' critical thinking skills, with most students reaching the "practicing thinker" level (Mutakinati et al., 2018). The integration of STEM with Education for Sustainable Development (ESD) in project-based learning has also proven effective in enhancing problem-solving skills related to environmental concepts like the greenhouse effect (Solihah et al., 2024). Furthermore, incorporating local wisdom into STEM-PjBL (Ethno-STEM-PjBL) has been found to improve higher-order thinking skills and reduce misconceptions in physics topics, highlighting the potential of culturally relevant approaches in STEM education (Martawijaya et al., 2023).

When combined with Project-Based Learning (PjBL), STEM-based education significantly enhances student engagement and performance, particularly in physics education (Sulaeman et al., 2022; Uden et al., 2023). According to studies, this integration not only enhances problem-solving skills but also scientific literacy, allowing students to better approach difficult challenges. Comparative studies reveal that the combination of STEM and PjBL not only improves problem-solving skills but also enhances scientific literacy, making students better equipped to tackle complex challenges than traditional learning methods (Solihin et al., 2021; Uden et al., 2023).

This study introduces the STEM-Project Approach for Real-World Knowledge (SPARK), designed to address gaps in previous research on STEM education in physics. SPARK provides an immersive learning experience that focuses on solving real-world problems in rotational dynamics. Unlike previous methods that only partially integrate STEM, SPARK takes a fully interdisciplinary approach, allowing students to apply their physics knowledge in everyday situations (Shanta & Wells, 2022; Sinha & Kapur, 2021). The SPARK model enables students to gain a better understanding of complex physics concepts while also developing critical problem-solving skills for success in the twenty-first century. It entails identifying daily problems, using STEM concepts to analyze them, involving students in hands-on projects, encouraging multiple solutions, and integrating their knowledge into broader physics applications (Prasad et al., 2017; Shanta & Wells, 2022).

The design refers to the STEM design as a science-learning supplement developed by Bybee, can be seen in Figure 1 (Bybee, 2013).

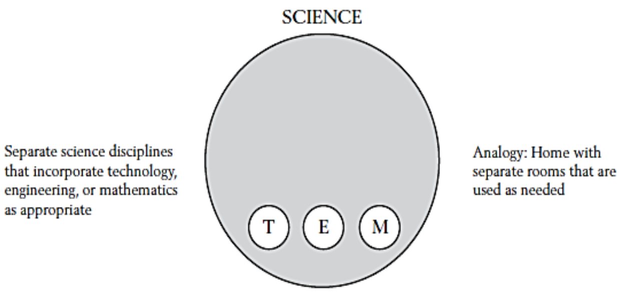

Figure 1. Design that shows the position of STEM in learning.

Figure 1 show the position of STEM in learning, this design was chosen because the STEM approach was used in the physics class, where the concept of balance was introduced early on as the foundation for scientific reasoning when completing the project. To complete the project, math, technology, and engineering procedures will be required. The PjBL stages associated with the learning process and its relation to the solving of problem-solving skills can be expressed through Table 1.

Table 1. PjBL learning model phase combine with problem solving skills indicators

Stage of PjBL	Problem solving indicator skill
Start With the Essential Question	Identify the problems
	Using of literature
	Alternative solution submission
Design a Plan for the Project	Solution selection
	Concept usage in solution
Create a Schedule	Designing a product
Monitor the Student and the Progress of the Project	Usage of math formulas
Assess the Outcome	
Evaluate the Experience	Evaluate the result

Thus, the aim of this study was to enhance high school students' problem-solving skills in rotational dynamics through the STEM-Project Approach for Real-World Knowledge (SPARK) model. It addresses challenges for teachers, including the need for adequate support, teaching methods, and resources, by providing an evidence-based model that supports STEM education and improves students' practical problem-solving abilities.

Method

This quasi-experimental study used a one-group pre-test-post-test design to assess the SPARK model's effectiveness in improving students' rotational dynamics problem-solving skills. The study included 150 first-year high school students from Bandung, Indonesia, with 30 randomly selected participants (15 males and 15 females). This random sampling ensured balanced representation and reduced biases, which increased the study's validity.

To measure student performance accurately, the study employed multiple assessment tools, including observation sheets and a set of 24 validated essay questions. Here are examples of the questions used:

Scenario:

Rian works as a caretaker at a coffee shop. In the shop, there are several long wooden benches where customers usually sit to enjoy their meals. One day, two customers were sitting at opposite ends of a bench. When one customer at one end suddenly stood up after finishing their meal, the other person on the opposite end fell off the bench, accidentally spilling their food.

Feeling responsible for the incident, Rian decided to fix the bench to prevent such accidents in the future. However, Rian is unsure how to design a more stable bench. Since you often eat at the shop and have learned about the principles of equilibrium in physics, you want to help Rian design a safer bench.

How would you help Rian? Share your design ideas and include detailed calculations before creating a prototype of the bench to present to Rian.

Questions:

1. *What is the main problem in the story?*
2. *What information can you gather from the story?*
3. *List several possible solutions to solve the problem.*
4. *Calculate the important aspects of the physics concepts involved in designing the bench.*
5. *Choose the best solution from your list and explain why it is the most effective.*
6. *Design a project to solve the problem using materials that are easy to find in your environment. Include physics*

concepts in your design and calculations.

7. *What are the strengths and weaknesses of the technology or design you created to solve the problem?*
8. *What improvements can you make to your design?*

These essay questions were meticulously crafted to assess various dimensions of problem-solving in physics, targeting skills like problem identification, conceptual application, and solution formulation. The validation process for these instruments yielded a reliability coefficient of 0.7 and a validity coefficient of 0.6, indicating that they were both reliable and valid for educational research purposes. The reliability coefficient of 0.7 suggests consistency in the results across different applications, while the validity coefficient of 0.6 reflects a reasonable measure of the intended skills, thus affirming the instruments' suitability for accurately assessing students' problem-solving abilities.

In addition to the essay questions, a student worksheet and its corresponding rubric were used to gauge student responses to the learning process. The worksheet and rubric were validated by experts using interrater reliability techniques to ensure consistency and accuracy in scoring. The students' work on the worksheet was assessed based on their problem-solving approach, with scores ranging from 0 to 4, following the detailed scoring criteria presented in Table 2. These criteria allowed for a nuanced evaluation of students' ability to apply concepts, consider constraints, and choose appropriate problem-solving procedures.

Table 2. Assessment Criteria Based on Answer Sheets

Score	Criteria for Scoring
0	Blank, or is simply filled by repetition of the problem information that has been presented, no other information based on analysis written, the solution and the information does not solve the problem.
1	There is an imprecise solution response but the effort to solve the problem because there are things like; The constraints or variables mentioned and then considered, the basic concepts of written material and intended to solve the problem, the procedure performed less precise
2	Students have chosen the right procedure, but the solution is not appropriate because of things like; The existence of some concept errors are considered, the consideration of some concepts that are not relevant to the purpose, the procedure is not complete.
3	Students have chosen the right procedure, but the solution is not entirely correct because there are such things as; The existence of the concept error with a small amount in considering the problem solving, the error considering the situation of the mentioned problem, the procedure is not complete.
4	Students have chosen and applied relevant concepts and appropriate procedures, students have considered the constraints experienced, there are only minor errors.

The study also utilized portfolio analysis to assess the development of 21st-century skills, particularly in problem-solving, through the use of the SPARK model. The effectiveness of the learning intervention was further evaluated using normalized gain (N-Gain) analysis (Hake, 1998). The normalized gain value measures the improvement in student performance, and the criteria for interpreting the N-Gain values are presented in Table 3.

Table 3. N-Gain Criteria

N-Gain	Criteria
$\langle g \rangle \geq 0.7$	High
$0.3 \leq \langle g \rangle < 0.7$	Medium
$\langle g \rangle < 0.3$	Low

The analysis of the normalized gain helped to quantify the impact of the SPARK model on different aspects of students' problem-solving skills, such as problem identification, the application of physics concepts, and the formulation of alternative solutions. These findings were used to determine the effectiveness of the SPARK model in enhancing students' problem-solving abilities, especially in a STEM context.

These results underscore the SPARK model's potential to enrich STEM learning by fostering hands-on, real-world applications that deepen conceptual understanding. The increases in skills like problem identification and concept application indicate that SPARK effectively engages students beyond traditional methods, enabling them to tackle physics problems with greater confidence and creativity. This evidence positions the SPARK model as a promising approach for bridging theoretical knowledge with practical problem-solving in STEM subjects.

Result and Discussion

Effectiveness of Problem-Solving Skills

The effectiveness of the SPARK model in enhancing problem-solving skills was measured through normalized gain (N-Gain) values calculated from pre-test and post-test results. The normalized gain values across three sessions are shown in Table 4.

Table 4. The Value of Normalized Gain

Number of Meet	Pretest	Postest	N-Gain
1	37.73	56.94	0.31
2	32.64	56.48	0.35
3	36.81	62.50	0.41

As shown in Table 4, N-Gain scores gradually increased from 0.31 to 0.41 over the course of the three learning sessions, indicating a medium level of improvement. This suggests that the SPARK model is moderately effective in enhancing students' problem-solving skills, though there is still room for further improvement. The increasing trend in N-Gain values highlights progress in several areas, such as identifying problems, applying scientific concepts, and selecting solutions. However, aspects like proposing alternative solutions and designing tools showed less improvement, suggesting that these areas require further development to fully realize the model's potential.

The SPARK model takes a more thorough and interdisciplinary approach to issue solving. Studies by Mutakinati et al. (2018) and Solihah et al. (2024) have shown that STEM-based PjBL can improve critical thinking and problem-solving skills, but they frequently focus on specific themes or only partially integrate STEM. SPARK, on the other hand, brings together all STEM fields and applies them to real-world challenges, such as those involving rotational dynamics. While SPARK's effectiveness is moderate, it delivers a more immersive learning experience by encouraging hands-on projects and real-world applications, offering a new approach to developing crucial problem-solving abilities that surpasses previous models.

Improvement on each Aspects of Problem-Solving Skills

The instrument used in this study was designed to evaluate various aspects of problem-solving skills, based on an established domain framework (Gurat, 2018). The aspects assessed include: (1) identifying the problem, (2) proposing alternative solutions, (3) obtaining relevant literature and sources as a basis for solutions, (4) selecting the most appropriate solution, (5) applying scientific concepts to solutions, (6) using mathematical calculations and science concepts in design, (7) designing tools, and (8) evaluating results based on test data. Table 5 presents the N-Gain values for each aspect of problem-solving skills.

Table 5. The Normalized Gain Value for Every Aspect of the Problem-Solving Skills

Indicator	N-Gain	Category
Identify the problem (IP)	0.59	Medium
Proposing alternative solutions (AS)	0.23	Low
Literature and source of readings (LS)	0.33	Medium
Choose the solution (CS)	0.53	Medium
Using concept to solution (UC)	0.53	Medium
Using math formulation (MF)	0.46	Medium
Designing tools (DT)	0.16	Low
Evaluate the result (ER)	0.19	Low

The data in Table 5 reveal that the SPARK model has been moderately effective in improving some aspects of problem-solving skills, particularly in identifying problems (IP), choosing solutions (CS), and applying scientific concepts (UC). These aspects showed medium-level improvements, indicating that the SPARK model successfully engages students in tasks requiring analytical thinking and the application of theoretical knowledge to real-world problems. The SPARK model was particularly successful in helping students identify problems through contextual projects that incorporated equilibrium concepts. These tasks made the learning process more engaging, helping students to recognize and define problems more effectively. The combination of PjBL with the STEM approach was instrumental in connecting scientific concepts with math, engineering, and technology, which facilitated problem identification. This approach supports previous research by Firman (2015) and Sulaeman et al. (2022), who found that the integration of STEM disciplines enhances students' ability to recognize and define real-world problems.

The study revealed that students showed more improvement in selecting solutions than in proposing alternative ones. The worksheet provided during the learning process helped students to consider potential solutions, but due to the limited scope of the intervention, students did not have sufficient opportunity to explore alternative solutions fully. While they were able to suggest solutions, they were not thoroughly supported to test alternatives when the first solution failed, an area that future research should address. This limitation is consistent with findings by Bell (2010) and Sulaiman et al. (2023), who suggested that problem-solving instruction should encourage experimentation and resilience in the face of failure.

This difference in skill development suggests that while students were guided effectively in choosing suitable solutions, the intervention did not place as much emphasis on fostering a mindset of experimentation and resilience when initial attempts proved unsuccessful

(Fitriani et al., 2020; Simanjuntak et al., 2021). Proposing alternative solutions is a crucial part ofS problem-solving as it encourages students to think creatively, evaluate multiple pathways, and refine their approaches when faced with challenges. Without sufficient opportunities to explore and test alternatives, students may develop a limited approach to problem-solving, relying on a single method rather than adapting flexibly (Niemi, 2021). Future interventions could enhance this aspect by integrating tasks that prompt students to consider and experiment with multiple solutions, fostering adaptability and deeper problem-solving skills that are essential in STEM learning contexts.

The SPARK approach was effective in improving students' abilities to connect literature and scientific concepts with real-world problems. Students were able to use the knowledge gained from their coursework to inform their solutions, placing them in the medium category for these aspects. This finding aligns with (Uden et al., 2023), who highlighted the importance of integrating coursework knowledge with real-world applications. However, the aspects of using math formulas and designing tools showed less improvement, with students struggling to create and apply mathematical formulas to design tasks. The SPARK (PjBL-STEM model) was still relatively new in the school, and students were not yet accustomed to activities requiring the integration of math and science into the design process. Further study is needed to enhance students' competence in these areas. This limitation supports the findings of Solihin et al. (2021), who emphasized the need for more targeted interventions to build students' competence in these areas.

The effectiveness of the SPARK model in evaluating results was limited, particularly due to the restricted instructional hours available. This constraint was most evident in the final stages of the learning process, where students had less time to reflect and evaluate their problem-solving approaches, as noted by Shanta & Wells (2022) and Sinha & Kapur (2021)who stressed the importance of time for reflection in problem-solving development.

Some indicators showed low scores, particularly in the Alternative Solutions (AS) aspect, where minimal improvement was seen despite 100% teacher-led activities. Students often relied on a single solution, requiring verbal guidance from the teacher to explore alternatives. Engagement with subtopics like torque, center of gravity, and equilibrium remained at 67%. In the first session on torque, students proposed only one solution, but by the third session, after teacher prompts, they provided multiple solutions. Despite improvement in the equilibrium subtopic, the score remained low due to limited student imagination caused by demonstrations and excessive teacher intervention. This reliance on the teacher stifled independent thinking. To address this, future teaching should encourage collaborative exploration of alternatives, fostering active student participation rather than passive reception.

In the Designing Tools (DT) aspect, teacher implementation was exceptionally high, focusing on skill development due to students' unfamiliarity with design activities. However, teacher implementation in mathematical formulation was lower. During the guidance process, students worked on designing a balance scale, but few included scales, likely due to misconceptions about the balance scale resembling a crane and not considering scaling or mathematical formulation. After further guidance, students revised their designs to include calculations, but scaling issues persisted. These challenges arose from students' limited design knowledge and the novelty of the STEM-based PjBL model. Future research should ensure students have sufficient foundational knowledge to engage more effectively in design and planning activities.

In the Evaluating Results aspect, practiced during the fifth and sixth phases of project-based learning, student groups tested their tools under teacher supervision. While the tools generally aligned with concepts, they often did not match the designs outlined in the worksheets due to students' unclear understanding of proper design. During phase six, after each group tested their prototype, they engaged in discussions comparing their designs with those of other groups, identifying strengths and weaknesses. Students mentioned issues like instability and narrow fulcrum but also noted strengths such as aesthetic value and comfort. Despite strong teacher guidance, post-test responses showed minimal improvement, indicating that students had not fully recognized their design errors. To enhance their ability to evaluate results, students must first develop metacognitive skills to reflect on their thinking and recognize errors.

This finding is consistent with the work of Fitriani et al. (2020), who emphasized that metacognitive skills are crucial for students to evaluate and improve their problem-solving approaches. Furthermore, research by Simanjuntak et al. (2021) highlights the importance of providing opportunities for students to independently assess and revise their designs, promoting deeper learning and reflective thinking. Therefore, fostering metacognitive awareness and independent evaluation should be central to future interventions, helping students become more self-directed learners who can recognize and correct their errors effectively.

Conclusion

This study demonstrated that the SPARK model successfully improved high school students' problem-solving skills in rotational dynamics, particularly in areas such as problem identification, solution selection, and the application of scientific concepts. The model facilitated an engaging and immersive learning experience, effectively integrating STEM concepts and real-world applications, which resulted in moderate improvements in problem-solving skills. However, the study also revealed areas where the SPARK model could be enhanced. Key challenges included limited student progress in proposing alternative solutions, designing tools, and evaluating results, which were critical aspects of fostering creativity, resilience, and adaptability in problem-solving. The study's findings suggest that while the SPARK model showed positive results in some aspects of problem-solving, future implementations should focus on providing more opportunities for students to experiment with alternative solutions and engage in reflective practices. This will help students develop a mindset of experimentation, adapt more flexibly when their initial attempts fail, and enhance their problem-solving strategies. Additionally, more time should be allocated for students to integrate mathematical concepts and design tools, ensuring that they are better equipped to handle complex, real-world STEM challenges. To address the limitations observed in the study, future research should prioritize the development of metacognitive skills and extend instructional time, allowing for deeper reflection and more comprehensive evaluation of problem-solving outcomes. By addressing these areas, the SPARK model can more effectively prepare students for the challenges they will encounter in the twenty-first century.

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