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ASSESSMENT OF STUDENTS' MATHEMATICAL PROBLEM-SOLVING SKILLS AND THE FACTORS INFLUENCING THEM

SUMMARY OF THE DISSERTATION

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Background and Rationale: Theoretical and Policy Perspectives on Mathematical Problem-Solving Skills

The main aim of the present study is to assess Indonesian middle school students mathematical problem-solving skills and the factors influencing them. To achieve this aim, a review study (Study 1) and four empirical studies (Studies 2-5) were conducted.

This study focuses on mathematical problem-solving as it is important to answer the issue of students difficulty in practice-oriented mathematics to bring contextual problems into the mathematics classroom (Jurdak, 2016). Mathematical problem-solving is a thinking process in which a solver tries to understand the problem situation using mathematical knowledge to obtain the new information about the situation to reach the goal (Chamberlin, 2008). It has two important characteristics: the task and the process (Chamberlin, 2008; Jäder et al., 2020). The process begins with exploring and understanding a problem, mathematizing a situation, creating assumptions, revising current knowledge, creating a new technique, defining a situation, applying mathematics knowledge, and evaluating the solution (Chamberlin, 2008). The important characteristic of the task is using realistic context by giving a realistic scenario for students to apply relevant mathematics concepts (Jäder et al., 2020).

In response to the demands and challenges of the 21st century, mathematical problem-solving tasks need to be shifted from a monodisciplinary to a realistic interdisciplinary context by combining Science, Technology, Engineering, and Mathematics (STEM) (Maass et al., 2019). STEM are possible and relevant to be integrated with mathematics due to their focus on scientific skills and overlapping concepts (Csapó & Molnár, 2017). However, previous studies have underrepresented mathematics in the development of interdisciplinary STEM problem-solving tests (Maass et al., 2019). Therefore, it is important to develop a mathematical problem-solving test that integrates the STEM context, in which mathematics is the core for solving the problem, while STEM participates in the methodologies and context (Jurdak, 2016; Shaughnessy, 2013). Mathematics has a role in the content used, way of thinking, problem handling, modelling, represent, analyze, predict, and reasoning (Jurdak, 2016; Shaughnessy, 2013). Science participates in the context used, methodology and way of thinking through scientific inquiry (Shaughnessy, 2013). Engineering and technology use in the methodology for connecting mathematics and science through engineering-based design (Shaughnessy, 2013). Technology also provides tools to solve problems. Prior to developing the test, a review study is required on the assessments and frameworks available in this area.

The Indonesian government has participated in addressing the need to integrate STEM context into the classrooms through curriculum 2013, with the latest version in 2016 (Government Regulation Number 24 Year of 2016 Attachment 15, 2016). It emphasizes on integrating the STEM context through problem-solving in mathematics and science subjects, specifically for middle school students, but there is no integrated STEM curriculum. Mathematics, science, and technology subjects are compulsory and are taught separately for middle school students. There is no engineering subject at the kindergarten to middle school levels. Technology is also used as a tool in the teaching and learning process and students need to apply engineering thinking in the problem-solving using a design-based process.

Despite the curriculum requiring students to master mathematical problem-solving in integrated STEM context, the trend of mathematical problem-solving assessment in Indonesian is monodisciplinary (Amalina & Vidákovich, 2022b). Consequently, when the government

assesses mathematical problem-solving skills based on the curriculum, students encounter difficulties due to the lack of appropriate assessment tools for daily instructions and their limited familiarity with such tasks (Suratno et al., 2020). The difficulties of Indonesian middle school students in solving mathematical problems are also shown in the Program for International Student Assessment (PISA) 2018 where Indonesia ranked 72nd out of 78 countries (OECD, 2019). Hence, it is essential to develop mathematical problem-solving tasks in the integrated STEM context and how to improve Indonesian students' achievement in it.

Some scholars addressed several ways to improve students' mathematical problem-solving by conducting studies, including: (1) investigating the profiles and development across grades to optimize teaching method in their best period of development; (2) evaluating the differences according to background variables to reach equality in mathematics education; (3) examining the factors influencing them to prepare appropriate instructional strategies that consider these factors (Csapó & Molnár, 2017; Molnár et al., 2013; Ramos et al., 2021; Scherer & Beckmann, 2014). They concluded that mathematical problem-solving skills develop and differ based on gender, grades, and school locations (Lee & McIntire, 2000; Molnár et al., 2013; Ramos et al., 2021). They also showed that mathematics domain specific prior knowledge (DSPK), science knowledge, text comprehension, and socioeconomic status (SES, including parental education and income) have important roles in mathematical problem-solving skills (Csapó & Molnár, 2017; Pangeni, 2014; Scherer & Beckmann, 2014; Vista, 2013). However, previous studies have drawbacks, including (1) the use of monodisciplinary tasks; (2) have inconsistent results; (3) mostly examining a single factor; and (4) lack of a relevant assessment tool to measure mathematics DSPK as a factor influencing mathematical problem-solving (Bahar, 2013).

Therefore, a comprehensive study is needed to assess the development and differences of students' mathematical problem-solving skills through an integrated STEM-based mathematical problem-solving task and examine the cognitive and SES factors that influence them. The scenario essay task used in this study emphasized process using local environmental issue contexts. Additionally, the study also described a detailed of subsamples that contribute to the development and difference in mathematical problem-solving skills, and constructed a different theoretical model of factors affecting mathematical problem-solving skills. Prior to this assessment, a review study of the trend assessment in this area and the development of the relevant tests are required.

Participants in this study were selected from A-accreditation schools (the highest accreditation) in East Java, Indonesia, as these schools emphasize higher-order thinking skills and offer a stable and well-structured educational system. There are 1,886 A-accreditation schools in East Java, Indonesia with approximately 2 million students (npd.kemendikbud.go.id).

STUDY 1: Assessment in STEM Problem-Solving: A Systematic Review

The issue of low interest and performance in STEM has prompted scholars to develop instruments to assess them. Although some scholars have developed instruments in this area, the complexity of assessing STEM has led to questions regarding which assessment tools and frameworks are appropriate for different STEM disciplines (Gao et al., 2020). Additionally, several worthwhile assessments still need to be explored for further development in STEM

problem-solving. However, there is inadequate study highlighting the need for a detailed evaluation of assessment frameworks and the best assessment for future studies.

To address these gaps, Study 1 aims to review the assessment in the STEM field, including: (1) general information (year, participants, and disciplines) of assessment in STEM problem-solving; (2) the most common assessment in these fields; and (3) detailed information of instruments, topics, participants, and frameworks in these fields (Amalina & Vidákovich, 2022c). By conducting this study, it provides information on trends, the best assessments and frameworks to be used, and the drawbacks and advantages of each assessment tool in each STEM discipline.

The PRISMA method is used to filter articles in English between 2010 and 2020. The inclusion criteria are: (1) middle and high school participants without disabilities; (2) individual assessments; (3) framework availability; and (4) empirical studies. The results revealed:

1. Problem-solving in STEM education among middle school students remains a relevant topic for study, as the majority of studies were published between 2016-2020 with middle school participants. A lack of studies in the STEM interdisciplinary area highlights the need for further studies and for curriculum and policy reforms, as most studies focus on the monodisciplinary area in mathematics and science.
2. Different trends were observed regarding the assessment tools used in each STEM discipline, providing a basis for developing or adapting more relevant tools. A closed-ended essay question is the most common type of assessment in cognitive monodisciplinary problem-solving, with the use of essay tests rising over the years. In cognitive interdisciplinary areas, complex scenario problems were the most prevalent, with studies using complex problem scenario tests almost every year. The questionnaire was the most common assessment in metacognitive monodisciplinary areas, but other in-depth assessments were also used (e.g., 'think aloud').
3. The drawbacks and frameworks used in the existing instruments were addressed to provide insights for future tool development. (a) Essay tests to measure problem-solving in the cognitive monodisciplinary area were closed-ended and routine with questionable reliability. They used frameworks such as Polya's heuristic and PISA creative problem-solving for mathematics, and scientific inquiry for science problem-solving. A non-routine essay test is recommended for monodisciplinary mathematical problem-solving to explore the process of students' thinking. (b) Assessments on interdisciplinary STEM problem-solving included both open-ended and closed-ended essay scenario tests, but some lacked psychometric evidence. Some tasks required student reading comprehension. It is suggested to split the task by giving metacognitive prompting questions. Common assessments combine frameworks from each STEM discipline: heuristic, engineering-based design, scientific inquiry, and technology, through complex design-based tests, games, and complex problem scenarios. Several mathematics topics, such as number, quantity, ratio, and geometry, are possible to be integrated into the STEM context.

STUDY 2: An Integrated STEM-based Mathematical Problem-Solving Test: Developing and Reporting Psychometric Evidence.

Infusing problem-solving into mathematics classes can improve mathematics achievement. Several researchers have developed, validated, and examined students' mathematical problem-

solving skills, but they have mostly used well-defined, monodisciplinary, and structured tests, which are fundamentally contradict the 21st-century emphasize on the integrated STEM area (Gao et al., 2020).

The need to integrate STEM into problem-solving has prompted the development of tests in this area; however, these tests often underrepresent mathematics, are complex and practically challenging, focus on product-based outcomes, and lack well-articulated frameworks (Gao et al., 2020; Maass et al., 2019). Additionally, there is a lack of assessment tools within the Indonesian context that integrate STEM into mathematical problem-solving tasks (Amalina & Vidákovich, 2022b).

To address these gaps, Study 2 aims to develop and validate an integrated STEM-based mathematical problem-solving test for assessing grades 7-9 mathematical problem-solving in an integrated STEM context (Amalina & Vidákovich, 2022a).

The framework for an integrated STEM-based mathematical problem-solving test uses the PISA creative problem-solving framework as a ground theory. The indicators were developed by combining several frameworks from each STEM discipline (heuristic, mathematics experimentation, inquiry-based mathematics, scientific inquiry, and engineering-based design), while eliminating duplicate indicators.

The developed test presents mathematical scenario-based problems related to environmental phenomena, utilizing engineering-based design and scientific inquiry method in the process of solving the problem with the help of technology. There are three scenarios for each grade, including 1-2 anchor scenarios. Each scenario has a challenge and includes 8 prompt items designed to scaffold students through the problem-solving process. The test covers number & measurement, ratio & proportion, geometry, and statistics topics. The scenarios are (1) eco-friendly packaging; (2) school park; (3) calories versus greenhouse gas emission; (4) flood water reservoir; (5) city park; and (6) infiltration well. The maximum score for each prompt item is 5.

This test serves as a tool for both classroom practice and large-scale assessment, evaluating problem-solving within an interdisciplinary STEM context and enabling students to tackle real-world problems. The novel use of metacognitive prompt items ensures that students responses are consistent, accurately address students' abilities, and explore all problem-solving indicators, addressing the gap left by product-based assessment in STEM problem-solving. Additionally, it is practical for classroom use within limited timeframes, as a single scenario can provide a detailed picture of students' mathematical problem-solving skills.

The test was validated with the participant of grades 7—9 (n = 286). Data were analyzed using the content validity index (CVI) and the intraclass correlation coefficient (ICC) to evaluate the content validity. Rasch analysis was used to obtain detailed information about construct validity, that is barely used in previous studies.

The test is proven to cover all the mentioned topics for measuring mathematical problem-solving in the context of STEM, although it required other skills such as science knowledge and text comprehension. The scenarios are proven to accurately measure mathematical problem-solving skills, with the "school park" scenario being the most difficult scenario because students struggled to differentiate between area and circumference concepts and failed to hypothesize and critically choose the best option. The easiest scenario is "flood water reservoir".

All prompting items were acceptable for accurately measuring mathematical problem-solving indicators, but required some revisions for language clarity. The most difficult item was item 47, which requested student to calculate the price to build an infiltration well, that required complex skills and concepts. Common errors were related to surface area and volume concepts. Item 25 related to understanding the goal was the easiest item.

The strong psychometric evidence ensures that the test is a robust tool for assessing mathematical problem-solving within an integrated STEM context, effectively identifying students' strengths and weaknesses. Additionally, the detailed and acceptable psychometric evidence of the test serves as an important basis for its adaptation and further validity testing in other relevant studies, specifically in Indonesia.

STUDY 3: The Development of a Mathematics DSPK Test and Its Psychometric Properties.

Mathematics DSPK is a crucial factor influencing mathematical problem-solving skills within a STEM context, as mathematics plays a central role in conceptual and content applications. Previous studies have developed DSPK instruments, but they primarily focused on science or targeted monodisciplinary and specific mathematics topics (Al-Mutawah et al., 2019). Additionally, the DSPK test should align with the knowledge researchers aim to assess in their main test or measure prior knowledge relevant to the primary assessment. Consequently, not all existing mathematic DSPK tools are suitable to be adapted for assessing prior mathematics knowledge in the integrated STEM-based mathematical problem-solving test developed in Study 2.

Study 3 addresses these gaps by developing and validating a mathematics DSPK test for assessing prior mathematical knowledge (Amalina & Vidákovich, 2023a). The mathematics DSPK test consists of 30 multiple choice items with four options, assessing both conceptual and procedural knowledge. The topics include those applied in the integrated STEM-based mathematical problem-solving test and topics that overlap across grade levels in the Indonesian mathematics curriculum for middle school. The topics are integer, fraction, measurement, ratio, proportion, geometry, and statistics. The test is beneficial for mathematics education as a preliminary test in mathematical problem-solving, specifically for Indonesian users. Additionally, it measures both procedural and conceptual knowledge essential for the integrated STEM-based mathematical problem-solving test, making it a comprehensive and interconnected tool.

The mathematics DSPK test was validated with grade 7 participants (n= 175). The CVI and ICC used to analyze the content validity. Rasch analysis was employed to explore construct validity in detail, an approach barely used in previous studies to validate the multiple-choice test.

The test demonstrated consistency in measuring mathematics DSPK and adequately covered all the mentioned topics, although revisions are needed to include more relevant information and improve item wording. The test also accurately measured indicators of mathematics DSPK, with item 1 being the easiest (assessing understanding of a concept) and item 30 being the hardest (measuring students' ability in evaluating procedures).

The strong psychometric evidence establishes the test as a robust and reliable tool for assessing mathematics DSPK. Additionally, the comprehensive validation process provides a

solid basis for adapting and further validating the test in other relevant studies, specifically in Indonesia.

STUDY 4: Development and Differences in Mathematical Problem-Solving Skills: A Cross-Sectional Study of Differences in Demographic Background

Fostering the development of mathematical problem-solving skills enhance mathematical performance. Therefore, teachers must understand students' profiles and the best periods for their skill development to optimize teaching methods during phases of rapid skills development (Molnár et al., 2013). Additionally, identifying the differences in mathematical problem-solving skills helps teachers address the needs of underrepresented groups to reduce the disparities. Hence, scholars recommend both approaches to improve low mathematical problem-solving performance.

Differences in mathematical problem-solving skills have been identified based on gender and school locations (Lee & McIntire, 2000; Li et al., 2018). However, previous studies present mixed findings on which groups are underrepresented, often focusing on a single grade without in-depth analysis. Similarly, studies on students' development in problem-solving yield mixed results, with some revealing growth while others claim stability. Additionally, previous studies have predominantly implemented monodisciplinary mathematics task and have not been conducted in Indonesia, despite its municipal education system which may lead to disparities in skills, and its curriculum that require students to master mathematical problem-solving in STEM context.

To address these gaps, Study 4 aims to examine the profiles, development, and differences of mathematical problem-solving skills based on their grades, gender, and school locations (Amalina & Vidákovich, 2023c). This study uniquely investigates the specific subsamples contributing skill differences and development in each phase of problem-solving by using an interdisciplinary STEM-based task.

The study involved 1,067 participants from grades 7—9 using an integrated STEM-based mathematical problem-solving test. Descriptive statistics and compare mean analyses were used to investigate the development, profiles, and differences in students' skills.

Overall, students' mathematical problem-solving skills were categorized as average. However, improvements are needed in representing and formulating, planning and executing, and monitoring and reflecting phases, where students face increasing difficulties and have low performance. These findings help stakeholders target specific problem-solving phases where students struggle most through instruction, curriculum, textbooks, and teacher training programs.

The finding also suggests focusing on improving mathematical problem-solving skills from grades 7 to 8, as this period is the optimal period for rapid skills development. Interventions should prioritize urban students and in the knowledge acquisition phases (i.e., exploring and understanding, and representing and formulating phases). Strengthening these areas can improve mathematical problem-solving skills in grade 9 where their performances tend to decline.

Rural school students also required special attention, particularly in grades 7 and 8, as they significantly underperformed compared to their urban counterparts. The difference is strongly affected by the availability of facilities, teacher quality, and instructional quality. In Indonesia,

the policies for the public educational system for middle schools are set at the municipal level. Urban schools mostly have a better policy. Hence, improving the instructional, teacher qualities, and policies in rural schools is crucial to narrowing the performance gap.

Male students, particularly those in urban school and grades 7 and 9, also need focused interventions, as they significantly underperformed compared to female students. The difference may be attributed to female Indonesian students are typically more diligent, thorough, responsible, and serious about their tasks. The intervention and reforms should aim to improve male students' motivation and responsibility in mathematics classes.

STUDY 5: Cognitive and Socioeconomic Factors that Influence the Mathematical Problem-Solving Skills of Students

Mathematical problem-solving requires complex skills, which increase students' difficulties in this area. Despite mastering the mathematical computation skills required to solve the problems, students often struggle with mathematical problem-solving within the STEM context because they must also identify relevant numerical information, understand the science context used, and interpret the corresponding linguistic information in the text. Hence, success in this skill is influenced by mathematics DSPK, science knowledge, and text comprehension skills.

Studies have demonstrated that mathematics DSPK, science knowledge, text comprehension skills, parents' education, and family income influence mathematical problem-solving skills (Scherer & Beckmann, 2014). However, most studies fail to consider all these factors simultaneously using structural-equation modeling (SEM), or they analyze them separately. Furthermore, while many studies confirm the importance of parents' education and family income as SES indicators, they often treat these variables as unconnected even though they are strongly related.

Thus, Study 5 examines the factors influencing mathematical problem-solving skills, focusing on cognitive (mathematics DSPK, science knowledge, and text comprehension skills) and SES (family income and parents' education) factors (Amalina & Vidákovich, 2023b). This study employed SEM, an advanced analysis that allows for simultaneous testing direct and indirect relationships rather than a single separate factor.

The study involved 1,067 students from grades 7—9. They completed several tests, including an integrated STEM-based mathematical problem-solving test, a mathematics DSPK test, a text comprehension test, and science tests. The text comprehension test was a standardized diagnostic test of an Indonesian language literacy test. The science tests were validated and reliable diagnostic tests provided by the books of the ministry of education. Additionally, the students provided SES information, including parents' education and income.

A model was developed in which all the variables mentioned were served as independent variables that directly affect mathematical problem-solving skills. We also put family income as a mediating factor between parents' education and mathematical problem-solving skills, as well as science knowledge as a mediator in the relationship between text comprehension skills and mathematical problem-solving skills. This novel model integrated cognitive and SES factors to identify comprehensive relationships affecting mathematical problem-solving skills. It can be adapted for relevant studies, as it demonstrated statistical robustness and suitability for the analyzed data. Additionally, this model was compared with an alternative model

(excluding the direct impact of parents' education on mathematical problem-solving skills) to give accurate and convincing results.

The findings revealed that the cognitive factors were the most significant in affecting students' mathematical problem-solving skills. The mathematics DSPK had the strongest effect, followed by science knowledge and text comprehension skills. Text comprehension skills also indirectly influenced mathematical problem-solving skills through science knowledge. Therefore, enhancing text comprehension could influence science knowledge, further influencing mathematical problem-solving skills. Hence, it is crucial for improving these three factors to enhance mathematical problem-solving skills through instruction, assessments, textbooks, teacher professional developments, and policies.

Although its effect was weak, family income still played a direct role in influencing mathematical problem-solving skills. Hence, providing support or resources to economically disadvantaged students can impact their skills. Meanwhile, parents' education only indirectly influenced mathematical problem-solving skills through family income. In Indonesia's teacher-centered system, parents' education has no direct impact because students rely more on teachers and have limited academic interaction at home.

Conclusions

Few studies have measured mathematical problem-solving in interdisciplinary STEM context, as reviewed studies have focused on monodisciplinary using routine essay tests. Those that do address STEM interdisciplinarity typically employ essay complex scenario-based problem that integrate problem-solving frameworks in each STEM discipline. Therefore, there is a significant need for research on mathematical problem-solving within an interdisciplinary STEM context, particularly in Indonesia.

To address the lack of interdisciplinary STEM assessment, an integrated STEM-based mathematical problem-solving test was developed by emphasizing mathematics in STEM context, Indonesian curriculum, and an applicable process-based test. The results confirmed the robustness of the test after language revisions. Additionally, a mathematics DSPK test was also developed to provide a relevant assessment for measuring prior mathematical knowledge. The test also confirmed strong validity and reliability, particularly for Indonesian participants.

Through the interdisciplinary STEM task, mathematical problem-solving skills can be optimized between grade 7 and 8, as their skills develop rapidly, particularly in the knowledge acquisition and among urban students. However, there is a pressing need to enhance mathematical problem-solving skills of rural school students and male students as these groups are underrepresented compared to their counterparts. Special attention should be given to rural students in grades 7 and 8 and male students from urban schools in grades 7 and 9.

Moreover, emphasizing cognitive factors, particularly mathematics DSPK, is important, as they were discovered to be the most crucial factors influencing students' mathematical problem-solving skills. Although family income has a weak effect, it still played a role in influencing mathematical problem-solving skills. Additionally, improving text comprehension skills impacts science knowledge and positively influences mathematical problem-solving skills.

Further research should include longitudinal studies with diverse samples and incorporate additional influential factors (e.g., working memory) using in-depth instruments.

Educational Implications

The systematic review informs trends in STEM problem-solving and helps identify the most suitable instruments for adaptation. It also supports reforms in Indonesia's curriculum, tasks, textbooks, and assessments by emphasizing interdisciplinary competencies (e.g., introduce specific interdisciplinary courses or projects).

The integrated STEM-based mathematical problem-solving test offers a robust, process-oriented tool for Indonesian classroom. Each scenario in the test comprehensively represents mathematical problem-solving steps, making it suitable for both classroom use and large-scale diagnostics to inform future STEM or math curriculum development in Indonesia.

The mathematics DSPK test provides a relevant prelaminar assessment of students' prior knowledge. Together with the integrated STEM-based mathematical problem-solving test, it provides a comprehensive test package to assess mathematical problem-solving and can be adapted further based on its validated results.

Detailed student profiles and developmental skills will lead teachers and curriculum developers to implement student-centered problem-solving activities (e.g., math experimentation) in grades 7-8, where problem-solving skills develop maximally. Emphasizing phase-based instruction and clearly defining phases in textbooks is also essential, given students' challenges in certain phases of problem-solving.

The description of skills differences highlights the need for more equitable approaches in rural schools and among male students, through gender-neutral instruction and tasks, strategies to boost motivation, resource allocation, policy standardization, and targeted teacher training.

Cognitive background knowledge significantly affects mathematical problem-solving. Therefore, instruction should strengthen prior knowledge and use non-routine problems in science contexts with constructivist strategies. The Indonesian curriculum should allocate time for reviewing prerequisite concepts, with clear guidance in teacher materials. The theoretical model examined in this study can also be replicated to different demographic context.

Finally, this study informs the development of teacher training modules focused on interdisciplinary, process- and phase-based strategies, and guides policymakers in directing resources and professional development to support underrepresented groups.

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Relevant Publications

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2. Amalina, I.K. & Vidákovich, T. (2022d). Validation of an integrated STEM-based mathematical problem-solving test. In Steklács, János & Molnár-Kovács, Zsófia (eds.) 21. Századi képességek, írásbeliség, esélyegyenlőség: XXII. Országos Neveléstudományi Konferencia, November 17-19, 2022. Pécs, Hungary: Pécsi Tudományegyetem BTK Neveléstudományi Intézet, p. 271.
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4. Amalina, I. K., & Vidákovich, T. (2024). Structural Equation Modelling: Associating Cognitive Factors to Mathematical Problem-Solving Skills. Abstract book: In JURE 2024: Education and the Need for Dynamic Solutions: Shaping the Future of the Field, Sevilla 24-28 June 2024, Spain, p. 38. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.earli.org/assets/files/JURE2024-BOA-180624.pdf