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UNVEILING CAUSAL COMPLEXITY IN MATHEMATICS ACHIEVEMENT: A RESEARCH DESIGN USING FUZZY-SET QUALITATIVE COMPARATIVE ANALYSIS (FS/QCA)

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Keyword

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Abstract

Mathematics achievement is a critical indicator of educational success and a key determinant for future STEM careers. However, national assessments in Indonesia reveal persistent challenges and significant learning gaps in student numeracy. Existing research has identified a multitude of influencing factors, yet predominantly relies on linear models (e.g., regression, SEM) that estimate the 'net effect' of each variable in isolation. This approach overlooks the complex causal configurations where different factors interact synergistically. This paper addresses this methodological gap by proposing a research design that employs fuzzy-set Qualitative Comparative Analysis (fs/QCA). The study will utilize secondary data from the Indonesian National Assessment to analyze how combinations of school, family, and student-level conditions lead to high mathematics achievement. The expected contribution is the identification of multiple, distinct pathways—or 'causal recipes'—to success, offering a more nuanced foundation for developing targeted and context-specific educational policies.

INTRODUCTION

Mathematical proficiency is a fundamental competency essential for individual success in both academic and professional domains in the 21st century. Mathematics achievement at the secondary school level not only serves as a primary gateway to higher education, but it is also a key predictor of participation and success in Science, Technology, Engineering, and Mathematics (STEM) career pathways (Zhao & Perez-Felkner, 2022; Wille et al., 2020). Given that STEM-based industries are a major driver of economic growth, ensuring students have a strong mathematical foundation is a critical priority in the global educational landscape (Burrus & Moore, 2016).

However, numerous studies consistently show that the relationship between mathematics achievement and STEM career choices is not straightforward, but is mediated by a series of psychological factors. Students' perceptions of their own mathematical ability and their vocational interests have proven to be significant predictors in determining college major choices (Wille et al., 2020). Furthermore, students' beliefs and attitudes towards mathematics, including self-efficacy, directly influence their likelihood of choosing and persisting in STEM majors, especially for minority student groups (Alhaddab & Alnatheer, 2015). This confirms that effective interventions must target not only test scores, but also students' beliefs and motivation (Mau & Li, 2018).

This challenge in mathematics achievement is particularly significant in the Indonesian educational context. International reports from PISA and TIMSS consistently indicate that the mathematical capabilities of Indonesian students remain low (Fenanlampir et al., 2019), revealing significant learning gaps where students struggle with complex information and problem-solving (Zaini, 2018). This national-level challenge is also reflected at the regional scale. Based on data from the 2024 West Java Province Education Report, six out of ten secondary education students have not yet reached minimum competency in numeracy (Kemdikbud, 2024). This underachievement is not a simple issue, but rather the result of a complex interplay of various factors.

Efforts to understand this multi-dimensional interaction have pushed researchers toward more sophisticated models. However, an in-depth review of the current literature reveals a heavy reliance on quantitative linear approaches, such as Regression Analysis and Structural Equation Modeling (SEM). The underlying logic of these methods is to estimate the 'net effect' of each factor, assuming that their individual contributions can be isolated. This reliance on linear logic, however, presents a fundamental limitation.

The 'net effect' approach inherently simplifies causal reality, as it risks producing 'false negatives' by overlooking factors that are not significant in isolation but are crucial as part of a causal 'recipe' or combination (Tóth, Henneberg, & Naudé, 2017). This indicates a significant methodological gap: current research primarily answers "what factors have an influence?" but is ill-equipped to answer the more complex question, "what combination of factors is sufficient to produce a high outcome?" (Rasoolimanesh & Olya, 2025). Therefore, this study proposes an innovative research design using fuzzy-set Qualitative Comparative Analysis (fs/QCA) to identify the various causal configurations that lead to high numeracy achievement.

METHOD

This study employs a quantitative approach with a focus on configurational analysis. The research design is explanatory and non-experimental, utilizing secondary data from the Indonesian National Assessment (AN). The objective is not to manipulate variables, but to explain the phenomenon of mathematics achievement by identifying the configurations of antecedent conditions that lead to high performance. By using a large-scale secondary dataset, this research aims to build a complex causal explanation of how various combinations of factors collectively produce high numeracy outcomes.

The data source for this study is the publicly available microdata from the 2023 National Assessment for the senior high school level in the West Java province, officially released by the Center for Educational Assessment (Pusmendik). This comprehensive dataset combines three main instruments: (1) the Minimum Competency Assessment (AKM), which measures students' cognitive learning outcomes in literacy and numeracy; (2) the School Learning Environment Survey (Sulingjar), which measures the quality of teaching and learning inputs and processes; and (3) the Character Survey, which measures students' non-cognitive outcomes. For this study, the analysis will be conducted at the school (educational unit) level of aggregation.

This study involves one outcome variable and several causal conditions operationalized from the 2023 National Assessment secondary data. The outcome variable is Student Numeracy Achievement, conceptually defined as the ability to reason and solve real-world problems using mathematical concepts and tools. Operationally, this is measured by the school's average numeracy score as provided in the dataset.

The causal conditions are the antecedent factors hypothesized to combine to produce the outcome. The selection of these conditions is based on the dominant findings from a comprehensive systematic literature review and the availability of relevant proxies in the dataset (Pusmendik, 2023). The conditions include multi-dimensional factors such as (a) teacher quality (proxied by qualifications and certifications), (b) learning quality (proxied by classroom management and affective support), (c) school climate (proxied by safety and inclusivity indices), and (d) family socioeconomic status (proxied by parental education and occupation).

The data analysis will be conducted using fuzzy-set Qualitative Comparative Analysis (fs/QCA), a set-theoretic method designed to analyze causal complexity (Ragin, 2008). This approach was chosen over traditional linear methods (e.g., regression) because the research aims to identify different combinations of factors—or 'causal recipes'—that are sufficient for high numeracy achievement, rather than estimating the net effect of each individual factor. The analysis will follow three main stages.

The first and most crucial stage is the calibration of all variables. This process transforms the raw interval-scale data (e.g., average numeracy scores) into fuzzy-set membership scores, which range from 0 (full non-membership) to 1 (full membership). This is achieved by setting three qualitative anchors based on theoretical knowledge and the distribution of the data, a process critical for ensuring the rigor of the results (Tóth, Henneberg, & Naudé, 2017).

Following calibration, an analysis of necessary conditions will be performed. A condition is considered necessary if it must be present for the outcome to occur. This test determines if any single factor is a prerequisite for achieving high numeracy performance and is evaluated by a high consistency score, typically above 0.9 (Ragin, 2008).

The final stage is the analysis of sufficient conditions. This stage begins with the construction of a truth table, which lists all logically possible combinations of the causal conditions and their associated outcomes. This table is then subjected to a process of Boolean minimization to identify the simplest configurations of conditions that are consistently sufficient for high numeracy achievement. The strength of these configurational pathways is evaluated using two primary parameters: consistency (the degree to which a configuration reliably leads to the outcome) and coverage (the empirical relevance of a configuration) (Rasoolimanesh & Olya, 2025). This systematic methodology is expected to yield results that provide a configurational understanding of student achievement, as will be discussed next.

RESULTS (PROPOSED RESEARCH DESIGN)

This study proposes a comprehensive research design to investigate the complex causal factors influencing high school mathematics achievement. The result of this design phase is a systematic and replicable methodology, as outlined below.

The research will employ a quantitative approach, utilizing secondary data from the Indonesian National Assessment (AN) 2023 for the West Java province. The unit of analysis will be the school. The outcome variable is defined as Student Numeracy Achievement, measured by the school's average numeracy score. The antecedent conditions are multi-dimensional factors based on a systematic literature review, including (a) teacher quality, (b) learning quality, (c) school climate, and (d) family socioeconomic status, all of which are operationalized using available proxies in the AN dataset.

The core of the data analysis technique will be fuzzy-set Qualitative Comparative Analysis (fs/QCA). This method was specifically chosen to move beyond traditional linear models and to identify various causal 'recipes' leading to success. The analysis will proceed in three stages: (1) calibration of all variables into fuzzy-set membership scores; (2) analysis of necessary conditions to identify any prerequisite factors; and (3) analysis of sufficient conditions through the construction and Boolean minimization of a truth table to uncover the final configurational pathways.

DISCUSSION

The research design outlined in this paper is expected to generate significant contributions to the field of mathematics education. By employing fs/QCA, the primary anticipated outcome is not merely a list of influential factors, but the identification of multiple, configurational pathways to high numeracy achievement. This approach allows for the discovery of equifinality, where different combinations of school, family, and student-level conditions can lead to the same successful outcome.

The practical implications of such findings are substantial. Uncovering these "causal recipes" can provide policymakers and educators with more targeted and context-specific intervention strategies. For instance, the results may empower school leaders to move away from a "one-size-fits-all" approach by demonstrating that for schools serving students from low-SES backgrounds, a specific combination of high-quality teaching and a supportive school climate might be the most effective pathway to success. This configurational understanding, therefore, has the potential to contribute to a more equitable and effective mathematics education ecosystem.

CONCLUSION

This paper has presented a comprehensive research design aimed at addressing a critical methodological gap in the study of mathematics achievement. The primary result is a robust, theory-driven framework for applying fuzzy-set Qualitative Comparative Analysis (fs/QCA) to large-scale secondary data. The discussion highlights that the novelty of this approach lies in its ability to move beyond the limitations of traditional linear models. Instead of identifying the 'net effect' of single variables, this research design is poised to uncover multiple, complex causal configurations—or 'recipes'—that lead to high student performance. The expected contribution is a more nuanced, holistic, and equitable understanding of student success, providing a foundation for more targeted and context-specific educational policies and interventions.

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