

Unveiling Causal Complexity in Mathematics Achievement: A Research Design Using Fuzzy-set Qualitative Comparative Analysis (fs/QCA)

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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 learning gaps in student numeracy. Existing research predominantly relies on linear models (e.g., SEM) that estimate the 'net effect' of influencing factors, thereby overlooking complex causal configurations. This paper addresses this methodological gap. The primary result of this study is a comprehensive research design that employs fuzzy-set Qualitative Comparative Analysis (fs/QCA) to analyze secondary data from the Indonesian National Assessment. The proposed methodology is designed to identify multiple, distinct pathways—or 'causal recipes'—to success. The main contribution, therefore, is a robust framework that moves beyond linear analysis, offering a more nuanced foundation for developing targeted and context-specific educational policies.

KEYWORDS: causal complexity; configurational analysis; fs/qca; mathematics achievement; research design

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, achieving this goal is a multifaceted issue influenced by a complex combination of student, teacher, and school factors (Ayebale, Habaasa, & Tweheyo, 2020). Numerous studies consistently show that students' attitudes and non-cognitive factors, such as confidence and enjoyment in the subject, are strongly linked to better performance (Wakhata, Mutarutinya, & Balimuttajjo, 2022). Furthermore, teacher-related factors, including the quality of teaching staff and the level of affective support provided to students, significantly impact student attitudes and subsequent achievement (Davadas & Lay, 2020).

This challenge in mathematics achievement is particularly significant in the Indonesian educational context. National assessments reveal persistent learning gaps, and perspectives from local educators highlight that these challenges are exacerbated by a combination of resource limitations and student background variables (Kusdinar & Kismiantini, 2022). This mirrors the situation in many developing countries where a combination of school resources, teacher quality, and students' socioeconomic status creates a complex web of influences on academic outcomes (Wang, King, & Leung, 2023).

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.

METHODOLOGY

Research Design. 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.

Population and sample used. 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). The analysis will be conducted at the school (educational unit) level of aggregation. The target population is all senior high schools in West Java that participated in the 2023 National Assessment. The final sample will consist of all schools within this population that have complete data for all variables included in the analysis.

Figure 1
Conceptual Framework of the Research

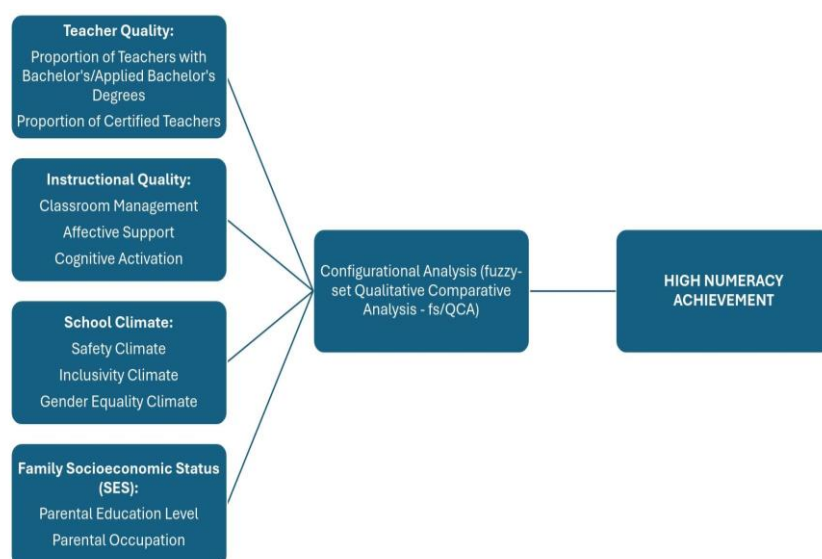


Table 1
Operationalization of Causal Conditions

Causal Condition	Dimension	Indicators in Dataset	Data Source
Teacher Quality	Qualification & Professionalism	- Proportion of teachers with Bachelor's/Applied Bachelor's degree (<i>prop_guru_sl</i>) - Proportion of certified teachers (<i>prop_guru_sert_pend</i>)	Dapodik
Learning Quality	Classroom Practice	- Classroom Management - Affective Support - Cognitive Activation (Measured by the <i>kualitas_pembelajaran</i> index)	School Learning Environment Survey (Sulingjar)
School Climate	Safety & Diveristy	- School Safety Climate Index (<i>iklim_keamanan_sekolah</i>) - Gender Equality Climate Index (<i>iklim_kesetaraan_gender</i>) - Diversity Climate Index (<i>iklim_kebinekaan</i>)	School Learning Environment Survey (Sulingjar)
Family Socioeconomic Status (SES)	Parental Background	- Proportion of parents with education below Bachelor's degree (<i>prop_orangtua_pendidikan_nond3</i>) - Proportion of parents with non-professional occupations (<i>prop_orangtua_pekerjaan_nonprof</i>)	School Learning Environment Survey (Sulingjar)

Research Variables and Operationalization. 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. The detailed operationalization of each causal condition is presented in Table 1.

Data Collection Techniques. This study utilizes secondary data, meaning the data collection was conducted by the Indonesian Ministry of Education, Culture, Research, and Technology through the 2023 National Assessment. The data combines three main instruments: (1) the Minimum Competency Assessment (AKM), which measures students' cognitive learning outcomes in numeracy; (2) the School Learning Environment Survey (Sulingjar), which measures the quality of teaching and learning processes; and (3) the Character Survey, which measures students' non-cognitive outcomes.

Tools or Instruments Used. The primary instruments used to generate the data were those developed by Pusmendik for the National Assessment. For the data analysis phase, this research will

utilize the fs/QCA (fuzzy-set Qualitative Comparative Analysis) software, version 3.0, which is specifically designed for configurational comparative analysis (Ragin, 2008).

Data Analysis Methods. The data analysis will be conducted using the fs/QCA method. This approach was chosen over traditional linear methods (e.g., regression) to identify various 'causal recipes' that are sufficient for high numeracy achievement. The analysis will follow three main stages. The first is the calibration of all variables, transforming raw data into fuzzy-set membership scores (0 to 1) based on qualitative anchors (Tóth, Henneberg, & Naudé, 2017). Following calibration, an analysis of necessary conditions will be performed to identify any prerequisite factors. The final stage is the analysis of sufficient conditions, which involves constructing a truth table and using Boolean minimization to uncover the simplest configurational pathways to the outcome, evaluated by their consistency and coverage parameters (Rasoolimanesh & Olya, 2025).

RESULTS AND DISCUSSION

This study proposes a comprehensive research design to investigate the complex causal factors influencing high school mathematics achievement. The primary result of this design phase is a systematic and replicable methodology. 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, and the antecedent conditions are multi-dimensional factors (teacher quality, learning quality, school climate, and family SES) operationalized from 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 main 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.

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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