Project-Based Learning and Mathematical Competencies in Primary Education: A Neutrosophic Cognitive Map Reading of a Critical Integrative Review

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Abstract: Developing mathematical competencies in primary school is essential for interacting with the environment. Faced with the limitations of traditional direct instruction, project-based learning (PBL) has emerged as an active alternative. This study analyzes, through a critical integrative review of ten reference studies (2016-2026), whether PBL determines the development of basic mathematical competencies in primary school students, and formalizes the resulting conceptual system as a neutrosophic cognitive map (NCM) with eight concepts and nine causal connections classified as positive, negative, or indeterminate. The static analysis of the map identifies PBL as the most central concept, with total centrality 6 + I, and makes the core epistemic finding of the review explicit: the mediated path through real-context problem solving and motivation is consistently positive, while the direct edge from PBL to mathematical competencies remains indeterminate (I) given the scarcity of pure experimental and longitudinal evidence. Documented gaps in early primary grades and in rural contexts with digital divides complete the indeterminacy inventory. We conclude that PBL acts as a catalyst whose effect is conditional on authentic problem situations, curricular flexibility, and teacher training, and that the neutrosophic representation preserves this conditionality instead of collapsing it into a binary verdict.

Keywords: Project-based learning; basic mathematical competencies; problem solving; primary education; integrative review; neutrosophic cognitive maps; indeterminacy.

1. Introduction

The teaching of mathematics in primary education has historically been the object of intense pedagogical and institutional controversy. Traditionally, the transmission of this discipline has rested on a paradigm of direct, passive instruction characterized by the mechanization of algorithms, decontextualized memorization of formulas, and the solving of abstract exercises disconnected from the immediate reality of pupils [1]. This reductionist approach not only provokes disinterest and mathematical anxiety in children, but also severely limits their capacity to transfer knowledge to authentic problem situations. In this context, there is a pressing need to move toward active, constructivist teaching methodologies that place the student at the center of the formative process, allowing mathematics to be experienced not as a set of finished truths but as a functional tool for describing, explaining, and predicting real-world phenomena.

Project-based learning (PBL) stands out in the contemporary educational literature as one of the most promising pedagogical strategies for bringing about this curricular transformation [2]. By organizing the school curriculum around collaborative inquiry and the resolution of complex questions drawn from everyday life, PBL transcends the traditional classroom and gives practical meaning to scientific learning. Nevertheless, despite the theoretical optimism surrounding this approach, important questions persist about its actual capacity to determine, directly and systematically, the development of the mathematical competencies that are indispensable in middle and late childhood.

Against this background, the present study is structured around the following atomic research question: does project-based learning determine the development of basic mathematical competencies in primary school students? Analyzing this question requires clearly delimiting the variables at play. The independent variable is PBL, conceived as the active methodology that restructures conventional classroom dynamics; the dependent variable is the development of basic mathematical competencies, understood in the multidimensional terms of current international frameworks [3]. Primary education defines both the study population and the critical developmental frame, while the verb "determines" posits a direction of direct influence or causality that demands rigorous, dogma-free scientific evaluation.

Answering such a question from a literature review poses an epistemic difficulty: the available evidence mixes consolidated consensus, documented tensions, and open gaps, and a binary verdict would erase precisely the part of the answer that matters most. For this reason, this study adopts a neutrosophic representation, in which truth, falsity, and indeterminacy are treated as independent components [4]. Specifically, the conceptual system that emerges from the review is formalized as a neutrosophic cognitive map (NCM), a directed graph whose causal connections may be positive, negative, or indeterminate [5, 6]. The NCM makes it possible to state formally which relations the literature supports, which it contradicts, and which remain undecided.

The general objective of this article is to analyze critically, through an integrative review of the scientific literature of the last decade (2016-2026), whether PBL determines the development of basic mathematical competencies in primary school students, and to formalize the answer as a neutrosophic cognitive map. Three specific objectives follow: first, to characterize the theoretical and didactic foundations of PBL in primary school mathematics; second, to analyze the systemic relation between PBL (cause), real-context problem solving (mediator), and basic mathematical competencies (outcome); and third, to identify the empirical gaps, methodological tensions, and areas of scientific ignorance in the current literature and to encode them explicitly as indeterminacy in the map.

2. Theoretical Foundations

2.1. Constructivism and active learning as pedagogical substrates

The conceptual scaffolding that sustains PBL in the mathematics classroom is deeply rooted in constructivism and theories of active learning. Historically, as recent syntheses recall [7], PBL recovers the fundamental contributions of John Dewey, who proposed that genuinely meaningful learning emerges from direct experience and social interaction in real settings. Dewey held that school is not a preparation for life but life itself in its communal and collaborative dimension. William Kilpatrick later systematized these ideas in his "project method," arguing that pupils' intrinsic commitment is strengthened when schoolwork responds to purposeful aims that the learners themselves plan, execute, and evaluate autonomously.

On the cognitive plane, Jean Piaget's account of the genetic development of mathematical knowledge is crucial for justifying PBL in primary school. Piaget showed that logical-mathematical thought is not transmitted through verbal language nor assimilated passively through the contemplation of abstract symbols, as synthesized in the author's previous work on PBL in primary mathematics [8]. It is, rather, the result of a process of reflective abstraction originating in the subject's concrete sensorimotor actions on the objects of their environment. During the primary school years, which correspond largely to the period of concrete operations, children need to interact actively with perceptible situations in order to build mental schemes of conservation, classification, seriation, and numerical correspondence before they can fluently manipulate decontextualized algebraic or geometric formalisms.

Lev Vygotsky's socio-constructivist theory, in turn, provides the social frame for the collaborative dimension of project work [8]. Vygotsky argued that higher psychological functions originate first at the interpsychological level, in social interaction, and are then consolidated at the intrapsychological level. By structuring work around collaborative groups facing a common challenge, PBL promotes interactive scaffolding within students' zone of proximal development [8]. Through co-construction of knowledge, reasoned discussion, the defense of viewpoints, and the contrast of mathematical hypotheses among peers, students overcome cognitive conflicts and develop more complex, integrated conceptual structures.

2.2. The multidimensional character of basic mathematical competencies

To evaluate whether PBL actually shapes mathematical performance and development, it is essential to specify what basic mathematical competency means in contemporary primary education. Far from being reduced to arithmetic calculation or the rote memorization of solution algorithms, mathematical competency is currently defined as the multidimensional capacity of an individual to formulate, employ, and interpret mathematics in a wide variety of real contexts [3]. The construct involves using mathematical reasoning, concepts, procedures, facts, and tools to describe, explain, and predict phenomena, enabling well-grounded decisions in everyday life.

According to international assessment frameworks such as PISA [3] and their national curricular adaptations, basic mathematical competency unfolds into four interconnected dimensions that should be consolidated progressively during primary school: quantity problems (number sense, elementary arithmetic, estimation, measurement); regularity, equivalence, and change (patterns, elementary functions, proportionality, basic algebraic expressions); shape, movement, and location (plane and spatial geometry, properties of two- and three-dimensional figures, spatial orientation); and data management and uncertainty (collecting, organizing, representing, and analyzing data, together with an intuitive grasp of probability). Optimal development of these dimensions requires conceptual, procedural, and attitudinal knowledge alike, including persistence in the face of error and mathematical self-efficacy [7]. Traditional approaches, by fragmenting teaching into linear, merely numerical units, limit the integrated mobilization of these four dimensions, an obstacle PBL seeks to remove through holistic projects that demand simultaneous use of arithmetic, geometry, and statistics within one inquiry challenge [8].

2.3. Real-context problem solving as cognitive mediator

Within the systemic relation linking PBL to students' competency development, real-context problem solving is not simply one more curricular content but the fundamental mediating mechanism and the epistemic bridge that gives the whole pedagogical process its dynamism [9]. An authentic mathematical problem is a challenging situation whose solution path is not evident in advance, demanding exploration, articulation of fragmentary information, and modeling of reality [1].

Contemporary research in mathematics education underlines the cognitive superiority of this approach over the artificial "word problems" that populate conventional textbooks. Whereas the latter are direct applications of operations previously explained by the teacher, authentic contextualized problems lack a clean initial structure: the student faces redundant, incomplete, or noisy data and must traverse the mathematical modeling cycle described by PISA [3] — formulating the real situation mathematically, employing the pertinent concepts and procedures, and interpreting and evaluating the results back in the original context — together with the transversal capability of communicating arguments and conclusions with precision. This modeling cycle is the essence of PBL's pedagogical intent [7]. By systematically confronting projects built on community problems — designing a school garden (geometry and measurement), planning a family budget (arithmetic and percentages), analyzing the school's water consumption (statistics and change) — primary pupils move from repetitive, algorithmic memorization toward functional abstraction and effective transfer of knowledge [9].

2.4. Neutrosophic cognitive maps

A fuzzy cognitive map represents a system as a directed graph whose nodes are concepts and whose weighted edges encode causal influence. Neutrosophic cognitive maps extend this formalism by admitting indeterminate connections: an edge e_{ij} may take a value in {+1, −1, I}, where I denotes a causal relation whose existence or sign the available evidence cannot yet decide [5]. This third value operationalizes the neutrosophic principle that truth, falsity, and indeterminacy are independent components of knowledge [4], and it has proven useful precisely where expert or documentary evidence is qualitative and incomplete [6]. In this study the NCM is used in its static form: rather than simulating dynamics, we analyze the structure of the map through degree-based centrality measures, keeping the indeterminate contributions symbolically separated as coefficients of I.

3. Materials and Methods

3.1. Type and design of the study

To answer the research question, a documentary study was implemented following the integrative literature review method [10]. This design is particularly pertinent for mathematics education because it allows the confluence of studies with diverse methodological approaches — qualitative, quantitative, and mixed — facilitating a global, systemic, and updated view of the state of the art. Through critical integrative review, the analysis moves beyond a summative cataloguing of findings toward a hermeneutic, reflective reading that confronts the epistemological tensions persisting between active learning theories and the systemic rigidity of institutional practice.

3.2. Inclusion and exclusion criteria and corpus delimitation

The documentary corpus was delimited through a structured search of indexed databases and academic repositories (Scopus, Web of Science, PubMed, and Dialnet). Inclusion required: a) peer-reviewed scientific articles, refereed conference proceedings, or graduate-level theses addressing PBL in mathematics; b) empirical research of experimental, quasi-experimental, descriptive, or case-study character explicitly situated in primary education (pupils aged 6 to 12); c) documents in Spanish or English published between 2016 and 2026. Exclusion criteria removed opinion pieces and purely divulgative essays, studies of PBL at other educational levels, and research on generic active methodologies without specific results for mathematical competencies. The screening and critical quality appraisal consolidated a definitive corpus of ten reference documents — nine empirical or synthesis studies and one international assessment framework used as conceptual benchmark [3] — spanning Ibero-American, Anglophone, and Indonesian production [1-3, 7-9, 11-14]. Meta-analyses and systematic reviews were admitted as syntheses of secondary evidence [2, 9], and one study of problem-based learning in primary mathematics was admitted specifically as evidence on the mediating role of problem solving, not as a PBL implementation study [13].

3.3. Analysis procedure: coding, mapping, and neutrosophic formalization

The analytical treatment of the corpus was structured in four successive stages; Figure 1 presents the resulting map. First, the sources were coded by deconstructing the information into units of meaning corresponding to the four nuclear concepts of the research: PBL, basic mathematical competencies, real-context problem solving, and primary education as developmental context [1].

Second, the functional and causal relations among the variables were mapped, together with the institutional factors that the corpus consistently reports as enablers or inhibitors (teacher training, traditional instruction, curricular rigidity) and the intermediate outcome of motivation and self-efficacy [8, 9]. Third, an analytical audit of gaps in the literature was performed [8], oriented to the sufficiency of the evidence for the causative verb "determines," the geographic representativeness of the contexts, and the overall methodological rigor of the studies.

Fourth, the qualitative map was formalized as a neutrosophic cognitive map [5, 6]; this formalization is a methodological extension introduced in the present article and is not claimed by the primary studies. Each concept became a node; each relation asserted by the corpus became a directed edge with value +1 (reinforcing) or −1 (inhibiting); and each relation on which the audit found the evidence inconclusive became an indeterminate edge I. The static analysis uses the outdegree and indegree of Equation (1) and the total centrality of Equation (2), computed over determinate edges, with indeterminate incidences carried separately as coefficients of I. The coding of nodes and edges, with their documentary grounding, is reported in Tables 1 and 2, and the computation script is available from the corresponding author.

$$od(C_i) = \sum_j |e_{ij}|, \; id(C_i) = \sum_j |e_{ji}| \qquad (1)$$

$$td(C_i) = od(C_i) + id(C_i) \qquad (2)$$

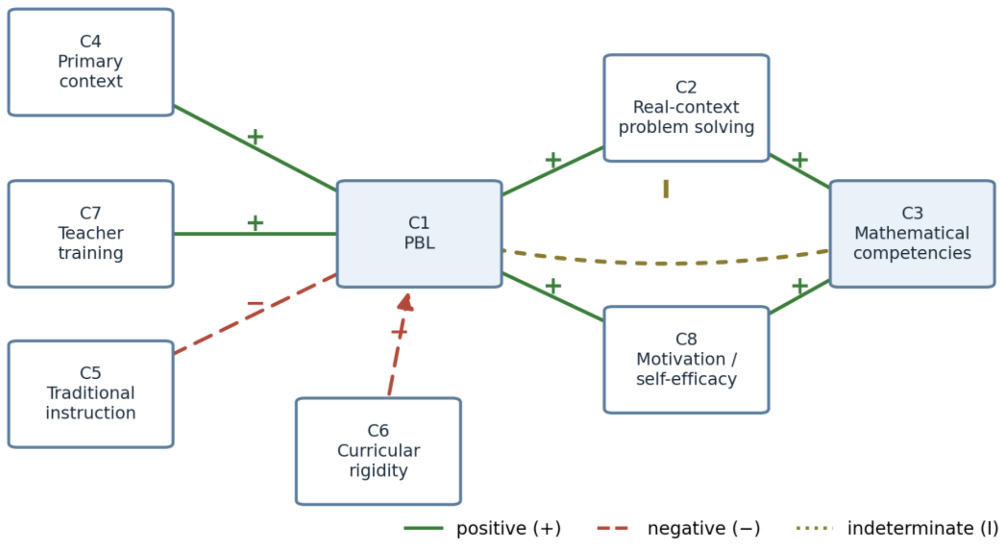

Figure 1: Neutrosophic cognitive map of the reviewed system. Solid green edges are positive, dashed red edges negative, dotted edges indeterminate (I). Source: authors' elaboration from the corpus coding.

4. Results and Discussion

4.1. The system as a neutrosophic cognitive map

The integrated reconstruction of the corpus shows that the impact of PBL on basic mathematical competencies is not produced linearly or in isolation, but through a dynamic, structured system [9]. Tables 1 and 2 present the eight concepts and nine connections of the resulting NCM with their documentary grounding, and Table 3 reports the static analysis.

Table 1: Concepts (nodes) of the neutrosophic cognitive map and their documentary grounding.

Node	Concept	Role in the system	Grounding
C1	Project-based learning (PBL)	Driving cause	[2, 7]

C2	Real-context problem solving	Cognitive mediator	[9, 13]
C3	Basic mathematical competencies	Outcome	[3]
C4	Primary education context	Developmental enabler	[8]
C5	Traditional direct instruction	Inhibitor	[1, 8]
C6	Curricular rigidity / standardized testing	Institutional inhibitor	[8]
C7	Teacher training	Institutional enabler	[7, 8]
C8	Motivation and self-efficacy	Intermediate outcome	[2, 12]

Source: authors' coding of the corpus.

Table 2: Connections (edges) of the map, their neutrosophic value, and grounding.

Edge	**Value**	**Relation asserted by the corpus**	**Grounding**
C1 → C2	+1	PBL is articulated through authentic problem situations.	[7, 9]
C2 → C3	+1	Real-context problem solving develops competencies.	[9, 13]
C1 → C8	+1	PBL strengthens motivation and self-efficacy.	[2, 12]
C8 → C3	+1	Motivation supports mathematical achievement.	[2, 12]
C4 → C1	+1	The primary stage offers the evolutive conditions for PBL.	[8]
C5 → C1	−1	Traditional instruction culture inhibits PBL implementation.	[8]
C6 → C1	−1	Curricular rigidity and standardized testing inhibit PBL.	[8]
C7 → C1	+1	Teacher training enables the facilitator role.	[7, 8]
C1 → C3	I	Direct causal effect: evidence inconclusive (no	[1, 8]

		randomized or longitudinal designs; early-primary and rural gaps).	

Source: authors' coding of the corpus; I = indeterminate.

Table 3: Static analysis of the map: outdegree, indegree, and total centrality (Equations 1 and 2).

Node	**od**	**id**	**td**
C1	2 + 1I	4	6 + 1I
C2	1	1	2
C3	0	2 + 1I	2 + 1I
C4	1	0	1
C5	1	0	1
C6	1	0	1
C7	1	0	1
C8	1	1	2

Source: authors' computation (script ncm_yurithzi.py); indeterminate incidences carried as coefficients of I.

Three structural readings follow. First, PBL (C1) is by far the most central concept of the system, with total centrality 6 + I: it receives the influence of every contextual enabler and inhibitor and transmits influence through every outgoing path. This confirms its role as the driving variable of the classroom ecology [2]. Second, the outcome node C3 concentrates the system's uncertainty: its centrality 2 + I combines two well-supported positive inflows — through real-context problem solving (C2) [9, 13] and through motivation and self-efficacy (C8) [2, 12] — with the one indeterminate edge of the map, the direct connection C1→C3. Third, the negative edges from traditional instruction (C5) and curricular rigidity (C6) act on C1 rather than on C3: what the institutional environment inhibits is the implementation of PBL itself, not the mathematical development of pupils once authentic projects are in place [8]. Symmetrically, the corpus grounds the enabling edges: the primary stage offers the evolutive conditions under which pupils move from informal to structured mathematical learning (C4→C1) [8], and specific teacher training is repeatedly identified as the condition for teachers to shift from transmitters of content to facilitators of inquiry (C7→C1) [7, 8].

4.2. The positive mediated path

The map's dominant positive path runs C1→C2→C3. The evidence analyzed underlines that implementing a generic classroom project is not enough; for PBL to have a positive impact on mathematical performance, the didactic proposal must be rigorously articulated through an authentic problem situation that obliges the student to model mathematically, justify solution proposals, interpret available data, and functionally employ non-obvious algorithms [9, 13]. When this mediation is present, students cease to be receivers of mechanical formulas and become critical inquirers who mobilize conceptual, procedural, and attitudinal resources in a coordinated way [12]. The parallel path C1→C8→C3 is also well supported: the meta-analytic evidence reports improvements in mathematics achievement together with substantial strengthening of intrinsic motivation and self-efficacy compared with traditional direct transmission [2].

4.3. The negative edges: institutional friction

Despite the documented benefits, the map reveals serious tensions between the theoretical postulates of active methodology and the organizational realities of primary schooling [8]. The clearest contradiction lies in the negative edge from traditional methods (C5): while PBL demands learner autonomy, flexible pedagogical time, and open inquiry spaces, the prevailing school culture is constrained by content-overloaded linear curricula and by standardized tests that prioritize memorization of algorithmic procedures over conceptual understanding (C6) [8]. A second, technical-didactic tension opposes the playful or social intent of the project to the necessary mathematical rigor of the formative process [1]: there is a real risk that enthusiasm for the tangible final product eclipses the cognitive objectives of the curriculum, producing superficial activities of low cognitive demand in which pupils manipulate materials or technology without deepening mathematical conceptualization, modeling, or logical argumentation [1].

4.4. The indeterminate edge: audit of gaps

The audit of the corpus grounds the single indeterminate edge of the map, C1→C3, in three convergent findings. First, a thematic imbalance: most empirical research documenting PBL's effectiveness in mathematics is situated in upper primary grades (fourth to sixth), with severe scarcity of rigorous evidence on adapting the methodology to early primary (first to third grade), where children are in a critical transition from intuitive to concrete operational thought. Second, a methodological ceiling: current production rests almost exclusively on quasi-experimental designs without random assignment, action-research studies, and short case studies, which precludes direct causal inference and casts doubt on the causative verb “determines”; longitudinal studies verifying whether the benefits persist after the intervention are also lacking. Third, a geographic and technological bias: the literature is centered on urban or well-resourced institutions where PBL is integrated with digital tools such as dynamic geometry software or augmented reality [11, 14], leaving the viability of PBL in extreme rural communities, multigrade schools, and contexts of absolute digital divide as an open question [8]. In neutrosophic terms, these gaps are not noise to be averaged away but a constitutive component of the current answer: the edge remains I until experimental and longitudinal evidence resolves it.

4.5. Limitations of the study

This study has limitations that bound its conclusions. The corpus was consolidated through critical appraisal rather than a PRISMA-type protocol, and comprises ten studies. The NCM was derived from the corpus by a single coder, so no inter-coder agreement measures were computed. The static analysis weighs all edges equally and does not simulate dynamics; a natural next step is to elicit edge weights from expert panels as single-valued neutrosophic numbers and to study the map's dynamic behavior, as well as to validate the structure with primary school teachers in Mexico. A further limitation is the weight of the author's own previous work [8] in the documentary grounding of several edges; future versions should triangulate those relations with independent sources.

5. Conclusions

The critical, integrative examination of the corpus provides a grounded answer to the question of whether PBL determines the development of basic mathematical competencies in primary education, and the neutrosophic cognitive map makes the logical form of that answer explicit. PBL is positioned as a highly effective didactic strategy that strengthens cognitive, attitudinal, and procedural competencies to a degree superior to conventional direct instruction; in the map, this appears as the consistently positive mediated paths through real-context problem solving and through motivation. However, the categorical claim that the methodology “determines” that development by itself is methodologically risky in the current state of the science; in the map, this appears as the indeterminate direct edge C1→C3, sustained by the scarcity of pure experimental designs, the absence of longitudinal evidence, and the underrepresentation of early grades and rural contexts.

The relation between PBL and mathematical competency is therefore systemic and conditioned. Its real effectiveness resides in the explicit incorporation of authentic problem situations as the engine of the learning process: a project lacking a genuine situation-problem that demands modeling, data analysis, and justification of procedures is reduced to a merely recreational activity of low cognitive demand. The success of the paradigm shift is likewise subordinated to institutional and cultural variables — specific teacher training and curricular flexibility — whose absence appears in the map as the negative edges acting on the implementation of PBL.

Future research should prioritize randomized experimental studies and longitudinal analyses capable of resolving the indeterminate edge, the adaptation of the methodology to early primary grades, and its exploration in rural contexts marked by technological exclusion. On the formal side, eliciting edge weights as single-valued neutrosophic numbers from expert panels and simulating the dynamics of the map would turn the present static representation into an instrument for scenario analysis. A transcultural and methodologically plural agenda along these lines would allow the remaining indeterminacy of the map to be resolved on evidence rather than on enthusiasm.

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