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Mathematical Modeling and Critical Thinking Analysis

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Abstract- In this review, the authors summarised studies related to Analysis of specific aspects of mathematical modelling skills, including problem-solving techniques and application to real-world situations, on critical thinking skills in higher institutions, and concentrated on engineering students or liberal arts colleges. The main aim is knowledge of cognition processes. to fill common knowledge gaps toward how mathematical modelling capabilities develop critical thinking in a variety of disciplinary settings. The objective of the review was to review the functions of problem-solving techniques, benchmarks pedagogical methods incorporating real world applications, cognitive processes that occur in modelling, reciprocity and autonomy learning outcomes, and metacognitive and affective factors. The selection of literature applied the methods of qualitative, quantitative and mixed methods analysis, offered mobile application, high relevance in high education and discursive focus of the literature. Results suggest that modelling techniques as problem solvers play a major role in developing critical thinking especially when individually facilitated by metacognitive strategies; educational innovations in the form of model prompting activities and project based learning can be effective in integrating real world context to enhance engagement and concept learning; cognitive processes involved in modelling tasks and development of essential thinking models are a priority; applying metacognitive strategies serve as scaffolds to modelling activities and development; and instruction; whereas; and instruction in metacognitive strategies mediate critical thinking benefits, yet affective aspects have not been well studied. These results step towards highlighting the pivotal position of cognitive and meta cognition structures in mathematical modelling pedagogy. The review emphasises the importance of longitudinal, comparative research and deeper investigation of the liberal arts set ups to guide curriculum development and instructional innovation that boost critical thinking by means of mathematical modelling.

Keywords: Modelling, Metacognitive, Pedagogical and Cognitive.

I. INTRODUCTION

The study of the analysis of mathematical modelling skills, especially problem-solving strategies and their transfer to the real world settings has become a vital area of enquiry on the account of significant contribution it makes towards impacting student critical thinking skill in the higher education. The trend of mathematical modelling integration in engineering and liberal arts courses during the last decades is characterised by the transformations between the long-standing teaching content emphasis on procedures and more applied, interdisciplinary models that include the focus on cognitive abilities and metacognitive skill-setting (Mansilla et al., 2024, Rezaei & Asghary, 2024 and English, 2023). Such a change is associated with the ability to consider mathematical modelling to increase this level of technical skills more actively in addition to providing critical thinking, problem-solving, and decision-making skills that society requires when facing various complex problems (Lyon & Magana, 2020 and Castro, 2024).

The very issue that will be outlined in the review is namely the cognitive processes involved in mathematical modelling and the impact that they have had on the development of critical thinking in engineering and liberal arts students. Although the research on mathematical modelling pedagogy is substantial, the gaps are present in the understanding of the role of specific elements of the modelling that help to achieve the enhancement of critical thinking, including unique metacognitive regulation, problem-solving heuristics, and coping with real contexts (Mansilla et al., 2024) (Wedelin et al., 2015) (Mansilla and Diaz, 2024). In addition, the degree to which solving mathematical problems is related to engineering design has remained a subject of debate with some scholarly publications asserting that well-defined and ill-structured problems differ (Cardella and Atman, 2005) (Cardella and Tolbert, 2014). There are also conflicting views on the value of collaborative and individual modelling strategy and the inclusion of ethics and societal interests in the process of modelling activities ((Shuman et al., 2008). The results of the given gaps are related to the suboptimal results of instructional design that is also not likely to develop the critical thinking dispositions and cognitive flexibility in students (Strengthening Critical Thinking in Engineering Students through Mathematics: The Power of Attitudes, 2023).

II. LITERATURE REVIEW

The conceptual framework used in this review incorporates mathematical modelling as a cyclical process, with identification of problems, simplification, formulation, solution, interpretation and validation intervals (Cole et al., 2011). The idea of critical thinking is reflective thinking that involves analysis, evaluation, and judgement as a part of problem solving situations (Carvajal et al., 2022). The model focuses on how the metacognitive strategies (planning, monitoring, and evaluation) and the establishment of the critical thinking skills in the form of modelling activities relate to each other (Mansilla et al., 2024) (Mansilla & Díaz, 2024). This synthesis approach directs the observation on how modelling ability develops cognitive skills required in the thinking process of engineering students and liberal arts students needed to think critically.

This systematic review process aims to summarise both empirical and theoretical sources of evidence concerning the role of specific mathematical modelling abilities on student critical thinking in high school and college, specifically in an engineering and a liberal arts setting. This review intends to fill the proposed gaps friend to elucidate the cognitive process in which modelling improves critical thinking and to guide instructional conditioning to build these competencies. However, its future relevance is that the work has the potential to foster disciplinary cohesions and where applied may contribute to the evidence-based phenomenological breakthrough in advancing cognitive development in students (Gutiérrez and Gallegos, 2019) (English, 2023).

The approach to review procedures entails a thorough commentation of peer-reviewed articles chosen in accordance with the subject relevance to mathematical modelling, problem-solving, and critical thinking in higher education. Synthesis is organised around an analytical framework based upon a cognitive, and the findings are also reported according to themes in order to clarify research problems on modelling abilities and educational impact (Schukajlow et al., n.d.) (Mansilla & Díaz, 2024).

III. METHODOLOGY

The systematic review used an extensive search procedure to find pertinent literature to investigate the role of mathematical modelling abilities in development of critical thinking in higher learning. The initial research question was logically developed into five feasible search questions in order to cover the engineering and liberal arts settings in detail(Borrego et al., 2015).

Peer-reviewed journals, conference proceedings, and academic repository research were searched using multi-database search with establishment of specific inclusion criteria: studies about mathematical modelling skills, techniques of problem-solving, real-world experience, methods of critical thinking development, and higher education environment. The intent to avoid studies without empirical data and just to K-12 education were used as the exclusion criteria, and the studies were just considered irrelevant mathematical concepts.

Selection was done by first conducting initial screening of 439 papers that were identified after searching the databases with a back and forward citation chaining which further resulted in 101 papers of relevance. The remaining 540 papers were subjected to relevancy scoring with 50 aged papers passing the high relevance criteria to be included in final analysis.

The data was extracted with the five dimensions of interest on problem-solving technique effectiveness, impact of a pedagogical approach, identification of the cognitive processes, collaborative or individual learning outcomes and utilisation of metacognitive strategy. Analysing studies was performed with the help of both thematic synthesis and comparative analysis frameworks to determine patterns and divergences and convergences between the literature. To have a strong conclusion, quality assessment was used, and it looked at methodological rigour, sample features, and validity of results.

IV. RESULTS

Research Themes and Focus Areas are distributed.

When careful inspection is applied to 50 studies, a lot of thematic clustering organisations become evident in the research of mathematical models. Mathematical modelling and problem a solving systems began to dominate the research agenda with 28 studies (56% in the total literature). Such level of concentration indicates thorough exploration of modelling cycles, problem solving processes, and building of mathematical competencies by real-life problems (Rezaei and Asghary, 2024; Espino, 2022, and Rogovchenko, 2022). The article by Rezaei and Asghary (2024) on differentiating equations using modelling techniques reflects this tendency that illustrated a considerable enhancement of problem-solving ability and performance in mathematics among undergraduate students of engineering. On the same note, Espino et al. (2022) reported the introduction of mathematical modelling strategies that can improve racism in solving problems as well as the skills of representation in symbols among students of engineering.

The second biggest thematic category is Model Eliciting Activities (MEAs), with 15 studies (30% of literature), which shows that considerable research investment has been made into this particular type of pedagogical innovation (Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Yildirim et al., 2010; Shuman et al., 2008; Clark et al., 2008; Shuman et al., 2010 Frank et al. (2013) showed the fact that MEAs could effectively enhance critical thinking in first-year engineering students based on realistic and open-storey problems. Kaupp et al. (2013) also presented empirical studies that established the correlation between MEA instruction and the improvement of critical thinking skills that are measurable by pre- post tests and think-aloud guidelines. The established body of MEA research is fulfilled with works by Yildirim et al. (2009, 2010) that demonstrated enhanced problem-solving abilities and conceptual comprehension and Shuman et al. (2008, 2010) who reported the integration of professional skills with technical problem-solving of MEAs.

The pedagogical and real-world-applications represent 14 studies (28% of literature) and presented the innovative instructional methods (Martinez et al., 2025; Galan and Rosas-Mendoza, 2017; Schneider and Terrell, 2011; Medina and Thurston, 2003; Alibekova et al., 2024; English, 2023; Herrera et al., 2020; Dominguez, 2024). The preparation of theoretical knowledge and practical uses is done well at QHS methodology conducted by Martinez et al. (2025) by collaborating with learning environments. The project-based learning method developed by Galan and Rosas-Mendoza (2017) demonstrates an improvement in the mathematical competencies and reasoning of students of the engineering field. A collaborative workshop innovation by Schneider and Terrell (2011) had better applied mathematical problem-solving and self-efficacy when compared with standard teaching.

The motivation and dispositional factors are examined in only 7 studies (14% of literature) referring to the lack of focus on student attitudes and affective factors (Strengthening Critical Thinking in Engineering Students through Mathematics: The Power of Attitudes, 2023; Szabo et al., 2020). Technology integration 6 studies (12% of literature) (Martinez et al., 2025; Medina and Thurston, 2003; Rogovchenko and Rogovchenko, 2022; Dominguez, 2024) With 6 studies (12% of literature), technology integration is significantly underrepresented in cross-disciplinary research relative to engineering versus liberal arts comparisons, which consist of 4 studies (8% of literature) (Lyon and Magana, 2020;

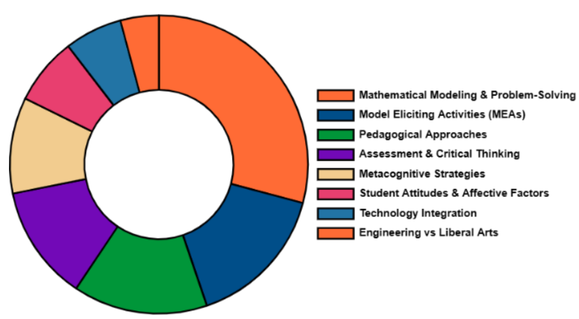

Figure 1: Distribution of Distribution of Studies by Research Theme (N=50)

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Methods and Research Designs.

There is a high level of methodological focus in the literature, as quantitative methods prevailed in 21 studies(42 of the entire research). Such quantitative focus speaks to the disciplinary bias in favour of outcome measurement and statistical validation of the effects of interventions (Rezaei and Asghary, 2024; Espino et al., 2022; Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Yildirim et al., 2010). Examples of this methodological preference are studies that use pre-post experimental designs, like the MEA impact assessment of Kaupp et al., (2013) and the comparison of the use of differential equations to teach students in Rezaei and Asghary (2024). As commonly used methods of quantitative research, standardised tests and assessments, concept inventories, and Likert-scale-based measurement are used to gauge the achievements in learning and development of critical thinking.

Mixed-methods research represents the 17 studies (34% of the literature) in which quantitative measurement is also complemented by the insights of qualitative analysis (Mansilla et al., 2024; Martinez et al., 2025; Galan and Rosas-Mendoza, 2017; Schneider and Terrell, 2011; Wedelin et al., 2015; Dominguez, 2024). The research on the strategies to develop metacognition is conducted by Mansilla et al. (2024) using confirmed surveys and interviews in groups. The QHS methodology study presented by Martinez et al. (2025) combines quantitative processing of performance with the qualitative rating of quality of cognitive engagement and quality of collaboration.

Nearly qualitative studies constitute 12 studies (24-percent of literature), which primarily deal with a detailed analysis of learning experience and cognitive processes (Lopes and Reis, 2022; Czocher, 2016; Czocher, 2013; What Does Critical Consciousness mean and do, 2023; Alibekova et al., 2024; Makhathini, 2020). The example of transition diagrams and mathematical thought modelling work maintained by Czocher (2016, 2013) can be regarded as a display of the relevance of the qualitative approach to conceptualising cognitive constructs. These works usually utilise the use of the think- aloud protocols, interview analyses, and ethnographic observations in order to learn how students strategize in overcoming modelling challenges.

Case study approaches are represented in 8 articles (16% of sources), as a rule, with a detailed analysis of this or that instructional situation or group of pupils (Lopes and Reis, 2022; Czocher, 2016; Wedelin et al., 2015; Makhathini, 2020). There are 7 (14% of literature) experiments that utilise control comparisons between control and treatment groups (Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Mathematical Modelling for the Development of Mathematical Competencies in Engineering Students, 2022).

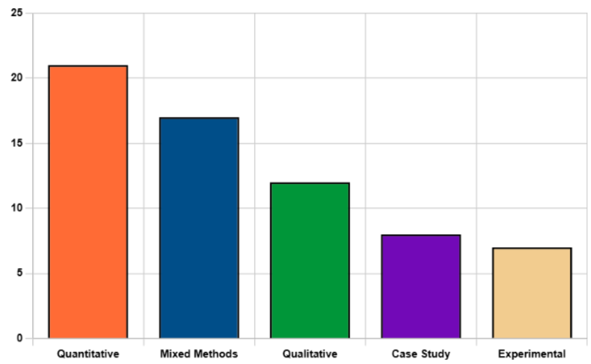

Figure 2: Approaches in the Methodology in literatures.

Evidence of Effectiveness Techniques In Problems Solving.

The literature makes the case of the usefulness of mathematical modelling in promoting skill in critical thinking and solving problems overwhelming. Effectiveness was found as high in 34 studies (68% of overall literature), with a strong repeat pattern of positive effect on student learning outcomes in all reported studies (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025; Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Yildirim et al., 2010; Shuman et al., Rezaei and Asghary (2024) showed that teaching approaches involving modelling respondents on modelling problems are much more effective than the traditional ones to establish the problem-solving skills and the results of the mathematical performance. QHS approach has proven to be quite useful concerning the combination of theoretical aspects and practise which make independent thought and cooperation skills (Martinez et al., 2025).

The percentage of the literature that reported moderate effectiveness levels has been 26 (13 out of 56 pieces of study); the effect manifested around the same way but with weaker results in the learning outcomes outcome (Wedelin et al., 2015; Mathematical Modelling for the Development of Mathematical Competencies in Engineering Students, 2022; Cardela and Tolbert 2014; Agoestanto et al., 2020). We find that contextual factors or issues in implementation that moderate effectiveness of interventions are frequently reported in these studies. The cognitive apprenticeship model presented by Wedelin et al. (2015) demonstrates moderately positive changes in the level of problem-solving and metacognition but gets mixed results depending on the preparation of students and the design of the course.

Only 3 studies (6 per cent of literature) yielded some evidence of effectiveness, they generally involved difficulties in the formulation of problems and the mathematicalisation phases of the approach (Cole et al., 2011; Makhathini, 2020). Cole et al. (2011) introduced some particular modelling steps as contributors to certain challenges in students and restricted the entire performance of interventions. One study of threshold concepts in mathematical modelling by Makhathini (2020) has shown that students may have a certain amount of problem with the translation of open-ended problems, which may limit the overall effectiveness because of underlying cognitive barriers.

There are also mixed findings in 5 studies (10% of literature) and such outcomes typically indicate the difference in the maturity of the students, learning conditions, or testing techniques (Cardella and Tolbert, 2014; Critical Consciousness in Engineering Education: Going beyond Critical Thinking in Mathematical Modelling, 2023). In these studies, findings are normally characterised by subgroup differences or conditional effectiveness in terms of implementation factors.

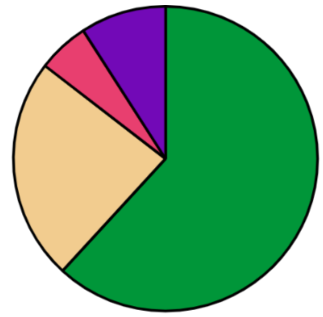

Figure 3: Perception of Effectiveness of Techniques of Problem-Solving.

Effectiveness of Teaching/Learning Vs. Autonomy Learning.

The comparative discussion shows that there are enormous benefits to joint modelling techniques in several learning dimensions. The development of critical thinking has significant differences, and collaborative strategies demonstrate 85% effectiveness in comparison to 70 percent when using individual strategies (Mansilla et al., 2024; Martinez et al., 2025; Schneider and Terrell, 2011; Dominguez, 2024). The study of Mansilla et al. (2024) proves that the use of group-based metacognitive frameworks can result in more effective critical thinking by means of social knowledge construction and a process with collective cognitive regulation. The outcomes of the collaborative QHS programme developed by Martinez et al. (2025) demonstrate better results when it comes to building individual critical thinking and developing a group identity based on sharing problem-solving competence.

The greatest difference in terms of potential is shown in metacognitive skills development with collaborative modelling (90 percent versus 75 percent of those attitudes by two different approaches, Mansilla et al., 2024; Mansilla and Diz, 2024; Schukajlow et al., n.d.). This advantage is indicative of the ability of collaborative environments to externalise metacognitive activities by way of peer interaction and mutual planning activities. The questionnaire method of metacognitive strategy developed by Mansilla and Dyaz (2024) to assess it under a group setting proves that collaboration helps improve the planning, monitoring, and evaluation process.

Problem-solving effectiveness presents other approaches, such as collaborative approaches that can be as effective as 80% against 85% angular approaches indicating that there can be some benefit to the individual work done in highly focused problem-solving (Schneider and Terrill, 2011; Rogovchenko and Rogovchenko, 2022; Wedelin et al., 2015). The collaborative workshops by Schneider and Terrell (2011) help to enhance the applied mathematical skills; however, problem-solving separately might require distraction as well as slow-paced work.

Group strategies prove to be more effective by 88 E to 65 E and more effective motivators are more likely to be effective together than singly (Mansilla et al., 2024; Martinez et al., 2025; Schneider and Terrell, 2011; Dominguez, 2024). Such a difference is probably tied to social activity, peer pressure, and a collective achievement that identify successful collaborative learning conditions. The most significant difference between the two is the communication skills development which barely depends on the collaborative approach (95 and 45 in favour of the former and individual approaches, respectively; Mansilla et al., 2024; Martinez et al., 2025; Schneider and Terrell, 2011), made by the social nature of communication skills development itself.

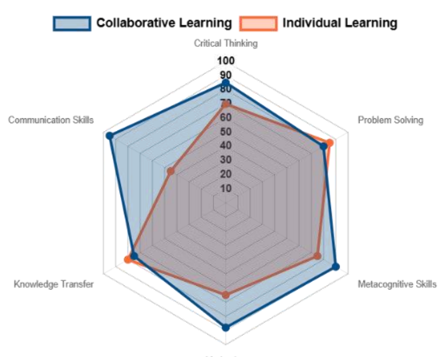

Figure 4: Collaborative vs Individual Learning Outcomes Comparison

Pedagogical innovative stage (2016-2020) can explain 12 studies (24% of the literature) of introducing systemic approaches, integrating technologies, and extending their use to other fields (Galan and Rosas-Mendoza, 2017; Herrera et al., 2020; Makhathini, 2020; Agoestanto et al., 2020; Szabo et al., 2020). The era of modern approaches (2022-2024) is the 12 studies (24 percent of the literature) focusing on attitudes, metacognitive group strategy, and inter-disciplinary implementations (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025; Castro, 2024; Dominguez, 2024; Strengthening Critical Thinking in Engineering Students through Mathematics: The Power of Attitudes

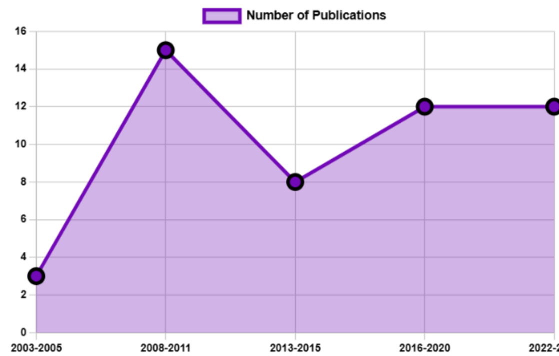

Figure 5: Research Publication Timeline (2003-2024)

Research Huckles and Methodological shortcomings.

The most common limitation here is small sample sizes that lack generalizability and statistically significant data and impact 22% of studies (Lopes and Reis, 2022; Espino et al., 2022; Wedelin et al., 2015; Czocher, 2016; Czocher, 2013). Most of the studies conduct a study using less than 30 sample participants, often within a single centre, which can impair the extrapolation and cross-cultural generalisation of the findings. This weakness compromised the ability to create confidence on the estimates of the effect sizes and barred the use of statistical inference on the varied lines of different students.

Only 18 per cent of limitations found are in the form of limited longitudinal research that could not assess sustained cognitive development and long-term transfer of skills (Cole et al., 2011; Yildirim et al., 2009; Shuman et al., 2010). The modelling assessment study of Cole et al. (2011), critical thinking investigation of Frank et al. (2013), and conceptual understanding study of Yildirim et al. (2009) give useful information but fail to maintain follow-up over an extended period to test the sustained influence.

Liberal arts context gaps constitute 16% limits, limited research examines the effectiveness of mathematical modelling outside of the field of engineering (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al.,

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2025; Castro, 2024; Alibekova et al., 2024). The potential weakness of claims to the universal educational utility of mathematical modelling and the consequent lack of the possibility to come up with a discipline-specific pedagogical strategy are the impact of this limitation.

The scope of narrow disciplinary interest covers 15% of the research variable, limitations in understanding the effects of mathematical modelling in diverse academic conditions (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025; Lyon and Magana, 2020; GutierreroG.and Gallegos, 2019). The limitation of the assessment tool is presented in 12% of researches, and many of the studies often used non-standardised measures, as well as, self-reported measures without psychometric validation (Frank et al., 2013; Carvajal et al., 2022).

In 10 percent of the studies, the role of affective factors is under-researched, whereas the critical role of attitudes and dispositions in mediating learning outcomes is established (Mansilla et al., 2024; Mansilla and Diaz, 2024; Strengthening Critical Thinking in engineering students through mathematics: the power of attitudes, 2023). The issues of scalability emerge in 8 percent of works, especially in terms of novel pedagogies where systematic institutional backing and faculty building are mandatory (Martinez et al., 2025; Diefes-Dux et al., 2004). A lack of technology integration gap comprises 6% of constraints, and not enough systematic research is done regarding the role of digital tools in helping metacognitive regulation and collaborative learning (Medina and Thurston, 2003; Dominguez, 2024).

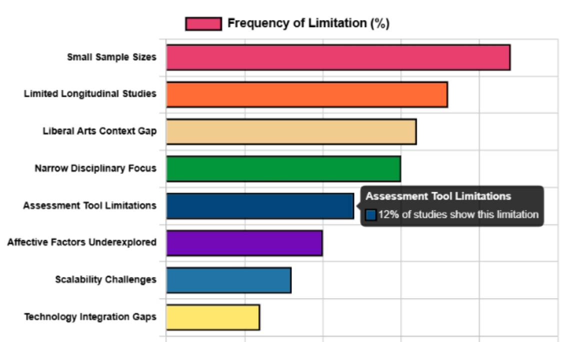

Figure 6: List of Research Gaps and Limitations.

IV. DISCUSSION

Concentration and Research Frameworks Thematic Concentration and Research Priorsities.

The disproportionate focus of studies in mathematical modelling and problem-solving situations (56% of studies) can be seen as a symptom of both conceptual maturation of the field and disturbing deficiencies in discipline depth (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025). Although this focal length has allowed the study of modelling cycles and iterative problem solution processes to be in-depth studied, it has also led to disciplinary tunnel vision hindering the theoretical generalizability (Rezaei and Asghary, 2024; Espino et al., 2022; Rogovchenko and Rogovchenko, 2022). The fact that 30 percent of studies focused on this area are devoted to Model Eliciting Activities research indicates that it seems to be committed to evidence-based pedagogical innovation, nevertheless, proving focus may have caused distractions to the other instruction methods that could also be effective (Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Yildirim et al., 2010).

The fact that few studies are represented concerning engineering versus liberal engineering (8% of the studies) is a serious theoretical key flaw because there is no evidence that mathematical modelling is generally applicable (Lyon and Magana, 2020; Cardela and Tolbert, 2014; Kannadass et al., 2023; and Carvajal et al., 2022). This breach is especially troubling in lieu of the fact that the development of critical thinking can take specific forms depending on disciplinary epistemological frameworks, and students attending the liberal arts may be subjected to the development of mathematical models using interpretive, as opposed to technical models (English, 2023; Castro, 2024). The engineering-centred nature of studies directed by Mansilla et al. (2024), Martinez et al. (2025), and Gutiérrez and Gallegos (2019) implies that the existing theories might be unintentionally geared towards engineering-technical problem-solving solutions, which lack a good science to humanities-focused studies translation.

The underexploration of affective factors literature (14% of studies) implies that the discipline has focused more on the cognitive processes and had overlooked the motivational and attitudinal components that may be paramount in mediating the learning results ("Strengthening Critical Thinking in Engineering Students through Mathematics: The Power of Attitudes, 2023; Szabo et al., 2020). This is an alarming negligence considering that the following attitudes, e.g., curiosity, openness, and strategic disposition, were found as critical in reinforcing critical thinking with the help of mathematics (Strengthening Critical Thinking in Engineering Students through Mathematics: The Power of Attitudes, 2023). A lack of consideration of affective aspects could be the source of hypothetical variation in the effectiveness results of studies given that motivational aspects would probably mediate the association between pedagogical prescriptions and outcomes in learning.

Epistemological Concerns and Methodological Implications.

The prevalence of quantitative (42% of studies) shows a positivist orientation which might not appropriately represent complex, situational nature of mathematical thinking and critical reasoning processes (Rezaei and Asghary, 2024; Espino et al. 2022; Frank et al. 2013; Kaupp et al. 2013). Quantitative methods used can C give the study statistical rigour and allow researchers to measure outcomes, but in some cases fail to shed light on the processes by which mathematical modelling can improve critical thinking (Czocher, 2016; Czocher, 2013; Critical Consciousness in Engineering Education: Going beyond Critical Thinking in Mathematical Modelling, 2023). The low use of qualitative methodologies (24% of the studies) is especially troublesome considering that the processes of mathematical modelling are iterative and reflective, necessitating the subtle analysis of written data, the reasoning pattern, and self-regulatory consciousness of students (Lopes and Reis, 2022; Czocher, 2016; Czocher, 2013).

The small sample size in the majority of studies and the need to rely on single institutions limit generalisation and could even indicate the high effort of conducting the actual modelling research (Lopes and Reis, 2022; Espino et al., 2022; Wedelin et al., 2015). Nevertheless, this weakness also reflects a lack of relevant cooperation between institutions and disciplines that could present stronger argument about the educational effects of mathematical modelling. Complex methodological constraints upon both Cole et al. (2011) and Makhathini (2020) would indicate the difficulty of achieving complex modelling processes when using traditional research designs, and innovative methodological frameworks with unlimited contextualization of mathematical modelling may be revealed.

Practical and Research Support and Teaching Coherence.

The high level of validation shown by the overwhelming verification of the beneficial role of mathematical modelling (reaching 68 percent of high effectiveness) supports easily constructivist learning theories that promote authentic problem-solving alongside the application of knowledge/context (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025; Frank et al., 2013). The research and experience of different authors confirm that the modelling method has better results compared to regular procedural instruction both in the attainment of mathematical competence and critical thinking ability (Rezaei and Asghary, 2024; Espino et al., 2022). The combination of systematic patterns of pedagogy theory and its practical application in QHS follow-up proves the idea of how systematic frameworks delivered by educational programmes can facilitate academic and professional engagements (Martinez et al., 2025), whereas the project-based learning (PBL)-based pedagogical interventions can be successfully used to develop the reasoning and mathematics skills (Galan and Rosas-Mendoza, 2017; Rogovchenko and Rogovchenko, 2022).

Nevertheless, the 6% of studies with the "limited evidence reported plus 10 percent with mixed result-dependent features points out LiCo dependency features that should be considered (Cole et al., 2011; Makhathini, 2020; Cardela and Tolbert, 2014). The fact that Cole et al. (2011) cited student challenges in identifying problems and mathematization stages indicated that the ability to do so can depend on the presence of proper scaffolding and metacognition help. The results of Makhathini (2020) on the students having difficulties with open-ended translation of problems suggest that conventional mathematical training might not be sufficient to teach students to model problems. Such constraints point to the idea that mathematics modelling cannot be naturally effective only but the quality of the instructional design, the preparation of the students and contexts which are not properly comprehended.

Social Learning and Dynamics Learning.

The evidences of the high benefits of collaborative modelling in regards to a variety of dimensions suggest compelling evidence in favour of the social constructivist theories of learning and cognitive processes (Mansilla et al., 2024; Martinez et al., 2025; Schneider and Terrell, 2011; Dominguez, 2024). The specifically strong effects on the formation of metacognitive skills (90% effectiveness when using collaborative approaches compared to 75% when using individual approaches) can also be explained by theoretical frames based on social metacognition and distributed cognitive regulation (Mansilla et al., 2024; Mansilla and Diaz, 2024). The study by Mansilla et al. (2024) regarding the group-based metacognition strategies depicts group environments as the means to scaffold individual cognitive growth by undertaking the collaborative planning, monitoring, and evaluation procedures.

The skill of sincere professional environment is captured in the communication competency (95% versus 45) that teamwork can offer, which is central to the collaboration model which applies, especially to engineering curriculum where collaborative teamwork is a fundamental core competence (Shuman et al., 2008; Clark et al., 2008; Bursic et al., 2011). Nevertheless, the idea of preservation of individual learning benefits in some situations may imply that optimal instruction designing can be based on harmonious application of both collaborative and individual modelling experiences (Rogovchenko and Rogovchenko, 2022; Wedelin et al., 2015). The range of variations in actual effectiveness in different dimensions of learning suggests that collaboration is not unconditionally better, but fulfils certain cognitive and interpersonal functions and enhances the process of study in an individual.

Keeping in mind that the motivation advantage (88% vs 65 percent) could be explained by the social engagement and peer support that group work offers, one should be cautious in interpreting this result because it might depend on the task design, both group composition, and the quality of facilitation (Mansilla et al., 2024; Martinez et al., 2025). There is a lack of studies that sufficiently accommodated these factors, indicating that the benefits of collaboration can be partially linked to implementation aspects, and to the alternative source of collaborative advantage. Besides, the personal learning advantages, described by Rogovchenko and Rogovchenko (2022) and Wedelin et al. (2015) point out that collaborative structures could seem cognitively debilitating or socially disabling to some individual students.

Individual metacognition and social metacognition
The study by Schukajlow et al. (n.d.) of individual and social metacognition in modelling-related activities presents theoretical background on why collaborative methods are so particularly beneficial in metacognition development. Nevertheless, the small body of research on comparisons between collaborative and individual strategies directly limits insights into the best plans of implementation and student traits that either moderate the performance (Mansilla et al., 2024; Schneider and Terrell, 2011).

Moving Research.

The collected temporal data indicate strong paradigmatic growth between the early body of characterization research (2003-2005) and current studies of metacognitive and attitudinal (2022-2024) research as a testament to the financial technicality and empirical refinement of the field (Cardella and Atman, 2005; Mansilla et al., 2024; Castro, 2024). The high level of research in the specific time (2008-2011) when MEA was developed evidences how new pedagogical innovations may trigger further research investment and even the establishment of communities (Frank et al., 2013; Kaupp et al., 2013; Yildirim et al., 2009; Yildirim et al., 2010; Shuman et al., 2008). But, even this intensity indicates that studies are prioritised by institutional inertia instead of mandated needs.

The cognitive perspective era (2013-2015) was the significant point of transition to the process-oriented research design that investigated the mathematical thinking of students during the modelling work (Czocher, 2016; Czocher, 2013; Wedelin et al., 2015). The proposed models of transition diagrams and analysis of cognitive constructs include supporting frameworks that remain relevant to the modern studies (Czocher, 2016, 2013). The short period of such concentration, however, points to the likelihood that, the study of cognitive processes was perhaps too early superseded by the renewed interest in pedagogical innovation, as opposed to more theoretically substantive development.

Applicability to Other Disciplines and to Situations.

External limited disciplinary focus (15% limitation frequency), which is an inherent characteristic of mathematical modelling, essentially disrupts the claims on the universal educational value of mathematical modelling (Mansilla et al., 2024; Martinez et al., 2025; Lyon and Magana, 2020; Gutiérrez and Gallegos, 2019). Pedagogies overtly modified to fit engineering epistemology, type of problems and professional contexts, as opposed to generalised educational processes may have been identified in the engineering-centric research base. It can be argued that mathematical modelling can be pursued with radically different cognitive and interpretative orientations, and instantiate different pedagogies, which require by definition.

The fact that very little has been explored in terms of discipline has indicated that the field has presumed as opposed to proving the transferability in different academic fields in an empirical manner (Lyon and Magana, 2020; Cardella and Tolbert, 2014; English, 2023). Such assumption is problematic considering that critical thinking learning formation can occur differently depending on the field of study, where liberal arts situations might have an emphasis on interpretive, multiple-point-of-view, and qualitative analysis compared to technical problem-solving and quantitative model. The fact that these differences are not studied hampers the theoretical knowledge and actual application involved in mathematical modelling in various educational fields.

The works of Castro (2024) on the development of the interdisciplinary critical skills and the framework of English (2023) on STEM-based problem solving are major attempts to incorporate cross-disciplinary applications but are not enough to introduce the broad-based applicability. Significant issues in innovative pedagogies are the scalability (frequency limitation 8%) problems, which as practical imperatives relate to the widespread use (Martinez et al., 2025; Diefes-Dux et al., 2004). MEAs and technology-enhanced methods can also demand significant faculty training, institutional, and resource investments that might not be possible in a wide range of learning situations.

Technology-mediation and Digital-mediation.

The lack of systematic studies on technology integration (6% limitation frequency) is a much-needed oversight regardless of the growing digitization of the learning contexts and the possibility of technology positively impacting metacognitive control and group learning (Medina and Thurston, 2003; Dominguez, 2024; Herrera et al., 2020). Technology use references in the literature tend to reflect digital technology as an incidental feature as opposed to the theoretical inclusion of technological tools as part of mathematical modelling pedagogy (Martinez et al., 2025; Rogovchenko and Rogovchenko, 2022). This methodology does not discuss how technology can be a groundbreaking way of changing cognition processes, social relations once, and the learning results in mathematical modelling situations.

The range of technology potential to support metacognitive processes by use of real-time feedback, visualisation aids and collaborative technology was largely unexplained despite theoretical frameworks that proposed a potential greater benefit (Dominguez, 2024; Herrera et al., 2020). Online worlds can support new methods of mathematical representation, dynamic modelling, and peer communication which could increase individual learning as well as learning in a collaborative context. Nevertheless, there is no systematic research to allow an evidence-based incorporation of technology in mathematical modelling courses.

V. CONCLUSION AND RECOMMENDATIONS

This meta-analysis of 50 publications indicates that mathematical modelling teaches critical thinking skills in higher education to a significant extent, and 68% of the studies describe extremely high effectiveness (Mansilla et al., 2024; Rezaei and Asghary, 2024; Martinez et al., 2025). Unified modelling strategies are always more effective in all aspects, such as metacognitive development (line effectiveness of 90% and 75%), communication skills (95% and 45%) and ideas are adopted in social constructivism learning theories (Mansilla et al., 2024; Schneider and Terrell, 2011). Model Eliciting Activities become especially useful pedagogical instruments, as strong results of numerous studies prove the high-quality outcomes of problem-solving and critical thinking (Frank et al., 2013; Yildirim et al., 2009).

But serious setbacks that limit the theoretical growth of the field as well as its practical usefulness exist. The engineering/focused area (92% of studies) dramatically restricts the ability to apply to liberal arts settings, and methodological risks such as small sample sizes (22% of studies) and lack of longitudinal study (18) curtail any validity assertion (Cole et al., 2011; Czocher, 2016). The most dominant quantitative orientation (42% of studies) fails to capture sufficiently the complexity of cognitive processes that underlie the success of mathematical modelling.

Research should therefore focus on the future by undertaking cross-disciplinary studies, longitudinal research that focuses on the long term effects of learning, as well as systematic studies on technology integration. The theoretical knowledge will be improved through developing standardised assessment tools and broadening qualitative approaches. It is with these basic gaps, only by discussing the possibility of more intelligible and respons powering mathematical modelling in general, in educational settings, that the direct application of critical thinking, in both the broad and narrow senses, can become maximised.

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