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Research articles

Computational thinking in mathematics instruction integrated STEAM education: Global trend and students' achievement in the last two decades

Suparman[1], Dadang Juandi[1], Turmudi[1], Wahyudin[1]

Abstrak Studi ini mendeskripsikan dan mensintesis tren global dan pencapaian berpikir komputasi siswa dalam pembelajaran matematika yang menggunakan pendekatan STEAM. Sebuah riviu sistematik yang menggunakan analisis bibliometrik dan meta-sintesis kualitatif diterapkan untuk melakukan studi ini. Lima ratus sembilan studi inklusi yang terindeks Scopus dan dipublikasikan antara 2004 dan 2023 digunakan sebagai data untuk analisis bibliometrik. Secara khusus, 14 studi empiris kualitatif diinklusikan dalam meta-sintesis kualitatif. Hasil penelitian ini mengungkapkan bahwa perkembangan publikasi dari studi-studi berpikir komputasi cukup meningkat, sedangkan perkembangan sitasi terhadap studi-studi berpikir komputasi relatif berfluktuasi pada periode 2004 – 2023. Terdapat beberapa tema yang muncul terkait studi-studi berpikir komputasi, seperti: komponen berpikir komputasi, domain kognitif, afektif, dan psikomotor, konten matematika, lingkungan belajar berpikir komputasi, intervensi teknologi dalam berpikir komputasi, metodologi penelitian, negara popular yang dilibatkan dalam berpikir komputasi, partisipan, jenjang pendidikan, dan komponen STEAM. Secara umum, siswa sudah mencapai lima komponen berpikir komputasi, seperti: pengenalan pola, abstraksi, dekomposisi, generalisasi, dan algoritma yang disebabkan oleh pengintegrasian pendekatan STEAM. Simpulan dan implikasi dari studi ini untuk pendidikan matematika secara komprehensif didiskusikan.

Kata kunci *Berpikir komputasi, Bibliometrik, Meta-sintesis kualitatif, Pembelajaran matematika, STEAM*

Abstract Present study describes and synthesizes global trend and students' CT achievement in mathematics instruction integrated STEAM education. A systematic review using bibliometric analysis and qualitative meta-synthesis was applied to do this study. Five hundred and nine studies indexed by Scopus and published between 2004 and 2023 were used as the data to bibliometric analysis. Particularly, 14 empirically qualitative studies were included in qualitative meta-synthesis. Results revealed that the publication development of CT studies slightly soared, whereas the citation development on CT studies relatively fluctuated in the period of 2004 – 2023. There were several emerging themes in CT studies, such as CT component, cognitive, affective, & psychomotor domain, mathematical content, CT learning environment, technological intervention in CT, research methodology, popular country involved in CT, participant, educational level, and STEAM component. Generally, students had achieved five CT components, such as pattern recognition, abstraction, decomposition, generalization, and algorithms caused by the integration of STEAM approach. The conclusion and implications of this study for mathematics education are comprehensively discussed.

Keywords *Computational thinking, Bibliometric, Qualitative meta-synthesis, Mathematics instruction, STEAM*

[1]Department of Mathematics Education, Universitas Pendidikan Indonesia, Bandung, Indonesia, arman95@upi.edu

Introduction

The sophisticated and fast development of science and technology in the 21st century require individuals, especially students in an educational context, to adapt to the emerging challenges, such as difficulties and problems. These challenges in lots of sectors, such as education, business, health, industry and others necessitate programming skills, a fundamental skill in computer science (Ehsan et al., 2018). The demands for educators with programming skills constrain them to have computational thinking (CT)─a central topic to be discussed on educational technology in numerous countries in the world (Abouelenein & Elmaadaway, 2023; Barrón-Estrada et al., 2022; del Olmo-Muñoz et al., 2020; Fry et al., 2023; J. Sung et al., 2023). In a literature, Molina-Ayuso et al. (2022) stated that CT, an integrated and comprehensive skill, can promote students in solving complex problems in many scientific fields, such as mathematics, science, technology, engineering, and art. Therefore, such a skill must be an essential consideration in the educational field by developing and enhancing it in the learning environment.

Many literatures mentioned that CT refers to the way of thinking to problem-solving containing effective, efficient, and comprehensive phases, such as algorithm, pattern recognition, abstraction, and decomposition as some basic concepts in computer science (e.g., Aho, 2012; Brackmann et al., 2017; Brennan and Resnick, 2012; Grover and Pea, 2018; Henderson et al., 2007; Lu and Fletcher, 2009; Wing, 2006). Particularly, CT is extremely related to mathematics as a basic language of sciences in that mathematical thinking activities require CT skills. Some literatures found that mathematics achievement and CT skills have a positive correlation in which the higher students' CT skills, the higher students' mathematics achievement, and vice versa (e.g., Aminah et al., 2022, 2023; Angraini et al., 2023; Hanid et al., 2022; Kaup et al., 2023). Some CT components (e.g., decomposition, pattern recognition, abstraction, and algorithm) promote students to get high math achievement. Meanwhile, some mathematical abilities, such as problem-solving and reasoning promote students to master CT components. These reveal that CT skills are crucial for students' mathematics achievement. Several empirical studies, however, revealed that the achievement of students' CT has not been optimal (e.g., Budiyanto et al., 2022; Cui and Ng, 2021; Fanchamps et al., 2021; Leonard et al., 2023; Moreno-León et al., 2015). Internationally, students' CT skills are still low (e.g., Cui and Ng, 2021; Leonard et al., 2023), in which CT skills are newly integrated into the educational field from computer science in the early 21st century so that they are still difficult to deal with this newly emerging issue (Kaup et al., 2023). Including CT skills in the environment of mathematics learning is one of the logical ways to cultivate students' CT skills in mathematics education. Therefore, effective interventions in the environment of mathematics learning are necessitated to optimize students' CT skills.

The optimization of CT skills for enhancing students' mathematics achievement can be carried out in mathematics learning environment because the CT components, such as problem decomposition, pattern recognition, abstraction, and algorithm are relatively related to students' mathematics activities in solving math problems (Fry et al. 2023). A few of learning environments in mathematics, such as guided inquiry learning, problem-based learning, project-based learning, and discovery learning offer some strengths in cultivating complex problem-solving (Chan et al., 2020; Rich et al., 2020; Rodríguez-Martínez et al., 2020). Since complex problem-solving become a main purpose in CT skills (Molina-Ayuso et al., 2022), these mathematics instructions are suitable to cultivate students' CT in mathematics activities. Moreover, the involvement of science, technology, engineering, art, and mathematics (STEAM) education as an educational approach in mathematics instruction can strengthen the optimization of students' CT skills. Some empirical studies showed that STEAM approach provides significant positive effect on the acquisition of students' CT (e.g., Budiyanto et al., 2022; Chookaew et al., 2020; Guimaraes et al., 2020; Hu et al., 2020; Juškevičienė et al., 2021). From those, there is a rational and logical expectation if mathematics instruction integrated STEAM approach can optimize students' CT in the learning environment of mathematics.

Since CT was widely popularized in 2006 by Jeannete M. Wing, CT studies in mathematics instruction integrated STEAM approach have been increasingly grown in the last two decades. Because of this, the information regarding the publication and citation development of CT studies in the period of 2004 – 2023 is adequately required. Moreover, the emerging themes related to CT studies in mathematics instruction integrated into the STEAM approach to construct the novelties in this topic for the future studies are absolutely necessitated as scientific information. Even though a few of bibliometric analysis studies have presented those in mathematics education (e.g., Ersozlu et al., 2023; Muhammad et al., 2024). Nevertheless, to date there have not been bibliometric studies which focus on CT studies in mathematics instruction integrated STEAM approach. Additionally, the information regarding the extent of students' CT achievement in mathematics instruction integrated STEAM approach in the last two decades is also required to provide the substantive theories of students' achievement in CT components, such as algorithm, abstraction, decomposition, generalization, and pattern recognition. Although Ye, Lai, and Wong (2022) has studied it in a qualitative meta-synthesis, but it does not focus on mathematics education. So, a comprehensive qualitative meta-synthesis presenting substantive theories related to students' achievement in CT components is urgently essential to do.

The present study describes and synthesizes the collection of previously relevant CT studies in mathematics instruction integrated into STEAM education. This study is expected to show the publication and citation development regarding CT studies in mathematics instruction integrated STEAM education in the last two decades, and the emerging themes to construct the novelties in CT topic for future studies in mathematics classroom. Additionally, this study is also expected to provide the substantive theories (conjectures) regarding students' achievement in CT components, such as pattern recognition, abstraction, decomposition, generalization, and algorithm based on educational level and some famous countries. Particularly, the following research questions are directed to achieve the purpose of present study as follows: How is the development of publication and citation regarding CT studies in mathematics instruction integrated STEAM education in the last two decades? What the themes have emerged from CT studies in mathematics instruction integrated STEAM education in the last two decades? To what extend students' CT achievement in mathematics instruction integrated STEAM education in the last two decades, particularly in the perspective of participant country and educational level?

Theoretical framework

Computational thinking

Computational thinking (CT) refers to a complex process of problem-solving used by individuals, mainly students in educational contexts worldwide. Actually, the term "computational thinking" was firstly introduced by Papert in 1980 as a fundamental skill in computer science (Chookaew et al., 2018; Tonbuloğlu and Tonbuloğlu, 2019). Some literatures mentioned that Wing, then, widely popularized CT as cognition process involved in formulating problems since 2006 in computer science (e.g., Ehsan et al. 2018; Guimaraes et al., 2020; Ye et al., 2022). Synthesizing of some literatures, CT can be defined as the thinking way to problem-solving containing effective, efficient, and comprehensive phases, such as algorithm, pattern recognition, decomposition, and abstraction as some basic concepts in computer science (e.g., Brackmann et al., 2017; Grover and Pea, 2018; Henderson et al., 2007; Lu and Fletcher, 2009; Wing, 2006). Moreover, Wing (2006) explained those phases as following: (1) decomposition─ an ability to decompose problems or processes into smaller to solve problems; (2) pattern recognition─ an ability to perceive resemblances among different patterns; (3) abstraction─ an ability to screen only the essential parts of the processes; and (4) algorithm─ an ability to follow and identify an ordered series of steps and apply and create an ordered series of instructions.

Subsequently, Fry et al. (2023) stated that Australian Mathematics Curriculum in Computational Thinking proposes five components of CT, such as: (1) decomposition─ breaking down problems into parts; (2) abstraction─ focusing on the essential data; (3) pattern recognition─ analyzing the data and looking for the pattern to make sense of the data; (4) algorithm─ creating a series of ordered steps to solve a problem; and (5) generalization─ evaluating, adapting, and implementing the chosen solution to relevant problems. Additionally, Brennan and Resnick (2012) argued that CT involves three dimensions, such as computational practices, computational perspectives, and computational concepts. Grover and Pea (2018) also presented that generally CT encompasses the following concepts and practices. Particularly, CT concepts consist of logical thinking, algorithmic thinking, pattern recognition, abstraction and generalization, evaluation, and automation. Meanwhile, CT practices consist of problem decomposition, computational artefacts, testing and debugging, iterative refinement, and collaboration and creativity. Some literatures also mentioned that International Society for Technology in Education (ISTE) proposes that CT has several indicators, such as problem-solving, critical thinking, creativity, algorithmic thinking, debugging, data analysis, and generalization (e.g., Angeli, 2021; Leonard et al., 2023; Sáez López et al., 2021; Sung et al., 2017; Tan et al., 2021). Moreover, Juškevičienė et al. (2021) also mentioned that National Research Council (NRC) proposes some CT indicators, such as representation, computing artifact, data analysis, abstraction, algorithm, collaboration & communication, computing & society, decomposition, and evaluation. The framework of Australian Curriculum for CT was adopted as CT components or CT indicators to measure students' CT achievement.

Mathematics instruction and STEAM approach

Mathematics instruction integrated STEAM approach was used to optimize the achievement of students' CT skills. Several mathematics learning environments integrated to ICT in STEAM approach. Lots of learning models implemented in mathematics instruction, such as cooperative learning, problem-based learning, project-based learning, guided inquiry learning, discovery learning, and others relatively have constructive characteristics. Some literatures explained that constructive learning refers to a perspective in the educational context that focuses to construct students' knowledge in their own minds (e.g., Liu and Zhang, 2023; G. Sung et al., 2023; Tan et al., 2022; Tsai et al., 2023). This perspective assumes that students actively construct their knowledge and understanding through the process of creative and reflective thinking.

The learning models are integrated to STEAM approach─ a learning approach to solve problems (Gu et al., 2023; Mang et al., 2023). This approach aims to enhance students' knowledge and understanding in solving problems and making a decision (Horvath et al., 2023; G. Sung et al., 2023). A few of literatures mentioned how to do STEAM approach in the process of learning environment that it can start with asking (finding problem and solution)─ students identify a certain problem or need emerging from the condition, imagining the product─ they must imagine how the solution can be realized really, planning the product─ they can represent the product in complete sketch, and creating and testing the product─ they create and test the product repeatedly (e.g., Aguayo et al., 2023; Bertrand and Namukasa, 2023; Camacho-Tamayo and Bernal-Ballen, 2023). Moreover, the implementation of STEAM approach in mathematics instruction is assisted by several technologies promoting the optimization of students' CT skills, such as robotics, Scratch, virtual reality, Arduino, math laboratory, and game application (Bertrand and Namakusa, 2023; Mang et al., 2023). Four-teen eligible documents included in present study utilize those technologies to assist mathematics instruction integrated STEAM approach in optimizing students' CT achievement.

Methods

Research design

A systematic literature review was performed to conduct this study. A lot of published literature from empirical and secondary studies regarding CT and mathematics instruction integrated STEAM education were reviewed systematically. Moreover, recent study involved some analysis techniques, such as bibliometric analysis and qualitative meta-synthesis. Particularly, bibliometric analysis ─ a well-known and rigorous method to explore and analyze large volumes of scientific data (Donthu et al., 2021; Fuad et al., 2022; Putra et al., 2024; Sulistiawati et al., 2023; Suyanto et al., 2023), was applied to present the publication and citation development of CT studies, and the emerging themes related to CT studies in the last two decades. On the other hand, qualitative meta-synthesis ─ an inductive research method involving theoretical sampling, rigorous qualitative data analysis, and the development of a process model (Finfgeld-Connett, 2018; Leary and Walker, 2018; Mohammed et al., 2016), was applied to generate conjectures regarding the extent of students' CT achievements for several components, such as algorithm, abstraction, decomposition, generalization, and pattern recognition. In a literature, Cronin (2011) stated that there were several phases to systematically review the literature, such as: (1) stating the problems, (2) deciding the inclusion criteria, (3) searching the literature comprehensively, (4) selecting the document, (5) extracting the data, (6) analyzing the data, and (7) interpreting and making the report. Each systematic review phase is explained in the following subsections.

Inclusion criteria

To restrict the breadth of stated problems, some inclusion criteria were decided. Firstly, every document title had to contain keywords: "computational thinking" AND "mathematics" because this study focused on CT in mathematics field. Secondly, the document was such as conference paper or paper written in English, moreover, it was sourced from journal or conference proceeding because English was an international language and the sources covered some document types, such as review, article, and conference paper. Thirdly, the document was published between 2004 and 2023 because CT was well-known in the early of 2000s, and it covered some subject areas, such as social sciences, computer sciences, mathematics, arts &

humanities, or multidisciplinary. Fourthly, the population in document was Asian, American, European, African, or Australian students in the level of pre-school, primary school, secondary school, or college/university. Fifthly, the document also provided some qualitative reports related to CT components, such as algorithm, decomposition, algorithm, generalization, or abstraction because this study focused to provide the substantive theories regarding students' CT achievement in every educational level and some famous countries in the world. The documents which did not meet the inclusion criteria were removed from present study in the step of document selection.

Literature search

The database of Scopus was used to find documents related to CT and mathematics instruction integrated STEAM education. A few of literatures stated that Scopus is one of scientific databases which has large volumes of credible and well-qualified documents (Montoya et al., 2018; Zhu and Liu, 2020). The initial search conducted on November 15th, 2023, specifically at 11.59 PM found 948 documents published between 1970 and 2023.

Document selection

To systematically select literatures found in the initial search, four steps, such as: (1) identification, (2) screening, (3) eligibility, and (4) inclusion had to be passed through (Juandi et al., 2023; Juandi, Suparman, et al., 2022; Juandi, Tamur, et al., 2022; Suparman et al., 2022; Suparman and Juandi, 2022; Susiyanti et al., 2022; Tawaldi et al., 2023; Yunita et al., 2022). The selection process on those documents is briefly and comprehensively explained in Figure 1. Such that there were 509 documents which were eligible to be bibliometric data and, moreover, 14 documents which were eligible to be the data in qualitative meta-synthesis.

Data extraction

Generally, 509 documents which had passed through the screening step were eligible to be the data in bibliometric analysis. These documents were downloaded from the database of Scopus in two formats, such as CSV (Comma Separated Values) and RIS (Research Information System). RIS format provided some descriptively statistical information, such as publication & citation year, number of papers, number of citations, cites per year, cites per paper, authors per paper, h-index, and g-index (Fuad et al., 2022, 2023). Additionally, CSV format provided some information, such as document title, author, country, source, institution, publisher, document type, keywords, number of citations, number of publication, and publication year (Muhammad et al., 2022; Putra et al., 2024). The information was used as data in bibliometric analysis.

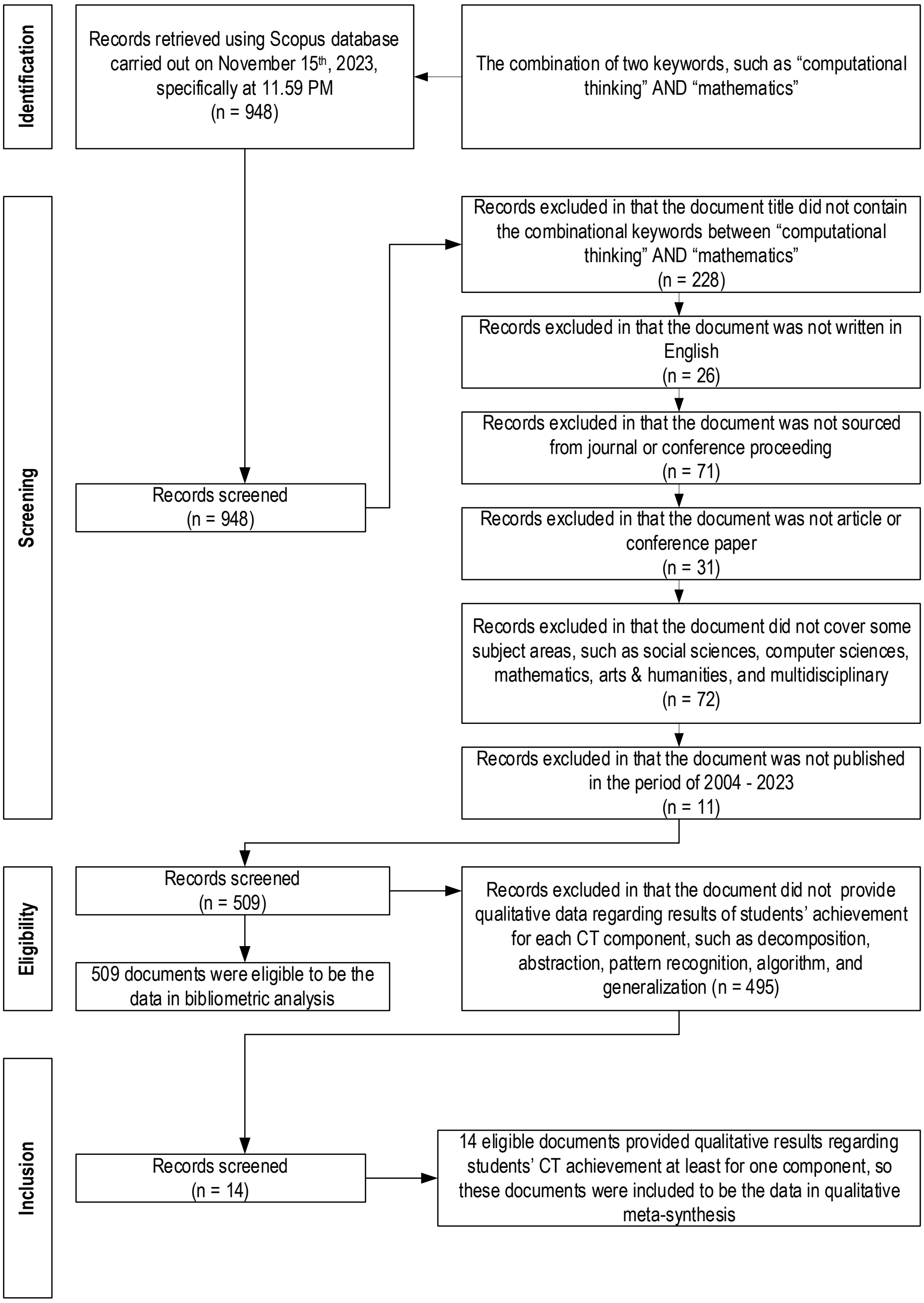

Figure 1. The systematic process of document selection

Particularly, 14 eligible documents included to be the qualitative meta-synthesis were extracted to the coding sheet. It consisted of code, author, research approach, research design, participant, instrument, qualitative results, document type, source type, journal or proceeding, email, and DOI or URL link. Some of the information, such as authors, methodology, sample size, participant, CT assessment, CT component, learning environment, ICT, and mathematical content were important to be presented in this text (see Appendix 1). Additionally, 14 documents were included to be the data in qualitative meta-synthesis whereby those provided qualitative results related to students' achievement for five CT components, such as algorithm, abstraction, decomposition, generalization, and pattern recognition. Some information on those documents, such as sample size, participant, and CT component are shown in Table 1.

Table 1. The existence of CT components of qualitative documents

Authors	Participant country	Educational level	N	CT component				
				C1	C2	C3	C4	C5
Fry et al. (2023)	Australia	Primary School	4	✓	✓	✓	✓	✓
Budiyanto et al. (2022)	Indonesia	College/University	8	✓	✓	✓	✓	✓
Leonard et al. (2023)	USA	Primary School	22	X	✓	X	✓	✓
Aminah et al. (2022)	Indonesia	College/University	21	✓	✓	X	✓	X
Hanid et al. (2022)	Malaysia	Secondary School	31	✓	✓	X	✓	✓
Cui and Ng (2021)	Hong Kong	Primary School	8	X	✓	X	X	X
Rich et al. (2020)	USA	College/University	1	✓	✓	✓	X	X
Dian (2020)	Indonesia	College/University	4	✓	✓	✓	X	X
Guimaraes et al. (2020)	Brazil	Primary School	2	✓	✓	✓	✓	X
Masfingatin and Maharani (2019)	Indonesia	College/University	3	✓	✓	X	✓	✓
Maharani et al. (2019)	Indonesia	College/University	3	✓	✓	X	✓	✓
Ehsan et al. (2018)	USA	Primary School	2	✓	✓	✓	✓	X
Pei et al. (2018)	USA	Secondary School	16	✓	X	✓	X	X
Shumway et al. (2021)	USA	Pre-School	36	✓	X	X	X	X

Note: C1: Decomposition; C2: Abstraction; C3: Pattern Recognition; C4: Algorithm; C5: Generalization; N: Research Subject; ✓: Exist; X: No Exist

The credibility and validity of the data used in the research had been required to provide the qualified reports (Cohen et al., 2018). Two experts in qualitative meta-synthesis were involved to verify and justify the data. After they re-coded and checked the data in the coding sheet, the coding consistency among coders for qualitative meta-synthesis part was performed. The Cohen's Kappa test was applied to describe and analyze the coding consistency among coders in that there were only two experts involved for each part (McHugh, 2012). In a literature, McHugh (2012) formulated the calculation of Cohen's Kappa as follows:

$$\kappa = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)}$$

$\Pr(a)$ represents the actual observed agreement while $\Pr(e)$ represents chance agreement. The Kappa value was categorized as 0.00–0.20 (None), 0.21–0.39 (Minimal), 0.40–0.59 (Weak), 0.60–0.79 (Moderate), 0.80–0.90 (Strong), and 0.91–1.00 (Almost Perfect) (McHugh, 2012). The results of Cohen's Kappa test are shown in Table 2.

Table 2. The results of Cohen's Kappa test

Coding item	Kappa value	Agreement level	Sig. value
Sample Size	0.832	Strong	0.017
Participant	0.849	Strong	0.017
Educational Level	0.875	Strong	0.011
Learning Environment	0.891	Strong	0.011
ICT	0.812	Strong	0.018
Mathematical Content	0.853	Strong	0.017
Decomposition	0.788	Moderate	0.022
Abstraction	0.714	Moderate	0.028
Pattern Recognition	0.794	Moderate	0.021
Algorithm	0.725	Moderate	0.027
Generalization	0.754	Moderate	0.024

From Table 2, it can be stated that the agreement level for each coding item was from moderate to strong. Moreover, the significant value for every coding item was less than 0.05 in which this interprets that they for each part significantly agree on the data (Fuadi et al., 2021; Jaya and Suparman, 2021; Suparman et al., 2021). Consequently, this provides strong evidence that the data included to qualitative meta-synthesis was credible and valid, and then the data can be analyzed.

Data analysis

Performance and co-occurrence analysis were performed to conduct bibliometric analysis. Particularly, performance analysis was applied to present the publication and citation development of CT studies in mathematics instruction integrated STEAM education in two last decades in which number of publications and citations for each of year were used to figure it in the line diagram (Fuad et al., 2022). Meanwhile, co-occurrence analysis was used to show the emerging themes and trends related to CT studies in the period of 2004 – 2023 whereby index keywords of every document were used to visualize the emerging theme and trend in network visualization (Suyanto et al., 2023). Performance analysis was supported by Publish or Perish (PoP) software and Microsoft Excel while co-occurrence analysis was promoted by VOSviewer software.

To analyze the data in qualitative meta-synthesis, coding paradigm in grounded theory was applied in which Corbin and Strauss (2015) stated that there were three coding phases in coding paradigm, such as open coding, axial coding, and selective coding. Particularly, in a literature, Qureshi and Ünlü (2020) explained that open coding focuses on the conceptualization and categorization of phenomena through an intensive analysis of the data. Practically, it breaks up the data into smaller parts which are deeply analyzed in which it aims to get the core idea of each part and develop a code to describe it. On the other hand, axial coding investigates the relationships between concepts and categories that have been developed in the open coding process. Meanwhile, selective coding integrates the different categories that have been developed, elaborated, and mutually related during axial coding into one cohesive theory. Furthermore, the context of coding paradigm proposed by Creswell (2012) was adjusted to the data in this qualitative meta-synthesis (see Figure 2).

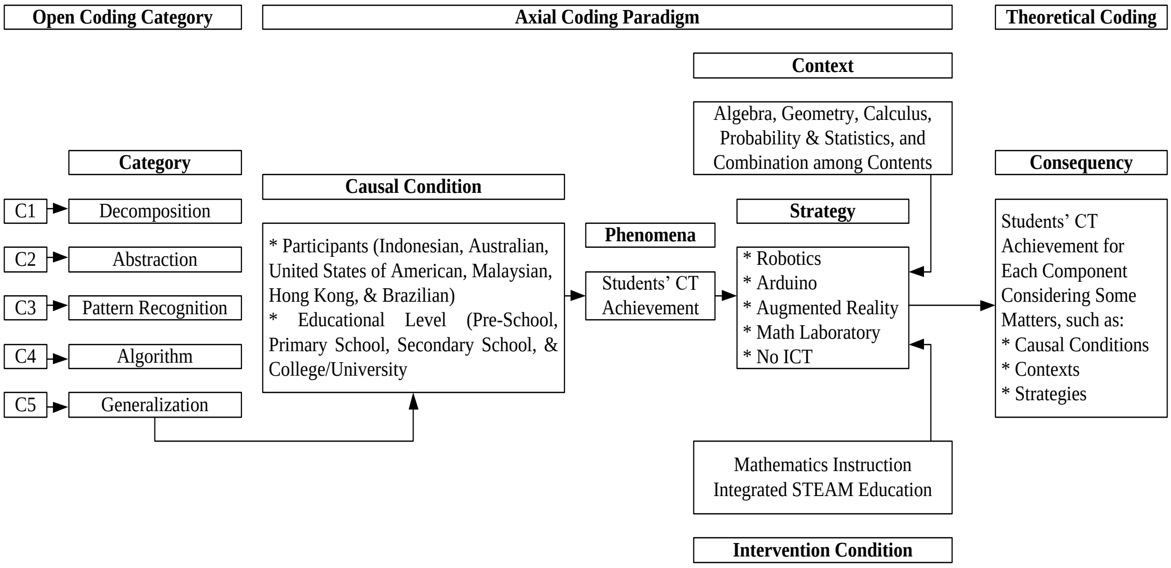

Figure 2. The coding paradigm of students' CT achievement for each component

From Figure 2, it can be stated that the coding paradigm of grounded theory generated some conjectures regarding students' CT achievement for five components, such as algorithm, abstraction, decomposition, generalization, and pattern recognition. Moreover, those conjectures would be substantive theories related to the extent of students' CT achievement in mathematics instruction integrated STEAM education in the last two decades. All of analyses in this qualitative meta-synthesis used Nvivo v.14 software.

Findings

Performance analysis

This analysis was used to present the publication and citation development of CT studies in mathematics instruction integrated STEAM education in the last two decades (Figure 3). In the period of 2004 and 2023, there were 509 documents consisting of 272 articles sourced from journal and 237 conference papers sourced from conference proceedings.

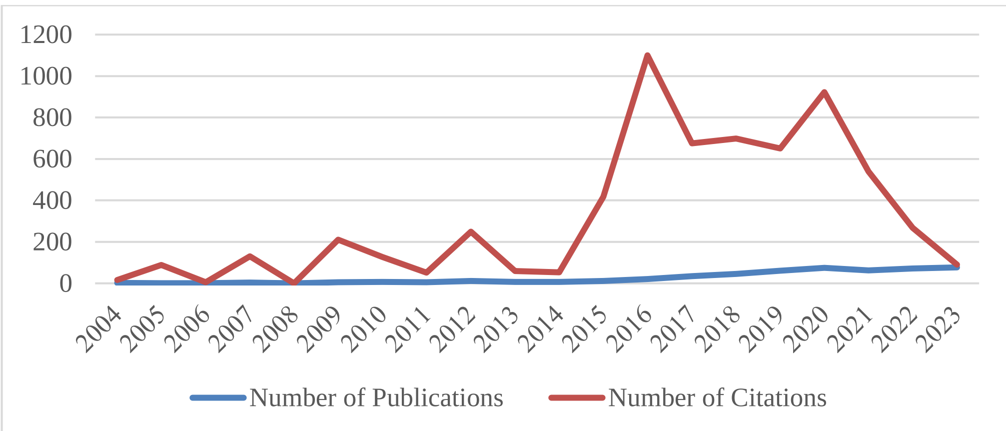

Figure 3. The publication and citation development regarding CT studies in the last two decades

From Figure 3, it can be stated that of 509 documents published between 2004 and 2023, there were two documents published in 2004, followed by one document in 2005, one document in 2006, four documents in 2007, five documents in 2009, seven documents in 2010, six documents in 2011, eleven documents in 2012, seven documents in 2013, seven documents in 2014, eleven documents in 2015, twenty documents in 2016, 34 documents in 2017, 46 documents in 2018, 61 documents in 2019, 74 documents in 2020, 63 documents in 2021, 72 documents in 2022, and 77 documents in 2023. This shows that the publication development related to CT studies in mathematics instruction integrated STEAM education slightly increased between 2004 and 2023.

Furthermore, of 6,350 citations on those documents, there were 16 citations in 2004, followed by 88 citations in 2005, five citations in 2006, 131 citations in 2007, 210 citations in 2009, 127 citations in 2010, 51 citations in 2011, 249 citations in 2012, 59 citations in 2013, 53 citations in 2014, 418 citations in 2015, 1,100 citations in 2016, 676 citations in 2017, 699 citations in 2018, 650 citations in 2019, 922 citations in 2020, 539 citations in 2021, 267 citations in 2022, and 90 citations in 2023. This reveals that the development of citations on those documents regarding CT studies in mathematics instruction integrated STEAM education sharply soared in the period of 2004 – 2016, whereas it sharply decreased in the period of 2016 – 2023. Consequently, these can be interpreted that the citation development on those documents regarding CT studies in mathematics instruction integrated STEAM education relatively fluctuated from 2004 to 2023.

Co-occurrence analysis

This analysis was used to show the emerging themes and trends regarding CT studies in mathematics instruction integrated STEAM education in the period of 2004 – 2023. Particularly, the network visualization analysis was applied to show the frequently emerging keywords regarding CT studies in mathematics instruction integrated STEAM education. The minimum number of occurrences of a keyword as many as one occurrence were selected, so 139 interconnected keywords appeared (Figure 4).

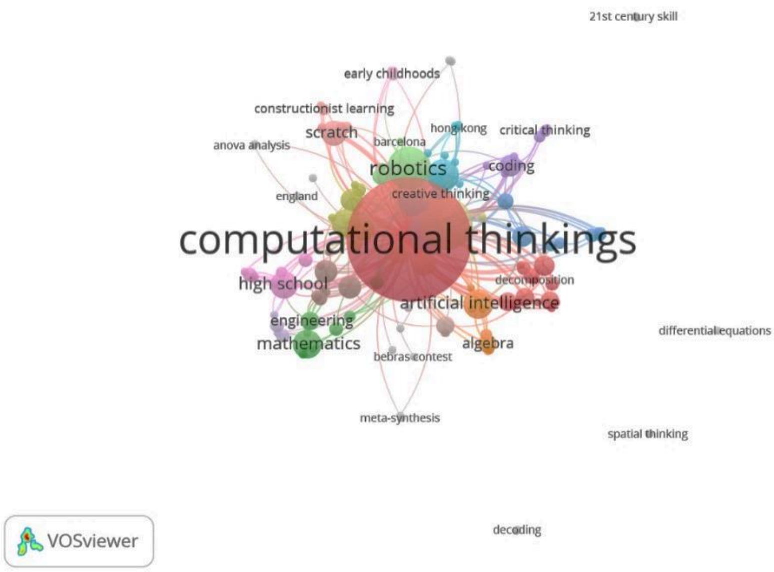

Figure 4. The network visualization of emerging keywords on CT studies in the last two decades

Moreover, thematic analysis was performed to group some similarly emerging keywords regarding CT studies in mathematics instruction integrated STEAM education into a theme (see Table 3). This analysis was more rigorous and precise than hierarchical clustering analysis in constructing the novelty of a certain research topic.

Table 3. The theme of emerging keywords regarding CT studies in the last two decades

Theme	Keyword	Frequency
CT Component	Decomposition	12
	Decoding	12
	Debugging Strategies	14
	Modelling Data	15
	Abstraction	39
	Algorithm	42
	Pattern Recognition	90
	Coding	90
	Generalization	13
	Logic	22
Cognitive Domain	Computational Thinking	2,755
	Problem-Solving	73
	21st Century Skill	11
	Spatial Thinking	11
	Creative Thinking	30
	Logical Thinking	27
	Abstract Thinking	14
	Algorithm Thinking	103
	Visuospatial Skills	11
	Coding Skills	14
	Critical Thinking	24
	Representation	22
	Deep Thinking	16
Affective Domain	Attitudes	9
	Self-Regulation	13
	Motivation	103
	Self-Efficacy	41
Psychomotor Domain	Decision Making	22
	Innovation	54
Mathematical Content	Arithmetic	18
	Number Patterns	8
	Geometry	12
	Three Dimensional	11
	Differential Equations	12
	Graph Theory	20
	Vectors	15
	Matrix	11
	Basic Mathematics	14
	Discrete Mathematics	46
	Number Theory	28
	Permutations	21
	Pigeonhole Principle	21
	Probability	32
	Composite Numbers	12
	Prime Number	12

	Algebra	62
Theme	Keyword	Frequency
	Functions	11
CT Learning Environment	ICT-based Education	13
	Robotics Education	14
	Blended Learning	14
	Problem-based Learning	30
	STEM Education	164
	E-learning	529
	Game-based Learning	102
	Project-based Learning	19
	Collaborative Learning	39
	Computational Learning	12
	Constructivist Learning	22
	Experiential Learning	25
	Asynchronous Teaching	8
	Computer aided Instruction	241
	Autonomous Learning	9
	Programming Education	63
	Unplugged Activities	21
Technological Intervention in CT	Web Application	10
	Scratch	98
	Augmented Reality	59
	Internet of Things	16
	Robotics	390
	Mathematics Software	13
	Math Laboratory	11
	Mobile Applications	35
	Mobile Games	8
	Digital Games	22
	Collaborative Games	25
	Arduino	55
	Artificial Intelligence	181
	Computer Algebra System	11
	Dynamic Geometry Software	13
Research Paradigm	Correlation Methods	13
	Pilot Studies	11
	Surveys	200
	Case Studies	25
	Qualitative Analysis	24
	Quasi-Experiments	23
	Questionnaire	18
	Mixed Method	32
Theme	Keyword	Frequency
	Systematic Literature Review	13
	Ethnographic Study	15
	Research and Development	20
	Meta-Synthesis	11
	Comparison Study	14
	ANOVA	8
	Confirmatory Factor Analysis	35
	Literature Reviews	21
	Regression Analysis	10

Theme	Keyword	Frequency
	Thematic Analysis	12
	Interview	18
	Focus Groups	12
	Empirical Experiment	10
Popular Country Involved in CT	Hong Kong	12
	Africa	26
	Belgium	14
	Swedish	13
	Mexico	10
	England	9
	Ireland	13
	Indonesia	11
	Portugal	11
Participant	Elementary Students	39
	Early Childhoods	26
	Undergraduate Students	109
	Middle School Students	80
Educational Level	High School	29
	Middle School	154
	Elementary Education	59
	Higher Education	53
	Primary Education	61
	Secondary Education	47
	Childhood Education	14
STEAM Component	Engineering	93
	Art	19
	Science	32
	Mathematics	169
	Technology	48

From Table 3, it can be stated that there were at least twelve emerging themes of 135 keywords regarding CT studies in mathematics instruction integrated STEAM education. Those themes were such as CT component, cognitive domain, affective domain, psychomotor domain, mathematical content, CT learning environment, technological intervention in CT, research methodology, popular country involved in CT, participant, educational level, and STEAM component. Moreover, the themes were explained in the discussion part to construct the novelty of CT studies in mathematics instruction integrated STEAM education.

Coding paradigm

This analysis was used to explore and investigate the extent to which students' CT achievement in the last two decades. Moreover, students' CT achievement was analyzed in the perspective of students' country, such as Indonesia, USA, Australia, Hong Kong, Malaysia, and Brazil, and students' educational level, such as pre-school, primary school, secondary school, and college/university. Coding paradigm was applied to promote this analysis in which three coding phases, such as open coding, axial coding, and selective coding (theoretical coding) were involved. Students' CT achievement was measured analyzing its components proposed by Australian Mathematics Curriculum in CT in Fry et al. (2023), such as algorithm, abstraction, decomposition, generalization, and pattern recognition. Particularly, the components have some indicators mentioned by Ehsan et al. (2018), such as decomposition: (1) breaking the data, processes, and problem into smaller and (2) managing the components to solve a problem; abstraction: (1) identifying the structure of concepts or main ideas and (2) utilizing the structure of concepts or main ideas; pattern recognition: (1) identifying a given pattern, (2) completing a missing pattern, (3) representing the pattern in a different way, and (4) creating an original pattern; algorithm: (1) following a series of ordered steps, (2) identifying the sequence of steps, (3) applying an ordered series of instructions, and (4) creating an ordered series of instructions; and generalization: (1) adapting the chosen solution to relevant problems, (2) implementing the chosen solution to relevant problems, and (3) evaluating the chosen solution to relevant problems.

Generally, from synthesizing 14 eligible documents in the last two decades, students had been able to master CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization (see Figure 5).

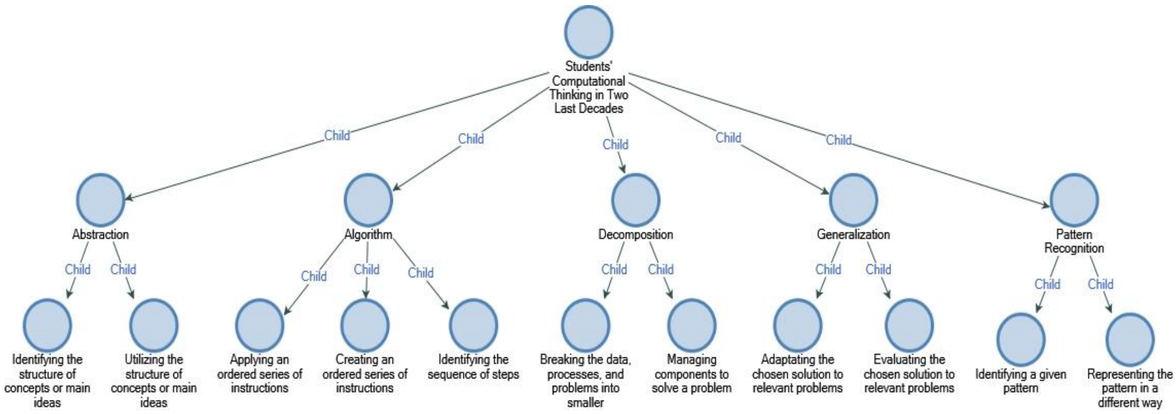

Figure 5. Students' CT achievement in the last two decades

From Figure 5, it can be stated that in two last decades, empirical CT studies revealed that students had relatively been able to break the data, processes, and problems into smaller, manage the components to solve a problem, identify and utilize the structure of concepts or main ideas, identify a given pattern, represent the pattern in a different way, identify the sequence of steps, apply and create an ordered series of instructions, and adapt and evaluate the chosen solution to relevant problems.

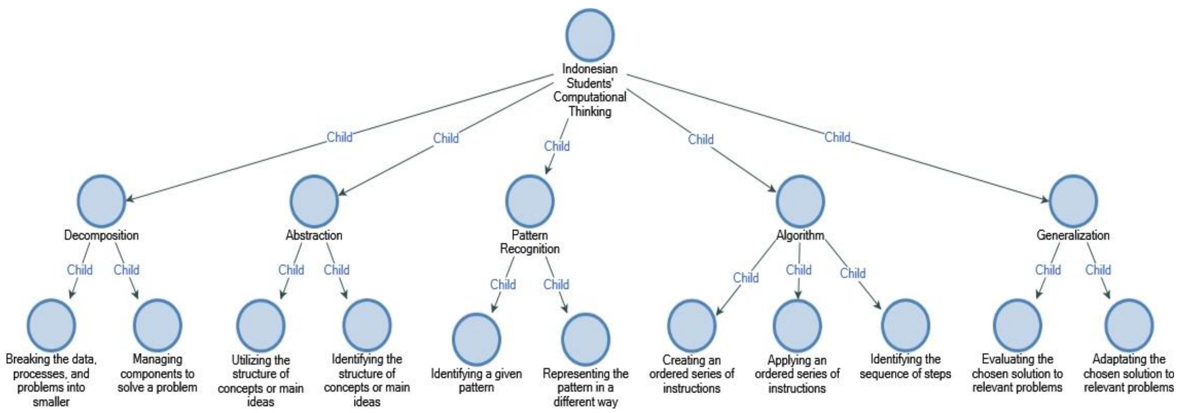

Figure 6. Indonesian students' CT achievement

There were six countries, such as Indonesia, USA, Australia, Hong Kong, Malaysia, and Brazil involved in this qualitative meta-synthesis based on the recorded documents. Firstly, synthesizing qualitative studies in five documents (e.g., Aminah et al., 2022; Budiyanto et al., 2022; Dian, 2020; Maharani et al., 2019; Masfingatin and Maharani, 2019) found that Indonesian students relatively could master five CT components, such as algorithm, abstraction, decomposition, generalization, and pattern recognition (see Figure 6). Moreover, this Indonesian students' CT achievement was intervened by mathematics education and STEM education in some mathematics contents, such as algebra, calculus, geometry, and combination among contents, and also promoted by the technology of robotics (see Figure 7).

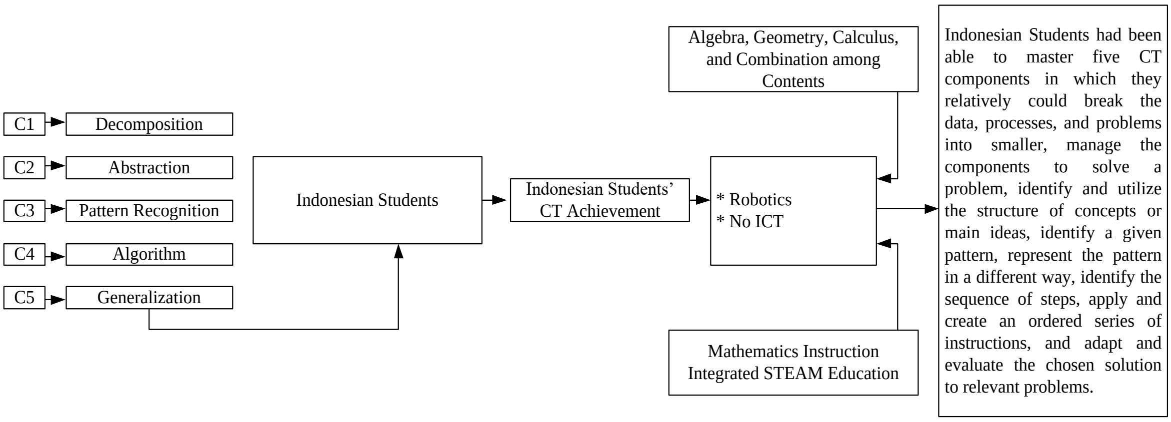

Figure 7. Conjectures of Indonesian students' CT achievement

Secondly, synthesizing qualitative studies in five documents (e.g., Ehsan et al., 2018; Leonard et al., 2023; Pei et al., 2018; Rich et al., 2020; Shumway et al., 2021) found that USA students relatively could master four CT components, such as algorithm, abstraction, pattern recognition, and decomposition (See Figure 8).

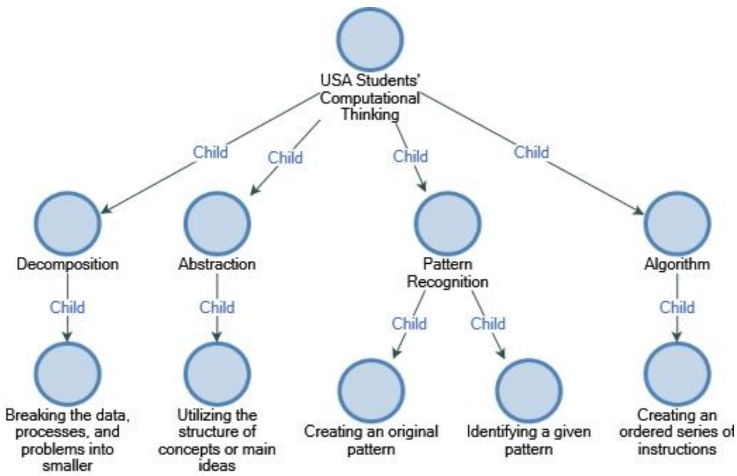

Figure 8. USA students' CT achievement

Furthermore, this USA students' CT achievement was intervened by robotics education, mathematics education and STEM education in a few mathematics contents, such as geometry and combination among contents, and also promoted by the technology of robotics (Figure 9).

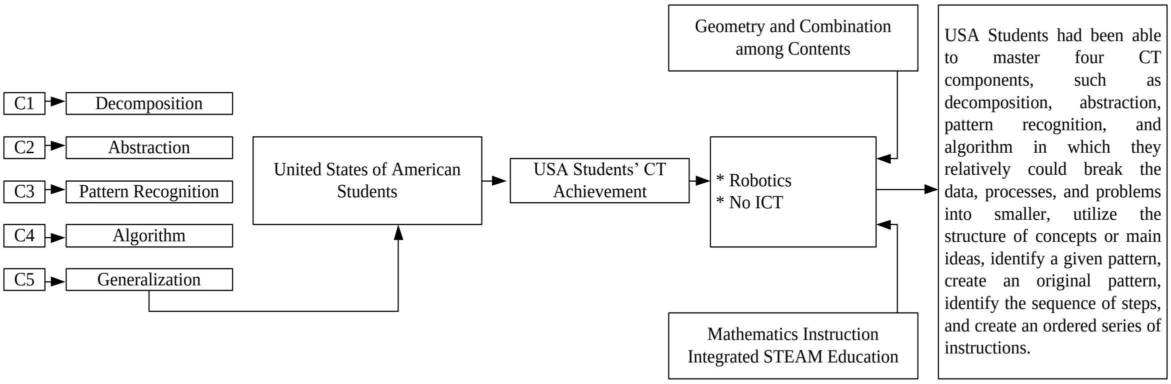

Figure 9. Conjectures of USA students' CT achievement

Thirdly, synthesizing qualitative study in a document (e.g., Fry et al., 2023) found that Australian students relatively could master five CT components, such as algorithm, abstraction, generalization, decomposition, and pattern recognition (Figure 10).

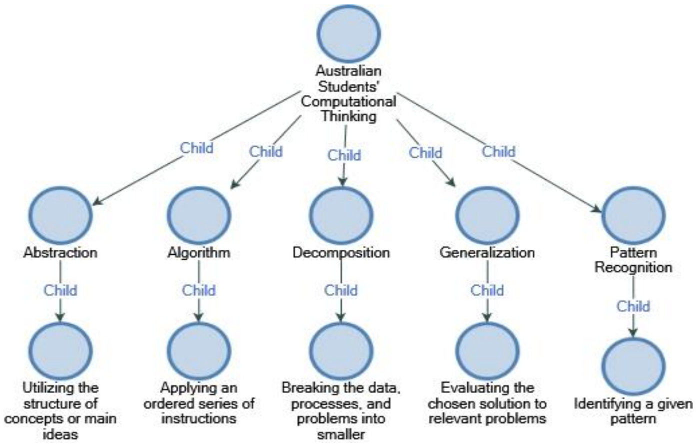

Figure 10. Australian students' CT achievement

Moreover, this Australian students' CT achievement was intervened by mathematics education in a content of probability and statistics (see Figure 11).

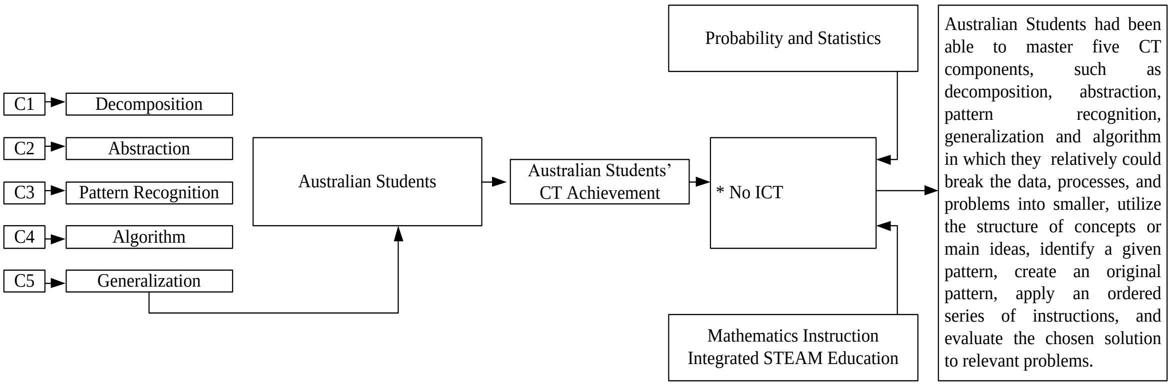

Figure 11. Conjectures of Australian students' CT achievement

Fourthly, synthesizing qualitative study in a document (e.g., Hanid et al., 2022) found that Malaysian students relatively could master four CT components, such as decomposition, abstraction, algorithm, and generalization (see Figure 12).

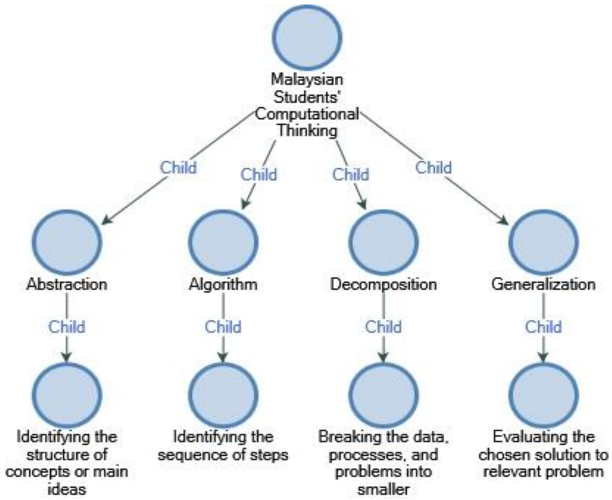

Figure 12. Malaysian Students' CT Achievement

Furthermore, this Malaysian students' CT achievement was intervened by mathematics education in a content of geometry and also promoted by the technology of augmented reality (Figure 13).

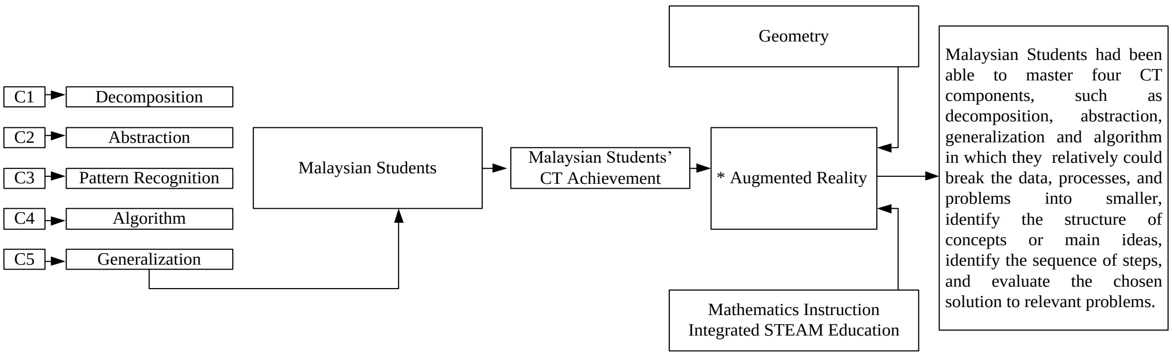

Figure 13. Conjectures of Malaysian Students' CT Achievement

Fifthly, synthesizing qualitative study in a document (e.g., Guimaraes et al., 2020) found that Brazilian students relatively could master three CT components, such as abstraction, pattern recognition, and algorithm (Figure 14).

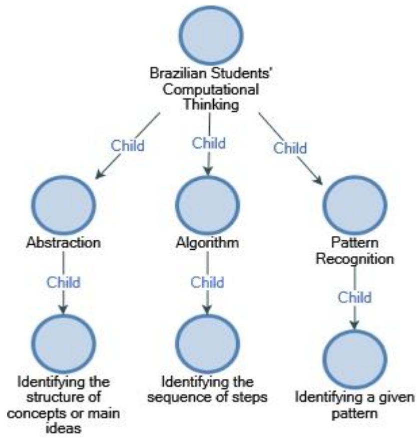

Figure 14. Brazilian students' CT achievement

Moreover, this Brazilian students' CT achievement was intervened by STEAM education in a content of geometry and also promoted by the technology of math laboratory (Figure 15).

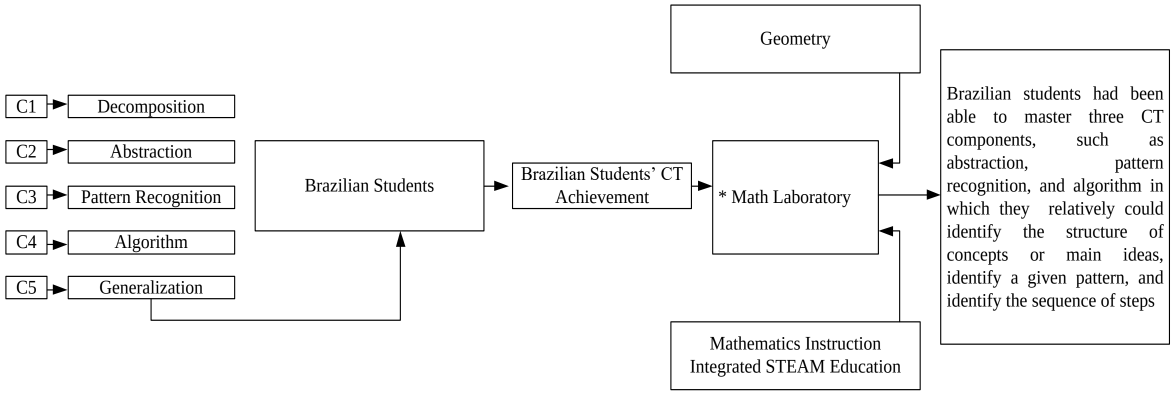

Figure 15. Conjectures of Brazilian students' CT achievement

Sixthly, synthesizing qualitative study in a document (e.g., Cui and Ng, 2021) found that Hong Kong students relatively could master one CT components, such as abstraction (Figure 16).

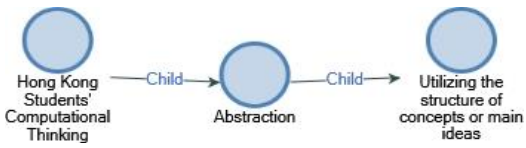

Figure 16. Hong Kong students' CT achievement

Moreover, this Hong Kong students' CT achievement was intervened by mathematics education in the combination among contents and also promoted by the technology of Arduino (Figure 17).

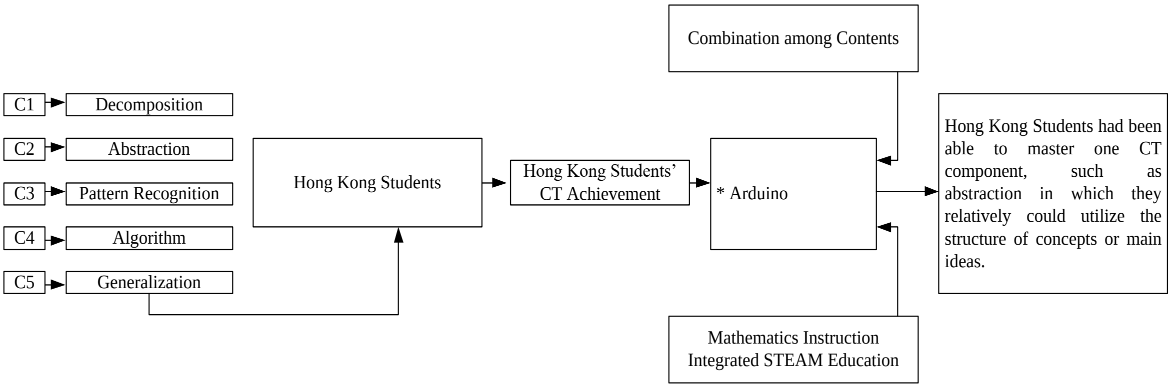

Figure 17. Conjectures of Hong Kong students' CT achievement

Furthermore, there were four educational levels, such as pre-school, primary school, secondary school, and college/university involved in this qualitative meta-synthesis based on the recorded documents. Firstly, synthesizing qualitative studies in six documents (e.g., Aminah et al., 2022; Dian, 2020; Maharani et al., 2019; Masfingatin and Maharani, 2019; Rich et al., 2020; Budiyanto et al., 2022) found that college/university students relatively could master five CT components, such as algorithm, abstraction, generalization, decomposition, and pattern recognition (Figure 18).

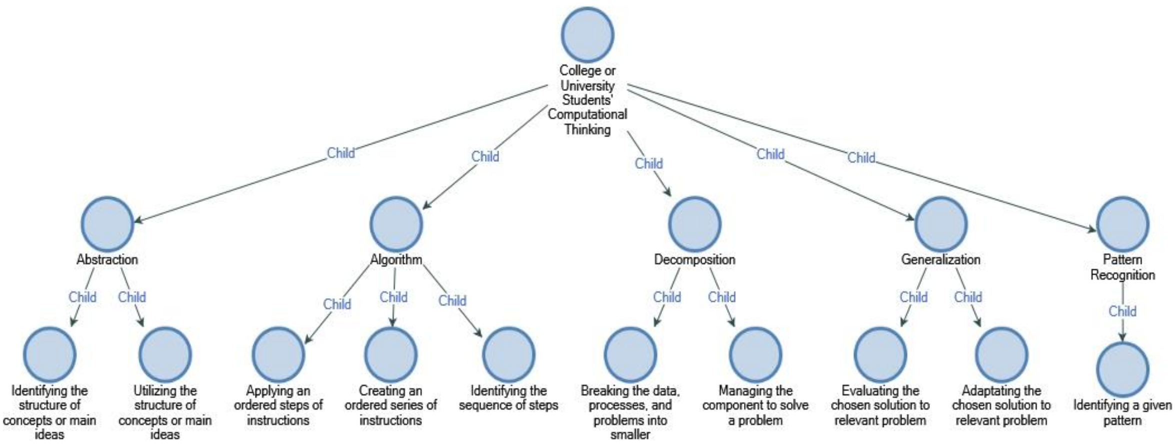

Figure 18. College/University students' CT achievement

Moreover, this college/university students' CT achievement was intervened by mathematics education and STEM education in some mathematics contents, such as algebra, calculus, geometry, and combination among contents, and also promoted by the technology of robotics (Figure 19).

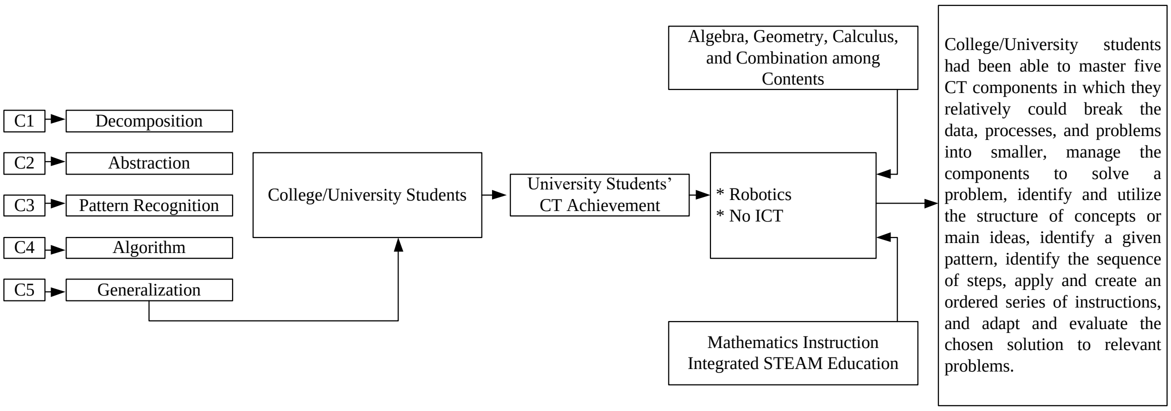

Figure 19. Conjectures of College/University students' CT achievement

Secondly, synthesizing qualitative studies in two documents (e.g., Hanid et al., 2022; Pei et al., 2018) found that secondary students relatively could master five CT components, such as algorithm, abstraction, generalization, decomposition, and pattern recognition (Figure 20).

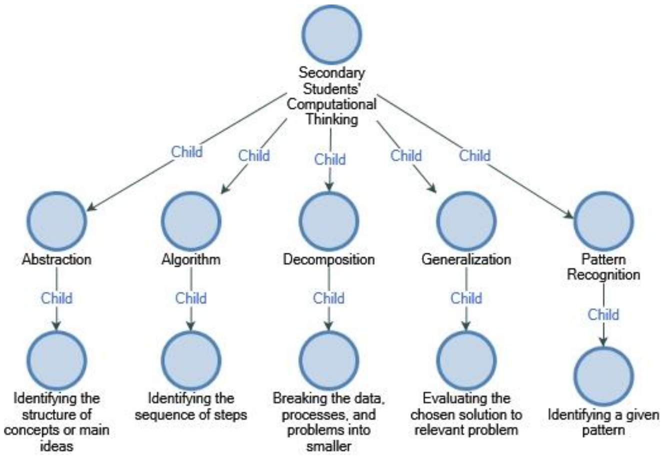

Figure 20. Secondary students' CT achievement

Furthermore, this secondary students' CT achievement was intervened by mathematics education in a content of geometry, and also promoted by the technology of augmented reality (Figure 21).

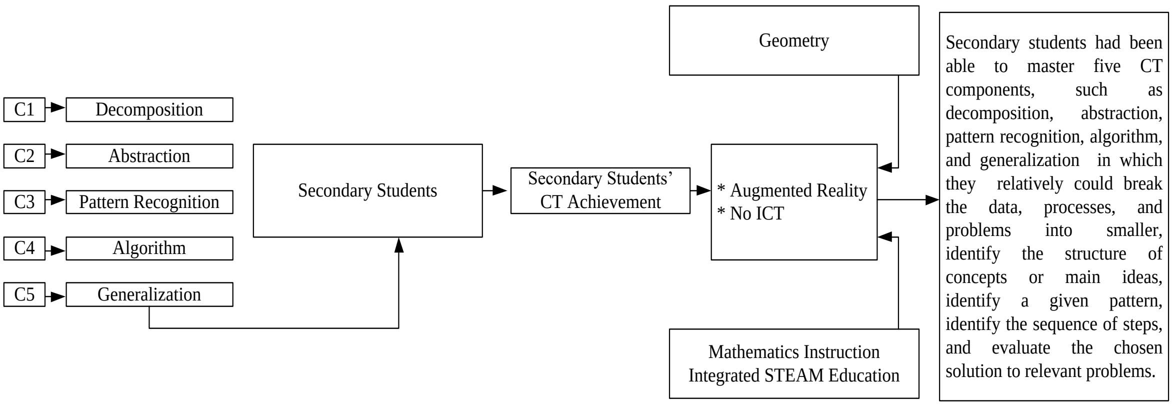

Figure 21. Conjectures of secondary students' CT achievement

Thirdly, synthesizing qualitative studies in five documents (e.g., Cui and Ng, 2021; Ehsan et al., 2018; Fry et al., 2023; Guimaraes et al., 2020; Leonard et al., 2023) found that primary students relatively could master five CT components, such as algorithm, abstraction, generalization, decomposition, and pattern recognition (Figure 22).

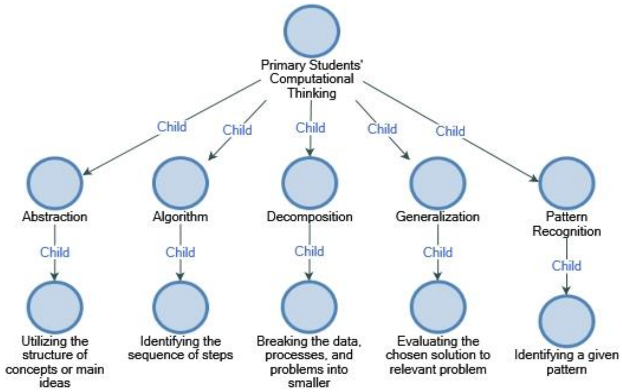

Figure 22. Primary students' CT achievement

Moreover, this primary students' CT achievement was intervened by robotics education, mathematics education, STEM education, and STEAM education in a few mathematics contents of geometry, probability and statistics, and combination among contents, and also promoted by the technology of robotics, Arduino, and math laboratory (Figure 23).

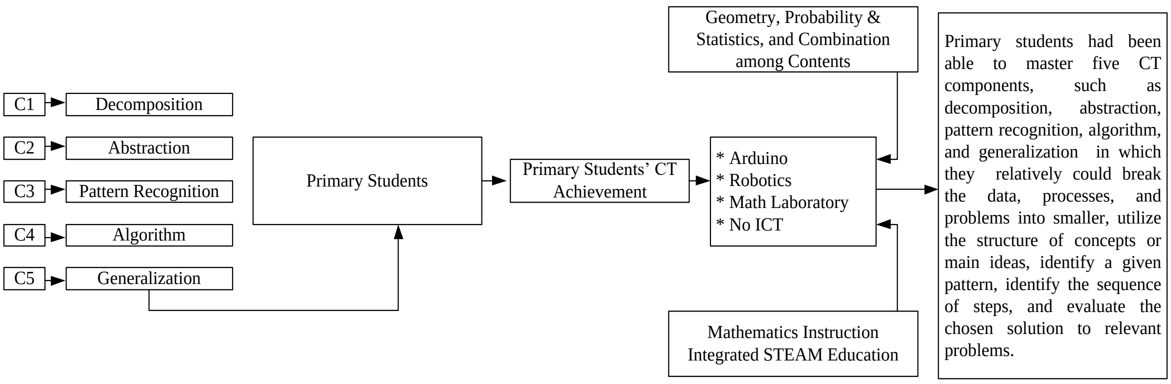

Figure 23. Conjectures of primary students' CT achievement

Fourthly, synthesizing qualitative study in a document (e.g., Shumway et al., 2021) found that pre-school students relatively could master one CT component, such as decomposition (Figure 24).

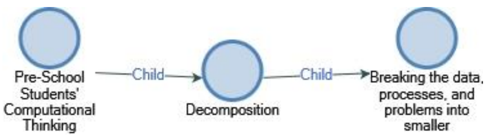

Figure 24. Pre-school students' CT achievement

Furthermore, this pre-school students' CT achievement was intervened by mathematics education in combination among mathematics contents, and also promoted by the technology of robotics (Figure 25).

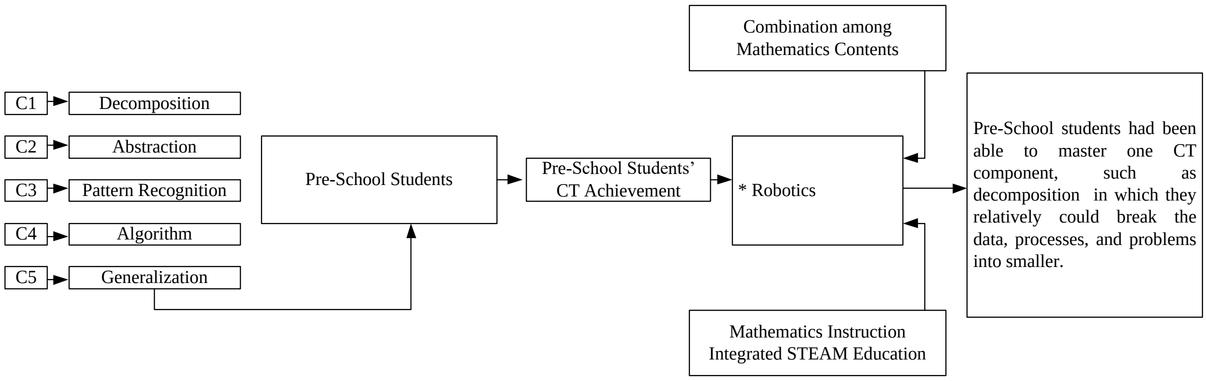

Figure 25. Conjectures of pre-school students' CT achievement

Discussion

Construction of the novelties for future CT studies in mathematics education

This study presents that the development of publication related to CT studies in mathematics instruction integrated STEAM education slightly increased in the period of 2004 – 2023. In a literature, Muhammad et al. (2024) also reported that the development of CT studies in mathematics learning slightly soared from 2011 to 2022. Additionally, Ersozlu et al. (2023) also revealed that the development of publication regarding CT studies in mathematics sharply jumped up in the period of 2018 – 2021. From these reports, it can be interpreted that since 2004 to date, CT has become a research topic gradually gained interest by many researchers worldwide, especially in the field of mathematics education. On the other hand, the development of citation on the documents regarding CT studies in mathematics instruction integrated STEAM education is relatively fluctuated from 2004 to 2023. Ersozlu et al. (2023) also reported that the development of citation on the documents regarding CT studies in mathematics relatively fluctuated in the period of 2018 – 2021. Muhammad et al. (2024), however, showed that the development of citation on the documents related to CT studies in mathematics learning slightly increase between 2011 and 2022. This interprets that the development of publication regarding CT studies in mathematics education is not parallel to the development of citation on the documents focusing on CT studies in mathematics education. Moreover, this indicates that the influence of published documents regarding CT studies in the field of mathematics has not been consistent to the development of research topics in CT.

Furthermore, this study shows that there were several emerging themes of published documents focusing on CT studies in mathematics instruction integrated STEAM education, such as CT component, cognitive, affective, & psychomotor domain, mathematics content, CT learning environment, technological intervention in CT, research methodology, popular country involved in CT, participant, educational level, and STEAM component. From those themes, there were a few main themes to construct the novelties for the future CT studies in mathematics education. Firstly, it was CT component containing some keywords, such as decomposition (12), decoding (12), debugging strategies (14), modelling data (15), abstraction (39), algorithm (42), pattern recognition (90), coding (90), generalization (13), and logic (22). From those keywords, the frequency of decomposition, decoding, modelling data, and generalization was relatively rare emergence. This indicates that the enhancement of students' CT skills in the component of decomposition, decoding, modelling data, and generalization has not been carried out optimally. Fry et al. (2023) stated that decomposition, modelling, and generalization are three of the essential CT components proposed by Australian Mathematics Curriculum in CT. Consequently, future CT studies, especially in mathematics education should focus on the optimization of students' CT skills in the component of decomposition, modelling, and generalization.

Secondly, it was affective domain in the optimization of students' CT skills consisting of attitudes (9), self-regulation (13), motivation (103), and self-efficacy (41). It can be stated that the emerging frequency of attitudes, self-regulation, and self-efficacy was rare. Meanwhile, Suparman and Juandi (2022) revealed that self-regulation and self-efficacy are essential parts in mathematics learning to promote the optimization of students' mathematics achievement. Therefore, the future CT studies in mathematics education should involve the optimization of students' affective domain, such as self-efficacy and self-regulation, besides the optimization of students' CT achievement.

Thirdly, it was mathematics content containing several keywords, such as arithmetic (18), number patterns (8), geometry (12), three dimensional (11), differential equations (12), graph theory (20), vectors (15), matrix (11), basic mathematics (14), discrete mathematics (46), number theory (28), permutation (21), pigeonhole principle (21), probability (32), composite numbers (12), prime number (12), algebra (62), and function (11). This shows that some mathematics contents, such as algebra, geometry, number and operation, calculus, combinatorics, and probability have covered the optimization of students' CT skills in mathematics education. Statistics, however, as one of essential parts of mathematics content has not been relatively involved in the optimization of students' CT achievement. Consequently, future CT studies in mathematics education should involve statistics as a mathematics content to optimize students' CT skills.

Fourthly, it was CT learning environment consisting of ICT-based education (13), robotics education (14), blended learning (14), problem-based learning (30), STEM education (164), e-learning (529), game-based learning (102), project-based learning (19), collaborative learning (39), computational learning (12), constructivist learning (22), experiential learning (25), asynchronous teaching (8), computer aided instruction (241), autonomous learning (9), programming education (63), and unplugged activities (21). From those keywords, the emerging frequency of ICT-based education, robotics education, blended learning, project-based learning, computational learning, asynchronous teaching, and autonomous learning was rare. Some literatures stated that robotics learning, computational learning, and autonomous learning are the precisely effective learning to optimize the achievement of students' CT skills (e.g., Hanid et al., 2022; Kaup et al., 2023). As consequence, future CT studies in mathematics education should use robotics learning, computational learning, and autonomous learning to optimize students' CT achievement.

Fifthly, it was participant containing several keywords, such as Hong Kong (12), Africa (26), Belgium (14), Swedish (13), Alabama (16), Mexico (10), Pennsylvania (20), Pittsburgh (20), California (10), Barcelona (14), England (9), Ireland (13), Indonesia (11), and Portugal (11). This shows that the optimization of students' CT skills was relatively rarely conducted in Indonesia. Meanwhile, a few of empirical studies found that Indonesian students' CT achievement has not been optimal (e.g., Aminah et al., 2022; Maharani et al., 2019; Budiyanto et al., 2022). Consequently, the optimization of Indonesian students' CT skills must be massively conducted in Indonesia by doing research in CT topic.

Sixthly, next theme was related to technological intervention in CT consisting of web application (10), Scratch (98), augmented reality (59), internet of things (16), robotics (390), mathematics software (13), math laboratory (11), mobile applications (35), mobile games (8), digital games (22), collaborative games (25), Arduino (55), artificial intelligence (181), computer algebra system (11), and dynamic geometry software (13). From those keywords, the emerging frequency of mathematics software, math laboratory, mobile games, computer algebra system, and dynamic geometry software was relatively rarely used to promote the optimization of students' CT skills in mathematics instruction integrated STEAM education. Several literatures found that technological approach in mathematics education like the mathematics software, such as math laboratory, mobile games, computer algebra system, and dynamic geometry software is effective to promote the optimization of students' CT achievement (e.g., del Olmo-Muñoz et al., 2023; Guimaraes et al., 2020; Presser et al., 2023). Consequently, the future CT studies in mathematics education should utilize some technologies, such as math laboratory, mobile games, computer algebra system, and dynamic geometry software to optimize the achievement of students' CT skills in mathematics instruction.

The conjectures of students' CT achievement in mathematics instruction integrated STEAM approach

Overall, students in the worldwide had been able to master CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. Particularly, they had relatively been able to break the data, processes, and problems into smaller, manage the components to solve a problem, identify and utilize the structure of concepts or main ideas, identify a given pattern, represent the pattern in a different way, identify the sequence of steps, apply and create an ordered series of instructions, and adapt and evaluate the chosen solution to relevant problems. This shows that they have mastered all indicators of decomposition and abstraction, but they can't complete a missing pattern, create an original pattern, follow a series of ordered steps, and implement the chosen solution to relevant problems. Ehsan et al. (2018) stated that abilities to complete a missing pattern, create an original pattern, follow a series of ordered steps, and implement the chosen solution to relevant problems are the important parts of pattern recognition, algorithm, and generalization.

In the perspective of participant country, Indonesian students relatively could master five CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. Particularly, they had relatively been able to break the data, processes, and problems into smaller, manage the components to solve a problem, identify and utilize the structure of concepts or main ideas, identify a given pattern, represent the pattern in a different way, identify the sequence of steps, apply and create an ordered series of instructions, and adapt and evaluate the chosen solution to relevant problems. On the other hand, USA students could master four CT components, such as decomposition, abstraction, pattern recognition, and algorithm. Specifically, they could break down the data, processes, or problems into smaller, utilize the structure of concepts or main ideas, identify a given pattern, create an original pattern, and create an ordered series of instructions. Meanwhile, Australian students relatively could master five CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. In detail they could break down the data, processes, or problems into smaller, utilize the structure of concepts or main ideas, identify a given pattern, apply an ordered series of instructions, and evaluate the chosen solution to relevant problems.

Moreover, Malaysian students relatively could master four CT components, such as decomposition, abstraction, algorithm, and generalization. Specifically, they could break down the data, processes, or problems into smaller, identify the structure of concepts or main ideas, identify the sequence of steps, and evaluate the chosen solution to relevant problems. Meanwhile, Hong Kong students relatively could master one CT components, such as abstraction whereby they relative could utilize the structure of concepts or main ideas. On the other hand, Brazilian students relatively could master three CT components, such as abstraction, pattern recognition, and algorithm. Particularly, they could identify the structure of concepts or main ideas, identify a given pattern, and identify the sequence of steps. All of the explanations of students' CT achievement in mathematics instruction integrated STEAM education in two last decades in the perspective of participant country, Indonesian students' CT achievement is relatively better than USA, Australian, Malaysian, Hong Kong, or Brazilian students CT achievement. This indicates that the optimization of Indonesian students' CT skills has been optimal. This is line to a few of empirical studies conducted in Indonesian that mathematics instruction integrated STEAM education significantly optimized the achievement of students' CT skills (e.g., Aminah et al., 2023; Angraini et al., 2023). However, Indonesian students' CT skills still must be comprehensively optimized in a few of indicators of CT component by implementing mathematics instruction integrated STEAM education, such as completing a missing pattern, creating an original pattern, following a series of ordered steps, and implementing the chosen solution to relevant problems.

In the perspective of educational level, college/university students relatively could master five CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. Particularly, they had been able to break the data, processes, and problems into smaller, manage the components to solve a problem, identify and utilize the structure of concepts or main ideas, identify a given pattern, identify the sequence of steps, apply and create an ordered series of instructions, and adapt and evaluate the chosen solution to relevant problems. Meanwhile, secondary students could master five CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. Specifically, they could break down the data, processes, or problems into smaller, identify the structure of concepts or main ideas, identify a given pattern, identify the sequence of steps, and evaluate the chosen solution to relevant problems. On the other hand, primary students could master five CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization. In detail, they could break down the data, processes, or problems into smaller, utilize the structure of concepts or main ideas, identify a given pattern, identify the sequence of steps, and evaluate the chosen solution to relevant problems. Pre-school students, nevertheless, could master one CT component, such as decomposition in which they could break down the data, processes, or problems into smaller.

All of the explanations of students' CT achievement in mathematics instruction integrated STEAM education in the last two decades in the perspective of educational country, college/university students' CT achievement is relatively better than secondary, primary, and pre-school students CT achievement. Molina-Ayuso et al. (2022) revealed that college students relatively have adequate competences in utilizing educational technologies to enhance their CT skills. This indicates that the optimization of college/university students' CT skills has been optimal. This is line to several empirical studies conducted in the institution of college/university that mathematics instruction integrated STEAM education significantly optimized the achievement of students' CT skills (e.g., Hu et al., 2020; Leonard et al., 2023; Maharani et al., 2019; Molina-Ayuso et al., 2022; Rich et al., 2020; Budiyanto et al., 2022). Meanwhile, students' CT skills in the educational level of pre-school, primary school, and secondary school must be comprehensively optimized in mathematics instruction because there are many indicators of CT component that they have not achieved in two last decades, such as managing the components to solve a problem, completing a missing pattern, representing the pattern in a different way, creating an original pattern, following a series of ordered steps, applying an ordered series of instructions, creating an ordered series of instructions, adapting the chosen solution to relevant problems, and implementing the chosen solution to relevant problems.

Implications for mathematics education

Two approaches of analysis used in this study provide some implications in the future CT studies in mathematics education. Firstly, the optimization of students' CT skills in the component of decomposition, decoding, modelling data, and generalization has not been carried out optimally. Fry et al. (2023) stated that decomposition, modelling, and generalization are three of the essential CT components proposed by Australian Mathematics Curriculum in CT. Consequently, future CT studies, especially in mathematics education should more focus on the optimization of students' CT skills in the component of decomposition, modelling, and generalization. Secondly, the involvement of affective aspects, such as attitudes, self-regulation, and self-efficacy has not been massive. Meanwhile, Suparman and Juandi (2022) revealed that self-regulation and self-efficacy are essential parts in mathematics learning to promote the optimization of students' mathematics achievement. Therefore, the future CT studies in mathematics education should involve the optimization of students' affective domain, such as self-efficacy and self-regulation, beside the optimization of students' CT achievement. Thirdly, statistics— one of essential parts of mathematics content has not been relatively involved in the optimization of students' CT achievement in mathematics instruction integrated STEAM education. Consequently, future CT studies in mathematics education should involve statistics as a mathematics content to optimize students' CT skills.

Furthermore, several CT learning environments, such as ICT-based education, robotics education, blended learning, project-based learning, computational learning, asynchronous teaching, and autonomous learning have not been massively implemented in learning activities. Meanwhile, some literatures stated that robotics learning, computational learning, and autonomous learning are the precisely effective learning to optimize the achievement of students' CT skills (e.g., Hanid et al., 2022; Kaup et al., 2023). As consequence, future CT studies in mathematics education should use robotics learning, computational learning, and autonomous learning to optimize students' CT achievement. Fifthly, the optimization of students' CT skills has not been relatively conducted in Indonesia. Meanwhile, a few of empirical studies found that Indonesian students' CT achievement has been optimal (e.g., Aminah et al., 2022; Maharani et al., 2019; Budiyanto et al., 2022). Consequently, the optimization of Indonesian students' CT skills must be massively conducted in Indonesia by doing research in CT topic, especially in mathematics education. Sixthly, some educational technologies, such as mathematics software, math laboratory, mobile games, computer algebra system, and dynamic geometry software have not been relatively used to promote the optimization of students' CT skills in mathematics instruction integrated STEAM education. Several literatures, however, found that technological approach in mathematics education, specifically mathematics software, such as math laboratory, mobile games, computer algebra system, and dynamic geometry software is effective to promote the optimization of students' CT achievement (e.g., del Olmo-Munoz et al., 2023; Guimaraes et al., 2020; Presser et al., 2023). Consequently, the future CT studies in mathematics education should utilize some technologies, such as math laboratories, mobile games, computer algebra system, and dynamic geometry software to optimize the achievement of students' CT skills in mathematics instruction.

Subsequently, the students have mastered all indicators of decomposition and abstraction, but they can't complete a missing pattern, create an original pattern, follow a series of ordered steps, and implement the chosen solution to relevant problems. Ehsan et al. (2018), in a side, stated that abilities to complete a missing pattern, create an original pattern, follow a series of ordered steps, and implement the chosen solution to relevant problems are the important parts of pattern recognition, algorithm, and generalization. This implies that students' CT skills in those specific indicators must be enhanced using a variety of CT interventions in mathematics education. Eighthly, even though Indonesian students' CT skills have achieved all of CT components, particularly most of CT indicators, but Indonesian students' CT skills still must be comprehensively optimized in a few of indicators of CT component such as completing a missing pattern, creating an original pattern, following a series of ordered steps, and implementing the chosen solution to relevant problems by implementing mathematics instruction integrated STEAM education. Moreover, students' CT skills in the educational level of pre-school, primary school, and secondary school must be comprehensively optimized in mathematics instruction because there are many indicators of CT component that they have not achieved in two last decades, such as managing the components to solve a problem, completing a missing pattern, representing the pattern in a different way, creating an original pattern, following a series of ordered steps, applying an ordered series of instructions, creating an ordered series of instructions, adapting the chosen solution to relevant problems, and implementing the chosen solution to relevant problems.

Limitations and suggestions

Bibliometric analysis in this present study only involves performance and co-occurrence analysis to show the global trends and the emerging themes of CT studies in mathematics instruction integrated STEAM education. Meanwhile, it can be explored more regarding the productive and influential documents, authors, countries, institutions, and sources contributing most to CT studies in the instructional approach and presented more related to the social interactions among authors, countries and institutions in CT studies in mathematics instruction integrated STEAM education. Consequently, the future CT studies in mathematics education using bibliometric analysis as an analysis approach should involve citation analysis and co-authorship analysis. Additionally, meta-data used in bibliometric analysis only comes from Scopus database, so the future CT studies in mathematics education may use the meta-data from other sources, such as Web of Science, PubMed, Dimensions, and Lens to do bibliometric analysis. Furthermore, qualitative meta-synthesis in this current study only uses 14 eligible documents as the data. In a view, it can be stated that those are the minimum data. Therefore, the future CT studies in mathematics education using qualitative meta-synthesis should extend the publication period of the documents and increase the source of document search to get more eligible data.

Conclusion

Present study concludes that the development of publication related to CT studies in mathematics instruction integrated STEAM education slightly increases in the period of 2004 – 2023. Meanwhile, the development of citation on the documents regarding CT studies in mathematics instruction integrated STEAM education relatively fluctuates from 2004 to 2023. This indicates that the development of publication regarding CT studies in mathematics education is not parallel to the development of citation on the documents focusing on CT studies in mathematics education. Moreover, there are several emerging themes of published documents focusing on CT studies in mathematics instruction integrated STEAM education, such as CT component, cognitive, affective, and psychomotor domain, mathematics content, CT learning environment, technological intervention in CT, research methodology, popular country involved in CT, participant, educational level, and STEAM component. Subsequently, students in the worldwide have been able to master CT components, such as decomposition, abstraction, pattern recognition, algorithm, and generalization in mathematics instruction integrated STEAM education. Particularly, they can break the data, processes, and problems into smaller, manage the components to solve a problem, identify and utilize the structure of concepts or main ideas, identify a given pattern, represent the pattern in a different way, identify the sequence of steps, apply and create an ordered series of instructions, and adapt and evaluate the chosen solution to relevant problems.

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Authors' contribution

All authors contributed to the study conception and design. Suparman: Conceptualization, Data Collection, Writing-Original Draft; Dadang Juandi: Validation and Supervision; Turmudi: Conducting Bibliometric Analysis; Writing - Review & Editing; Wahyudin: Conducting Qualitative Meta-Synthesis, Writing – Review & Editing.

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