The Application of Fuzzy Cognitive Mapping in Education: Trend and Potential

Chee Siong Teh [1], Ahmad Ridzuan Kudus [1]

[1] *Faculty of Cognitive Sciences and Human Development, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Malaysia*

Abstract **– Fuzzy cognitive mapping (FCM) is a valuable tool for understanding complex issues due to its ability to express complex and uncertain knowledge domains with dynamic modelling capabilities. This study focuses on the application of FCM in education, using a bibliometric analysis and systematic review of publications in the Scopus database from 2000 to October 2023. Using keywords related to FCM and education, the study retrieved fifty-four publications for frequency analysis and citation metrics. This study showcases its results by leveraging standard bibliometric indicators, encompassing metrics such as publication growth, top-cited publications, country contributions, and preferred publication titles. Findings from the systematic review reveal the potential of FCM in providing explanatory, predictive, reflective, and strategic insights and solutions to numerous educational issues.**

Keywords **– Fuzzy cognitive mapping, educational applications, bibliometric analysis, systematic review.**

1. Introduction

As the real world is complex, Fuzzy Cognitive Mapping (FCM) assumes knowledge can be obtained from the perspectives of those relevant to a particular issue [1].

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Corresponding author: Chee Siong Teh,
Faculty of Cognitive Sciences and Human Development, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Malaysia.
Email: csteh@unimas.my

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FCM, developed by Kosko [1], is a dynamic method, either qualitative or semi-quantitative, used to structure expert knowledge, aiming to visually represent an individual's perception of a given situation [2]. The resultant diagram, referred to as a fuzzy cognitive map, is a method for knowledge representation and reasoning based on directed graphs. It illustrates a collection of interconnected concepts within a domain, depicting cause-and-effect relationships [3]. Kokkinos *et al.* [2] asserted that FCM graphs offer a loosely structured procedure to help the modeller and the expert or stakeholder provide their beliefs, insights, and conceptions about a specific subject. The connections and dependencies among these ideas or concepts are also made clear, illustrating how changes in one concept may impact others [2]. The main objective of FCM is to explore how these causal influences propagate throughout a system when it undergoes modification or intervention [4].

Despite its complexity, the developed model remains accessible to non-technical audiences, as each parameter carries a tangible meaning and can depict the quantitative and qualitative data gathered from stakeholders' perspectives [1], [5], [2]. Moreover, Van Vliet, Kok, and Veldkamp [6] state that FCM implementation is simple, customizable in parameterization, and offers flexibility in representation, accommodating multiple interconnected concepts or phenomena. They also suggested that FCM effectively addresses complex knowledge acquisition and management challenges, adeptly managing dynamic effects owing to its feedback structure. Moreover, it can deal with qualitative and quantitative inputs and outputs simultaneously, unlike the separate analyses of a situation using the conventional qualitative and quantitative approaches [6], [7].

1.1. Theoretical Foundations of FCM

FCM is founded on several core theories and concepts. Firstly, it is grounded in fuzzy logic, a mathematical framework introduced by Zadeh [8].

Fuzzy logic allows for the representation of vague and uncertain information using linguistic variables, expressing truth as a degree of membership in fuzzy sets. This approach adeptly captures the subjective and uncertain aspects of human knowledge and perception [9]. Secondly, the 'cognitive' aspect of FCM draws from cognitive science, which studies how individuals perceive, process, and interpret information. In the context of FCM, it is employed to develop and analyze causal models that simulate human decision-making processes [10]. Thirdly, the complex systems theory serves as another foundational pillar for FCM. This theory revolves around analysing systems with multiple interdependent and interconnected components, and FCM is a tool employed to model and scrutinize the relationships and interactions among these system components [11]. Lastly, FCMs are typically depicted as directed graphs or networks. The study and manipulation of these networks draw from graph theory, encompassing concepts such as nodes, edges, and path analysis [12].

1.2. FCM Approaches – Causal versus Dynamical

According to Felix *et al.* [3], the concepts, variables, or factors are depicted as nodes of the graph, and graph edges or connections representing the causal relationships between nodes are signed and weighted. Figure 1 depicts a sample fuzzy cognitive map. The following describes the two main approaches of how FCM is used [4], [13].

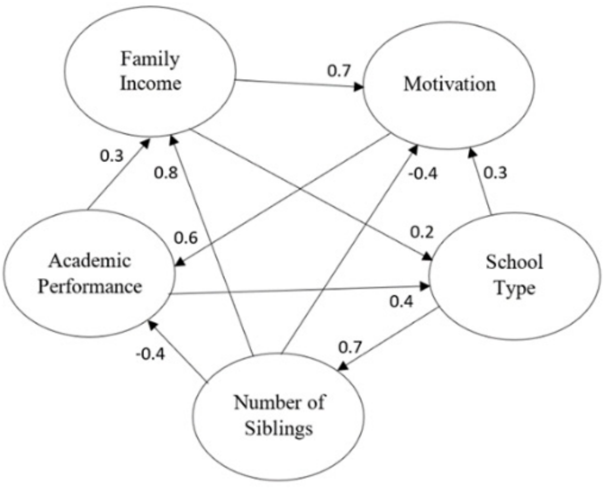

Figure 1. A sample fuzzy cognitive map

The first approach, known as the causal approach, is closely tied to the original FCM proposed by Kosko [1] and preserves the same mathematical formulation. The degree of connection between two nodes representing concepts, variables, or factors is indicated by a weight ranging from 0 to 1, reflecting the extent of uncertainty or fuzziness in the causal relationship.

A link value of 1 indicates absolute certainty that X causes Y.

As the value decreases, the certainty that X causes Y diminishes. The link between node X and node Y is marked with a positive sign to denote positive causation, which means that the occurrence of X will cause Y to occur or a negative sign to denote negative causation, which means that the occurrence of X will decrease the occurrence of Y. The states of nodes in the cognitive map are also made fuzzy, and any state can have a value from 0 to 1. The value shows how strongly a node is caused or activated by changes in other nodes. In other words, the nodes' values reflect how certain we are that changing one node would change another. These values do not represent the actual magnitude of the nodes.

The second approach, known as dynamical, uses the actual magnitude of the nodes. Hence, this approach examines how much (relatively) different nodes' magnitudes will be impacted by a change and how much they will be influenced or influence others. This article does not describe the mathematical formulations used in both approaches. Helfgott *et al.* [13] provide a detailed description of these formulations.

1.3. FCM Functions – Explanatory, Predictive, Reflective, Strategic

Referring to an article written in Italian by Codara Lino [14], FCM is classified into four functions. First, FCM can provide an explanatory function in which it rebuilds the assumptions underpinning the behavior of a given circumstance, provides insights into the reasons behind the stakeholders' decisions and behaviors, and identifies any distortions and limitations in the stakeholders' depiction of the circumstance. Second, FCM can offer a predictive capability to forecast future decisions and actions or to anticipate the reasoning a particular stakeholder may employ in response to new events. Third, FCM can serve a reflective function to help decision-makers ponder over the 'what-if' scenario and could lead to necessary interventions. Fourth, FCM can provide a strategic function by better depicting a challenging scenario.

2. FCM Applications

FCM stands out as a highly effective tool for modeling intricate processes. [15]. It is widely used in many fields [10], including computer sciences [16], [17]; engineering [18], [19]; medicine [20], [15]; commerce and management [21], [22], [23], [24]; robotics [25], [26]; environmental science [27], [28]; and education [29], [30].

2.1. Review Studies Related to FCM

Several review papers have been published since 2011, focusing on several aspects of FCM. First, Papageorgiou [14] conducted a review of research dedicated to learning approaches and algorithms associated with FCM. Papageorgiou and Salmeron [31] then reviewed 485 FCM studies from 2001 to 2010, which were retrieved from the Scopus database. Their review underscores that FCM commonly addresses a variety of problem types including modeling, prediction, interpretation, monitoring, decision-making, classification, management, and planning. Papageorgiou and Salmeron [31] also provided a review of FCM-extended methodologies that were proposed during the period. They uncovered that the primary application domains of FCMs span across various fields including computer science, engineering, mathematics, and so forth. Papageorgiou [32] provided another review with a somewhat similar focus. Felix *et al*. [3] then extended the review by [31] by detailing the advancements in FCM learning algorithms and software tools for FCM modeling.

2.2. Review Studies Related to FCM in Specific Disciplines

Amirkhani *et al.* [15] reviewed FCM, specifically in medicine. Their review centers on studies conducted in this field between 2000 and 2015, sourced from the Scopus database. It revealed that the utilization of FCM in the medical domain could be categorized into four main tasks: decision-making, diagnosis, prediction, and classification. Amirkhani *et al.* [15] also summarize the most widely used FCMs within the four tasks and describe some representative applications of FCM in medicine. Bakhtavar *et al.* [33] offer a specialized review through the analysis of 89 articles on Fuzzy Cognitive Maps (FCM) in systems risk analysis, sourced from the Web of Science database up to the end of 2020. This review highlights that the predominant use of FCM in systems risk analysis, which focuses on concepts such as failure, accident, incident, hazard, risk, error, and fault, is found within the fields of engineering, medicine, and management sciences. They indicate that FCMs are primarily utilized for risk-based analysis in various applications, including decision-making, analysis, prediction, systematic learning, classification, or their combinations.

As of now, according to the researchers' knowledge, there is not a detailed review available on the application of Fuzzy Cognitive Maps (FCMs) in education, despite the significant potential they hold in this area.

Therefore, this study aims to conduct both a bibliometric analysis and a systematic review to provide insights into the studies related to FCMs in education. It aims to explore the following research questions:

RQ1: What is the trend in the number of publications concerning FCM in the education sector?

RQ2: In what ways are FCMs being applied in the educational field, in terms of their context of use, approaches, functions, algorithms, and software tools?

3. Method

Bibliometric analysis is a quantitative method valuable for mapping, rating, and analyzing academic research output [34], [35]. This is a widely recognized and substantial research method, grounded in the principles of knowledge-based systems and diffusion theory [36]. It is often used for forecasting, analyzing, and describing research development, progress, trends, knowledge status, and characteristics of a specific area or research topic [36], [37], [38]. Using bibliometric analysis will automatically assist scholars in locating the most reputable journals and leading authorities in a given field of study. Additionally, it provides researchers with a basic overview, overarching structure, direction, and knowledge of an investigation, which will inspire further studies [38].

3.1. Data Source and Search Strategy

This study conducted a bibliometric analysis on the use of fuzzy cognitive maps (FCM) in the education sector, examining publications up to 26 October 2023, found in the Scopus database. The aim was to provide current insights into the development of this research area and to highlight its main topics. The Scopus database, managed by Elsevier, provides access to a wide range of peer-reviewed materials, including scientific journals, books, and conference proceedings [39], featuring titles from over 5,000 publishers which encompass more than 20,000 serial titles, 150,000 books, and over 70 million items [40]. The study also systematically reviews these publications to gain insights into the existing use of FCM in the education domain.

Figure 2 illustrates the search strategy flowchart. To find articles pertinent to the study's objectives, the research employed search terms "Fuzzy cognitive map*" AND "education" within the titles, abstracts, and keywords of articles. The study considered all articles published in all years, from 2000 to 26 October 2023, and written in English. The source types include journals and conference proceedings.

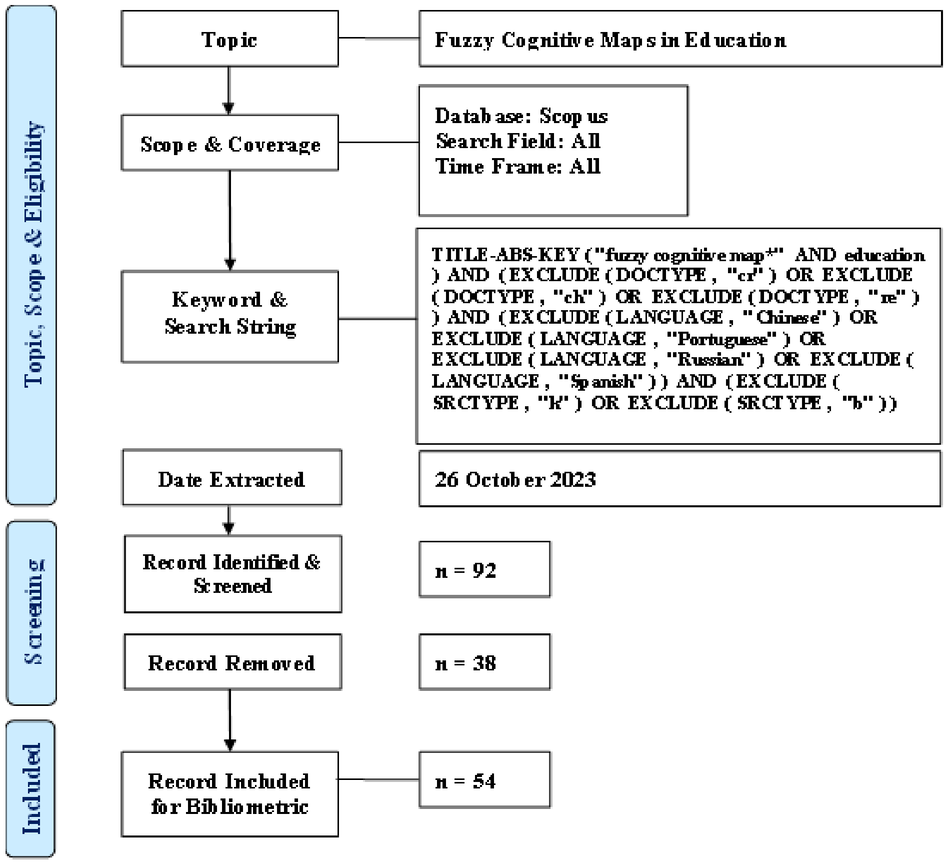

Figure 2. Flow diagram of the search strategy

3.2. Information Extraction

The initial search revealed 92 publications. The researchers then performed manual screening to remove any irrelevant publications. A total of 38 publications were removed as they either do not relate to the education domain or solely focus on proposing variations to the original FCM algorithm. All remaining 54 publications, labelled from D1 to D54 in chronological order, were subjected to bibliometric analysis.

Appendix A lists the title, authors, and publication year for each paper. In this study, (i) Microsoft Excel was utilized for determining the frequencies and percentages of publications as well as for creating pertinent charts and graphs, and (ii) Harzing's Publish and Perish software was employed to assess the citation metrics. The study also systematically reviewed 50 of the identified 54 publications to extract information relevant to RQ2. This review excluded four publications as the full papers for these four publications (D22, D23, D32, D35) are unavailable.

4. Findings

This section describes the bibliometric analysis results related to RQ1. The analysis involved 54 publications from two source types, as shown in Table 1.

Table 1. Source type

Source Type	Total Publications (TP)	Percentage (%)
Journals	29	53.7
Conference Proceedings	25	46.3
Total	54	**100.0**

4.1. Publications Growth

The researchers analyzed the growth trend across 54 publications, focusing on their publication years. Overall, Figure 3 demonstrates a rising trend in the volume of publications over the study period, although the growth rate is minimal. According to Table 2, the year 2020 witnessed the peak of productivity, with a total of 7 publications. The highest citation count per publication was achieved by a sole publication [30] from the year 2000.

In this publication, Cole and Persichitte [30] explore FCM's potential within the educational sector through two illustrative examples of its application.

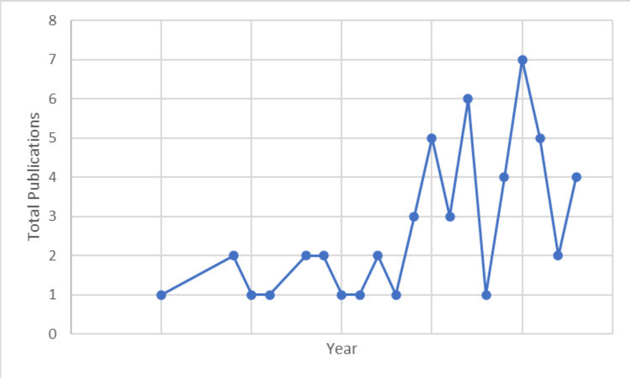

Figure 3. Total publications by year

Table 2. Citation metrics by year

Year	TP	%	NCP	TC	C/P	C/CP	h	g
2023	4	7.4	1	2	0.50	2.00	1	1
2022	2	3.7	1	9	4.50	9.00	1	2
2021	5	9.2	4	35	7.00	8.75	3	5
2020	7	12.9	4	8	1.14	2.00	2	2
2019	4	7.4	2	1	0.25	0.50	1	1
2018	1	1.8	1	16	16.0	16.0	1	1
2017	6	11.1	5	17	2.83	3.40	3	4
2016	3	5.5	2	7	2.33	3.50	2	2
2015	5	9.2	4	125	25.0	31.2	4	5
2014	3	5.5	2	11	3.67	5.50	2	3
2013	1	1.8	1	16	16.0	16.0	1	1
2012	2	3.7	2	9	4.50	4.50	2	2
2011	1	1.8	1	2	2.00	2.00	1	1
2010	1	1.8	1	45	45.0	45.0	1	1
2009	2	3.7	2	134	67.0	67.0	2	2
2008	2	3.7	2	76	38.0	38.0	2	2
2006	1	1.8	1	1	1.00	1.00	1	1
2005	1	1.8	1	7	7.00	7.00	1	1
2004	2	3.7	2	15	7.50	7.50	2	2
2000	1	1.8	1	52	52.0	52.0	1	1
Total	54							

4.2. Country Contribution

Figure 4 shows the distribution of publications by country. India, the top contributor, produced seven publications, followed by China and Greece, which produced six publications each. This distribution differs from the distribution of publications when all FCM studies, not limited to FCM in education, were analyzed. By limiting to journal articles and conference papers written in English, the search on the Scopus database revealed 2379 publications. Hence, publications related to FCM in education only account for about 2.3% (54) of the overall publications. As shown in Figure 5, Greece produced the most publications (372), followed by China (341) and the United States (288).

Further analysis of the source titles of these 54 publications reveals that ACM International Conference Proceeding Series and Sustainability Switzerland have two publications each. The remaining publications were published in 50 different source titles. Only 14 of the 48 source titles are education-related sources, with eight conference proceedings and six journals. The six journals are Computers & Education, Journal of Information Technology Education: Research, International Journal of Emerging Technologies in Learning, Computer Applications in Engineering Education, IEEE Transactions on Learning Technologies, and International Journal of Mobile Learning and Organisation. This phenomenon indicates that the adoption of FCM is still in its infancy among educational researchers.

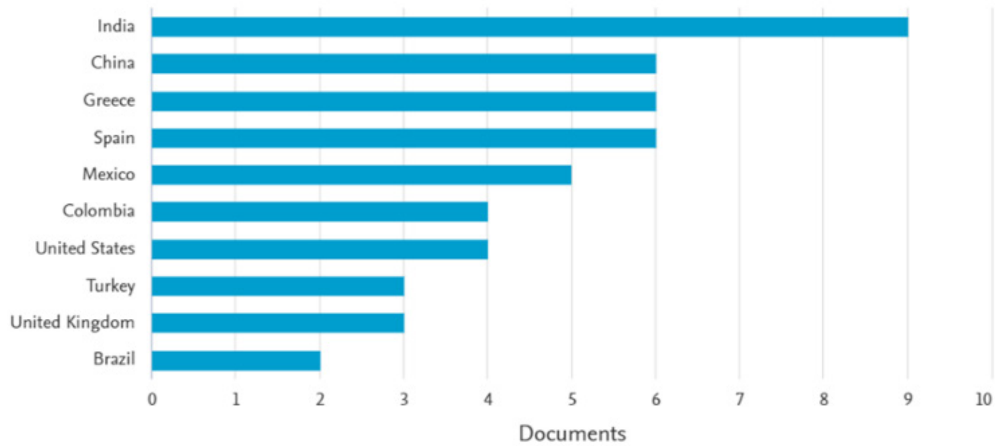

Figure 4. Total Publications by country (FCM in education studies)

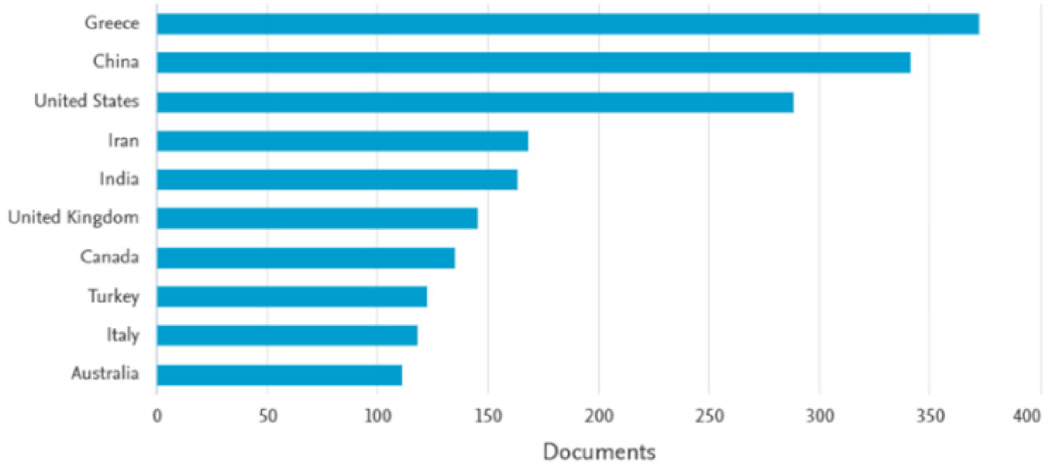

Figure 5. Total Publications by country (all FCM studies)

4.3. Use of FCM

The following describes the systematic review findings related to RQ2. The systematic review revealed that out of 50 publications, there are 49 empirical studies and one conceptual article (D37). The first FCM application in the education domain was published in 2000 by [30], although FCM has existed since 1986. The following describes how FCM is used in terms of its utilization context, approach, function, algorithm, and software tool used.

4.3.1. Utilization Context

Referring to Appendix A, 32 of the publications (D1, D2, D4, D11, D14, D15, D17, D18, D20, D23, D24, D25, D26, D30, D32, D33, D34, D37, D38, D39, D41, D42, D44, D45, D47, D48, D49, D50, D51, D52, D53, D54) reported FCM studies in the higher education context, 10 (D5, D6, D12, D13, D16, D19, D27, D28, D29, D31) in the school context, and one (D46) involved the general public. The remaining seven publications (D3, D7, D8, D9, D10, D36, D42) do not specify the context of their studies. This finding shows that most studies employed FCM in the higher education context.

4.3.2. Approach

According to Barbrook-Johnson and Penn [4] and Helfgott *et al.* [13], causal and dynamical are the two main approaches used in FCM. The review discovered 35 publications adopted the causal approach (D1, D2, D3, D4, D5, D6, D8, D9, D10, D11, D12, D13, D14, D20, D25, D26, D28, D30, D34, D36, D37, D38, D39, D40, D41, D42, D43, D44, D45, D46, D48, D49, D51, D53, D54) and 15 publications (D7, D15, D16, D17, D18, D19, D23, D24, D27, D29, D32, D33, D47, D50, D52) employed the dynamical approach.

In brief, the causal approach is based on the original FCM algorithm proposed by Kosko [1], in which the nodes' values reflect how certain we are that changing one node would change another. In contrast, in the dynamical approach, these values represent the actual magnitude of the nodes. The majority of the research, spanning from the earliest study in 2000 (D1) to the latest in 2023 (D54), documented the adoption of the causal approach. The dynamical approach was first noted in 2008 (D7), with the years 2014 to 2023 marking a phase of increased utilization of this methodology.

4.3.3. Function

Referring to Codara Lino [14], there are four functions of FCM implementations: explanatory, predictive, reflective, and strategic. The analysis of the publications reveals that FCM is most used for explanatory (32 publications), followed by strategic (32 publications), reflective (18 publications), and predictive (3 publications) purposes.

4.3.4. Explanatory

In contrast to traditional cognitive maps, fuzzy cognitive maps (FCM) integrate the benefits of cognitive mapping with fuzzy logic. This combination better captures the nuances of natural human language and effectively addresses the uncertainty or imprecise knowledge domains [30]. The use of FCM for explanatory purposes produced fuzzy cognitive maps that rebuild the premises underpinning the behavior of given circumstances and provide insights into relationships between these premises. Although the formation of fuzzy cognitive maps in all 50 reviewed publications enabled this explanatory function, not all maps were derived for this purpose.

Thirty-two, 32 (D1, D5, D6, D9, D11, D12, D14, D17, D18, D23, D25, D26, D27, D30, D33, D34, D37, D38, D39, D40, D41, D42, D43, D44, D45, D46, D47, D48, D49, D51, D53, D54), of the identified 30 publications used the maps to describe the premises such as factors, strategies, or criteria of the examined phenomena. For example, in two recent publications, Bermeo-Córdova *et al.* [29] in D50 find out the views of academics, public, and private sectors on strategies that encourage sustainability of pre-professional activities in Ecuador's agricultural careers. In addition, Infante-Moro *et al.* [41] in D49 identify critical factors of e-proctoring implementation in the Spanish university system.

The maps are also used to engineer the domain knowledge of specific groups, also known as cognitive modeling [30]. Three publications (D1, D37, and D46) reported using FCM to explain or model domain knowledge. O'Garra *et al.* [42] in D46 involved the general public in building their mental maps on social-ecological systems and comparing them before and after the gameplay intervention. Gaibova [43] in D37 involved data science and analytics experts to form a data analyst's competency model or fuzzy cognitive map. Cole and Persichitte [30] in D1 posited the potential of FCM in creating expert knowledge modeling for intelligent tutoring systems. According to them, having experts draw diagrams of their knowledge is more cognitively efficient instead of stating rules in the conventional practice of expert knowledge modeling. Furthermore, since all maps have a similar structure, it is easier for experts to combine their knowledge. In addition, fuzzy concepts can represent soft knowledge domains in FCM, which refers to the ability to represent hazy degrees of causation between hazy causal items. Cole and Persichitte [30] also highlighted the potential of FCM for modeling student knowledge or understanding.

4.3.5. Predictive

Over the period from 2000 to October 2022, only three publications (D17, D32, and D47) reported the use of FCM for predictive purposes. Takács, Rudas, and Lantos [44] in D17 devised a novel learning FCM algorithm to forecast factors and states affecting students' grades in their forthcoming semesters. Yu and Qi [45] in D32 employed a three-layer network that mimics an artificial neural network to predict aerobic learners' emotions in a smart learning environment. In D47, Mansouri, ZareRavasan, and Ashrafi [46] proposed a learning fuzzy cognitive map to predict student performance with a limited sample size. The original FCM algorithm does not integrate the learning algorithm needed to perform prediction, possibly explaining the lack of studies focusing on this FCM function. All three publications reported such a predictive function had integrated a learning algorithm into the original FCM.

4.3.6. Reflective

The review identified 18 publications (D1, D2, D3, D13, D14, D15, D16, D18, D19, D20, D23, D24, D41, D43, D45, D50, D51, D53) that used FCM reflective function. The reflective function simulates scenarios by changing the node(s) or concept(s) value. For example, in D20, the dynamicity of FCM affords dynamic adaptive instruction in an e-learning environment to provide personalized learning based on learners' needs and preferences [47]. Yesil *et al.* [48] in study D14 conducted six simulations by adjusting the values of input concepts to determine their significance as success factors in control engineering education. They aimed to explore the optimal adoption strategy of blockchain technology to enhance the performance of the government-supported free basic education system in India. Sonje, Pawar, and Shukla [49] in D53 carried out a real-time scenario analysis using FCM for critical parameters identified through value-focused thinking.

4.3.7. Strategic

The strategic function affords decision-making based on the FCM depiction of the complex scenario. The review discovered 32 publications (D1, D4, D5, D6, D7, D8, D9, D10, D11, D12, D13, D14, D15, D18, D20, D26, D28, D29, D33, D34, D37, D39, D40, D41, D42, D43, D45, D49, D51, D52, D53, D54) that reported the strategic function of FCM. For example, Hossain and Brooks [21] in D6 highlight the usefulness of the visual FCM model in assisting strategic decisions on adopting educational software. Georgopoulos, Chouliara, and Stylios [50] in D15 reported the FCM-based medical decision support system for education purposes that allows intuitive decision-making. Another study by Mourhir and Kissani [51] in D41 involved students and faculties in providing views on soft skills integration into the existing engineering curricula in which the reasoning and interconnections between these stakeholders' views provide insights into potential curricula revisions.

4.4. Algorithm

Most publications reported using the original FCM algorithm proposed by Kosko [1].

However, referring to appendix A, 12 of the reviewed publications (D5, D7, D9, D18, D25, D30, D32, D37, D38, D42, D47, D48) employed different variants of FCM algorithms in their respective contexts. These include Induced Linked Fuzzy Relational Mapping in D5, Three Layers FCM Schema in D7, Augmented FCM in D9, FCM-QoL in D18, Hesitant FCM in D30, 3-layer FCM in D32, Rules-based FCM in D37, FCM and Linguistic Concentric Fuzzy Hypergraphs in D38, Intuitionist FCM in D42, Learning FCM in D47, and Neutrosophic Cognitive Maps & Triangular FCM in D48.

4.5. Software Tool

Referring to appendix A, earlier publications from D1 (2000) to D13 (2012) do not report using FCM tools to create maps and perform simulations and predictions. Then, Yesil *et al.* [48] in D14 and Dias, Hadjileontiadou, Hadjileontiadis, and Diniz [52] in D18 reported the use of Matlab for FCM implementation. Albayrak and Albayrak [53] in D23 used the CMap tool (https://cmap.ihmc.us/). Two publications, Bagány and Takács [54] in D27 and Sonje, Pawar, and Shukla [49] in D53, employed Mental Modeler (https://www.mentalmodeler.com/). The most used FCM software tool is FCMapper (http://www.fcmappers.net/joomla/). Bagány and Takács [54] in D27 is the earliest reviewed publication that utilized FCMapper, followed by Córdova *et al.* [55] in D39, Infante-Moro *et al.* [56] in D44, and O'Garra *et al.* [42] in D46. The two most recent publications, Infante-Moro *et al.* [41] in D49 and Bermeo-Córdova *et al.* [29] in D51 also utilized FCMapper.

5. Discussion

As revealed by bibliometric analysis, the gradual increase of FCM publications in the education domain indicates the growing acknowledgement of FCM in providing insights into educational issues. However, the growth rate is still slow compared with the overall growth of FCM-related publications. So far, the 54 FCM in education publications only involve 14 source titles related to education.

The systematic review reveals the enormous potential of FCM in creating helpful cognitive tools for gaining insights into various educational issues because it combines the ability of fuzzy logic to represent complex, and uncertain or soft knowledge domains with dynamic modelling capabilities. As a result, FCM is suited to provide explanatory, predictive, reflective, and strategic insights into educational issues at learner, teacher, institutional, and cross-institutional levels.

In addition, the graphical depiction of FCM is also easy to understand for non-technical audiences, which is pertinent for stakeholders in the education sector.

Findings from the systematic review reveal several potentials of FCM in education. First, in line with the FCM's explanatory function, the cognitive map can visually depict the intricate educational system to help stakeholders comprehend and convey its complexity. Second, FCM can be utilised as a tool to facilitate collaboration among many stakeholders in the education system. It can improve communication and foster consensus around common objectives by incorporating various stakeholders in the mapping process.

Thirdly, FCM facilitates the identification of causal relationships among different elements of the educational system, enabling the development of interventions that address root causes rather than merely treating symptoms. Fourthly, due to its analytical and strategic capabilities, FCM serves as an effective tool for making informed decisions in education. FCM can assist stakeholders in making more informed decisions by detailing the system and identifying possible outcomes of specific actions, taking into account the possible effects on the overall education system. Finally, applying FCM for predictive modelling in education enables stakeholders to foresee the effects of various interventions or changes to the educational system. This can be extremely useful when looking for potential unexpected effects of changes.

6. Conclusion

This paper has discussed the growth and use of FCM in education. However, the growth rate could be faster, and the adoption of FCM among educational researchers could be more robust. Findings from the systematic review also reveal the tremendous potential of FCM in providing explanatory, predictive, reflective, and strategic insights and solutions to numerous educational issues. FCM implementations have employed causal and dynamical approaches, with variants of FCM algorithms and software tools produced over the years.

FCM can also deal with qualitative and quantitative inputs and outputs simultaneously, unlike conventional qualitative and quantitative methodologies that involve separate investigations into these two types of data. The availability of user-friendly FCM software tools further affords FCM adoption among educational researchers, as coding is not required to implement FCM.

Future studies may consider a more comprehensive bibliometric analysis and systematic review of related publications unavailable in the Scopus database but available in other academic databases such as Web of Science, Lens, and so forth. Findings from this study serve to inspire educational researchers to employ FCM in their investigation of relevant educational problems to bring about insights and solutions that are unachievable via conventional qualitative and quantitative methodologies.

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Appendix A

				Context			Approach		Function				Algorithm	Tool
				Higher	School		Causal	Dynamical	Explanatory	Prediction	Reflective	Strategic		
1	J.R. Cole, K.A. Persichitte	Fuzzy cognitive mapping: Applications in education	2000	/			/		/		/	/		
2	R.L. Pacheco, R. Carlson, L.H. Martins-Pacheco	Engineering education assessment system using fuzzy cognitive maps	2004	/			/				/			
3	A.L. Laureano-Cruces, J. Ramírez-Rodríguez, & A. Terán-	Evaluation of the teaching-learning process with fuzzy cognitive maps	2004			NS	/				/			
4	A. Peña, J.S. Sossa, & F. Gutiérrez	Negotiated learning by fuzzy cognitive maps	2005	/			/					/		
5	T. Pathinathan, J.M. Arul, K. Thirusangu, J.M. Mary	On tensions and causes for school dropouts - An induced Linked Fuzzy Relational Mapping (ILFRM) analysis	2006		/		/		/			/	Induced Linked Fuzzy Relational Mapping	
6	S. Hossain, L. Brooks	Fuzzy cognitive map modelling educational software adoption	2008		/		/		/			/		
7	D.A. Georgiou, S.D. Botsios	Learning style recognition: A three layers fuzzy cognitive map schema	2008			NS		/				/	Three Layers FCM Schema	
8	X. Luo, X. Wei, J. Zhang	Game-based learning model using fuzzy cognitive map	2009			NS	/					/		
9	J.L. Salmeron	Augmented fuzzy cognitive maps for modelling LMS critical success factors	2009			NS	/		/			/	Augmented FCM	
10	X. Luo, X. Wei, J. Zhang	Guided game-based learning using fuzzy cognitive maps	2010			NS	/					/		
11	K. Bulut, G. Kayakutlu	Analysing the impact of universities on regional development: A case study using Fuzzy Cognitive Maps	2011	/			/		/			/		
12	P. Nownaisin, K. Chomsuwan, N. Hongkrailert	Utilization of fuzzy cognitive map in modeling of Thailand science-based technology school	2012		/		/		/			/		
13	J. Lin, Ailiya, C. Miao, Z. Shen	A FCM based approach for emotion prediction in educational game	2012		/		/				/	/		

14	E. Yesil, C. Ozturk, M.F. Dodurka, A. Sahin	Control engineering education critical success factors modeling via Fuzzy Cognitive Maps	2013	/		/		/		/	/		Matlab for creating simulations
15	V.C. Georgopoulos, S. Chouliara, C.D. Stylios	Fuzzy Cognitive Map scenario-based medical decision support systems for education	2014	/			/			/	/		
16	H.B. Baron, M.M. Rojas, J.T. Diaz, A.V. Contreras	Graph isomorphism in fuzzy cognitive maps for monitoring of game-based learning	2014		/		/			/			
17	M. Takács, I.J. Rudas, & Z. Lantos	Fuzzy cognitive map for student evaluation model	2014	/			/	/	/				THE IAN US SOFTWARE The software was written in the Microsoft Visual Studio 2010 C# environment,
18	S.B. Dias, S.J. Hadjileontiadou, L.J. Hadjileontiadis, J.A. Diniz	Fuzzy cognitive mapping of LMS users' Quality of Interaction within higher education blended-learning environment	2015	/			/	/		/	/	FCM-QoL (combined with a model visualizer)	Matlab 2014a
19	H.B. Barón, R.G. Crespo, J. Pascual Espada, & O.S. Martínez	Assessment of learning in environments interactive through fuzzy cognitive maps	2015		/		/			/			Specific tool for LAS
20	K. Chrysafiadi, M. Virvou	Fuzzy logic for adaptive instruction in an e-learning environment for computer programming	2015	/		/				/	/		
21	P. Selvam, A. Rajkumar	A study on the causes for educational development of tribal children at Valparai in Coimbatore district, Tamilnadu using trapezoidal fuzzy cognitive maps [TpFCMs]	2015	The full paper is unavailable.									
22	N. Vijayaraghavan, B. Kumaresan	A study on significance of globalization of higher education in India using fuzzy cognitive maps	2015	The full paper is unavailable.									
23	A. Albayrak, M. Albayrak	Performance evaluation of practice courses using fuzzy cognitive maps	2016	/			/	/		/			CmapTools
24	R. dos Santos Guimarães, V. Strafacci, & P.M. Tasinaffo	Implementing fuzzy logic to simulate a process of inference on sensory stimuli of deaf people in an e-learning environment	2016	/			/			/			
25	N. Martin, J. Kaliga Rani, L. Vinotha	Determination of a global action plan to mitigate the fear of mathematics among the engineering students using multi-step fcm approach	2016	/		/		/				Multi-step FCM	

26	P. Nayak, S. Madireddy, D.M. Case, C.D. Stylios	Using fuzzy cognitive maps to model university desirability and selection	2017	/		/		/		/		
27	I. Bagany, M. Takacs	Soft-computing methods applied in parameter analysis of educational models	2017		/		/	/				Mental Modeler & FCMapper
28	P.-M. Blanca-Estela, G.G. Josefina	Semiautomated cognitive tutor, to serve as a support in upper secondary students in solving algebra problems	2017		/	/				/		
29	P.M. Blanca-E, G.C. Juan-M, G. G. Josefina, C. Cesar, & R.C. José-F	Attach me and detach me: An interactive device to help to teach algebra	2017		/		/			/		
30	H. Ghaderi, H. GItInavard, S.M. MousavI, B. VahdanI	A hesitant fuzzy cognitive mapping approach with risk preferences for student accommodation problems	2017	/		/		/			Hesitant FCM	
31	V. Gorshenin, O. Prichina, S. Aliukov, V. Orekhov, A. Pechurochkin	Cognitive technologies to build models for operation of business school	2017	The full paper is unavailable.								
32	Y. Yu, A. Qi	Teaching system of smart learning environment for aerobics course	2018	/			/		/		3-layer FCM	
33	T. Kovaliuk, A. Ustimenko, N. Kobets, V. Pasichnyk, N. Kunanets	Cognitive modeling of students' competencies development in Higher Education system	2019	/			/	/		/		
34	N. Martin, W. Ritha, J. Merline Vinotha, I. Antonitte Vinoline	Education and employment are at two poles-A research using fuzzy cognitive linguistic multimaps	2019	/		/		/		/		
35	D.D.A.D. Devi, J.F.M. Rani, P. Vijayalakshmi, C. Yamini, N. Martin	Exploration of the impacts of blended learning in higher education using CBDL H FCM	2019	The full paper is unavailable.								
36	C. Sudhagar	Role of fuzzy cognitive maps in smart education system	2019		NS							
37	T.V. Gaibova	Support for the personalization of master's studies based on a fuzzy competency model (on the example of data analysis disciplines)	2020	/		/		/		/	Rules-based FCM	
38	N. Martin, N.R. Gandhi, A. Aleeswari, P. Pandiammal, F.X.E. Deepak	Fuzzy cognitive maps with linguistic concentric fuzzy hypergraphic approach to rank the benefits of outcome based education	2020	/		/		/			FCM and Linguistic Concentric Fuzzy Hypergraphs	

39	B.B. Córdova, J.L. Yagüe Blanco, M. Satama, & C. Jara	Identification of variables that cause agricultural graduates not to return to the rural sector in ecuador. Application of fuzzy cognitive maps	2020	/			/		/			/		FCMapper
40	L. Xu, Y. Zhang	Study on factors affecting preschool education service quality: An empirical analysis based on fuzzy cognitive map and evidential theory	2020		/		/		/			/		
41	A. Mourhir, I. Kissani	Foundation courses' soft skills evaluation using fuzzy cognitive maps	2020	/			/		/		/	/		
42	M.R.A. Purnomo, A.R. Anugerah, B.T. Dewipramesti	Sustainable supply chain management framework in a higher education laboratory using intuitionistic fuzzy cognitive map	2020	/			/		/			/	Intuitionistic FCM	
43	B.E. Pedroza Méndez, J.M. González Calleros, C.A. Reyes García, & J. Guerrero García	Fuzzy Models for Implementation of the Decision-Making Module in Networked Didactic Prototypes	2020			NS	/		/		/	/		
44	A. Infante-Moro, J.C. Infante-Moro, J. Gallardo-Pérez, & A. Luque-de la Rosa	Motivational factors in the use of videoconferences to carry out tutorials in Spanish universities in the post-pandemic period	2021	/			/		/					FCMapper
45	D. Damigos, G. Valakas, A. Gaki, K. Adam	The factors impacting the incorporation of the sustainable development goals into raw materials engineering curricula	2021	/			/		/		/	/		
46	T. O'Garra, D. Reckien, S. Pfirman, E.B. Simon, G.H. Bachman, J. Brunacini, J.J. Lee	Impact of gameplay vs. Reading on mental models of social-ecological systems: A fuzzy cognitive mapping approach	2021			General public	/		/					FCMappers
47	T. Mansouri, A. ZareRavasan, A. Ashrafi	A learning fuzzy cognitive map (LFCM) approach to predict student performance	2021	/				/	/	/			Learning FCM	
48	M. Fabiana Jacintha Mary, M. Mary Mejrullo Merlin	A comparative study using neutrosophic cognitive map and triangular fuzzy cognitive map for analyzing the factors for quality training of elementary education student-teachers in Tamilnadu	2021	/			/		/				Neutrosophic Cognitive Maps & Triangular FCM	
49	A. Infante-Moro, J.C. Infante-Moro, J. Gallardo-Pérez, & F.J. Martínez-López	Key Factors in the Implementation of E-Proctoring in the Spanish University System	2022	/			/		/			/		FCMapper

50	K. Oqaidi, S. Aouhassi, K. Mansouri	A Comparison between Using Fuzzy Cognitive Mapping and Machine Learning to Predict Students' Performance in Higher Education	2023	/		/		/		
51	B. Bermeo-Córdova, J.L. Yagüe Blanco, M. Satama Bermeo, & A. Satama Tene	Pre-professional practices in the training of agricultural graduates: the case of Ecuador using fuzzy cognitive maps	2022	/	/		/	/	/	Rstudio & FCMapper
52	Zhang, J.	The integration of English teaching and ideological and political education based on cognitive mapping constructs	2023	/		/			/	
53	S.A. Sonje, R.S. Pawar, S. Shukla	Assessing Blockchain-Based Innovation for the 'Right to Education' Using MCDA Approach of Value-Focused Thinking and Fuzzy Cognitive Maps	2023	/	/		/	/	/	Mental Modeler
54	J. Pimentel, P. López, J. Rincón, (...), C. Correal, I. Sarmiento	What facilitates or prevents academic fraud in a Colombian faculty of medicine–Protocol of a study using fuzzy cognitive mapping	2023	/	/		/		/	