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APPLICATION OF COMPLEXITY THEORY IN CONSTRUCTION INDUSTRY: A REVIEW

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ABSTRACT

Complexity theory considers objects as systems. A system is understood as a set of elements linked together by a common objective. In this way, construction is a system composed of a numerous element that originate an emergent behavior that cannot be explained in these elements taken in isolation. Currently, there has not been studied and identified the application of complexity in construction industry. Therefore, in this paper, the attempt is to provide a systematic review of application of complexity theory in construction industry. On this subject, the Scopus database has been chosen to select 567 papers from 1971 to 2021. Articles were analyzed according to various aspects: co-occurrence, keywords and timeline, and with the help of the softwares tools VOS viewer and Cite Space, it was built the visualizing network of keywords and co-occurrence. Five areas involving different applications of complexity theory in construction are identified, including: (1) safety risk, (2) project management, (3) building contractor, (4) cac system, (5) construction waste management. The analysis results reveal that the most cited papers related to complexity theory and construction are in safety risk. Lastly, trends and results investigation of the areas identified of application are shown.

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INTRODUCTION

In general, building process is understood as a linear, orderly and simple process and therefore it is considered as a systematic development that can be divided into individual components (Bertelsen & Koskela, 2003). Moreover, the construction process is not a linear, iterative project where all activities and all outcomes are the same everywhere (Matilla and Park, 2003). Fernández-Solís (2013) describes the general nature of construction as a deterministic, dynamic, non-linear flow consisting of several elements that are interrelated. In this sense, complexity theory could be a theory that can be related and applied to construction industry, however, there is not a lot of data on the application of complexity theory in construction industry. The aim of this study is to use two bibliometric tools, CiteSpace and VOS viewer, to identify and describe the relationship between complexity theory and construction industry. Investigation is carried on analyzing timeline publications, countries/regions and clusters analyses.

Complexity Theory: Objects do not exist in isolation, but in dynamic interaction with the environment, coexisting in a web of relationships. Complexity theory asserts that the world is not merely subjective, but the result of interactions between objects and contexts (Kane, 2000).

The term "complexity science" originated in 1984 with the founding Of the Santa Fe Institute in New Mexico, which was dedicated to the study of the behavior of complex systems and the application of interdisciplinary concepts to the study of nonlinear phenomena. In complexity theory, an object is viewed as a system. A system is a set of elements that interact with each other to achieve a goal. The main characteristic of the system is therefore the mutual influence of its components. Complex systems are characterized by the fact that their behavior is unpredictable and non-linear. They consist of a large number of elements that give rise to emergent behavior that cannot be explained by considering elements in isolation. Likewise, they are unstable and a small change in the relationship between their elements can change the behavior of the whole. According to Iarozinski and Leite (2010), a phenomenon can be said to be complex if the observer attributes the following properties to it:

- The system consists of a large number of components or elements that have multiple functions and different behaviors.
- Elements are constantly evolving and are influenced by events that cannot be predicted with certainty.
- Information about the state of all these elements is not fully known.
- Various elements are interconnected by a variety of interrelationships.

The product of a complex system is not merely the sum of its parts. The new properties that emerge cannot be attributed to any single element, and on the other hand some of their inherent properties are limited. The systematic behavior of a group of factors can only be understood when it is studied as a whole. (Prudencio Muñoz, 2016). Complexity theory has key concepts such as attractors, fractals, bifurcation, and entropy, that have been studied and explained to understand the workings of a complex system in detail (Lu, Clements-Croome, & Martti , 2010).

Attractors: Prudencio (2016) explains an attractor as the set to which system evolves after a sufficiently long time. However, attractors can also be seen as the states to which the system eventually settles and which help to bring order out of chaos. (Lu, Clements-Croome, & Martti , 2010). In general, an attractor is the set of variables and their probable configurations that explain the tendency of a dynamical system. Attractor can be considered as the way chaotic motions of a system are self-organized. Its behavior is represented in an abstract mathematical space called phase space, which is defined as the space formed by generalized positions and their conjugate moments. The concept of attractor sets the stages for a better understanding of dynamic balance and its implications for the evolution of dynamical nonlinear systems. However, despite the difficulties in understanding what is behind this phenomenon, the strange attractors indicate, a state of equilibrium to which the system aspires. (Vieira, Cordeiro Martins, & Gonçalves, 2014)

Bifurcation: Bifurcation is a change in the qualitative pattern of attractors. Values of fluctuations begin to increase significantly as the objects approach the bifurcation points. This interpretation explains the butterfly effect, which means that a small change in the system parameters can lead to a significant change in the system. Bifurcations are closely related to attractors because they represent a qualitative change from one type of attractor to another, implying a jump in phase space. They describe the most fundamental properties of all complex systems: stability and change (Lu, Clements-Croome, & Martti , 2010).

Fractal: Within the chaotic regions, smaller areas of stable periodicity are discernible and these areas appear on a much smaller scale. Such repetition of the same pattern at different scales is called fractal (Lu, Clements-Croome, & Martti , 2010). According to Prudencio (2016), a fractal can be defined as a geometric representation of an attractor. It is a geometric representation of a basic structure that is repeated at different scales and has the following characteristics:

- Has details at arbitrarily small scales.
- Too irregular to be described in traditional geometric terms.
- It has self-similarity (exact or statistical).
- Can be defined recursively, that is, they are self-referential.

Entropy: The second law of thermodynamics reflects the quality of mixing, disorder, and randomness that increase in systems, including all types of flows (Elnashaie & Grace, 2007). In this arrangement, complexity theory is emphasized when open systems that engage with their environment, continue to grow and evolve and tend towards diversity and complexity (Fernandez Solis, 2013). In thermodynamic equilibrium, entropy has its maximum value when the system is isolated in situations that approach equilibrium. The steady state then corresponds to a minimum of entropy production. Entropy indicates the degree of disorder in a system, i.e. the system is organized, the lower its entropy (Vieira, Cordeiro Martins, & Gonçalves, 2014).

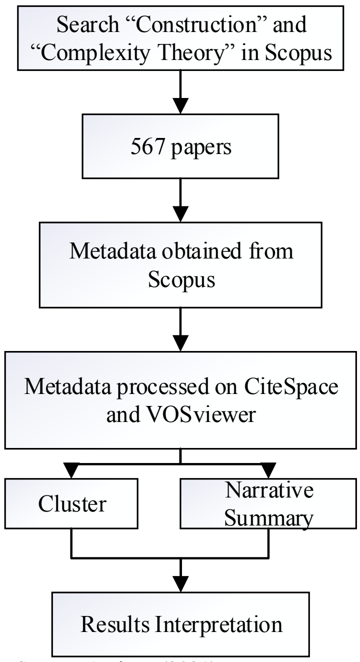
MATERIALS AND METHODS

Research methodology used for this study consists of a literature review and draws its conclusions from various peer-reviewed and published bibliographic sources. For the objective of this paper, the bibliographic database selected is Scopus, which is recognized as the largest database of abstracts and citations of peer-reviewed literature. To conduct this study, journal and conference papers were selected for analysis to provide more comprehensive and quality information on complexity theory and its application in the construction industry. Literature search was conducted using two keywords: "construction" and "complexity theory". The full string search is as follows:

> *("Construction Industry" or "Construction Building Industry" or "Building Industry" or "AEC") and ("Complexity Theory" or "Complex Systems" or "Chaos Theory" or "chaos model" or "Complex Systems Theory" or "Paradigm of Complexity" or "Complex Adaptative System" or "System Theory" or "Systems Analysis")*
> *(date: 01/11/2021)*

Search found 567 papers from 1971 to 2021 on the topic of construction and complexity theory. For the aim of this investigation, article metadata was extracted from Scopus for the systematic reviews and meta-analyses. The programs selected for analyses are Cite Space and VOS viewer. The selection of these programs is particularly valuable in broad research areas. Systematic reviews are used to provide a complete overview of complexity theory and its application to date, and meta-analysis can be used to find relationships between references, authors, and keywords to provide a detailed overview of the application of complexity theory in construction. Interpretation of the results obtained from CiteSpace is based on the concept of cluster provided by Cite Space, which cross-references of the metadata obtained from Scopus. The articles are categorized into different clusters including construction industry, project management, construction waste management, and other application areas. Consequently, a narrative summary was also obtained from Cite Space to observe in detail at each cluster formed and identify the most cited papers that configuring the cluster. A detailed assessment of each article was then undertaken to determine the application of complexity theory in construction.

The entire systematic review process and Meta analyses are illustrated in Figure 1.



Source: Authors (2021)

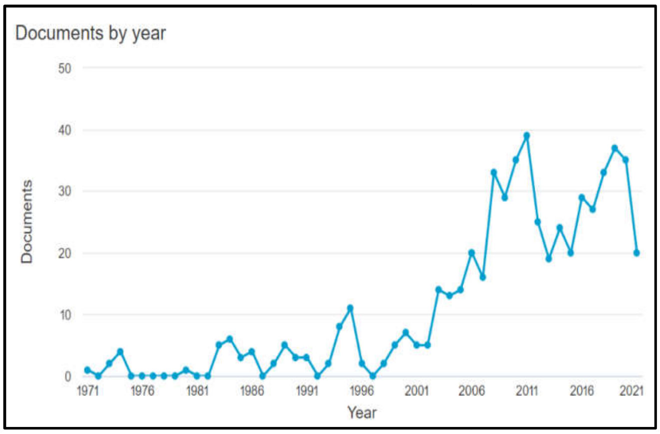
Figure 1. Research process

RESULTS AND DISCUSSION

Data Analysis: The results of this paper are presented in two categories. Descriptive results are the first category of research results. In this first category, descriptive results show the values for the number of articles published by year and country/region. In this order, Scopus database was used to determine the descriptive results.

The second category is the evaluative results, where 567 articles were analyzed and visualized using VOS viewer and CiteSpace software.

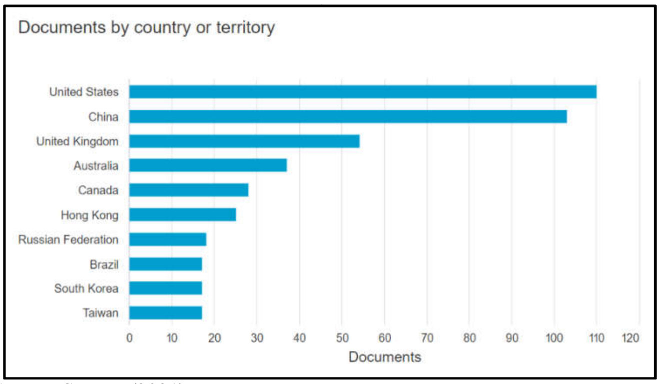
Descriptive Results: Results are given in terms of years, authors, institutions, journals and countries. Figure 2 shows the total number of articles by year.



Source: Scopus (2021)

Figure 2. Number of articles per year

No filter by year was used in Scopus database, and a total of 567 articles were found. Figure 2 shows that the first article on construction and complexity theory was published in 1971. This shows that sixty-six articles were published by the year 2000. Moreover, it shows an increase in the number of articles in the period between 2008 to 2012. In addition, more articles were published in 2008, 2010, 2011, 2016, 2018 and 2019 than in the other years. Figure 3 shows the top 10 most productive countries/regions of the total 49 obtained.

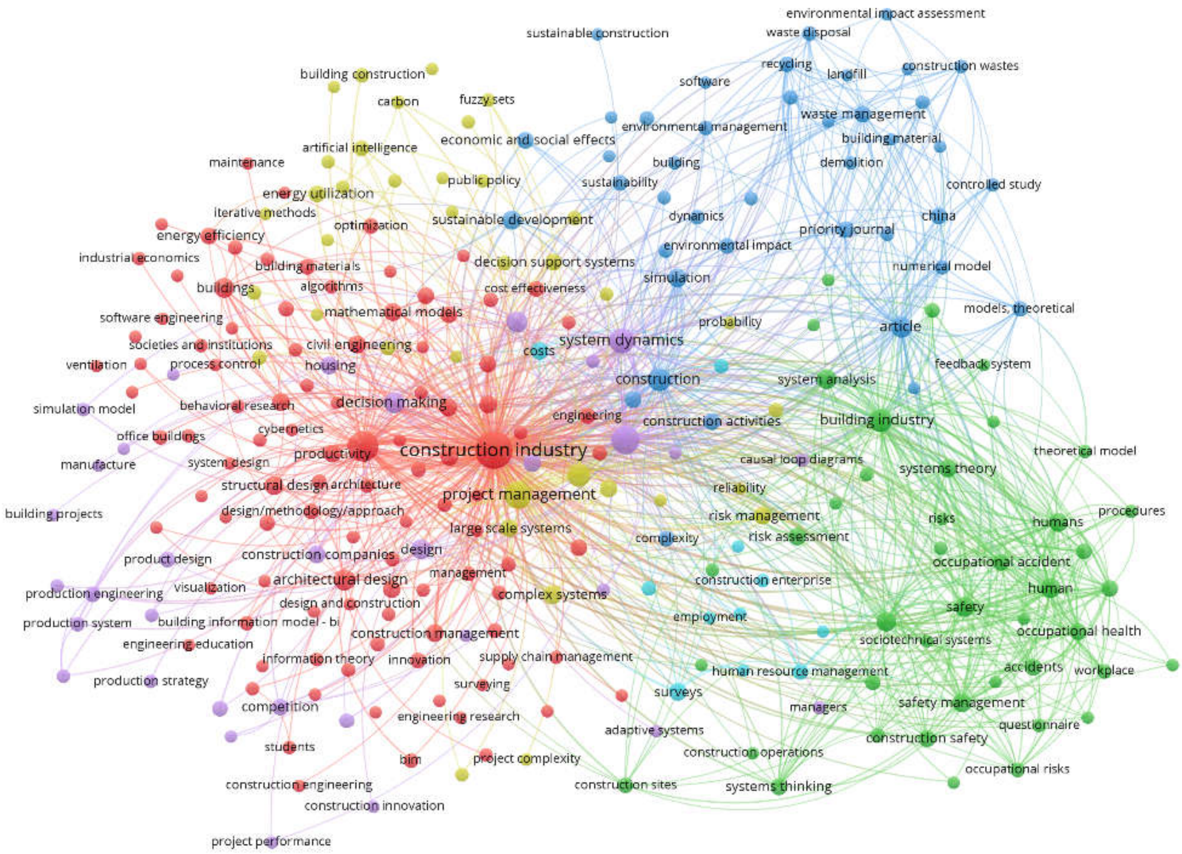


Source: Scopus (2021)

Figure 3. Number of articles for per country/region

The Figure above shows that United States is the first country to publish 110 investigations. Furthermore, China has published 103 articles, and the United Kingdom is third with 54 papers.

Evaluative Results: In this section, evaluative results regarding co-occurrence keywords and co-occurrence terms are given obtained from VOS viewer. Figure 4 shows the visualization map of co-occurrence keywords for construction industry and complexity theory. A total of 267 keywords were extracted. Analysis of the clusters shows the knowledge structure of relationships between complexity theory and construction. The network was divided into six clusters according to the link strength of keywords co-occurrence. Cluster 1 in red color is the largest cluster with 103 co-occurrence keywords: chaos theory, systems analysis, construction industry, etc. Cluster 2 in green color contains 42 keywords: accident, accident prevention, safety, building industry, systems analysis.



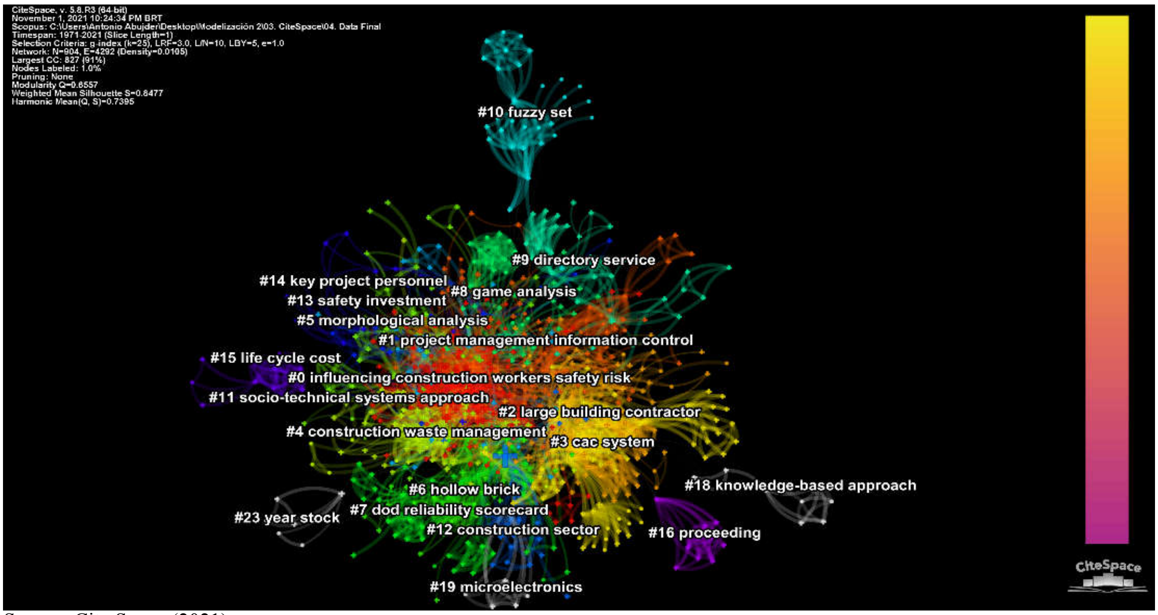
Source: VOS viewer (2021)

Figure 4. Co-occurrence keywords visualization map

Cluster 3 in blue color contains 41 keywords: Construction, industrial waste, waste management. Cluster 4 (yellow) with 37 keywords: construction project, project management, construction process, project complexity. Cluster 5 in purple includes 33 keywords: systems theory, systems dynamic, buildings projects. Finally, cluster 6 (light blue) with 11 keywords: surveys, construction enterprise. Keywords cluster was created by CiteSpace, which clearly displays high-frequency keywords. CiteSpace software was used to find studies published from 1971 to 2021 using the key words, with the aim of establishing a link between complexity theory and construction. Results of cluster map in Figure 5 confirm that the application of complexity theory in construction is very related to safety management covered by 123 items. Based on the clusters map relation with project management information is also displayed among 97 items. The relationship with large building contractor contains 84 items. Cac systems known as system dynamics with 74 items. Finally, with 70 item construction waste management is also shown in figure 5. The previously mentioned clusters are the ones most related to complexity theory and construction, and these clusters are analyzed in detail for the purpose of this study.

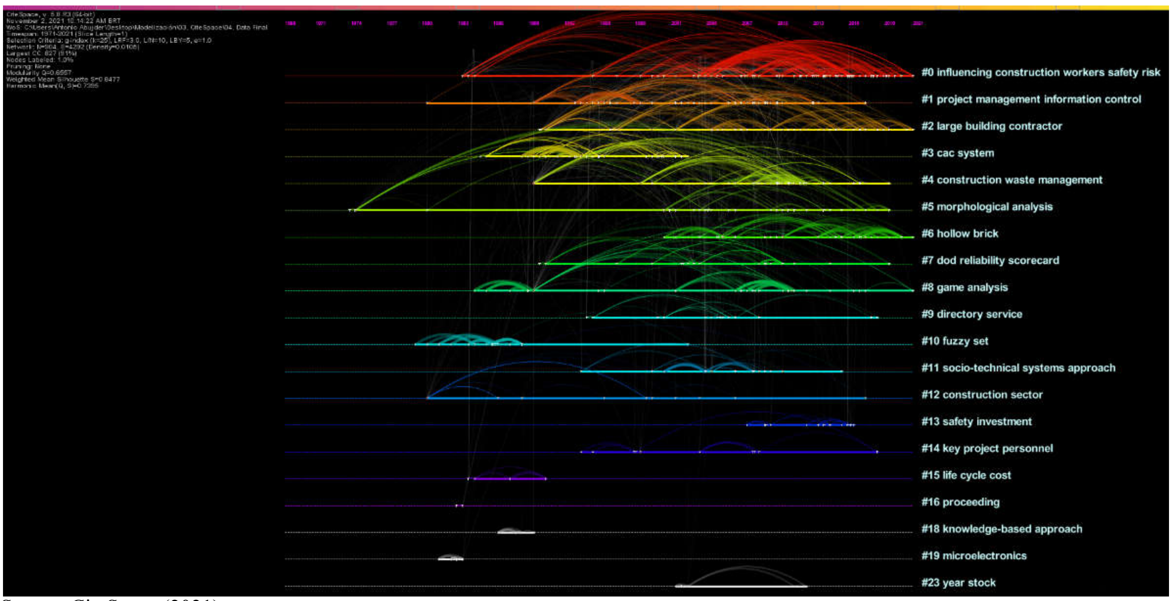
Thus, after generating the keywords cluster map, the timeline map of keyword network could be obtained as well. Timeline view exhibits time evolution and relation with the clusters identified (Figure 6). Figure 5 below presents the characteristics of time evolution and keywords for the 23 clusters identified. Taking the field represented by cluster # 0 at the top of the figure (# 0 influencing construction workers safety risk) as an example, the time evolution is from 1983 to 2021. From 1989 to 2021, the cluster categories with the largest time span for the cited references are #1 project management information control, # 2 large building contractor and # 3 cac system. The most frequently cited cluster categories are # 0 influencing construction workers safety risk and #1 project management information control. In recent years, the cluster categories of the most concentrated citations were # 0 influencing construction workers safety risk and # 4 construction waste management.

Application of Complexity Theory in Construction: According to Fernández Solís (2008). The nature of construction is systemic, construction operation and organization is a deterministic dynamic, nonlinear flow involving an extremely large number of actors.



Source: Cite Space (2021)

Figure 5. Visualization of keywords clusters of 567 studies published from 1971 to 2021



Source: CiteSpace (2021)

Figure 6. Timeline view of keywords analysis

Construction outputs are not proportional to inputs, and the whole is different from the sum of its parts, where the sum of its parts is much larger than final product. Construction must be considered an open social system and the interoperability of each participant involved. It is nested in a social system with a varying team where communications and cooperation are emergent phenomena in each project. This emergent nature also helps the system learn from itself and achieve its self-organized goals towards the completion of the design intent. All these characteristics of a building construction's project system are favor in considering it as a complex system. Construction process is a complex and dynamic process (Bertelsen, 2003). Therefore, complexity theory can be applied to understand the building process. However, as can be seen in the clusters identified above, complexity theory is applied in different areas of construction process. In 1990, Jamal F. Al-Bahar1 and Keith C. Crandall published the most widely cited study (221) on systematic risk management. In this study, a new risk model entitled Construction Risk Management System (CRMS) was introduced based on a systematic approach due to the complex nature and many uncertainties in construction process. The proposed model was developed to be a logical and systematic tool for contractors to help identify, analyze and manage risks in a construction project. (Al-Bahar & Crandall, 1990). Construction Risk Management Systems consists of four processes arranged in a logical and sequential order to provide a systematic way of managing risk. Processes are interrelated and cannot exist in isolation, variation in one component of model can vary the entire process. Mingyu Shina et al. (2014) published the second most cited study about systems dynamic and risk management. In this study, a model was developed to better understand the cognitive processes of constructions workers to achieve safe behavior (Shin, Lee, Park, Moon, & Han, 2014). The model was based on a system dynamics approach to focus on the feedback structure and resultanting behavior as a complex system. The third most cited publication on systems theory for construction accident prevention was published in 2013 by Seokho Chi & Sangwon Han.

This publication presented a model for understanding the relationships between safety hazards in construction. Relationships between accidents and human, mechanical, and physical risks were identified. Referring to the relationship between project management information control and complexity theory, Bertelsen (2003) states in a detailed study that construction has characteristics such as a nonlinear, complex and dynamic phenomenon. The notion of an orderly and linear project is a misconception, mainly due to the nature of construction projects. This is confirmed by Bertelsen and Koskela (2005) when they referred to the complexity and dynamic nature of projects as the starting point and management systems should be designed and operated with this in mind. Complexity is a concept related to construction projects. Ingeneral, construction projects have many interconnected parts (L Wood & Gidado, 2008). The most common situation in construction is that process cannot be accurately predicted due to interdependence and variability. (Bertelsen & Koskela, 2003) Seeing construction as a system with the characteristic of being a non-equilibrium phenomenon provides a new way of understanding the process as a complex process in which the structural emergence and organization interacts with elements. In this complex system, all elements are interconnected. Homer Dixon and Homer Dixon (2002) summarize the characteristics of complex systems, and Xiao and Fernandez Solis (2016) apply them to construction management as it can be seen below.

- **Multiplicity:** Construction stake holders consist of owners, architects, engineers, consultants, etc.
- **Interdependence:** With respect to construction process, none of the tasks, parts, or entities involved in the process can be easily removed or replaced, making the construction process complex.
- **Openness:** Relationship with the context, politics, economic situation, and advanced technologies regularly influence the construction process.
- **Emergence:** The degree to which the whole system is more than the sum of its parts. A built project has no value until it is delivered to the owner and used for its intended purpose; the value of the whole building is greater than the sum of its parts.
- **Nonlinear behavior:** The impact on the system is not proportional to the magnitude of change in a component. The nonlinearity of the building project carries over to the nonlinearity of the subsectors and the nonlinearity of industry and the general economy.
- **Adaptability:** Organizations are adaptable in that they do not simply react to events, but evolve or learn. Each component or actor, in the construction system is guided by its own schema or rules of behavior and also by a schema that is shared with others in the system.

Cluster # 2 in Figure 6 highlights the relationship between large building contractors and complexity theory. The most relevant paper establishing this relationship was published in 2017 by Abdulaziz M. Jarkas. The results of the study prove that large contractors operating in Kuwait discern projects with a high level of interdependencies, interactions and interrelationships between parts as the most complex to construct. Moreover, during the research, he establishes the general consensus of contractors operating in Kuwait on the perception of the concept of complexity and identifies the perceived importance of contributors underlying the principles of project complexity.(Jarkas, 2017). As for clusters # 3 and # 4, their relationship is based on the cac system or also known as system dynamics and construction waste management. When the clusters are analyzed in detail, it is found that most of the relevant articles of the clusters are the same because there is a strong relationship between system dynamics and construction waste management. It is also evident that the relevant articles for clusters # 3 and # 4 are entirely from China, which is also related to what is observed in figure 3 where China is the second country with the most articles per country. Hongping Yuan et al. in 2012 published "A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste". This research proposes a model that help as a decision support tool for projecting construction and demolition waste reduction in order with waste management situation of a construction project (Yuan, Chini, Lu, & Shen, 2012). Model was conducted using system dynamics and used complexity, interrelationships and dynamics of any social, economic and managerial system. The model proposed integrates major variables that affect construction and demolition waste reduction. Second relevant study was conducted by Hongping Yuan and Jiayuan Wangb in 2014. This study proposed a model developed with the guidelines of system dynamics. It is particularly useful in determining the properties of systems and the overall behavior of these systems by analyzing interactions between elements involved. Interactions between elements evidence that a change in a particular element affects the overall behavior of the system. (Yuan & Wangb, 2014) Finally, Zhikun Ding et al. in 2016 develop a model of construction waste reduction management in construction phase based on system dynamics. Model includes components such as: (1) source reduction measures, (2) reduction behaviors, (3) government policies and regulations and (4) environmental benefits. During the process investigation, all variables affecting construction waste reduction management were identified and their interrelationships were described.

CONCLUSION

In this study, a systematic review of complexity theory and construction industry in various application areas was conducted. A total of 567 articles were obtained from Scopus during the period 1971–2021. The data were analyzed using both CiteSpace and Vos Viewer, which led to results about the application of complexity theory in construction industry in various fields. Areas includes influencing construction workers safety risk, project management information control, large building contractor, cac system, construction waste management. Publications analyzed in the different areas are mostly proposed models from a systematic perspective and under the guidelines of systems theory. In many of them, the identification of different variables and determination of relationships between the variables was demonstrated. Similarly, in the various models proposed in publications, the concept of system is established, i.e. the variation of a component of the system can affect the entire system and the whole is different from the sum of the parts. When publications analyzing the publication in the timeline, it was found that there the number of articles published in educational contexts increased significantly after 1990. It was also found that the most frequently cited cluster categories were #0 influencing construction workers safety risk and #1 project management information control. As for the number of articles per year, sixty-six articles were published until 2000. However, from 2008 to 2012, the number or articles increased. Moreover, more articles were published in 2008, 2010, 2011, 2016, 2018 and 2019 than the other years. Country analysis showed that United States was the most active country in complexity theory and construction industry. China ranked second one and United Kingdom ranked third.

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