STRATEGY AND MODELS OF BUILDINGS MAINTENANCE – A LITERATURE SURVEY

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Abstract

In the article comprehensive insights into the field of building maintenance, emphasizing the importance of keywords, collaborative efforts among authors, and the evolving research landscape are provided. The study conducts a thorough literature review using Scopus as a search engine, employing the full-counting method for authorship, and VOSviewer software for bibliometric analysis. The results reveal distinct data sets focusing on building maintenance from general to specific, with each set reflecting unique aspects and considerations. Bibliometric maps illustrate author collaboration and keyword connections within each set, highlighting evolving research trends and areas of focus. The study concludes with recommendations for future research, emphasizing the ongoing need for exploration and development in building maintenance.

Keywords: building maintenance, university building, cost, renovation

1. INTRODUCTION

The use stage is the longest phase of buildings' life cycle [1, 2]. It is a process which involves economic, technical and social activities which should be organized in a proper way. In the use stage of a building, proper activities connected with the building operation as well as building maintenance have to be properly planed. The use stage can be divided into 6 sections: maintenance, repair, replacement, refurbishment, operational energy use, operational water use [3].

Many scientists discuss the broad topic of building maintenance. Examples can be mentioned: methods of maintenance prioritization [4], improvement actions on building maintenance management [5], providing the guidelines on maintenance decision making [6], procedures and determination of factors affecting building maintenance success [7], implementing extensive models for use in building maintenance processes like multi-criteria decision-making model developed in [8] as well as on buildings' maintenance cost estimation models assessment [9].

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Moatassem et al. [10] delves into an optimization analysis of maintenance and operational costs, using a public building as an illustrative example. This underscores the importance of cost-effective maintenance planning and its complexity, as it necessitates an assessment of both maintenance requirements and costs based on historical data and prior experiences, a challenge for facility managers. With reference to historical data, Salvado et al. [11] present interesting data based on a large number of public school buildings erected from 1940 onwards, listing key performance indicators and presenting a portfolio of economic results.

A significant context is the age of the European building stock, with 90% of buildings constructed before 1990 [12]. This context underscores the need for effective multi-year maintenance programs to address aging infrastructure. Such programs are crucial not only for cost management but also for the well-being of building occupants [13].

Moreover, building degradation due to aging, as emphasized by Kwon et al. [14], not only escalates repair costs but also impacts the usability, aesthetics, and historical value of structures [15]. Hence, proper maintenance strategies are imperative to preserve the condition of buildings and optimize maintenance costs. Hashempour et al. [16] suggest that there is a need to build an original decision-making tool that decreases the computational time of optimization and improves the effectiveness of optimal energy modernization and renovation of existing buildings. Case study in the article by Ghafoori and Abdallah [17], presents the model that is able to optimize building upgrade measures to reduce the building maintenance up to 38% while meeting the specified budgets.

In the field of maintenance standards, ISO standard 15686-5:2017 and European standard EN 13306:2017 define two primary maintenance types: preventive and corrective maintenance. Various authors in the literature propose alternative maintenance type classifications, such as planned and unplanned maintenance [18], predictive and emergency maintenance [19], or preventive and predictive maintenance strategies [20]. Maintenance is also categorized into different levels based on the timing of required repairs, as noted by Przesmycka and Wieczorek [21]. Lean maintenance principles, discussed in [22, 23], have gained attention for building maintenance optimization.

Numerous models have been developed by scientists to optimize building renovation processes. These models consider factors like technology choices, sustainable solutions, occupants' comfort, and costs. Pereira et al. [24] introduces a condition-based maintenance model using Petri nets. Plebankiewicz and Grącki [25] use a regression model to predict renovation cost. Multi-criteria decision-making (MCDM) and multi-objective optimization are employed by several authors [26 -28] to study the trade-offs between conflicting objectives in building maintenance. Nowogońska and Korentz [29] present model for accurate assessment of renovation works costs in a certain stage of building use based on prediction of reliability according to Rayleigh distribution (PRRD). Moreover, artificial neural networks (ANN) have gained popularity in building maintenance modeling, with hybrid models integrating ANN with other methods, as highlighted by Liu et al. [30].

The use stage of a building is the longest in its life cycle and also the most complex. Comprehensive assessment of a building allows to determine renovation needs and determine the best strategy for building maintenance. Another issue related to the building maintenance is the problem of building maintenance cost optimization, which is particularly important in public buildings such as universities. This paper presents the results of a literature survey aimed at investigating the current issues raised by researchers related to building maintenance. In particular, attention was paid to university and educational buildings. This will allow to learn about possible research gaps and determine further research directions.

The rest of the paper is organized as follows: Section 2 presents the software used in order to comprehensively expand the literature review and datasets sourced from the database. The results are described in Section 3. Section 4 concludes this paper.

2. MATERIALS AND METHODS

The multi-disciplinary citation database of Scopus was used as search engine, to find articles related to the topic of building maintenance. The full-counting method was used by Gauffriau [31], which means that all authors of publications on the author's publication list have been counted as 1, also if co-authors have occurred. The counting method is not only important to choose indicators properly but also to analyze the bibliometric network [32]. Various types of bibliometric networks have been studied in the literature [33, 34].

In order to comprehensively expand the literature review and gain deeper insights into the prevailing trends in global scholarly research, VOSviewer software [35] was used. The software's capabilities extended to the creation of bibliometric networks, manifesting as intricate network visualizations, all derived from carefully curated and pre-processed datasets. These maps allowed the authors to visually represent the complex web of connections and relationships within the vast body of literature that was explored. The literature analysis drew upon a reasonably chosen set of keywords, each of them linked to the central research problem. Furthermore, the authors introduced specific constraints and parameters during the advanced search process within the SCOPUS database. These measures ensured that the analyzed literature was extensive and fitting to the research objectives. One of the features of the VOSviewer program was its ability to facilitate visualizations of dependencies among authors, documents, citations, and keywords. This functionality enabled to gain a holistic understanding of the scholarly landscape surrounding the research area.

The authors conducted a series of test searches to precisely identify the most fitting keyword groups for their research. This cautious approach was deemed necessary due to the potential ambiguity of certain terms when used as separate keywords, as they could be associated with multiple contexts in the scientific literature. For instance, consider the keywords "educational" and "building." These terms not only find relevance within life cycle assessment and various engineering domains but also have substantial presence in scientific literature encompassing fields such as psychology, sociology, and the broader domain of pedagogy.

However, the authors recognized that the power of keyword selection lay not only in the individual terms themselves but also in their potential to synergize when paired or grouped with complementary keywords. Therefore, an approach to improve the literature search strategy by combining some keywords was made. The authors aimed to exploit the interrelationships between them, thereby discovering articles related to their research interests.

Network visualization also introduces the concept of "clusters." Clusters emerge as groups of items that share thematic or conceptual similarities. However, clusters in VOSviewer do not overlap, ensuring clarity of thematic groups within the visualization. Each cluster is assigned a cluster number, simplifying the identification of these thematic domains.

This study presents datasets sourced from the Scopus database, focusing on the global literature connected with educational building renovation and maintenance plans. Interpretation of the selected data sets in VOSviewer included the "co-authorship" analysis of a group of authors publishing in a given area limited by chosen keywords for the full counting method, which consists in the number of publications on author's publication list. The program allows to select number of co-authors in published documents. As part of the keyword interpretation, the "co-occurrence" analysis type for the full counting method was selected and the unit of analysis - all keywords. The minimum number of keyword occurrences varies depending on the volume of the data set.

The analyzes were conducted on datasets sourced from the Scopus database, focusing on the global literature within the specific subject area of educational building renovation and maintenance plans. To ensure relevance and precision, the search criteria were carefully defined. The search was

limited to specific fields, including "TITLE-ABS-KEY," and specific document types, such as articles, reviews, and conference papers. Additionally, the subject area was restricted to engineering, aligning the dataset closely with the research objectives. The "TITLE-ABS-KEY" restriction proved particularly valuable, enabling targeted searches within the content of titles, abstracts, and keywords provided by authors. This ensured that the resulting dataset captured the desired terms and content related to the subject matter, facilitating a focused and comprehensive analysis of the research landscape.

The research was conducted as follows. First, keywords related to the research topic were identified. Their scope is presented in Fig. 1.
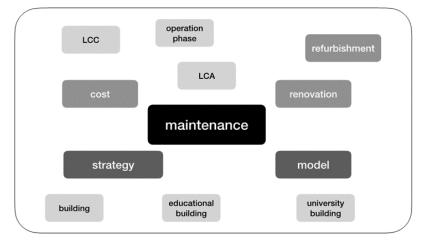

Fig. 1. Analyzed keywords

In the next step, an attempt was made to combine the keywords into sets, so that, none of the sets contained more than 5 words. The authors found that a larger number of words in a single set produces so many results that they are difficult to analyze. The results have been presented for the outcomes of a comprehensive literature review conducted on eight distinct data sets whose basis was the maintenance of the building. These data sets were selected based on combinations of words related to the broadly considered building maintenance in the context of the EU renovation wave trend, focusing on maintenance strategies in the building life cycle and on renovation plans for educational buildings. Additionally, aspect of costs connected with the operation phase were taken into account. The literature review data sets were ordered from the most extensive data set to the most specific one. The most general collection of articles in the researched area consists of 19,758 articles, while the least developed data set considers only 10 publications. Considered data sets consist of various levels of detail and accuracy in the analyzed area.

Keywords in chosen data sets are presented in Fig. 2.

Set 1	maintenance	strategy	model				building
Set 2	maintenance	strategy	model			LCA	building
Set 3	maintenance	strategy		refurbishment	cost		educational buidling
Set 4	maintenance	strategy		renovation		LCC	university building
Set 5	maintenance	strategy	model			operation phase	building
Set 6	maintenance		model	renovation	cost		educational building
Set 7	maintenance	strategy		renovation			university building
Set 8	maintenance			renovation	cost	LCC	educational buidling

Fig. 2. Keywords in chosen data sets

Details of created data sets:

For "Set 1," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "strategy" AND "model" AND "building"

For "Set 2," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "strategy" AND "LCA" AND "model" AND "building"

For "Set 3," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "refurbishment" AND "cost" AND "strategy" AND "educational building"

For "Set 4," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "renovation" AND "strategy" AND "LCC" AND "university building"

For "Set 5," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "strategy" AND "operation phase" AND "model" AND "building"

For "Set 6," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "renovation" AND "cost" AND "model" AND "educational building"

For "Set 7," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "renovation" AND "strategy" AND "university building"

For "Set 8," the dataset is filtered based on the following criteria:

• TITLE-ABS-KEY included the terms "maintenance" AND "renovation" AND "cost" AND "LCC" AND "educational building"

Created data sets - Limitations:
•   The document type is confined to "article", "review", or "conference paper"
•   The subject area is limited to "Engineering"

For a more in-depth examination, the authors analyzed only two datasets "Set 1" and "Set 2". The aim was to find and decode the nuanced connections and relationships that underlie keywords such as "maintenance", "renovation", "plan", "educational" and "building". "Sets 3-8" were subjected to a different type of analysis.

3.   RESULTS AND DISCUSSION

3.1. Analysis of "Set 1"

The dataset denoted as "Set 1" included the terms "maintenance", "strategy", "model" and "building" consist of 19,182 authors that wrote together 19,758 documents – meaning here articles, conference papers and reviews. Set 1 includes not only a great variety of topics connected with maintenance but also the greatest time lapse in between all created data sets (Fig. 3).

The initial publications on building maintenance strategy models emerged as early as the 1970s. In the research the time range between 1970 and 2023 was checked. One of the first articles which was published in 1970s, was published by David R. Fairbanks named "Computer program to determine the optimum configuration of solar assist build heating and cooling systems based upon life-cycle cost" in 1975 [36]. Since the 1990s, there has been a discernible increase in interest in this subject. The culmination of this interest is notably traceable to the year 2018, during which over 1,000 publications were released. Subsequently, the volume of publications has continued to rise each year, reaching a highest number which equal over 3,000 publications in the year 2022.

Due to large number of researchers the set 1 bibliometric map (Fig. 4) creation was restricted to minimum number of documents of an author equal three at the first stage of analysis. As a result of limitations 78 groups of authors met the threshold creating 78 clusters not connected with each other. The created network indicates that researchers do not work together over common topics with other authors of similar interests around world. At the stage 2, publications threshold was set at minimum limit of 5 documents per researchers team. There are eleven groups of authors that constantly develop their work, who published at least 5 documents, in the analyzed area.

Only two groups published at least 7 publications and one of the authors' group research work development was analyzed precisely. All the publications were published in the years 2013-2017 by team Au-Yong, Ali and Ahmad. The first one was titled "Office building maintenance: Cost prediction model" [37], and the last one "Competency and commitment of facilities managers: Keys to safe-guard maintenance performance" [38].

It can be observed that one of the researchers of an analyzed group (Au-Young) has published much more publications than only within analyzed cluster. It can be seen that the researcher's interest in the maintenance topic has evolved over the time. Firstly, maintenance costs, mainly in the area of office buildings within the marked cluster in Fig. 4 were considered [38]. Then the author worked on maintenance of high-rise buildings [39] and finally focused on hospitals' maintenance [40]. In the meantime, literature review in the area of interests was prepared. One of the last paper was published in 2022, the title "Promoting employee participation in operation and maintenance of green office building by adopting the total productive maintenance (TPM) concept" [41].
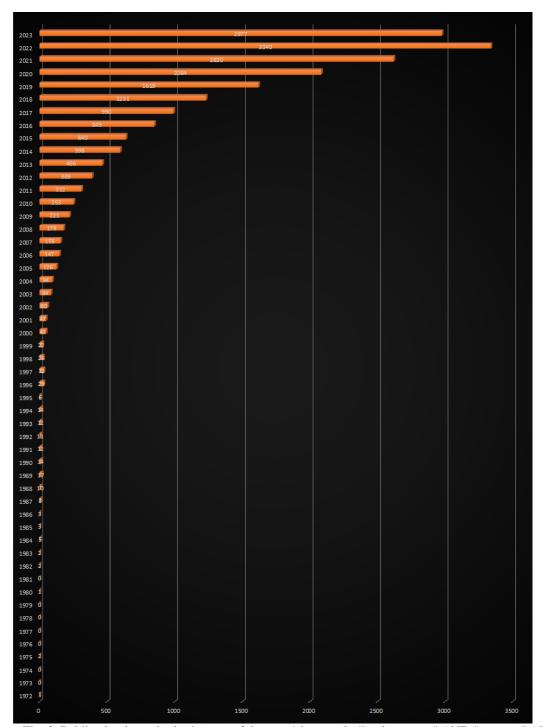
Fig. 3. Publication intensity in the area of data set 1 keywords ("maintenance" AND "strategy" AND "model" AND "building") in years 1972-2023

Other groups of authors publishing in the set 1 area include Rafaela Bortolini and Núria Forcada, authors of, among others, articles „Building Inspection System for Evaluating the Technical Performance of

Existing Buildings" 2018 [42] and "Analysis of building maintenance requests using a text mining approach: building services evaluation" 2020 [43]. Another significant group is the publications of Jaya Nepal and Hua-Peng Chen, who mainly deal with the maintenance of concrete facilities [44-45]. Similar issues are addressed by Aruz Petcherdchoo [46]. Also contributing significantly to Set 1 is the team of Desmond Eseoghene Ighravwe and Sunday Ayoola Oke, whose publications focus on the use of multi-criteria decision-making methods for selecting a suitable maintenance strategy [27, 28]. Another team is Yuling Fan and Xiaohua Xia [47, 48].
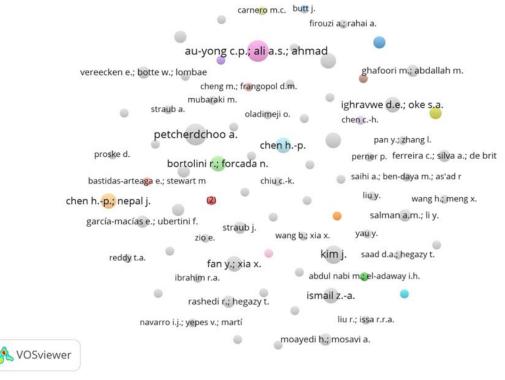

Fig. 4. Set 1 bibliometric map

Fig 5. reveals publication intensity over the last two years (2022, 2023). The map was created out of authors that published at least 2 publications. Map interpretation indicated in yellow color authors that published their work results in the analyzed area in 2023. It is visible that only several authors were active at that time, only 12 clusters occur as the one that published some works in the year 2023. Can be mentioned, for example: [49, 50].
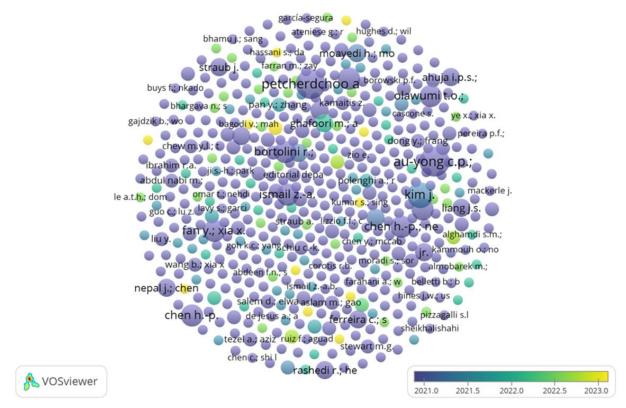
Fig. 5. Set 1 bibliometric map – time overlay

Subsequently, the keywords that occur in Set 1 publications were investigated. Due to enormous variety of keywords included in this set (91,539 terms), the occurrence threshold was imposed. In order to create better readability of keywords map the occurrence of one keyword was established as minimum 200 occurrences. Maintenance word associations were determined. Fig. 6 presents cluster maintenance connections.

   Map interpretation revealed that maintenance is strongly connected with the following topics: decision making [51 - 53], life cycle [54 -56], sustainable development [57, 58] and cost optimization [57]. The links between listed words show the highest total link strength. Moreover, looking at the time line of the key words occurrence it is visible that today researchers focus on sustainability and climate change in the area of building maintenance within the use of machine learning tools (Fig.7).
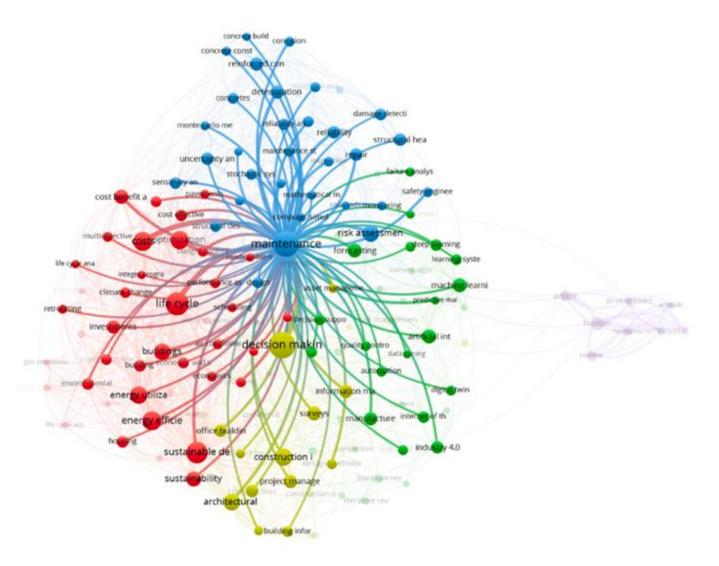
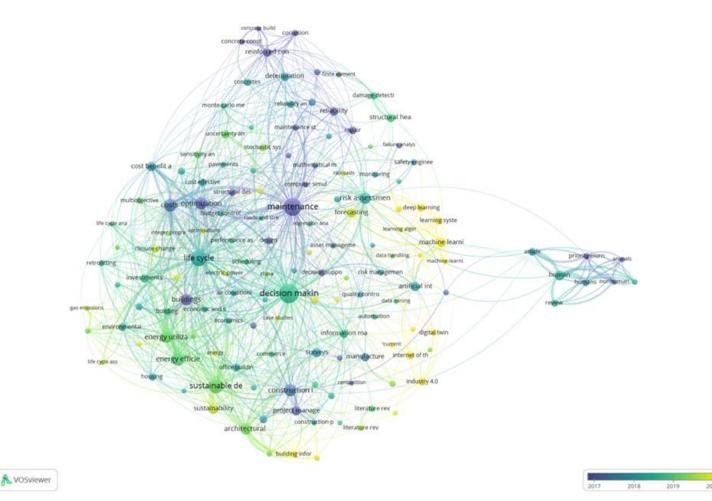Fig. 6. Bibliometric map of set 1 keywords

Fig. 7. Bibliometric map of set 1 keywords – time overlay

3.2. Analysis of "Set 2"

Set 2 diverges from Set 1 by additionally incorporating the term LCA (Life Cycle Assessment) into the discourse. LCA has been included due to the authors' orientation towards this theme in their scientific work, coupled with the intention to assess the quantity of publications within this thematic spectrum. The terms "maintenance," "strategy," "LCA," "model," and "building" serve as key axes around which the scientific discourse revolves, encapsulating the multifaceted dimensions of research within this field. Analysis of set 2 keywords was restricted to minimum occurrence of one keyword at the level of 50 occurrences. Analysis reveals that currently popular terms are mainly connected with sustainability, emission control as well as economic and social design. Label maintenance demonstrate quite strong link strength equal to 371 and 30 linked words that overlap to a large extent with the most current ones (Fig. 8).
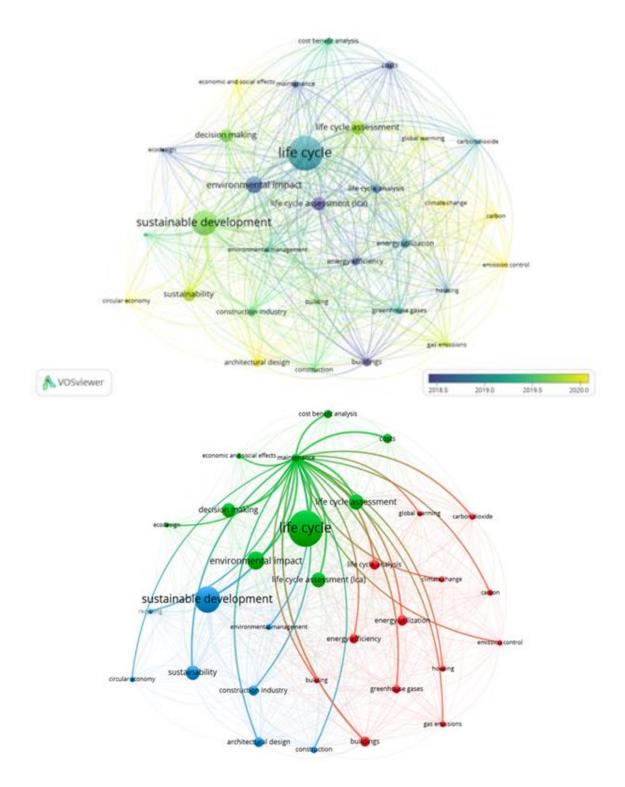
Fig. 8. Bibliometric map of set 2 keywords, keyword "maintenance" connections

3.3. Analysis of "Sets 3-8"

Due to large number of bibliometric maps and quite similar volume of gathered data Sets 3-8 were analyzed together for the purposes of this article.

First, an attempt was made to verify the level of similarity of publications. Despite the fact that set 5 & 6 consist of the same number of articles, only 2 articles duplicate. The highest lever of similarity is represented by comparison of set 3 and set 6. The number of duplicated publications in this case is equal to 47, while set 3 consists of 118 publications and set 6 out of 93 publications. Set 8 can be called the most specified one because due to implemented restrictions only ten publications were found. Verification of the titles of publications in this set shows that 9 out of 10 titles appeared in other sets. All the sets (3-8) consist of separated clusters and do not show connections between authors which means that they do not work together over common topics with other authors of similar interests around the world.

Keywords analysis show that the phrases representing the highest number of occurrences repeat among sets (3-8). The most interesting bibliometric map is created for set 8 (Fig.9) – it legibly shows connections between keywords and clearly indicated the most recent terms subjected to consideration.
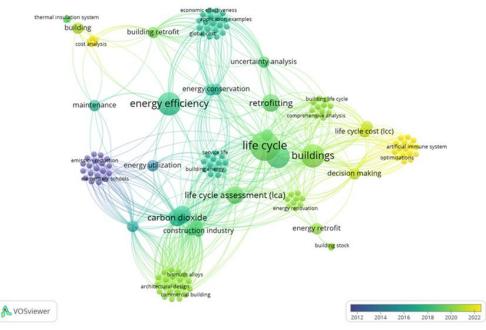

Fig. 9. Bibliometric map of set 8 keywords

4. CONCLUSION

In summary, this study provided valuable insights into the research landscape within the field of building maintenance, emphasizing the significance of keywords, collaborative efforts among authors, and the dynamic evolution of research interests over time.

The inception of publications addressing building maintenance strategy models can be traced back to the 1970s. Since the 1990s, there has been a noticeable increase in interest in this thematic area, with its peek marked around the year 2017. Map interpretation revealed that maintenance is strongly connected with the following topics: decision making, life cycle, sustainable development and cost

optimization. Additionally, contemporary research within building maintenance, leveraging machine learning tools, is notably focused on sustainability and climate change.

However, bibliometric networks reveal a trend where researchers frequently do not delve deeper or expand upon previously explored topics. A majority of researchers contribute only a single publication and exhibit limited collaboration with researchers sharing similar interests in the field. The sheer volume of publications underscores substantial interest in the discussed topics, yet it also signals the existence of numerous aspects that warrant further exploration and development within this domain. Furthermore, the study emphasizes the imperative for continued exploration in building maintenance, particularly in the context of higher education institutions, which the article's authors plan to do as part of further research.

REFERENCES

1. Ibn-Mohammeda, T, Greenougha, R, Taylorb, S, Ozawa-Meidaa, L, Acquaye, A 2013. Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings* **66,** 232–245.
2. EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings.
3. Oregi, X, Hernandez, P, Gazulla, C, Isasa, M 2015. Integrating simplified and full life cycle approaches in decision making for building energy refurbishment: benefits and barriers. *Buildings*, **5**, 354-380.
4. Cardinal, SM, Tosin, CE., Pilz, SE, Costella, MF 2020. Inspection method for building maintenance management in higher education institutions. *Journal of Performance of Constructed Facilities* **34**, 61.
5. Le, ATH, Domingo, N, Rasheed, E, Parkl, K 2021. Maturity model of building maintenance management for New Zealand's state schools. *Building Research and Information* **50**, 4.
6. Chang, C, Huang, S, Guo, S 2008. Setting a priority benchmark for building maintenance in Taiwan's national universities. *Journal of Architectural and Planning Research* **25**, 2, 162 – 175.
7. Hauashdh, A, Jailani, J, Rahman, IA, AL-Fadhali N 2021. Structural equation model for assessing factors affecting building maintenance success. *Journal of Building Engineering* **44**.
8. Besiktepe, D, Ozbek, ME, Atadero, RA 2020. Identification of the criteria for building maintenance decisions in facility management: First step to developing a multi-criteria decision-making approach. *Buildings*, **10**(9).
9. Plebankiewicz, E, Leśniak, A, Vikova, E, Hromadka, V. 2022. Models for estimating costs of public buildings maintaining – review and assessment. *Archives of Civil Engineering* **68**, 1, 335-351.
10. Moatassem, A, El-Rayes, K, Liang, L *Optimal selection of sustainability measures to minimize building operational costs*. Construction Research Congress: Construction in a Global Network, 2014, 2205-2213.
11. Salvado, F, De Almeida, NM, Azevedo, AV 2019. Historical analysis of the economic life-cycle performance of public school buildings. *Building Research and Information* **47**, 7, 813 – 832.
12. Galimshina, A, Moustapha, M, Hollberg, A, Padey, P, Lasvaux, S, Sudre, B, Habert, G 2020. Statistical method to identify robust building renovation choices for environmental and economic performance. *Building and Environment* **183.**
13. Alashari, M, El-Rayes, K, Attalla, M, Al-Ghzawi, M 2022. Multivariate time series and regression models for forecasting annual maintenance costs of EPDM roofing systems. *Journal of Building Engineering* **54**.

14. Kwon, N, Song, K, Ahn, Y, Park, M, Jang, Y 2020. Maintenance cost prediction for aging residential buildings based on case-based reasoning and genetic algorithm. *Journal of Building Engineering* **28**.

15. Eka Sari, W, Sudikno, A, Santosa, H 2021. Building maintenance assessment on official houses in Stilt Type at Jatiroto Sugar Factory Lumajang district, East Java, Indonesia., Local Wisdom, **13** (1), 84 – 99.

16. Hashempour, N, Taherkhani, R, Mahdikhani, M. 2020. Energy performance optimization of existing buildings: A literature review. *Sustainable Cities and Society*, **54.**

17. Ghafoori, M, Abdallah, M 2022. Simulation-based optimization model to minimize equivalent annual cost of existing buildings. *Journal of Construction Engineering Management* **48**, 21.

18. Burt, N. *Facilities Management—Good Practice Guide*; Facility Management Association of Australia Ltd.: Docklands, VIC, Australia, 2012.

19. Kampamba, J, Majingo, M, Kachepa, S 2020. An assessment of property maintenance in high rise buildings in Gabrone (CBD). *Am. Res. J. Civ. Struct. Eng.* **4**, 1, 1- 11.

20. Flores-Colen, I, De Britol, J 2010. A systematic approach for maintenance budgeting of buildings faades based on predictive and preventive strategies. *Construction Buildings Materials*, **24,** 9, 1718 – 1729.

21. Przesmycka, A, Wieczorek, D 2021. Maintenance strategies, periodic renovations and building modernisation in the aspect of the criterion of the whole life costs. *Civil and Environmental Engineering Reports*, **31**, 2, 15-29.

22. Abreu, A, Calado, J, Requeijo, J 2016. Buildings lean maintenance implementation model. *Open Engineering*, **6**, 397-406.

23. Mostafa, S, Lee, S, Dumrak, J, Chileshea, N, Soltan, H 2015. Lean thinking for a maintenance process. *Prod. Manuf. Res.*

24. Pereira, C, Silva, A, Ferreira, C, de Brito, J, Flores-Colen, I, Silvestre, JD *Information Systematisation Towards Rational Building Maintenance Decisions*. In: Bienvenido-Huertas, D., Moyano-Campos, J. (eds) New Technologies in Building and Construction. Lecture Notes in Civil Engineering, vol 258. Springer, Singapore. 2022.

25. Plebankiewicz, E, Grącki, J 2023. Analysis and prediction of universities' buildings' renovation costs using a regression model. *Applied Science* **13**(1), 401.

26. Wang, B, Xia, X, Zhang, J 2014. A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. *Energy and Buildings* **77**, 227-235.

27. Ighravwe, DE, Oke, SA 2019. A multi-criteria decision-making framework for selecting a suitable maintenance strategy for public buildings using sustainability criteria. *Journal of Building Engineering* **24**, 100753.

28. Ighravwe, DE, Oke, SA 2019. An integrated approach of SWARA and fuzzy COPRAS for maintenance technicians' selection factors ranking. *Int J Syst Assur Eng Manag* **10**, 1615–1626.

29. Nowogońska, B, Korentz, J 2020. Value of technical wear and costs of restoring performance characteristics to residential buildings, *Buildings*.

30. Liu, S, Chang, R, Zuo, J, Webber, RJ, Xiong, F, Dong, N 2021. Application of artificial neural networks in construction management: Current status and future directions *Applied Science* **11**(20), 9616.

31. Gauffriau, M 2021. Counting methods introduced into the bibliometric research literature 1970–2018: A review. *Quantitative Science Studies* **2** (3), 932–975.

32. Perianes-Rodrigueza, A, Waltmanb, L, Van Eck NJ 2016. Constructing bibliometric networks: A comparison between full and fractional counting. *Journal of Informetric* **10**, 4, 1178-1195.

33. Zhao, D, Strotmann, A *Analysis and visualization of citation networks*. 2015. Morgan & Claypool Publishers.

34. Van Eck, NJ, Waltman, L *Visualizing bibliometric networks*. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), Measuring scholarly impact: Methods and practice (285–320). Springer. (2014).

35. Van Eck, NJ, Waltman, L Manual for VOSviewer version 1.6.16, 25.11.2020, Universiteit Leiden.

36. Fairbanks, DR *Computer program to determine the optimum configuration of solar assist build heating and cooling systems based upon life-cycle cost* In: Energy 10; Annual Intersociety Energy Conversion and Engineering Conference, 10th, Newark, Del., August 18-22, 1975, Record. (A75-45920 23-44) New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p. 202-209.

37. Au-Yong, CP, Ali, AS, Ahmad, F 2013. Office building maintenance: Cost prediction model. *Gradevinar*, **65**(9), 803-809.

38. Au-Yong, CP, Ali, AS, Ahmad, F 2017. Competency and commitment of facilities managers: Keys to safe guard maintenance performance. *Malaysian Construction Research Journal* **22**, 2.|

39. Chua, SJL, Zubbir, NB, Ali, AS, Au-Yong, CP 2018. Maintenance of high-rise residential buildings. *International journal of building pathology and adaptation* **36** (2), 137-151.

40. Amos, D, Au-Yong, CP, Musa, ZN 2021. The mediating effects of finance on the performance of hospital facilities management services. *Journal of Building Engineering* **34**, 101899.

41. Au-Yong, CP, Azmi, NF, Myeda, NE 2022. Promoting employee participation in operation and maintenance of green office building by adopting the total productive maintenance (TPM) concept. *Journal of Cleaner Production* **352**, 131608.

42. Bortolini, R, Forcada, N 2018. Building inspection system for evaluating the technical performance of existing buildings. *Journal of Performance of Constructed Facilities* **32**, 5.

43. Bortolini, R, Forcada, N 2020. Analysis of building maintenance requests using a text mining approach: building services evaluation. *Building Research & Information* **48**, 2.

44. Chen, HP, Nepal, J 2015. Stochastic modelling and lifecycle performance assessment of bond strength of corroded reinforcement in concrete. *Structural Engineering and Mechanics* **54** (2), 319-336.

45. Nepal, J, Chen, HP 2015. Assessment of concrete damage and strength degradation caused by reinforcement corrosion *J. Phys.: Conf. Ser.* 628 012050

46. Petcherdchoo, A 2018. Probability-based sensitivity of service life of chloride-attacked concrete structures with multiple cover concrete repairs *Advances in Civil Engineering*.

47. Fan, Y, Xia, X *An optimal maintenance plan for building envelope insulation materials after retrofitting*, Chinese Automation Congress (CAC), Wuhan, China, 2015, 2068-2073.

48. Fan, Y, Xia, X 2017. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance. *Applied Energy* **189**, 327-335

49. El-Hassani, S, Charai, M, Moussaoui, MA, Mezrhab, 2023. A Towards rural net-zero energy buildings through integration of photovoltaic systems within bio-based earth houses: Case study in Eastern Morocco. *Solar Energy* **259**, 15-29.

50. Bortolini, R, Rodrigues, R, Alavi, H, Vecchia, LFD, Forcada N 2022. Digital twins' applications for building energy efficiency: A review. *Energies*, **15**(19), 7002.

51. Yang, Y, Xie, H 2021. Determination of optimal MR&R strategy and inspection intervals to support infrastructure maintenance decision making. *Sustainability*, **13**(5), 2664.

52. Xie, M, Zhao, J, Zuo, M, Tian, Z, Liu, L, Wu, J 2023. Multi-objective maintenance decision-making of corroded parallel pipeline systems. *Applied Energy* **351**, 1, 121822.

53. Adeyemi, IA, Rahman, MSN, Adeyemi, A 2022. Maintenance analytics for building decision making: A literature review. *Journal of Information System and Technology Management* **7** (25), 127- 138.

54. de Brito, J, Silva, Ana 2020. Life cycle prediction and maintenance of buildings. *Buildings* **10**(6), 112.

55. Zima, K, Wieczorek, D, Przesmycka, A 2020. Impact of the selected building maintenance strategy on costs and service life. *World of Real Estate Journal* **112**, 40.

56. Farahani, A, Wallbaum, H, Dalenbäck, JO 2019. The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings, *Sustainable Cities and Society* **44,** 715-725.

57. Hauashdh, A, Jailani, J, Rahman, IA, Al-Fadhali, N 2022.Strategic approaches towards achieving sustainable and effective building maintenance practices in maintenance-managed buildings: A combination of expert interviews and a literature review. *Journal of Building Engineering*, **45**, 103490.

58. Sholanke, AB, Basorun, U, Babalola D, Edia, J 2023. Review of maintenance strategies for achieving sustainable developments in tropical climates. *Covenant Journal of Research in the Built Environment* **11**,1.