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EXPLORING SCIENTIFIC DOMAIN OF OCCUPANCY ANALYSIS, POE, AND DT IN AECO INDUSTRY: A SCIENTOMETRIC APPROACH

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Building occupancy patterns strongly influence organizational effectiveness during the operation and maintenance (O&M) phase. Actual occupancy is highly variable over time and differs from the static occupancy levels considered during design phases. Consequently, poor levels of space management, use, and cleanness are detected during the O&M phase, affecting user well-being and satisfaction. Occupancy monitoring and analysis are needed to achieve effective and efficient facility management (FM) and user well-being. The article explores the scientific domains of occupancy detection and analysis, and related main approaches, i.e., post-occupancy evaluations (POEs) and digital twins (DTs) in the architecture, engineering, construction and operation (AECO) industry. A scientometric approach through science mapping and data visualization is applied to analyze 386 bibliographic records from Scopus database. The temporal trend analysis and conceptual structure of the scientific domain are investigated, drawing a picture of the body of knowledge. The performed analysis uncovered the temporal distribution of the publications and the relationships among the topics. DT is a recent topic in the early stages of investigation, while POEs are mature approaches related to sustainability, energy efficiency, productivity, building performance optimization, and user satisfaction. Occupancy detection and analysis are related to FM but less investigated topics in recent years. The research aims to uncover possible research gaps and open challenges in the field for further research aiming to support the optimization of occupancy and space management in the O&M phase, increasing workplace adaptability to changing conditions and needs and user satisfaction and well-being over time.

Keywords: Post-occupancy evaluation, Digital twin, Occupancy pattern, Building information modelling, AECO sector, Scientometric analysis.

1 INTRODUCTION

It is crucial to ensure building efficient management during the operation and maintenance (O&M) phase. During the design phase, spaces are typically sized according to use-based standardized occupancy data (Gorgolewski *et al.* 2016). Similarly, during the O&M phase, static schedules are considered as occupancy levels for space management and other FM services planning. However, actual occupancy and space uses can be highly variable over time and strongly affect organizational effectiveness and functioning (Zimmerman and Martin 2001, Bento Pereira *et al.* 2016). Consequently, actual occupancy values can differ from the values considered during the design phase, and spaces and FM services may be unsuitable for actual

uses, leading to inadequate levels of space use and cleanness, which in turn are related to user well-being and satisfaction (Kim and de Dear 2012, Agha-Hossein *et al.* 2013). Moreover, due to the recent COVID-19 pandemic, occupancy levels have become even more variable with the increasing adoption of remote working practices, which are expected to be an enduring feature of the current and future working world (Dua *et al.* 2022). Consequently, decision-making processes during the O&M phase and for FM planning, based on occupancy levels from the design phase or historical databases (DBs), seem unreliable. Continuous building occupancy monitoring and analysis can enable the achievement of effective and efficient FM processes, improving existing buildings' use, space management, and user satisfaction.

The article explores the research fields of occupancy monitoring, analysis, and related approaches, i.e., post-occupancy evaluations (POEs) and digital twins (DTs), via a scientometric analysis to uncover possible research gaps and open challenges. POEs aim at analyzing buildings once they have been occupied for some time, aiming at assessing building performances, users' behavior, feedback, and satisfaction during the O&M phase (Hadjri and Crozier 2009). Concerning DTs, the construction industry can be still considered in its beginning regarding the definition of a DT for buildings. A comprehensive definition was proposed by Al-Sehrawy and Kumar, which contains all the fundamental components of a DT: *"an approach for connecting a physical system to its virtual representation via bidirectional communication […] to allow for exploitation of Artificial Intelligence and Big Data Analytics by harnessing this data to unlock value through optimization and prediction of future state"* (Al-Sehrawy and Kumar 2021).

2 SCIENTOMETRIC ANALYSIS

Science mapping aims to analyze and visually describe a scientific knowledge domain uncovering significant patterns and trends in scientific literature and bibliographic data. Several science mapping tools are available (Moral-Muñoz *et al.* 2020). BiblioShiny was selected as the most complete tool (Aria and Cuccurullo 2017). In addition, VOSviewer was selected allowing the production of enlightening visualizations of network relationships (Van Eck and Waltman 2010).

2.1 Query String Definition

The bibliometric data collection was conducted in October 2022 following specific criteria. The documents were retrieved by the Scopus DB only for the faster indexing process than Web of Science (WoS) (Zhao *et al.* 2019, Locatelli *et al.* 2021). The search was restricted to already published, full English-text articles and conference papers, excluding the documents referred to the year 2023. The string to query the Scopus DB document titles, abstracts, and keywords is provided in Figure 1, allowing the selection of a set of publications and related bibliometric metadata. The query string includes Boolean operators (i.e., AND and OR) and wild cards to include spelling variations (i.e., the asterisk "*").

TITLE-ABS-KEY (("civil engineering" OR "construction engineering" OR "architectural engineering" OR "construction industry" OR "construction management" OR "construction sector" OR "AEC" OR "AECO" OR "facilit manag*") AND (("digital twin*") OR ("post-occupancy evaluat*" OR "post occupancy evaluat*" OR "postoccupancy evaluat*") OR (("sensor*" OR "IoT" OR "internet of thing*") AND "occupancy"))) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (EXCLUDE (PUBYEAR , 2023)) AND (LIMIT-TO (LANGUAGE , "English"))*

Figure 1. Query string for the scientometric analysis.

The first part of the query string represents the architecture, engineering, construction and operation (AECO) field. The second part represents the main occupancy monitoring and analysis topics, i.e., DTs, POEs, and occupancy monitoring. A set of 386 publications was selected, and all the useful bibliographic data, necessary for the scientometric analysis, were downloaded from Scopus. Data were downloaded in BibTeX format to be imported into BiblioShiny and in CSV format to be imported into VOSviewer. A Thesaurus was also defined to clean the dataset and merge similar keywords and synonyms into one single keyword.

2.2 Temporal Trend Analysis: Annual Scientific Production

The temporal trend analysis includes the investigation of the annual scientific production. Data were processed by BiblioShiny and then exported to produce the proposed chart (Figure 2).

The area chart shows that the topics date back to 1986, for a total of 36 years until now with an average annual growth rate of 12.53%. The temporal data shows that most of the articles have been published in recent years, with a considerable increase in scientific production since 2017. On the other hand, in the period before 2017, the research production on the topic is characterized by several fluctuations with a general upward trend throughout the years.

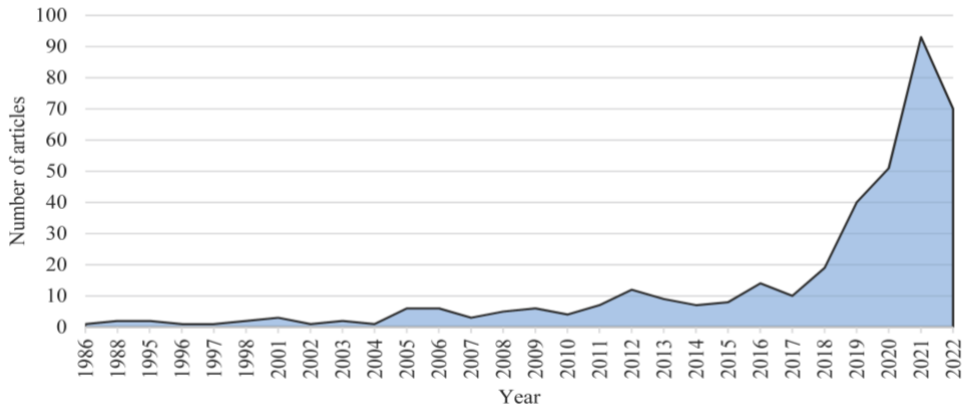

Figure 2. Annual scientific production (Data source: bibliometric data processed by BiblioShiny).

2.3 Conceptual Structure: Co-occurrence Keywords Network Map

The visualization of the Conceptual structure of the investigated topics aims to graphically represent the relations among concepts, i.e., keywords or words (Randall 2010), through a network visualization, e.g., a co-occurrence keywords network, to define the most important and recent topics.

A co-occurrence keywords network map was produced through VOSviewer (Figure 3). Keywords are grouped into clusters if they can be found together in documents. Circles and lines of the same cluster have the same color in the map, and the circle size represents the number of documents using that specific keyword. The network is visually divided into two main groups.
On the left side, the blue and purple clusters are close and strongly connected, since POEs are mainly performed in the O&M phase and with the main objective to optimize the FM and user satisfaction and well-being (Preiser 2005). POEs (blue cluster) are related to the topics of sustainability, user satisfaction, and building performance, while FM (purple cluster) is linked to green building, user feedback, and building management system (BMS). POEs, that were first introduced in the 1960s (Preiser 2005), are mature approaches with various applications (Li *et al.*

2018). However, they have some limitations which explain the still limited adoption in the industry, such as the limited effectiveness of visualization and reporting of POE results (Sanni-Anibire *et al.* 2016, Li *et al.* 2018), lack in knowledge about POEs among clients, professionals, and users (Zimmerman and Martin 2001), and lack of agreed and reliable benchmarks and indicators to evaluate POE outputs (Sanni-Anibire *et al.* 2016).

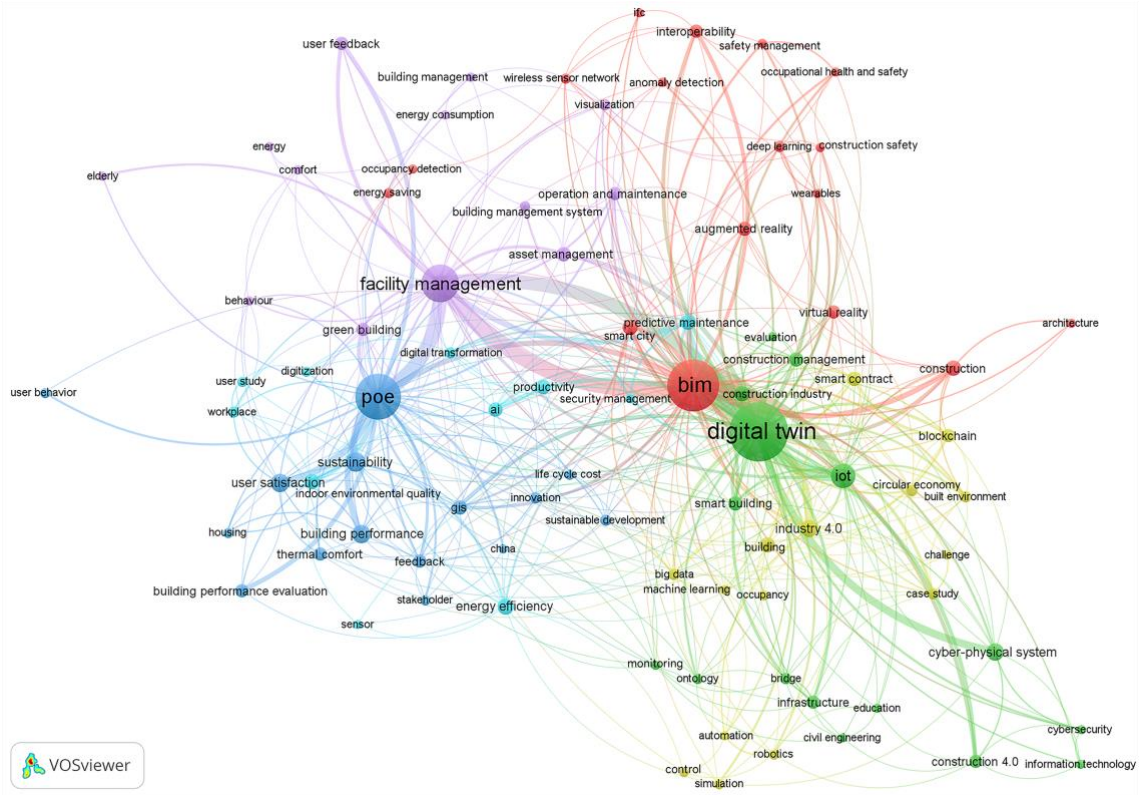

Figure 3. Co-occurrence keywords network map (Software: VOSviewer).

On the right side of the network, the red, green, and yellow clusters are close and strongly related, since the topics of DT (green cluster), Building Information Modelling (BIM) (red cluster), and information technology (yellow cluster) are strongly connected. The topics BIM and DT are close, since DTs can be seen as an evolution of BIM that enables real-world monitoring, data collection, and feedback (Brilakis *et al.* 2019, Boje *et al.* 2020). DTs showed great potential for the improvement of FM processes (Al-Sehrawy and Kumar 2021, Fialho *et al.* 2022), however, the investigation of DTs is still in the early stages with limited real case study applications. The green cluster also includes Internet of things (IoT), smart buildings, and monitoring, being sensing a vital aspect for the definition of DTs (Tao *et al.* 2019). The yellow cluster is also related to the green and partially red clusters, including aspects related to the recent technological innovations, such as blockchain and smart contracts, related to BIM and DTs for their capabilities of information management along the building life cycle (Götz *et al.* 2022).

Finally, the light blue cluster seems to connect the left and right sides of the network, including the topics of predictive maintenance, artificial intelligence (AI), productivity, energy efficiency, indoor environmental quality (IEQ), and workplace representing the main objectives

for the integration of AI tools and IoT monitoring, and FM processes investigations in recent years (Carvalho *et al.* 2019, Windapo and Moghayedi 2020, Fialho *et al.* 2022).

The network shows that the topics of occupancy, occupancy detection, and FM are not strongly linked, and FM is weakly connected with IoT and monitoring compared to BIM and DTs. However, the integration of such approaches and technologies could lead to the optimization of FM and space usage and management.

3 CONCLUSIONS

The article explores the research fields of occupancy monitoring, analysis, and related approaches, i.e., POEs and DTs, via a scientometric analysis.

The temporal trends, in particular the annual scientific production analysis, highlighted an average upward trend. Even if the time span of the selected dataset covers 36 years since 1986, most articles have been published in recent years, with a considerable increase in scientific production since 2017. The conceptual structure of the dataset was investigated via the co-occurrence keywords network map, highlighting that the topics of POEs and FM are connected, as well as BIM and DT. A common topic of the two areas of the chart is the focus on the sustainable development of the AECO sector, which is promoted at international level (United Nations Environment Programme 2019). Some terms connect the two main topics groups: predictive maintenance, productivity, IEQ, and energy efficiency, representing the main objectives for the integration of AI tools and IoT monitoring, and FM processes investigations in recent years. In addition, the network highlighted that the topics of occupancy, occupancy detection, and FM are not strongly linked, and the FM is weakly connected with IoT and monitoring compared to BIM and DTs, while the integration of such approaches and technologies could lead to the optimization of FM processes and space usage and organization.

In light of the outputs of the analysis, and in particular that occupancy and occupancy detection are less investigated topics for FM, even though occupancy is demonstrated to have a strong impact on building usage and performances, a possible research gap can be identified: the assessment and improvement of O&M processes according to actual occupancy via continuous occupancy monitoring over time. In addition, the analysis and successful application of systems integrating existing approaches that are among the components and enablers of DTs, can be beneficial and can lay the foundation for the future definition of DTs for FM in the AECO sector, which are still in the early stages of investigation in the sector with limited real case study applications.

References

Agha-Hossein, M. M., El-Jouzi, S., Elmualim, A. A., Ellis, J., and Williams, M., *Post-occupancy Studies of an Office Environment: Energy Performance and Occupants' Satisfaction*, Building and Environment, Elsevier, 69, 121–130, November, 2013.

Al-Sehrawy, R., and Kumar, B., *Digital Twins in Architecture, Engineering, Construction and Operations. A Brief Review and Analysis*, Proceedings of the 18th International Conference on Computing in Civil and Building Engineering (ICCCBE 2020), Lecture Notes in Engineering, 98, 924–939, São Paulo, Brazil, August 18-20, 2020.

Aria, M., and Cuccurullo, C., *bibliometrix: An R-tool for Comprehensive Science Mapping Analysis*, Journal of Informetrics, Elsevier, 11(4), 959–975, November, 2017.

Bento Pereira, N., Calejo Rodrigues, R., and Fernandes Rocha, P., *Post-Occupancy Evaluation Data Support for Planning and Management of Building Maintenance Plans*, Buildings, MDPI, 6(4), 45, December, 2016.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., *Towards a Semantic Construction Digital Twin: Directions for Future Research*, Automation in Construction, Elsevier, 114, 103179, June, 2020.

Brilakis, I., Pan, Y., Borrmann, A., Mayer, H.-G., Rhein, F., Vos, C., Pettinato, E., and Wagner, S., *Built Environment Digital Twinning*, Technical University of Munich, Germany, December, 2019.

Carvalho, T. P., Soares, F. A. A. M. N., Vita, R., Francisco, R. da P., Basto, J. P., and Alcalá, S. G. S., *A Systematic Literature Review of Machine Learning Methods Applied to Predictive Maintenance*, Computers & Industrial Engineering, Elsevier, 137, 106024, November, 2019.

Dua, A., Ellingrud, K., Kirschner, P., Kwok, A., Luby, R., Palter, R., and Pemberton, S., *Americans are Embracing Flexible Work—and They Want More of It*, McKinsey Insights, McKinsey & Company, June, 2022.

Fialho, B. C., Codinhoto, R., Fabricio, M. M., Estrella, J. C., Neves Ribeiro, C. M., Dos Santos Bueno, J. M., and Doimo Torrezan, J. P., *Development of a BIM and IoT-Based Smart Lighting Maintenance System Prototype for Universities' FM Sector*, Buildings, MDPI, 12(2), 99, February, 2022.

Gorgolewski, M., Brown, C., Chu, A. M., Turcato, A., Bartlett, K., Ebrahimi, G., Hodgson, M., Mallory-Hill, S., Ouf, M., and Scannell, L., *Performance of Sustainable Buildings in Colder Climates*, Journal of Green Building, College Publishing, 11(4), 131–153, Fall, 2016.

Götz, C. S., Karlsson, P., and Yitmen, I., *Exploring Applicability, Interoperability and Integrability of Blockchain-based Digital Twins for Asset Life Cycle Management*, Smart and Sustainable Built Environment, Emerald, 11(3), 532–558, November, 2022.

Hadjri, K., and Crozier, C., *Post-occupancy Evaluation: Purpose, Benefits and Barriers*, Facilities, Emerald, 27(1/2), 21–33, January, 2009.

Kim, J., and de Dear, R., *Nonlinear Relationships between Individual IEQ Factors and Overall Workspace Satisfaction*, Building and Environment, Elsevier, 49, 33–40, March, 2012.

Li, P., Froese, T. M., and Brager, G., *Post-occupancy Evaluation: State-of-the-art Analysis and State-of-the-practice Review*, Building and Environment, Elsevier, 133, 187–202, April, 2018.

Locatelli, M., Seghezzi, E., Pellegrini, L., Tagliabue, L. C., and Di Giuda, G. M., *Exploring Natural Language Processing in Construction and Integration with Building Information Modeling: A Scientometric Analysis*, Buildings, MDPI, 11(12), 583, December, 2021.

Moral-Muñoz, J. A., Herrera-Viedma, E., Santisteban-Espejo, A., and Cobo, M. J., *Software Tools for Conducting Bibliometric Analysis in Science: An up-to-date Review*, El Profesional de la Informacion, 29(1), e290103, 2020.

Preiser, W. F. E., *Building Performance Assessment – From POE to BPE , A Personal Perspective*, Architectural Science Review, Taylor & Francis, 48(3), 201–204, 2005.

Randall, J. H., *Conceptual Structure*, In Linking: The Geometry of Argument Structure, 11–34, Springer Netherlands, Dordrecht, 2010.

Sanni-Anibire, M. O., Hassanain, M. A., and Al-Hammad, A.-M., *Post-occupancy Evaluation of Housing Facilities: Overview and Summary of Methods*, Journal of Performance of Constructed Facilities, ASCE, 30(5), 04016009, August, 2016.

Tao, F., Zhang, H., Liu, A., and Nee, A. Y. C., *Digital Twin in Industry: State-of-the-Art*, IEEE Transactions on Industrial Informatics, IEEE, 15(4), 2405–2415, April, 2019.

United Nations Environment Programme, *Global Environment Outlook – GEO-6: Healthy Planet, Healthy People*, UNEP Publications, 2019.

Van Eck, N. J., and Waltman, L., *Software Survey: VOSviewer, A Computer Program for Bibliometric Mapping*, Scientometrics, Springer, 84(2), 523–538, August, 2010.

Windapo, A. O., and Moghayedi, A., *Adoption of Smart Technologies and Circular Economy Performance of Buildings*, Built Environment Project and Asset Management, Emerald, 10(4), 585–601, September, 2020.

Zhao, X., Zuo, J., Wu, G., and Huang, C., *A Bibliometric Review of Green Building Research 2000–2016*, Architectural Science Review, Taylor & Francis, 62(1), 74–88, 2019.

Zimmerman, A., and Martin, M., *Post-occupancy Evaluation: Benefits and Barriers*, Building Research & Information, Taylor & Francis, 29(2), 168–174, 2001.