

Circular Built Environment During the Digital Age: A Systematic Review

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As the effects of the Industrial Revolution have significantly contributed to global climate change and the studies reveal that by 2050, the world's energy demand will double while fossil fuel reserves are projected to deplete. To mitigate the risks associated with exceeding the 1.5°C global warming threshold, international organizations, including the United Nations, as well as governments and NGOs, are implementing strategies aimed at achieving carbon neutrality by mid-century. One such approach involves transitioning from the "take-make-waste" model of the linear economy to the circular economy (CE), which operates on principles of "make-use-reuse-recycle." The AECO (Architecture-Construction-Engineering-Operation) industry, a key driver of global economic activity, plays a central role in this transformation by rethinking and restructuring the AECO industry to align with CE principles. This study examines the intersection of circular economy principles and the built environment through the lens of Industry 4.0. A systematic literature review combining descriptive and bibliometric analysis, covering publications from 2016 to 2024 from Scopus and Web of Science (WoS), was conducted using keywords related to CE, the built environment, and digital technologies. Structuring the review is processed through PRISMA and selecting the literature is strengthened by Quality Assessment (QA). The analysis, performed with VOSviewer, highlights key trends, thematic connections, and potential areas for future research. Continuous and significant increase in number of publications obtained since 2016. United Kingdom, Netherlands and Italy were the leading countries in this research area. "Sustainability" is the pioneering journal in this field with highest number of publications and citations. Digital technologies such as building information modeling (BIM), blockchain, and the Internet of Things (IoT) have emerged as powerful tools to support CE implementation. By enabling resource optimization, reducing waste, and enhancing lifecycle assessments, these technologies facilitate the adoption of sustainable practices within the AECO sector. These studies underscore the importance of advancing frameworks like life cycle assessment (LCA) and cradle-to-cradle (C2C) to support circular transitions in the built environment. Furthermore, the results demonstrate the increasing momentum and global interest in leveraging digitalization to achieve sustainability goals in the sector. This study offers valuable insights for academics, industry professionals, and policymakers by mapping the current state of CE research in the AECO industry and identifying emerging trends. It emphasizes the need for comprehensive frameworks and strategic roadmaps to enable the circular transition of the AECO sector. Future research should focus on deepening interdisciplinary collaboration and integrating CE with related sustainability concepts to enhance understanding and accelerate implementation. By doing so, the AECO industry can make significant contributions toward global carbon neutrality and sustainable development goals.

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Dijital Çağda Yapılı Çevrede Döngüsellik: Sistemik Analiz

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Küresel iklim değişikliğinin etkilerini azaltmak için Birleşmiş Milletler ve diğer uluslararası kuruluşlar ile hükümetler ve STK'lar, özellikle 2050 yılına kadar karbon nötrlüğü sağlamayı hedefleyen stratejiler geliştirmektedir. Bu stratejilerden biri, lineer ekonomi modelinden ("al-yap-at") döngüsel ekonomi modeline ("üret-kullan-yeniden kullan-geri dönüştür") geçiştir. Mimarlık-İnşaat-Mühendislik-Operasyon (AECO) sektörü, küresel ekonomik faaliyetlerin temel itici gücü olarak, döngüsel ekonomi ilkelerine uyum sağlamak amacıyla yeniden yapılandırılmalıdır. Bu çalışma, döngüsel ekonomi ve yapılı çevre arasındaki ilişkiyi dijitalleşme perspektifinden incelemektedir. 2016-2024 dönemindeki yayınları kapsayan sistemik bir literatür taraması, Scopus ve Web of Science (WoS) veri tabanlarında "döngüsel ekonomi", "yapılı çevre" ve "dijital teknolojiler" anahtar kelimeleri kullanılarak gerçekleştirilmiştir. Literatür araştırmasının yapısı PRISMA yöntemiyle şekillendirilmiş, çalışmaların analizlere dahil edilmesi ise Kalite Değerlendirmesi ile gerçekleştirilmiştir. Analizler, Excel ve VOSviewer yazılımıyla yapılmış ve günümüzdeki eğilimler, anahtar kelimeler, tematik bağlantılar ve gelecekteki araştırma alanları belirlenmiştir. 2016 yılından itibaren bu alandaki çalışmaların sürekli ve artan ivme ile arttığı tespit edilmiştir. Aynı zamanda Birleşik Krallık, Hollanda ve İtalya bu araştırma alanının önde gelen ülkeleridir. "Sustainability" bu alanda en çok yayın yapılan ve atf alan dergidir. BIM, blockchain ve IoT gibi dijital teknolojiler, kaynak optimizasyonu, atık azaltımı ve yaşam döngüsü değerlendirmelerini iyileştirerek sürdürülebilir uygulamaların benimsenmesini desteklemektedir. Çalışma, AECO sektöründe döngüsel geçişi desteklemek için kapsamlı çerçeve ve stratejik yol haritalarının gerekliliğini vurgulamaktadır. Aynı zamanda da bulguların tartışılması kısmında farklı döngüsel ekonomi tanımlamaları analiz edilmiş, döngüsel ekonomi ile bağlantılı olan kavramlar ve anahtar kelimeler ortaya konmuştur. Bu çalışma, döngüsel ekonomi alanında akademisyenler, sektör uzmanları ve politika yapımcılar için değerli bilgiler sunmakta, sektörün karbon nötrlüğü ve sürdürülebilir kalkınma hedeflerine katkı potansiyelini ortaya koymaktadır.

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Anahtar Kelimeler: Döngüsel ekonomi, Yapılı çevre, Mimarlık, Bibliyometrik analiz, Sürdürülebilirlik.

1. INTRODUCTION

Since the Industrial Revolution, rapid urbanization, overpopulation, destruction of nature and energy consumption based on fossil fuels has caused global climate change (European Commission, 2015). The effects of climate change appear as fires, floods, water and agricultural crises throughout the world. In addition, it is predicted that most of the fuel resources will be depleted by 2050, but the energy need will double (European Commission, 2020). With an aim of achieving carbon neutrality by 2050 to avoid the catastrophic effects of a 1.5°C of climate change, governments, global institutions like United Nations (UN), and NGOs (non-governmental organizations) are developing action plans and key strategies. Allan Kneese indicated that resources are not endlessly renewable, mentioning the circular economy for the first time in 1988 (Kneese, 1988). It is found crucial to transform from the linear economy model based on the "take-make-waste" logic, which has spread all over the world with the rapid development of technology, especially since the second half of the 20th century, to the circular economy model based on the "make-use-reuse-recycle" system to minimize the impact of climate change. Additionally, according to the studies, linear economic models have ignored the economy-environment interrelationships (Eberhardt et al., 2020; Kirchherr and van Santen, 2019; Zhuang et al., 2023).

To achieve a circular economy, a holistic approach to sustainable thinking and practice needs to be integrated into all disciplines, including Architecture-Construction-Engineering-Operation (AECO) industry. AECO industry which has one of the largest global market sizes has to be redesigned and reorganised considering the carbon neutrality strategies. In addition, AECO industry are responsible for more than 40% of global CO₂ emissions and almost quarter of it derives from the embodied carbon of the constructions (World Green Building Council, 2019) including materials-related, transport-related and equipment-related. Furthermore, one-third of the total waste is also produced by the AEC industry (IEA, 2019). In this regard, it is crucial to rethink and redesign AECO industry, its processes and components by integrating circular economy principles. Circular thinking aims to transform the processes and products to reach UN's Sustainable Development Goals (SDGs) (UN SDG, 2019). The key aims of the circular economy are to obtain material efficiency, minimize waste and optimize energy usage.

To achieve the circular economy, innovative technologies should be adopted to the AECO industry. As it is mentioned in the study of Olawumi et al. (2022) digital technologies support facilitates the implementation of sustainability practices in the built environment.

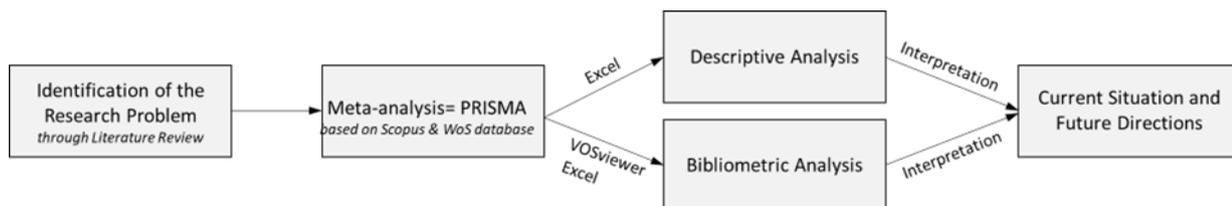
The purpose of this paper is to investigate how circular economy has emerged as a key research area for AECO industry to reach sustainable development targets and what is the role of digitalization in this transformation. This study utilises descriptive and bibliometric analysis to find major areas and intersections between CE, AECO, and digitalization which will provide significant insights for researchers, and policymakers. This paper adopts the visualization analysis method based on the theory of bibliometrics to reveal the development trend and future research directions of the circular & digital transition. The research questions addressed in this study are:

- Q1. What is the current situation of the subject in the literature?
- Q2. What research topics are being discussed within this subject?
- Q3. How can CE be defined with AECO?
- Q4. What are the related research areas?
- Q5. What are the limitations of current research and practices on CE?

2. METHODOLOGY

This chapter aims to present the status quo of involvement of digitalization in circular economy (CE) research, as the methodological flow chart as illustrated in **Figure 1**. A quantitative research method has been adopted. Methodology started with the identification of the research problem according to the trends in CE affected by emerging immersive technologies along with a systematic literature review.

Figure 1: Methodological flow chart of the systematic review. (by Authors).



To organize the systematic literature review (SLR), the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

meta-analysis flow diagram of Page et al. (2020) was adopted thanks to the advantages which were mentioned in the study of Shahrudin and Zairul (2020), such as identifying large databases of scientific literature through keyword and search strategies, screening inclusion and exclusion criteria and conducting eligibility process to analyse the data from the studies. To validate the findings of the SLR and to evaluate the sources according to quality, and relevant to the research question, Quality Assessment (QA) is utilised. Evaluating the validity of the included sources is an integral component of the SLR. In addition, Kitchanham et al. (2009), Kitchanham et al. (2015), Petersen et al. (2015), Yang et al. (2021), Amin et al. (2021) and Usman et al. (2023) mentioned the necessity of QA in SLR studies.

In this study, PRISMA provided an examination of data from several independent studies of CE and related domain to determine overall situation and trends. QA provided assessing study quality to proceed in SLR. A typical QA instrument is a checklist consisting of multiple factors that need to be evaluated for the studies. Yet, there is no one standard QA method, a quality checklist usually designed for a particular study could be derived from factors and the checklist is generally based on “Yes or No” type answers. **Figure 2** explains the conducting systematic reviews and data collection process through the PRISMA approach; and **Table 1** lists the QA criteria customized in this study as an inclusion-exclusion criteria. Q1–Q3 journal quartiles were chosen as they offer a standardized, field-normalized indicator of publication quality, widely used in research assessments (Bornmann et al., 2012; SCImago, 2024; Waltman et al., 2013). Quartile rankings were preferred over raw citation counts because articles published recently (e.g., within the last year) have had less time to accumulate citations compared to those published 8–10 years ago, making quartiles a more time-independent and standardized measure of journal quality.

QA Criteria	
1.	The paper is published in a Q1, Q2 or Q3 journal or Scopus - WoS indexed conference proceeding.
2.	The paper is available in full text.
3.	The paper is written in English.
4.	The paper is related to ‘Engineering’ or ‘Multidisciplinary’ area in Scopus – WoS.
5.	The paper is related to urban/ building / construction domain.
6.	The paper links digitalization topics into CE.

Table 1. Inclusion-exclusion criteria for QA.

The literature sample was retrieved from Scopus and Web of Science (WoS) databases. Scopus and WoS are considered to be the world's largest and reliable peer-review databases (Guz and Rushchitsky, 2009; Aghaei Chadegani et al., 2013). The keywords were utilized in the literature search: TITLE-ABS-KEY ("circular economy" OR "circularity") AND ("architecture" OR "construction" OR "built environment" OR "urban" OR "city") AND ("digital" OR "smart" OR "industry 4.0" OR "innovation" OR "digitalization" OR "technology" OR "platform" OR "automation"). The combined sets of keywords were 70 as result of "2 x 5 x 7". Accordingly, the first retrieval resulted in the identification of 189 publications, 106 from Scopus and 83 from Web-of-Science (WoS). The period selected for review was from 2016 to the end of December 2024.

The identification phase included the removal of duplicated publications, and 5 publications were excluded in this phase. The screening phase included removal of the same publications and filtering process according to certain criteria: articles in the English language and with full text available were considered in this study. Also, not related subject areas were excluded. In addition, other documents rather than article, conference paper, book, book chapter and review were removed. The number of excluded papers was 32, and 152 papers were continued to screen through title and abstract. In total, 20 papers were not retrieved because of lack of focus on urban/ building / construction related domain and also some of them were related to food, agriculture, water, material, chemistry, supply-chain and sensors. The number of publications assessed for eligibility was 132. According to criteria in screening, a total number of 52 papers were removed in two steps; 132 papers continued to the PRISMA protocol. The inclusion phase provided additional criteria as studies' aims and relations to the related topic were analysed in detail. In this phase, 3 papers were removed. At the end of the PRISMA protocol and QA, 129 papers remained. Later on, analyses were applied to these 129 papers. This PRISMA and QA based methodological process is shown in **Figure 2**.

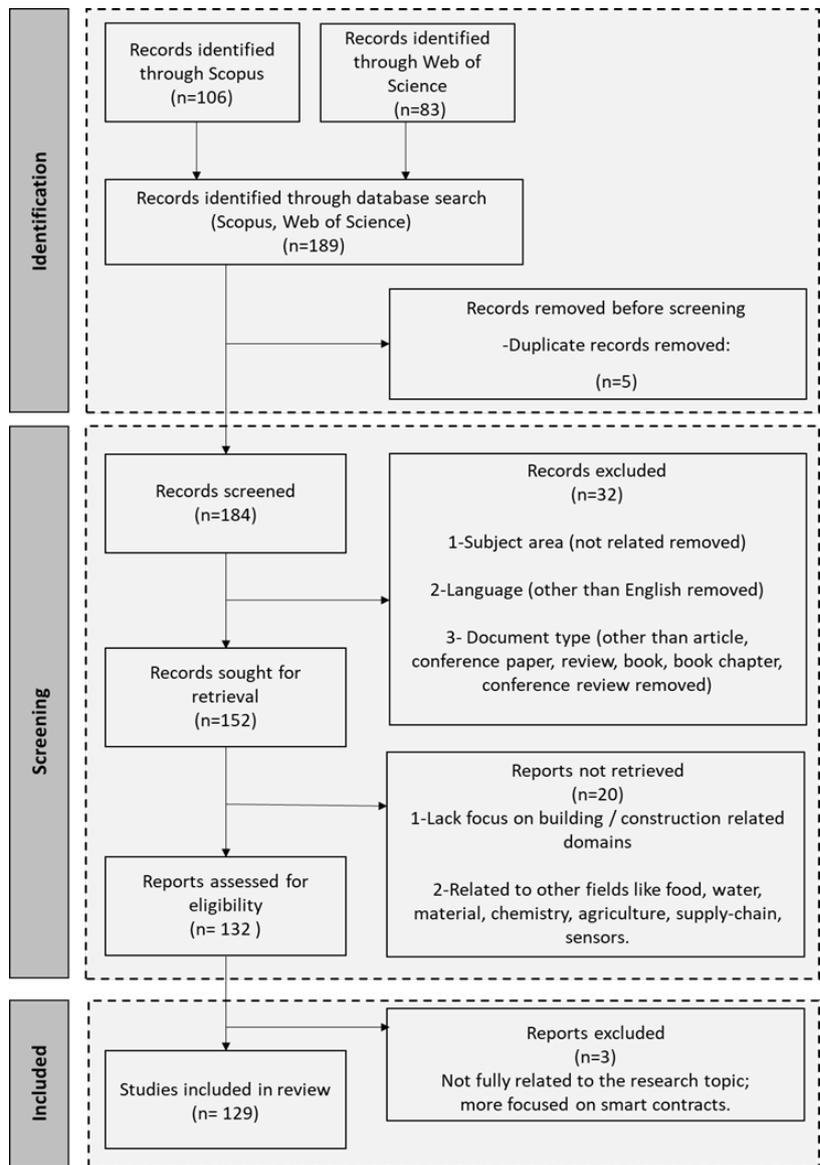


Figure 2: Research method for articles retrieval based on meta-analysis: PRISMA 2020. (by Authors).

The methodology of analyses was based on descriptive and bibliometric analysis to understand and state the current relations between CE, built environment and digitalization. Descriptive analyses presented an overview of the included papers in which Excel software was used to generate graphs. Bibliometric analyses employed the analyses through Excel and VOSviewer software focusing on the co-occurrence of keywords, country-based, source and citation analyses. Bibliometric analysis of scientific research has been considered one of the most common methods to evaluate the research performance of academicians, universities and even countries as well as academic journals (Konur, 2012). VOSviewer was selected as bibliometric

network software to construct and visualize bibliometric maps from the databases.

3. RESULTS

Results of descriptive and bibliometric analyses are presented, respectively.

3.1 Descriptive Analyses

Descriptive analyses are the process of using current and previous data to identify trends and relationships. It is a sort of data research that supports in describing, demonstrating, or summarizing data points so current and future patterns may develop.

3.1.1. Publications throughout the years

It is clear in the data that the concept of CE in built environment through digitalization gaining momentum. **Figure 3** shows the number of publications by year, demonstrating the growth of this field since 2016. During the past 8 years (2016–2024), the number of publications related to CE in built environment domain has increased by 43 times. Since 2017 considerable growth was seen. Only 6,9 % (19) of eligible papers were published before 2020, indicating rapid growth in related studies. 72% of papers were published during the last three years, in 2022, 2023 and 2024. Overall, it is obvious to state a growing trend in the number of publications for the near future.

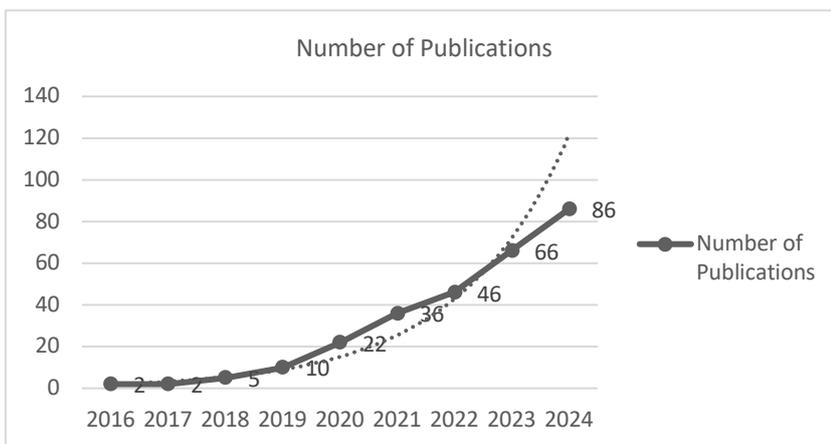


Figure 3: Number of publications per year. (by Authors).

3.1.2. Publications by country

Figure 4 illustrates the publications classified by the 40 countries of origin between January 2016 and December 2024. This diversity in various geographic distributions suggests a global interest in the technological transformation of construction management. Articles from the United Kingdom (48) are at the forefront of this new field, which accounts for 17.4% of all publications. Next comes the Netherlands and Italy with 45 publications, and these are followed by China (27), Germany (27), USA (22), Australia (20), and Austria (14). Turkey has 3 publications and all of them were published in 2023.

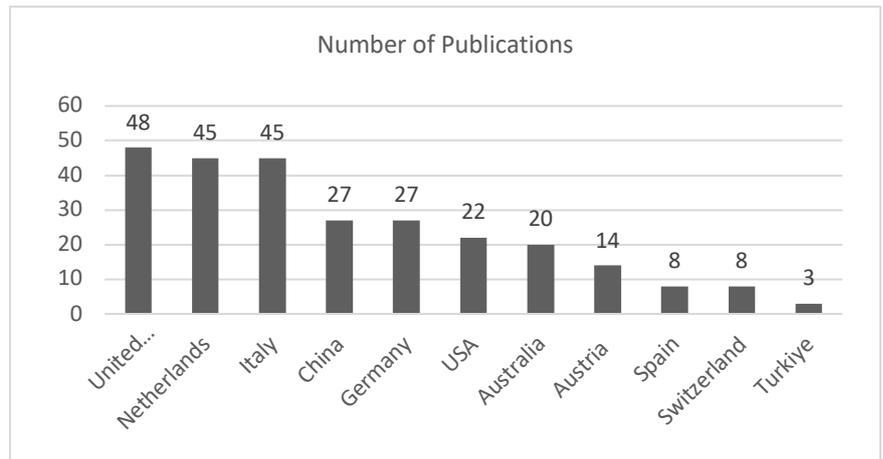


Figure 4: Number of publications per country. (by Authors).

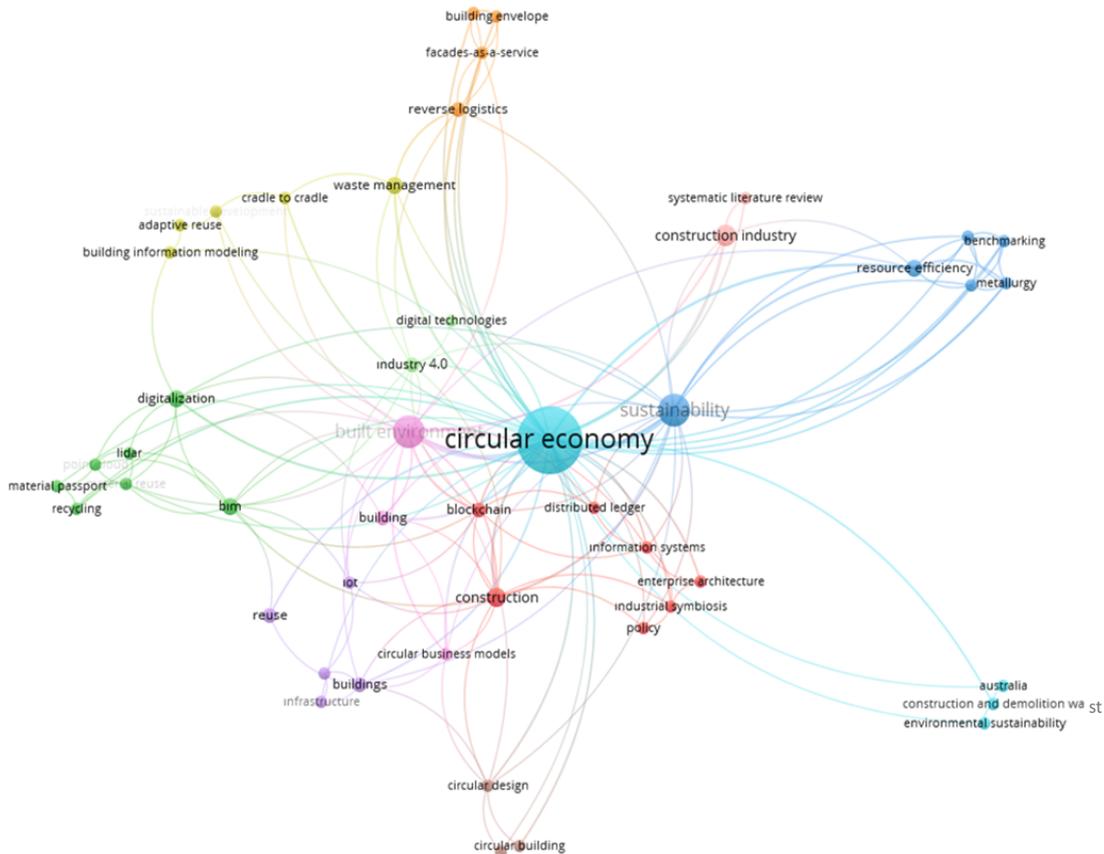
3.2 Bibliometric Analyses

The bibliometric analysis was applied to map the scientific retrieved data for evaluation of themes, dynamic aspects of data and processing a wide range of information (Tijssen and Van Raan, 1994; Cobo et al., 2011; Khan et al., 2021). Moreover, it provides impact measurement of journals and articles, institutes, countries, subjects and keywords, which delivers the indicators for policy management across the subject removing subjectivity issues among the pieces of literature (Hammersley, 2001; Khan et al., 2021). VOSviewer generates visual scientific landscapes about academic publications, researchers, organizations, countries, keywords or terms based on co-authorship, co-occurrence, citation, bibliographic coupling or co-citation and counts the number of links and the total strength of those links to prepare for a graphical network visualization (Van Eck and Waltman, 2010; Laengle et al., 2018). In this study, bibliometric analyses include the co-occurrence of keywords, citations, sources and the countries active in the targeted research by VOSviewer.

3.2.1. Co-occurrence of keywords bibliometric analysis

The mapping of co-occurrence of keywords indicates the frequency of appearance of study topics in one paper and the interrelatedness among topics (Jin et al., 2018). **Figure 5** provides an insight into the selected data from the eligibility phase of the PRISMA protocol, demonstrating the important keywords in the literature. The differentiation in the grayscale of keywords denotes their interconnections while circles' sizes denote their weights. The larger the circle of an item, the higher the weight in the network. The distance attribute says the relatedness among the keywords, which is in terms of co-occurrence linkage. Therefore, if two keywords are close, the connection between them is stronger. Keywords co-occurrence provides the mental map of research topics in the field and facilitates the researchers to identify the relation between those keywords. Moreover, this mapping helps to identify the clusters and frequency of keywords addressed, which paves the way to fill in the gaps for future studies.

Figure 5: Co-occurrence of keywords analysis.



The keywords which are the same in meaning but different in spelling are also combined. For instance, “ce” and “circular economy”; “building” and “buildings”; “sustainable” and “sustainability”; “BIM”, “bim” and “building information modelling” and “building information model” are merged. Since circular economy, sustainability and built environment have larger circles, respectively, they have a higher weight than the other keywords for the network. In addition, CR is the most connected keyword in construction management with 58 occurrences. Built environment and sustainability both have the second frequency of usage (14) and are followed by construction, resource efficiency, BIM, digitalization and waste management. Total link strengths are shown in **Table 2**.

Keyword	Occurrences	Total Link Strength
Circular economy	58	106
Built environment	14	42
Sustainability	14	42
Construction	11	30
Resource efficiency	8	21
BIM	6	13
Digitalization	6	19
Waste management	4	8
Adaptive reuse	3	12
Buildings	3	11
Reuse	3	10
Industry 4.0	3	9

Table 2. Total link strengths of the Keywords Analysis.

3.2.2. Citation bibliometric analysis

This analysis highlights the most notable academic contributions to research on the circular economy (CE) within the built environment. Certain authors have specialized in CE research, producing influential articles. **Table 3** provides further details on the most frequently cited articles, including the authors' names, full source titles, and total citation counts. Among them, Dervishaj, A. And Gudmundsson, K. have played a leading role in advancing CE concepts in the AECO industry with 6 publications, The article with the highest citations is about waste management. The second and third most cited works circular economy strategies and transition frameworks. The fourth article discusses circular building industry, while the fifth focuses on energy efficiency and circular economy.

Table 3. Author-Source-Citator analysis

Paper	Title	Citations
Esmailian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C., Behdad, S. (2018).	The future of waste management in smart and sustainable cities: A review and concept paper	219
Bonsu, N.O. (2020).	Towards a circular and low-carbon economy: Insights from the transitioning to electric vehicles and net zero economy	95
Gravagnuolo, A., Angrisano, M., Girard, L.F. (2019)	Circular economy strategies in eight historic port cities: Criteria and indicators towards a circular city assessment framework	95
Joensuu, T., Edelman, H., Saari, A. (2020).	Circular economy practices in the built environment	86
Gan, V.J.L., Lo, I.M.C., Ma, J., Tse, K.T., Cheng, J.C.P., Chan, C.M. (2020).	Simulation optimisation towards energy efficient green buildings: Current status and future trends	71
Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., Wang, J. (2021).	Enabling a circular economy in the built environment sector through blockchain technology	63
Heisel, F., Rau-Oberhuber, S. (2020).	Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster	60
Çetin, S., De Wolf, C., Bocken, N. (2021).	Circular digital built environment: An emerging framework	53
Hoosain, M.S., Paul, B.S., Ramakrishna, S. (2020).	The impact of 4ir digital technologies and circular thinking on the United Nations sustainable development goals	50

3.2.3. Source bibliometric analysis

Research results are usually shared and communicated in multiple published journals and conferences. In this study, the source journals of the collected documents were identified by VOSviewer and presented in **Figure 6**. In total, 66 different sources published the selected papers. This information signifies that this topic is highly popular among current researchers and conferences. “IOP Conference Series: Earth and Environmental Science (EES)” is the leading conference series. Of papers, 13 are published from these conferences during the selected period. “Sustainability” is the pioneering international journal in this research area with 12 papers. “Journal of Cleaner Production” is the second leading conference with 9.

In addition, “Automation in Construction”, “Buildings”, “Resources, Conservation and Recycling” and “Smart and Sustainable Built Environment” are retrieved from the principal journals for this particular subject.

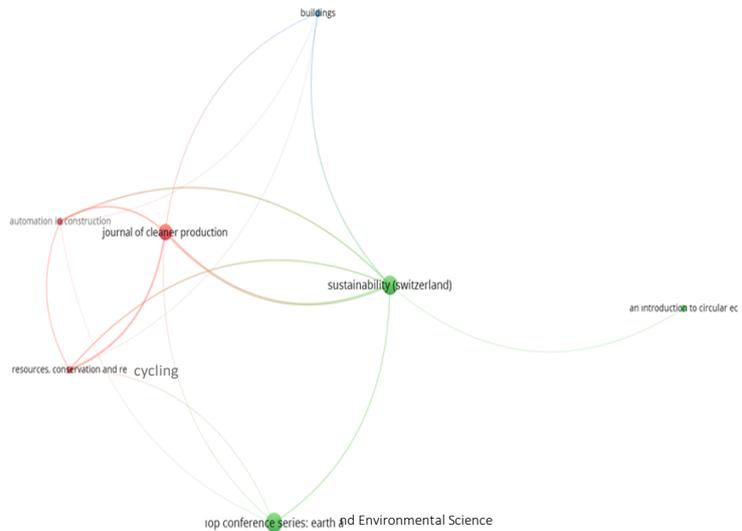


Figure 6: Source analysis.

4. DISCUSSION

In this study, the results of analyses have been discussed in terms of circular economy definitions, and circular economy related concepts. Based on the co-occurrence of keywords analysis, classification of keywords is generated whether there are about CE definitions and strategies or CE-related research areas, as shown in **Figure 7**. Thanks to the VOSviewer, keywords from similar or interrelated research areas are illustrated closer to each other. Also, interrelations between these keywords are linked to each other, allowing quicker interpretations.

For the further discussion in this study, CE definitions are investigated along with key theoretical perspectives; whereas CE-related concepts evaluated considering the relation with circularity and digitalization. These indicate the effective research areas of CE, which can help experts to conduct further research in this domain.

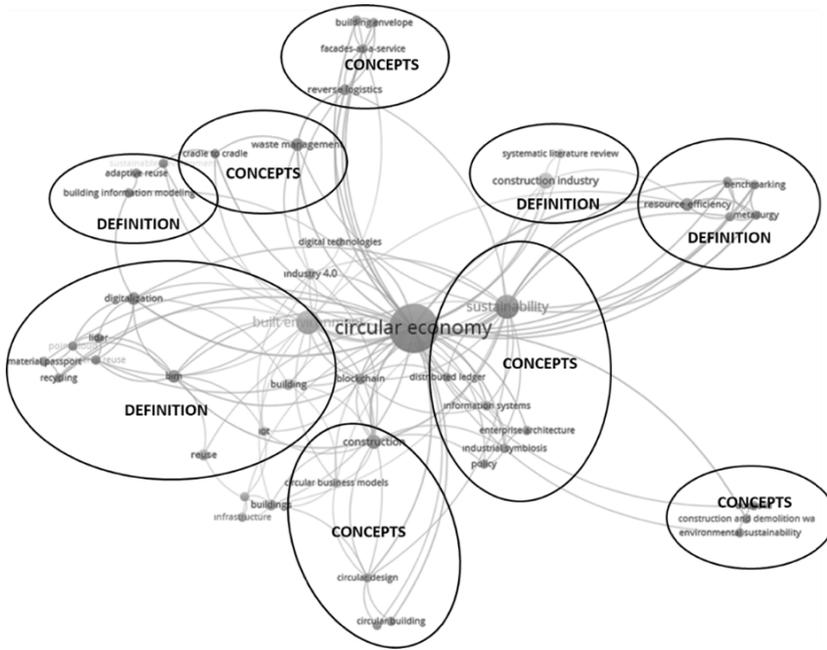


Figure 7: Classification of keywords into topics.

4.1. Circular Economy Definitions

This study highlights the most notable academic contributions to research on the circular economy (CE) within the built environment. The circular economy system offers a significant opportunity to reduce the consumption of primary materials, thereby conserving material resources and lowering the carbon footprint (EMF, 2013). In the literature, the concepts of the circular economy and circularity have been defined in various ways (Kirchherr et al., 2017). Kirchherr et al. (2017), after analysing 114 different definitions of the circular economy, identified the terms "reduce," "reuse," and "recycle," along with their various combinations, as the common elements across all definitions. The circular economy can be described as a business model and system design that is restorative and regenerative. By replacing the concept of life cycle and end-of-life with the principles of reuse and recycling, it aims to achieve sustainable processes (EMF, 2014). EMF and McKinsey (2015) have developed ReSOLVE Framework as a strategic approach in integrating sustainability and social responsibility into decision-making and business models. ReSOLVE (EMF and McKinsey, 2015) evaluates the systems according to six parameters: Regenerate, Share, Optimize, Loop, Virtualize and Exchange. UN Environmental Programme (UNEP, 2020) and Kirchherr et al. (2017) have defined circular economy strategies with 9Rs: Rethink, Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose and

Recycle. UNEP has developed conceptual context network and business model based on these 9Rs (UNEP, 2020). Three main concepts are named as Reduce, Reuse and Recycle in EU (2021) 's Circular Economy Action Plan (CEAP). According to EU (2023), circular economy has defined with 8Rs: Redesign, Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose. This strategy has ignored recycling as it will be the last choice. Doughnut economy (Raworth, 2017) evaluates rethinking the purpose and targets of economic activity, by systemic thinking to achieve social justice and ecological balance. A great deal of focus in the circular economy field is on the management of materials and ensuring that resource cycles are closed, in a similar way that occurs in natural ecosystems, where water and nutrients are continuously cycled. This approach has also studied in the literature throughout the years as "closed loops" or "closing the loop". Metabolic (2019) has developed "Seven Pillars of the Circular Economy" concept and defined these seven pillars as follows: materials are cycled at continuous high value, energy is based on renewable sources, water resources are extracted and cycled sustainably biodiversity is supported and enhanced through human activity, human society and culture are preserved, health and wellbeing of humans and other species are structurally supported and human activities maximize generation of societal value.

4.2. Circular Economy related Concepts

Considering the literature and systematic analysis, various concepts related to circular economy have defined. These are Cradle-to-Cradle, Industrial Ecology, Closed Loop, Regenerative Design, Performance Economy, Biomimicry, Green Economy, Blue Economy and (Bio-Based Economy). Additionally, Sustainability is the most frequently used term related to circular economy. To understand and reveal the current situation of CE and these concepts within the digitalization, further bibliometric search is conducted.

The **Table 4** highlights the intersection of digital technologies with various circularity-related concepts by showcasing the number of publications and the most relevant keywords associated with each concept. Among the identified themes, "sustainability + digital" emerges as the most extensively studied, with 7,280 publications. This reflects the growing integration of digital tools in promoting sustainability, encompassing topics such as digital transformation,

innovation, and sustainable development. Following this, "life cycle/life cycle assessment (LCA) + digital" and "closed loop + digital" also demonstrate substantial research interest, with 6,328 and 5,688 publications respectively. These themes emphasize the role of digital technologies in lifecycle analysis, product design, and closed-loop control systems, underscoring their relevance to sustainable production and resource management.

Table 4. Bibliometric search series through different keywords.

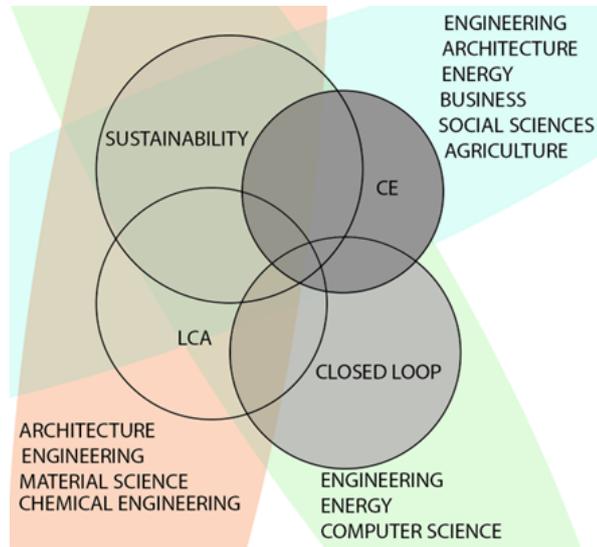
Keywords	Number of Publications	Most Relevant Keywords
sustainability + digital	7280	Sustainability, sustainable development, digital storage, digital transformation, innovation
life cycle / life cycle assesment / lca + digital	6328	Life cycle, digital storage, information management, digital twin, product design
closed loop + digital	5688	Digital control systems, closed loop, controllers, discrete time control systems, digital storage
performance economy + digital	1863	Digital storage, digital economy, digital transformation, economics, sustainable development
circular economy + digital	703	Circular economy, sustainability, sustainable development, industry 4.0, life cycle
green economy + digital	643	Digital economy, china, sustainable development, green economy, digital storage
retrofit + digital	519	Retrofitting, digital storage, energy efficiency, energy utilization, buildings
regenerative design + digital	263	Digital storage, regenerative braking, analog to digital conversion, integrated circuits, energy efficiency
cradle to cradle / C2C + digital	235	Life cycle, digital storage, environmental impact, LCA, sustainable development
industrial ecology + digital	188	Ecology, industrial ecology, digital storage, ecosystems, sustainable development
biomimicry + digital	36	Biomimicry, design, digital fabrication, architectural design, 3D printing

Themes such as "performance economy + digital" (1,863 publications) and "circular economy + digital" (703 publications) focus on the economic and systemic aspects of integrating digital solutions. The term "performance economy" aligns with sustainable development and economic transformation, while "circular economy" links directly to concepts like Industry 4.0 and life cycle management. Lower publication numbers in categories like "green economy + digital" (643), "retrofit + digital" (519), and "regenerative design + digital" (263) suggest these areas may be emerging fields, gaining traction as

sustainability efforts evolve. Similarly, "cradle to cradle (C2C) + digital" (235), "industrial ecology + digital" (188), and "biomimicry + digital" (36) represent niche but significant research directions. These concepts emphasize environmental impact, sustainable ecosystems, and innovative design approaches, particularly through digital fabrication and 3D printing.

The keywords associated with each category underline the diverse applications of digital technologies in advancing sustainability goals. They range from digital storage and control systems to cutting-edge tools like digital twins, which facilitate information management and system optimization. This diversity reflects the broad potential for digital innovations to transform sustainability practices across various sectors. **Figure 8** discusses the major subject areas related to the terminology and concepts.

Figure 8: Major subject areas related to the terminology.



The relatively low number of publications (703) combining "circular economy + digital" in the table may be attributed to several factors. One explanation could be the novelty of integrating digital technologies into CE practices. While CE principles have gained considerable attention in recent years, leveraging tools such as blockchain for material tracking, artificial intelligence for optimizing resource flows, or digital twins for circular design is still an emerging area of research. As such, it remains less established compared to more generalized topics like "sustainability + digital" or "life cycle assessment (LCA) + digital." Another contributing factor is the complexity of applying CE principles

at scale. Unlike broader sustainability topics, CE research often focuses on specific material loops, product lifecycles, or business models, which naturally narrows the scope. Furthermore, implementing circular economy systems requires systemic change across industries, often involving coordination between policymakers, manufacturers, and consumers. This interdisciplinary nature and the need for collaboration can pose challenges to rapid research advancements. In addition, the adoption of digital tools to support CE is highly dependent on technological infrastructure and policy frameworks, which vary across regions and industries. The lack of widespread standardization and alignment may also contribute to the limited volume of research in this area.

Despite the current disparity, the **Table 4** and **Figure 8** suggests that CE research involving digital technologies is advancing, as indicated by keywords such as "sustainability," "life cycle," and "Industry 4.0." These terms underscore the growing recognition of digital tools as enablers of circular strategies. As industries increasingly adopt innovative technologies to support circular systems, the number of publications in this field is expected to grow, reflecting the critical role of digital transformation in achieving a circular economy.

5. CONCLUSION

The aim of this study is to investigate how circular economy and built environment research have emerged as key topics for sustainable development during the Industry 4.0. This study acts as a systematic literature review, using descriptive and bibliometric analysis to reveal the current situation, connections and intersections between CE and built environment research, which will provide significant insights to the area. This study uses mapping knowledge on CE in the built environment research area between 2016 and 2024 by employing VOSviewer to generate the bibliometric analysis. This systematic literature review does not only describe the current state of the research, but also investigates new trends and prospective areas for future directions which ends in contributing to the literature. By utilising PRISMA, the structure of the review is shaped and the accuracy of the review and sources are tested with QA criteria.

The main contribution of this study is providing reliable and latest theoretical knowledge along with investigating the CE-related research areas on digital & circular potentials in the AECO industry.

Several key insights can be drawn from this study. Firstly, multidisciplinary research of CE and built environment, which has been significantly accelerating since 2016, indicates that circular transition of the built environment should be studied for further investigation and has significant potential contributions in real life applications. As the number of publications has been continuously increased during the last eight years, this trend indicates the strength and growing interest in the topic. Secondly, sustainability is the most connected keyword in CE research, which is followed by resource efficiency, BIM and digitalization. Thirdly, circular built environment studies are mostly related to BIM, blockchain and IoT as components of Industry 4.0 in terms of digitalization pillar. Another significant finding, UK, Netherlands and Italy are at the forefront of this domain followed by China and Germany. The journal-wise distribution of the selected articles indicated that most papers have been published Sustainability, and Esmailian et al. are the most cited authors about “waste management in cities” study. Consequently, the results of analyses have been discussed in terms of circular economy definitions and circular economy related terms. Especially, its relation with sustainable development, LCA and C2C should be studied deeply.

The findings of this study reveal valuable information for researchers, practitioners and policymakers, allowing them to gain an in-depth understanding of CE in AECO industry. The main contribution of this work is providing reliable and latest theoretical knowledge along with investigating the future potentials on CE for the AECO industry. Theoretical key implications are; being up-to-date review on CE within the AECO industry, providing detailed insight about circular economy, its definitions, its strategies and similar research areas. Practical key implications are; being a latest study that presents the current situation, key topics, papers and authors to follow; addressing the future direction of the digital & circular transition by mentioning the related technologies and discussing the related concepts. The study provides transparent and detailed review for AECO experts especially to be used in circular transformation or circular implementations.

The findings of this study suggest that combining circularity with similar knowledge concepts will contribute to a deeper understanding and quicker implementation. On the other hand, this study limited the databases with Scopus and WoS, for the further studies, grey literature can be included. Moreover, only sources in English language are taken into account, in this regard, the study excludes the rest. Future research can focus on the integration of frameworks and strategic roadmaps as robust circular transition of the built environment and the AECO industry.

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Conflict of Interest Statement

The manuscript is entitled “Circular Built Environment During the Digital Age: A Systematic Review” has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Author Contribution

All authors contributed equally to this article.

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