Application of Circular Economy Principles in Buildings: A Systematic Review.

Contents

Abstract

The transition from linear economy into circular economy is not realizable until circular economy principles are applied into the life-cycle stages of buildings which is a proactive design approach to manage buildings from cradle to cradle. Resources are depleted without any effective programme for recovering of materials. Hence, this study was aimed at identifying suggested advancements for the application of circular economy principles in buildings. The study objectives were to systematically review/analyse proposed circular economy interventions in buildings and finally conclude on findings whilst identifying research gaps. Therefore, the study gathered related articles for review under seven identified major circular economy strategies. Results revealed that there was a progressive awareness/research on circularity in buildings although its awareness/acceptance were still at their infancy. Sixty-four articles were analysed under the identified strategies, leading to discussion of major interventions. The review revealed practical approaches to the application of circular economy in buildings, also identifying aspects that received little attention, including research-gaps. It was recommended that future research should focus on obscured areas identified for a holistic approach. Conclusions were deducted from the analysis and recommendations made based on researchers work on the susceptibility of buildings to resource efficiency in a circular economy.

Keywords: Buildings; Circular Economy; Material Recovering; Resource Efficiency; Sustainability.

1 Introduction to circular economy

1.1 The concept of circular economy (research background)

Natural resources are currently being consumed at twice the rate they are produced and by 2050, this could be three times (EMF 2012,2013). The exponential growth of world's population from 7.5 billion to approximately 8.5 billion by 2030 will add to the existing demand for homes and services, putting unprecedented pressure on natural resources (EMF 2012; Ellen MacArthur Foundation 2013). Recession of resources (Rahman et al. 2017), competition for resources and disruptions of supply are creating uncertainty in the short term and increasing costs overall (Arup 2016). Stricter global environmental regulations aimed at protecting fragile ecosystems are also making it harder and more costly to extract and use certain resources (Lieder and Rashid 2016). The built environment is under increasing pressure to minimise this impact. A circular approach as proposed by Ellen MacArthur Foundation could help the sector to reduce its environmental footprint, and to avoid rising costs, delays, and other consequences of volatile commodity markets. In a work series, "buildings as material banks (BAMB)" Eberhardt et al. (2019b) made major life cycle assessment modelling comparison of linear and circular building components. A major conclusion from the study suggested that the potential benefit of reusing and recycling building material components is a future retrieval of resources (Eberhardt et al. 2019b).

Circular economy seeks to maintain building components and resources at their highest intrinsic value for as long as possible in which building components are kept in a continuous loop of use, reuse, repair and then recycled thereby reducing waste and prevent negative externalities such as CO_2 emissions (Ingemarsdotter et al. 2019). Geissdoerfer et al. (2017) defined circular economy as a regenerative model that reduces waste and emission (Geissdoerfer et al. 2017). The human population has continuously used more material resources, a direct reflection of population growth and income increase (Behrens et al. 2007; Roxburgh et al. 2011). Benton and Hazell (2013) asserted that it is likely for many material resources to become scarcer and more expensive to acquire and use (Benton and Hazell 2013). Building materials in recent years has proven even more difficult to source as resources are constantly being depleted without any significant regeneration (DEFRA 2012; Ecorys 2012).

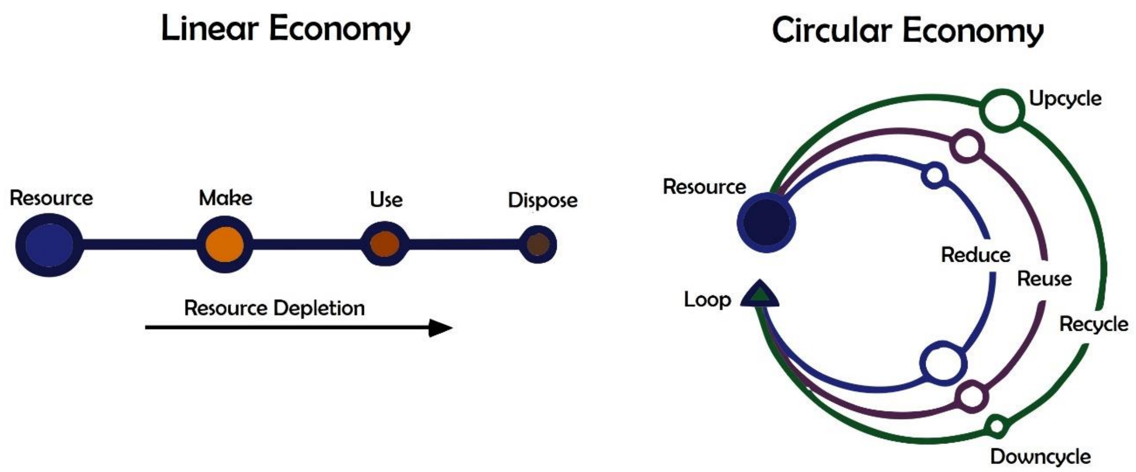

Figure 1: Linear and Circular Economy (Source: Authors, 2020)

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The circular economy system provides a great opportunity for the reduction of primary material usage, thereby protecting material resources and reducing the carbon footprint (EMF 2013,2015). Circular economy is important in ensuring material sustainability in any building (Eberhardt et al. 2019a). Some of the major benefits in the use of circular economy system cuts across economics, environmental and social sustainability. One of the social perspectives of circular economy lies in the provision of job opportunities (Morgan and Mitchell 2015). Ellen MacArthur Foundation described circular economy as a regenerative system in which resource input, emission, waste, and energy leakage are reduced by closing and narrowing energy and material loops (EMF 2012).

The application of circular economy in buildings would involve Building materials to undergo construction, use, deconstruction, reuse, recycle and back to material for construction (Bullen 2007). The increase in world population is a clear signal for resources to become more difficult and expensive to access (World Bank 2015). According to Ellen MacArthur Foundation, the adoption of circular economy will preserve and enhance natural capital, optimise renewable resources, prevent waste by design. The strategy allows materials, products and components to be held in repetitive loops, maintaining them at their highest possible intrinsic value (EMF 2012).

The current article focuses on the existing knowledge and the knowledge gaps in the published research works focusing on circular economy interventions in buildings. To that end, a systematic review of the available and relevant literature is carried out. This review reveals that there is an absence of a holistic intervention on a step by step basis how the proposed circular economy interventions and strategies could be employed in the delivery of a resource efficient building, these gaps were discussed in the paper.

2. Methodology for Systematic review

To explore circular economy interventions in the construction industry, with special emphasis on the application of its principles in buildings, it was imperative that a systematic review is conducted. This was a practical approach to account and evaluate the quantity and quality of studies/research that has been undertaken in the application of circular economy principles in buildings through a systematic review as an essential method for this kind of study (Esa et al. 2017). This method is set to provide a critical overview of previous studies as it relates to the subject matter and identify research gaps in the various works (Webster and Watson 2002). To accomplish the aim of this review, it was recommended by Briner and Denyer (2012) that the following adapted steps are adhere to:

1. Set a method for systematic review
2. Present method transparently
3. Method should be a repeatable process in arriving at same conclusion
4. Develop a general summary and connection to the subject of discussion

(Briner et al. 2012).

Table 1: Categorisation of systematic review steps

S/N	Step Categorization Briner and Denyer (2012)	Description Higgins and Green in (2008); Briner and Denyer (2012)	Outcomes	Stages Tranfield et al. (2003)
1	Methodology	Set a method for systematic review	Objectives	Preparation
2	Presentation	Presentation of method transparently	Analysis	
3	Replicability and updatability	Method should be repeatable with same conclusion	Accuracy	Execution

4	Summary and synchronization	A general summary and connection to the subject of discussion	Conclusion	Conclusions

Similar studies by Tranfield et al. (2003), established three stages for conducting a systematic review, he described the first stage as preparation/planning the procedure for the review, which is followed by conducting the review and lastly is making conclusions (Tranfield et al. 2003). A protocol for conducting a systematic review was developed by Briner and Denyer (2012) which was an adaptation from the work of Higgins and Green in (2008).

Integrating these above recommended procedures, the following was arrived upon:

(1) Conduct an initial review to identify the research gap.

(2) Establish research objective.

(3) Set selection criteria for previous studies for the review.

(4) Identify Strategies for obtaining literatures from databases.

(5) Eligibility and filters to acquire literatures.

(6) Mark out data collection methods.

(7) Develop method for quality assessment and accuracy of data collected.

(8) Synthetization of results and conclusions.

(Higgins and Green 2008; Briner et al. 2012)

The above protocol was employed in the execution of this review in the application of circular economy principles in buildings as adapted from Higgins and Green (2008).

Table 2: Stages for Systematic review (adapted from Higgins and Green, 2008)

	Stages	Investigation
1	Study Focus	Exploring the application of circular economy principles in buildings.
2	Research objective	Conduct a systematic review of literatures focused on the application of circular economy in buildings.
3	Selection Criteria	Strictly literatures on circular economy application in the built environment. related abstracts; related full articles; literatures with supplementary information.
4	Strategies for material acquisition	Extraction of high-quality literatures from databases, Ranging searches from the last 10 and 5 years (Science Direct, Web of Science and Scopus)
5	Filters and Eligibility	Publications from peer reviews and proceedings
6	Data collection	Use of marking matrix for the inclusion and exclusion of literatures. search steps: title search, abstract search, keywords search, full-text search, data extraction, bibliometric network.
7	Quality assessment and accuracy	Special releases and documentaries of circular economy principles and applications, inclusion of other relevant studies in circular economy that may be inferred in the building sector, exclusion of generic articles, exclusion of irrelevant literatures to the aim of this review.
8	Systematic review, Synthetization, results, and conclusion	Analysis, summary, and submission of findings.

Following the above steps, it was essential to define the aim of the review and evaluate targeted research in the subject area. The study was to explore and analyze literature materials on the application of circular economy principles in buildings. Hence, the main objective of the review was to identify and systematically review studies on the application of circular economy in buildings. Therefore, studies and research papers in the context of this discussion were collected and analysed. This included the creation of a bibliometric network of all related abstracts to find the most related topics with a focus on this research.

This strategy started with a preliminary investigation of articles by creating a bibliometric network. According to Van Eck and Waltman (2014), a bibliometric network is a constituent of nodes and edges showing the correlation of words and the strength of their connection through the edges (Van Eck and Waltman 2014). These keywords were obtained from the abstract/literatures and the network of the words were networked to the most researched areas under the theme and topic. To do this, a software called VOSviewer, developed by Nees Jan van Eck and Ludo Waltman was used to analyze the studies. The objective in creating this network for this review was to draw searches from the theme of circular economy and focus the review on the subject area of this investigation.

The VOS Viewer can reveal the most used keywords as it relates to the topic which it visualizes by the size of the nodes, therefore, the bigger the nodes, the higher the number of citations of the word. It also shows how closely related keywords in the fields of study by distance-based networks in which the network distance between two nodes indicates their correlation (Van Eck and Waltman 2014).

The software is programmed to delimit the use of specific database for bibliometric networking. Consequently, this research was carried out in three major databases (Web of Science, Science Direct, and Scopus). The search keywords chosen included.

(TITLE-ABS-KEY (*"circular economy"*) AND TITLE-ABS-KEY (*buildings*) AND TITLE-ABS-KEY (*recycle*)) They were decisively chosen to focus on the aim of this systematic review. Using these keywords in the preliminary search and limiting by date range within the last 10years, 32 document results were discovered in the Scopus database, 59 results were found in Science Direct, and

125 were found in Web of Science. The search done in the month of April 2020 had a total of 216 papers.

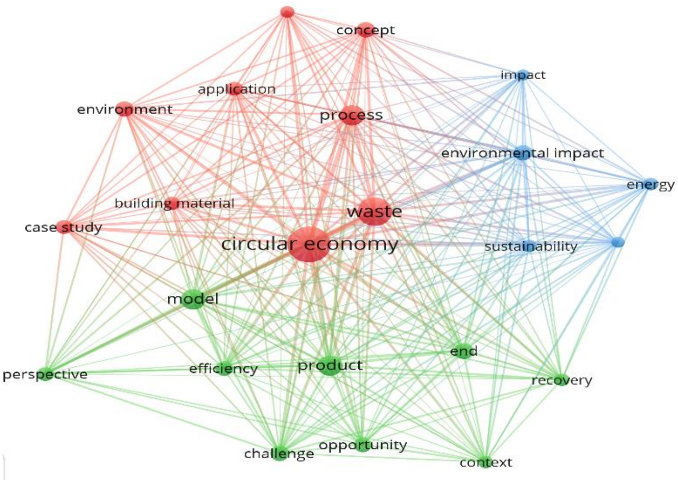

Figure 2: Bibliometric network of "circular economy", buildings and recycle (Analysis and visualisation by VOSviewer software).

(please use colour for figure)

Analysing these results with VOSviewer, the bibliometric network clearly divided the most used words into three areas of focus. This is depicted in the colours of red showing circular economy in the built environment, green depicting end of product life models, and blue showing environmental impact of sustainability. The bigger nodes represent keywords with the most citations and usage in the network. It can be seen that "circular economy" was the most cited or used in this bibliometric network followed by "waste".

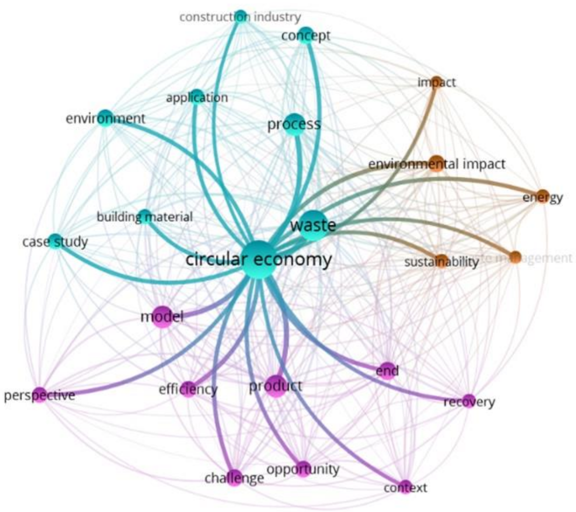

Figure 3: Circular economy bibliometric network with other aspects of resource sustainability

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The network shows the links between keywords or nodes, which is a correlation between them, with the distance of the links showing how closely related one keyword is to the other.

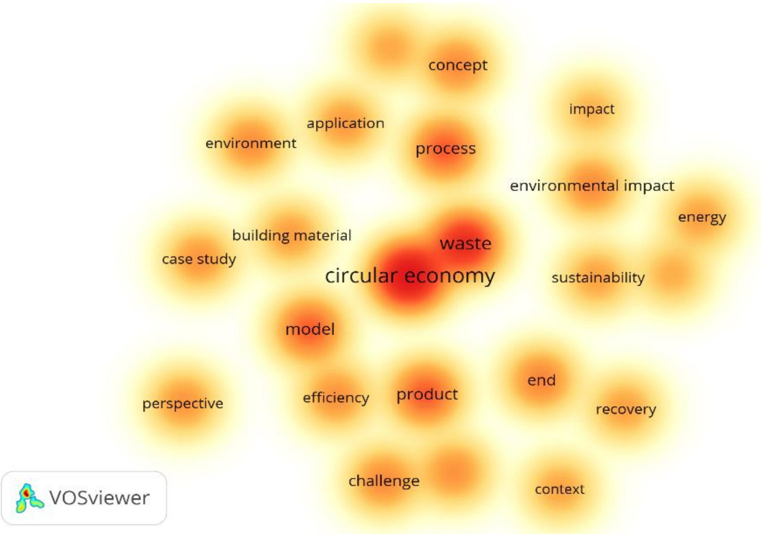


Figure 4: Density visualisation of Bibliometric network of "circular economy", buildings and recycle search keywords -

(please use colour for figure)

Using density visualisation tool, the darker the colour, the higher the number of keywords citation. In this search, it is easily noticeable that the densest areas are circular economy followed by waste. The density visualisation is very useful to easily spot most published subject area (Van Eck and Waltman 2014).

The next step was to filtered out papers whose focus was not in the subject area by an assessment of literature titles, which reduced the number of publications to 162 (Science Direct – 49, Scopus – 25, Web of Science – 88), this was also followed by papers that were not published within the last five years, which also reduced the number to 154 (Science Direct – 49, Scopus – 23, Web of Science – 82). However, an exemption for core literatures in subject area was made for 1 paper from the Web of Science database, bringing the number to 155. The exclusion process followed by deleting repeated papers from the collections. This reduced the total number to 116. At this stage, the analysis began by reviewing the content of the abstract of the remaining literatures. This was done by reading through the abstract, checking their relevance and eliminating the less relevant ones with regards to the application of circular economy in buildings. This reduced the number of publications to 64 (Science Direct – 15, Scopus – 13, Web of Science – 36). Finally, a complete read of the papers, this also eliminated papers that did not meet up with the selection criteria established for the systematic review.

It was essential that the papers were peer reviewed and all necessary proceedings/protocols observed as authentic information sources. The preliminary analysis concluded by obtaining 64 publications of high relevance to the subject matter. The systematic review concluded by analysing the findings and exactions by researchers in the published works. Finally, this systematic review was concluded with a content analysis, in which the various concepts of circular economy were reviewed and its application in buildings analysed. Following this was a summary/conclusion of the obtained results.

3. Results

The results of this review is presented in two categories, it started by providing a descriptive analysis of the central focus of obtained articles, giving a brief description of publications. The articles were further divided into seven major research themes of circular economy for content analysis.

3.1. Descriptive analysis

The bibliometric analysis was considered with the number of publications per year. It revealed that circular economy is generally a new trend of sustainable development globally which has started gaining momentum in the construction industry, the assessment showed that there is a gradual build of awareness in the field, which is evident by the number of publications since 2017. Majority of the works in this systematic review were published between 2017 to early 2020, which is a clear indication of a growing research interest. It can be seen from the chart (figure 5) that the number of publication in this subject grew from 4 in 2017, through 18 and 27 in 2018 and 2019 respectively, there is a growing number already recorded in 2020 and the projection from this analysis indicates that this number will continue to increase. It was of interest to know the Journal title of these works which usually reflects the research interests. It can be seen in figure 6 below that the highest publication title was the Journal of Cleaner Production which had a total of 11 papers, this Journal featured papers that employed some practical approach to a circular economy in buildings. The second highest publication title in this subject area was the Journal on Resources, Conservation and Recycling, with a total of 6 articles. Other high-quality Journals were published in other Journal titles as represented on the chart below (figure 6). The review went on to identify the places of publication, shown in the chart (figure 7) below.

Figure 5: Chart showing number of publications per year.

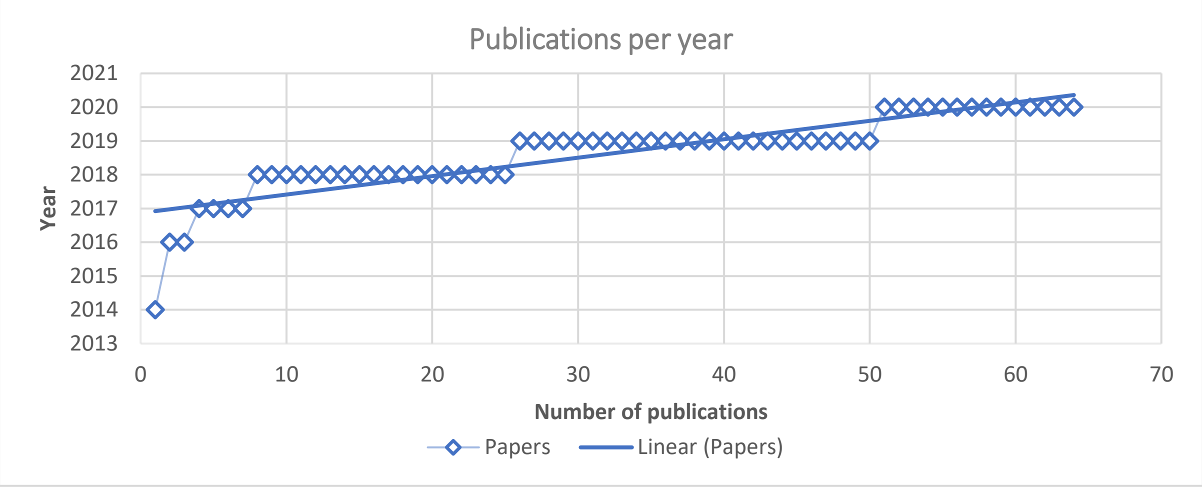


Figure 6: Chart showing number of articles per Journal.

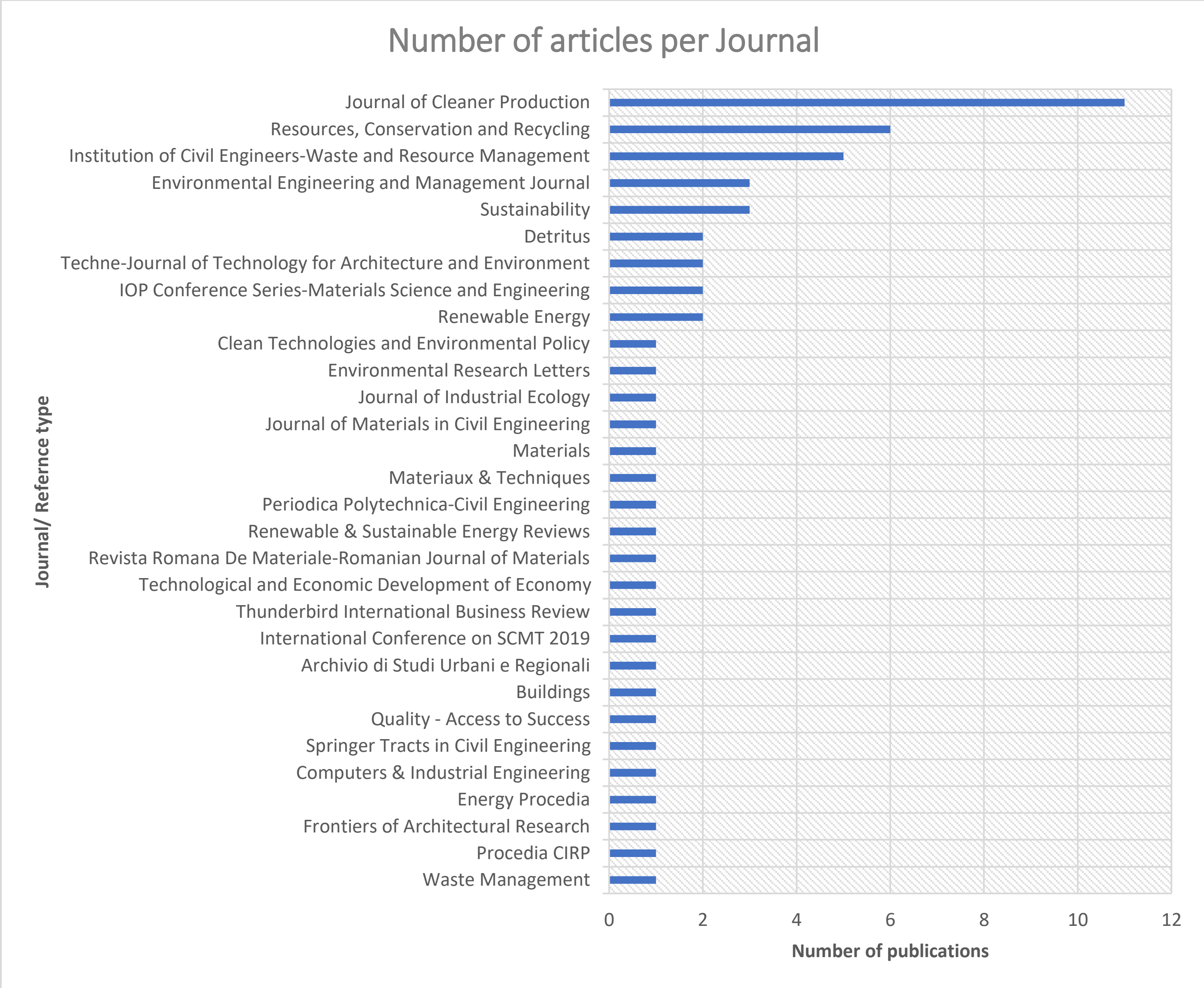
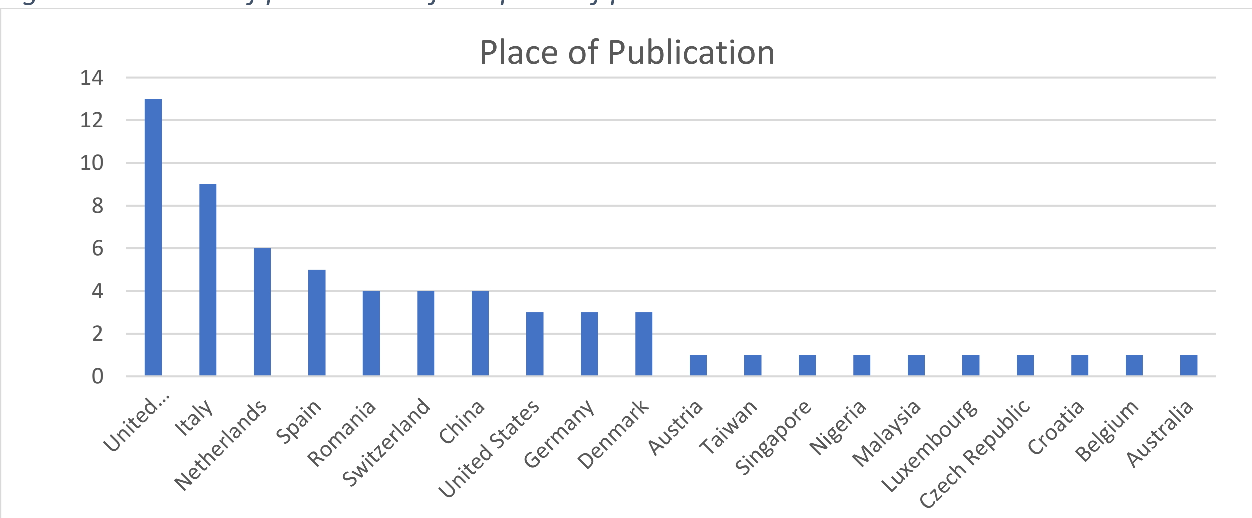


Figure 7: Number of publications from place of publication.



From the chat above (figure 7), the highest number of publications for this review came from the United Kingdom, with a total of 13 papers, followed by Italy with 9 papers, Netherlands with 6 papers, Spain with 5papers, Romania, Switzerland and China with 4 papers each, United states, Germany and Denmark with 3 papers each, Austria, Taiwan, Singapore, Nigeria, Malaysia, Luxembourg, Czech Republic, Croatia, Belgium, and Australia with 1 paper each. Most of these studies emanated from European countries which reflects the growing sustainability awareness building up in the continent.

3.2. Content analysis

To have an in-depth review of obtained works, it was necessary to divide the study into three stages of literature review:

1. Definition of circular economy in buildings.
2. Concepts of circular economy application in buildings.
3. Analysis of literature material according to circular economy research theme.

3.2.1. Definition of Circular Economy in Buildings

A review of the definitions in relation to the subject area was assessed as provided in the literatures. In all the selections, it was constantly noticed that there were several attempts to reduce waste, which is one of the major features of resource efficiency. References were constantly being cited from the concept of Ellen MacArthur Foundation, with 23 citations (EMF 2012; Ellen MacArthur Foundation 2013; EMF 2015). There are several published works from Ellen MacArthur Foundation that proposes possible interventions in circular economy. The work of Eberhardt et al. (2019) from the IOP Conference Series Materials Science and Engineering is also a good source of reference as the study saw circular economy principles potentially minimising the issues arising from the building industry through the adoption of recirculation of building materials (Eberhardt et al. 2019b).

Geissdoerfer et al. (2017) also defined circular economy as a regenerative closed loop system which is achievable through an appropriate design, accommodating maintenance, recycling or reuse (Geissdoerfer et al. 2017). It was observed from the preliminary review that although circular economy is gaining momentum, there is still very few researches in this field. Adams et al. (2017) stated that in the built environment, there has been limited research in the application of circular economy principles within the whole systems context. Similarly, Akanbi (2018) narrates that although the recycling of the entire building is becoming popular, direct reuse of recovered building material is a more beneficial use (Akanbi et al. 2018).

After a careful review of the above descriptions of the application of circular economy in buildings, Circular economy in buildings as it relates to this context can therefore be defined as a strategic programming of a building to easily change its configuration for longevity and potentially be susceptible to the loop of reduce, reuse and recycle for resource efficiency.

3.2.2. Concepts of circular economy application in buildings.

The literatures obtained for this review undertook studies on different aspects of a building's life stages. It was expedient that this review classifies these studies according to the aspects of emphasis. After a comprehensive read and analysis, the following aspects or themes were considered for the classification: design for disassembly, design for recycling, building materiality, building construction, building operation, building optimization, building end of life. The consideration of these seven aspects (circular economy themes) was inferred from several works on circular economy in buildings (Benachio et al. 2020; Foster 2020; Ghaffar et al. 2020). The aspects represent major themes of circular economy in buildings as outlined by the European standard EN 15978:2011, which specifies the calculation method for Life Cycle Assessment (LCA) of a building. It considers four main life cycle stages:

1. Product manufacture
2. Construction
3. Operation
4. End-of-life.

Below is a description of the following circular economy themes used in this study according to their life cycle stages.

Table 3: Themes of Circular economy strategies and life circle stages

S/N	Aspects/Themes (Circular economy strategies)	Description (Circular economy context)	Stages (European standard EN 15978:2011)
1	Design for disassembly (Kreilis and Zeltins 2017; Minunno et al. 2018; Brambilla et al. 2019)	Building design consideration for easy building deconstruction. Use of prefabricated modules in the context of assembly and disassembly. Modular design, design for disassembly, design for adaptability, design for deconstruction, standardization	Product manufacture
2	Design for recycling (Vyncke and Vrijders 2016; Honic et al. 2019; Ruiz et al. 2020)	Building design program from inception for recyclability. Reuse, recycling of building components and reduction of construction waste.	
3	Building materiality (Campioli et al. 2018; Cai and Waldmann 2019; Deetman et al. 2020)	Building materials analysis and selection as a major consideration for a circular economy. Material selection and recyclability.	
4	Building construction (Adams et al. 2017; Mangialardo and Micelli 2018; Ghaffar et al. 2020)	Building construction methods that can help facilitate the application of circular economy.	Construction
5	Building operation (Esposito et al. 2018; Giama et al. 2019)	Building in use and modalities for operation in line with circular economy principles.	Operation
6	Building optimization (Antoniol and Barucco 2019)	Optimization of building parts for durability and longevity. Repair activities, upgrades, component exchange, etc. to improve a building's durability, performance, etc.	
7	Building end of life (Hopkinson et al. 2019)	Building end of life program and loop systems. Interventions to either restore, reuse, recycle a building's components.	End of life

Table 5 below shows the focus of the obtained literature for this systematic review. The researchers focus was categorized under the 7 themes of circular economy, which is in accordance with the European standard EN 15978:2011. It can be seen from the analysis that design for recycling had the highest research focus (28). This is not surprising since the theme is a general requirement for circular economy in buildings and seems to form a major aspect of circular economy. The second aspect of focus in this study was end of life (24). From the studies, it is an essential aspect of circular economy for a regenerated loop of resource (cradle to cradle) as stated by the Ellen MacArthur Foundation (EMF 2015). Materiality (22) in circular economy in buildings is another major aspect of discussion, it seems to have formed the bedrock of the research in this review. 21 literatures focused on Construction as this is a major determinant for the ease of disassembly, reuse and recycling (Minunno et al. 2018). Design for disassembly and Operation both had (10) same level of focus, an indication of areas that has started gaining some attention. The least covered was optimization, with 6 papers of focus in this review. The study that had the most coverage (5 aspects) was by Minunno et al. (2018), a study that considered various strategies for applying circular economy in prefabricated buildings (Minunno et al. 2018). It is not surprising that this study (Minunno et al. 2018) has incorporated most themes of circular economy since the application of circular economy entails the implementation of all circular economy themes for a holistic approach towards resource efficiency.

Table 4: Table showing circular economy in building research themes focused by researchers.

	Circular economy themes for Buildings							
Article	**Design for disassembly**	**Design for recycling**	**Materiality**	**Construction**	**Operation**	**Optimization**	**End of life**	**∑**
(Adams et al. 2017)	•			•				2
(Akanbi et al. 2018)			•			•		2
(Antoniol and Barucco 2019)			•	•				2
(Baiani and Altamura 2018)	•	•	•			•		4
(Basti 2018)							•	1
(Boer et al. 2020)				•				1
(Brambilla et al. 2019)	•			•			•	3
(Cai and Waldmann 2019)		•	•	•				3

(Campbell 2019)	•		•	•				3
(Campioli et al. 2018)			•					1
(Casas-Arredondo et al. 2018)			•					1
(Crețu et al. 2019)				•				1
(Cruz Rios et al. 2019)		•			•		•	3
(Cuenca-Moyano et al. 2019)			•					1
(Deetman et al. 2020)			•					1
(Drochytka et al. 2020)		•					•	2
(Eberhardt et al. 2019b)	•	•				•	•	4
(Esposito et al. 2018)					•			1
(Ghaffar et al. 2020)		•		•				2
(Giama et al. 2019)		•			•			2
(Gorecki and Iop 2019)				•				1
(Gueret et al. 2019)			•					1
(Heisel and Rau-Oberhuber 2020)		•		•			•	3
(Hertwich et al. 2019)			•					1
(Honic et al. 2019)		•	•					2
(Hopkinson et al. 2019)							•	1
(Huang et al. 2018)		•					•	2
(Kerdlap et al. 2019)		•		•			•	3
(Kozma et al. 2018)	•							1
(Krause and Hafner 2019)	•		•					2
(Kreilis and Zeltins 2017)	•							1
(Lei et al. 2020)			•		•			2
(Lin 2018)		•						1
(Mangialardo and Micelli 2018)				•				1
(Merli et al. 2020)		•		•				2
(Migliore 2019)		•				•		2
(Migliore et al. 2018)			•				•	2
(Migliore et al. 2020)						•	•	2
(Mihai 2019)				•			•	2
(Milios and Dalhammar 2020)		•					•	2
(Minunno et al. 2018)	•	•	•	•		•	•	5
(Moreno-Juez et al. 2020)							•	1
(Noll et al. 2019)		•						1
(Nuñez-Cacho et al. 2018)		•		•				2
(Pomponi and Moncaster 2017)			•		•			2
(Pomponi and Moncaster 2019)				•				1
(Pujadas-Gispert et al. 2020)	•			•	•			3
(Rohan 2016)			•					1
(Rossetti et al. 2018)		•	•				•	3
(Rubino et al. 2019)			•					1
(Ruiz et al. 2020)				•			•	2
(Saez et al. 2019)			•	•				2
(Saint et al. 2019)		•			•		•	3
(Sansom and Avery 2014)		•					•	2
(Schiller et al. 2017)			•					1
(Shen et al. 2020)					•			1
(Silva et al. 2019)		•					•	2
(Spierling et al. 2018)			•					1
(Tallini and Cedola 2018)		•			•			2
(Tomic and Schneider 2018)		•					•	2
(Vyncke and Vrijders 2016)		•		•			•	3
(Williams 2019)		•					•	2
(Wong et al. 2018)		•					•	2
(Zhao et al. 2020)		•						1
	10	28	22	21	10	6	24	

3.2.3. Analysis of literature material according to circular economy research theme

Furthermore, the review analysed each article according to the seven research themes discovered in this review. These themes form a comprehensive approach towards the application of circular economy principles in buildings. However, many of the literatures had focused on certain themes. Therefore, to facilitate the discussion and understanding of the recent developments on the application of circular economy in buildings and analyse articles in similar areas of research, it was necessary to conduct this review in a systematic manner following these different aspects or themes.

The analysis went on to reveal basic circular economy concepts and principles found in the obtained literature for this review. This was done by listing the found concepts and principles in the 64 articles. In this systematic review, each concept and principle were attached to their life cycle stage. This gave a very realistic approach towards circular economy in building application. Hence, this analysis provides not only a holistic approach but also steps towards the implementation of circular economy in the buildings as well as identification of insufficiently covered areas for further research in this field.

4. Discussions

The discussions were divided into three sub-headings based on the collected literature materials. The descriptive analysis was based on the bibliometric results. The discussion later progressed to a critical review of literature content of the seven aspects of circular economy. The discussion was concluded with the identification of research gaps found in this literature review.

4.1 Descriptive discussion

According to the bibliometric data in this review, studies on Circular Economy in buildings are increasing. This is evident in the bibliometric data reported in this article. Moreover, a statistical exponentiation of articles has been doubled for the last three years. There are research groups hosting events such as BAMB (Building as Material Banks), which is based on pathways for a circular future. This has contributed greatly to the increase in circular economy research in buildings. However, a great consideration on life cycle stages, as well as the reusability and transformation of buildings was the focal point of the event (BAMB 2017). It was however noticed that some of the publications had specific interest of circular economy in buildings, while some based their research on a holistic approach towards the application of circular economy principles in buildings as buildings were seen as material banks for material extraction during use and at end of life (Akanbi et al. 2018).

4.2 Content discussion

The discussion for this review was based on seven found aspects of circular economy in buildings. (1) Design for disassembly (2) Design for recycling (3) Building materiality (4) Building construction (5) Building operation (6) Building optimization (7) Building end of life.

4.2.1. Design for disassembly

According to some of the obtained studies (from a total of 10 literatures), the concept of design for disassembly arose from the need for buildings to easily be deconstructed, which in turn increased components adaptability and flexibility to different configurations. Building components are usually prefabricated and later site assembled (Minunno et al. 2018).

The research into standardization of material sizes and types may be useful to complement the seven strategies circular economy since the construction industry is increasingly moving towards a closed-loop supply chain (Minunno et al. 2018). Other scholars lamented that the concept were being introduced slowly in the built environment as many stakeholders were yet to fully understand the practicality of applying the concept in the building sector (Adams et al. 2017; Eberhardt et al. 2019b).

Design for Disassembly (DfD) also known as design for deconstruction allows for futuristic disassembly or deconstruction of buildings and the reuse, recycling and remanufacturing of its components (Cruz Rios et al. 2019). Ruiz et al. (2020) explained that the implementation of design for disassembly is closely related to prefabricated components which has a good potential of reducing waste production in construction and deconstruction activities. At a significant rate, the waste produced during the construction and renovation stage and during demolition/deconstruction activities are cut down through dismounting (Ruiz et al. 2020). In the study conducted by Cruz Rios et al. (2019), they analysed the key principles for the application of the concept of Design for Disassembly which included:

(1) A proper documentation of material components and methods for disassembly.

(2) Design of accessible connections to ease building deconstruction, for example, the use of bolts, screws, etc. and minimizing welded connections hence, promoting prefabricated/modular design.

(3) The separation of components that are non-reusable and non-recyclable.

(4) Standardization of components parts to possess same dimensions, shape, and other attributes.

(5) Design to reflect best labour practices, productivity, and safety.

Design for deconstruction (DfD) is very relevant to circular economy in buildings as it increases flexibility and adaptability of components to easily be reuse, repaired and recycled, although the concept is still under research (Cai and Waldmann 2019).

4.2.2. Design for recycling

To analyse this section, the analyses were divided into two aspects. Firstly, the review analysed literatures that considered the reduction of material consumption through the design of reusable components. Secondly, literatures that considered products adaptability to different recycling phases (up-cycling and down-cycling). In addition, studies were also analysed with respect to the 3Rs hierarchy (reduce, reuse, and recycle) of circular economy. A total of 28 literatures carried out researches in this area (design for recycling), 8 studies in this review had published on the reduction of material consumption through the design of reusable components, notably the following literatures (Sansom and Avery 2014; Kreilis and Zeltins 2017; Akanbi et al. 2018; Migliore et al. 2018; Cruz Rios et al. 2019; Saint et al. 2019; Milios and Dalhammar 2020). 12 literatures had special interest on the adaptability of materials to recycling, studies such as (Huang et al. 2018) which focused on the 3Rs hierarchy was also reviewed.

Other studies revealed that dismountable buildings have more recycling potential, since they are highly adaptable and component parts can easily be reuse, upcycled or downcycled (Kreilis and Zeltins 2017; Kozma et al. 2018; Brambilla et al.

2019). In another study, it was highly recommended that material selection for building construction should be done with recyclability in sight (Casas-Arredondo et al. 2018). Minunno et al. (2018) recommend that whilst following the 3Rs (reduce, reuse, and recycle) hierarchy of circular economy, the building components that are not reusable or adaptable should be designed with preference to their recyclability potential (Minunno et al. 2018; Rossetti et al. 2018). Therefore, the recycling phase for each material component (whether reuse, upcycling or downcycling) should be considered at the early stages of the project design (Campioli et al. 2018).

4.2.3. Materiality

Papers reviewed under this heading had a special focus on building materials in a circular economy. Most of the studies are channelled towards building material specifications and how this can possibly be fitted into the 3Rs hierarchy. Hence, this section is reviewed in two parts based on focus of obtained literatures. The first part focuses on waste reduction through material design and specification. Pioneering papers gathered in this area include (Eberhardt et al. 2019b; Giama et al. 2019; Hertwich et al. 2019; Honic et al. 2019; Kerdlap et al. 2019). The second part focuses on Material storage using buildings as material banks (BAMB), major literatures of focus are (Cai and Waldmann 2019; Eberhardt et al. 2019b; Hopkinson et al. 2019). A total of 22 collected literatures explore materiality as one of the key drivers of circular economy.

However only a few researches had focused on Buildings as material bank (BAMB). To reduce construction and demolition waste, sustainable interventions should include enhancement of energy and environmentally efficient materials (Cai and Waldmann 2019). On the other hand, the use a strategic building material specification could potentially store the material to be recovered for reuse or recycling (Casas-Arredondo et al. 2018; Crețu et al. 2019). Cai and Waldmann (2019) state that using high-performance materials to minimize the amount of utilized material in the improvement of durable buildings to lengthen their life span and serve as material storage (Cai and Waldmann 2019). Honic et al. (2019) emphasise the need to maintain and recycle buildings at the end of a building's life cycle. They state that a major fraction of building materials stored in buildings are converted into waste, consequently, it is imperative to minimise the use of virgin resources, therefore a Material Passport (MP) becomes an important support-tool (Honic et al. 2019).

4.2.4. Construction

Nine articles in the systematic review has explored 'construction'. The construction phase is an important stage of a building's life cycle as it is a major determinant of the reusability, and recyclability of the building (Akanbi et al. 2018; Ghaffar et al. 2020). Ghaffar et al. (2020) emphasize the need to sustain building materials through the use of smart design, construction and circular value chains where buildings would function as banks for valuable materials and products (Ghaffar et al. 2020). The construction method of a building has been proven to be a major enabler for circularity, this is evident in the work of Ruiz et al. (2018), they state that a resource efficient construction approach is aimed at encouraging construction practices that reduces cost, waste and atmospheric emissions (Ruiz et al. 2020). However, Mangialardo and Micelli (2018) express concern that although other sectors are improving their efficiency through the adoption of a more circular pattern, the construction industry seems to be left behind (Mangialardo and Micelli 2018).

Some studies support the use of bolt and nut joints during construction instead of nails and gluing are part of other factors influencing the reusability of recoverable materials (Akanbi et al. 2018; Brambilla et al. 2019; Cruz Rios et al. 2019). Others have suggested that the use of prefabricated assemblies can drastically reduce the amount of waste during construction since building components parts are already manufactured and just needs assembly (Minunno et al. 2018; Cruz Rios et al. 2019; Hopkinson et al. 2019; Boer et al. 2020). It is observed that layering of building components or elements according to their anticipated life span is a decisive way for easy and cost effective recovery of building materials (Akanbi et al. 2018; Campioli et al. 2018). Also the use of unnecessary finishes on building materials has been seen to reduce the possibility of reusing such materials, similar to the use of toxic and hazardous materials which makes it impossible for the materials to be recovered or recycled (Casas-Arredondo et al. 2018). Studies also advise that during the construction phase of a building, the minimization of building components' variety is necessary to increase the availability of common standard components (Minunno et al. 2018; Eberhardt et al. 2019b). This is closely related to standardization of building components which could facilitate the circular principle of exchange (Kerdlap et al. 2019; Migliore 2019).

4.2.5. Operation

How a building is used during its lifespan dictates the reusability or recyclable potential of the building to a great extent (Cai and Waldmann 2019). This aspect received very little attention from researchers in this systematic review, with 5 papers discussing critical issues. Some researchers recommend the minimization of recuperative maintenance with preventive maintenance (Adams et al. 2017; Giama et al. 2019), which is a proactive approach to ensure buildings are in their best condition for as long as possible (Esposito et al. 2018). Buildings and infrastructure have been said to possess lifespans of decades or centuries but require an ongoing input of materials and energy for their smooth operation and maintenance (Hertwich et al. 2019). Heisel and Rau-Oberhuber (2020) also emphasise the need to keep products in use for as long as possible, such as the re-use or redistribution of material components during building use (Heisel and Rau-Oberhuber 2020). A very few available literatures on this aspect indicates insufficient awareness and knowledge in the preposition of strategies towards the operational stage of a building.

4.2.6. Optimization

Saint et al. (2019) classifies the following operational activities: use, maintenance, repair, replacement and refurbishment under the use stage of a building (Saint et al. 2019). These activities are usually parts of a building's maintenance regime and they form an integral part of the circular economy concept of Optimization (Arup 2016; Zimmann et al. 2016). Optimization in buildings may include component upgrade or enhancements to increase the building's longevity (Baiani and Altamura 2018; Migliore 2019). A total of 6 relevant papers are collected which indicates the lack of adequate studies in the area. However, the studies reveal that building optimization is geared towards making products and systems operate at maximum efficiency (Arup 2016; Baiani and Altamura 2018; Antoniol and Barucco 2019; Eberhardt et al. 2019b; Giama et al. 2019; Saint et al. 2019). Arup (2016) state that it is essential to maintain materials and components at their highest possible value during the employment of design and construction processes to eliminate waste, maximize efficiency, thereby promoting reuse and repurposing (Arup 2016). They also add that the design of durable components for longevity is another optimization strategy used in buildings (Arup 2016). This is necessary as it prolongs the useful period of the building whilst giving opportunities for component parts to be upgraded, renewed, repaired and exchanged in a circular economy (Minunno et al. 2018; Cruz Rios et al. 2019).

4.2.7. End of Life

This aspect receives one of the highest focus from researchers in this systematic review. The total number of reviewed literatures are 24. From the studies, it is observed that the end of life phase is a major consideration for circular economy in buildings as material components are either reused directly, upcycled, or downcycled (Kreilis and Zeltins 2017; Esposito et al. 2018; Minunno et al. 2018; Tomic and Schneider 2018; Wong et al. 2018; Cai and Waldmann 2019; Honic et al. 2019; Hopkinson et al. 2019; Migliore 2019; Williams 2019; Moreno-Juez et al. 2020). Hopkinson et al. (2019) concludes that to create a circular economy building system, it is required for the building system to employ both recovery and reuse of building components from end of life to stock replacement and maintenance (Hopkinson et al. 2019). They add that a larger percentage of construction and demolition waste are downcycled at the end of a building service life (Hopkinson et al. 2019). This is true due to low awareness on circular economy in buildings, consequently, buildings are not designed for recycling (Huang et al. 2018; Rossetti et al. 2018; Cruz Rios et al. 2019; Mihai 2019; Ghaffar et al. 2020). Ruiz et al. (2020) identifies an end of life strategy which is termed as 'selective deconstruction' meaning that the building components that have reached their end of life are selectively dismounted off from in-service components (Ruiz et al. 2020).

The literatures establish that looping of end of life materials to a great extent will help to increase resource efficiency and at the same time reduce waste (Akanbi et al. 2018; Wong et al. 2018; Brambilla et al. 2019; Cruz Rios et al. 2019; Boer et al. 2020; Lei et al. 2020). William (2019) observe that material looping actions such as reuse, recycling and recovery of resources can solve the problem of resource scarcity and waste in cities (Williams 2019). Akanbi et al. (2018) express concern over the sharp decrease in the amount of recoverable materials as the building approaches its end of life (Akanbi et al. 2018). Minunno et al. (2018) emphasise that the durability of materials, and the recyclable quality of components at their end of life are major factors for design for disassembly and reuse (Minunno et al. 2018).

4.3. Research Gaps

During this systematic review, some research gaps are identified from the analysis conducted. These research gaps are mainly identified from the application of circular economy in buildings. One of such gaps was a holistic intervention on a step by step basis how the proposed intervention and strategies could be employed in the delivery of a resource efficient building. Most of the studies were based on exploring the benefits of circular economy in buildings while other studies tried to evaluate the potential of circular economy in buildings. For instance, Eberhardt et al. (2019b) estimated that the environmental impact saving potential and the economic benefits could be improved through a more specific design for disassembly (Eberhardt et al. 2019b). In the same vein, Milios and Dalhammae (2020) also appraised the re-use potential of commodities whilst ascending the waste hierarchy

(Milios and Dalhammar 2020). These studies were specific to appraising certain aspects of circular economy and not necessary a system for its application. This was also the same case for Brambilla et al. (2019) who assessed the environmental benefits from dismountable steel concrete composite floor system in buildings also with the view of comparing the Life Cycle Assessment (LCA) of developed materials (Brambilla et al. 2019). While other studies focused on the 3Rs hierarchy as a principle to reduce, reuse and recycle products (Huang et al. 2018). Again, this has not addressed the application of circular economy in buildings since the studies were focused on researching on specialized areas and not establishing holistic systematic approach towards applying the identified principles of circular economy in buildings.

Major gaps noticed were in the incorporation of circular principles into passive design strategies for an energy and resource efficient building, the role of low-embodied energy material in circular economy, and material contribution for a better indoor air quality. Other gaps were identified in the areas of building construction, operation, and optimization as they obviously had very scanty literatures and yet to be properly explored for circularity in buildings.

5. Conclusion

This systematic review explores the existing knowledge and the knowledge gaps in the published research works focusing on circular economy interventions in buildings. The objectives were to conduct a systematic review of relevant studies on the subject area and review literatures that conducted substantial research in the area. A total of 64 publications were gathered for this study, with which a bibliometric network was created revealing 2 most discussed areas of circular economy in buildings in this review. Following the initial review of the articles, 7 major circularity aspects were identified, and the articles were divided into these aspects for further analysis and discussion. While reviewing literature, it was observed that most studies were articulated around two major aspects namely: recycling of waste components and end of life. It was envisaged that dismountable buildings were more adaptable to circular economy principles as components parts can be reuse, renewed, optimized, or exchanged for others. The studies emphasized the need to shift from the linear economy to a circular economy. However, some studies had identified some barriers to this progression. Some of these barriers included inadequate guidance for the effective acquisition and categorization of construction and demolition waste in addition to undeveloped market for the reuse of building products and lack of standardization for the reuse and recycling of construction and demolition waste. There were areas that did not receive enough attention from researchers such as construction, and mainly optimization, and operation. It was observed that both optimization and operation shared some common modalities such as they were both under the use stage of the building. Optimisation was found to be more associated with building maintenance while operation was related to building use for longevity. Twenty-four articles attempted to uncover end of Life interventions, most of the researchers agreed that material looping at the end of life to a great extent would help to increase resource efficiency and reduce waste. The studies on building construction and materiality also had their fair share of research attention. The studies on materiality suggested waste reduction through material design, calculation, and specification. Another study proposed that designing out waste, design for waste prevention stood as one of the best opportunities in the reduction of waste generation while others recommended the use of buildings as material banks. In circular construction, studies supported the use of bolt and nut joints during construction instead of nails or/and gluing, welding, or any other permanent assembling technic that may negatively affect the reusability of recoverable materials.

A major deficiency of research identified from the analysis of articles is that there is a lack of holistic approach towards a systematic application of circular economy in buildings. Although, the studies on major circularity interventions have demonstrated the possibility for the application of circular economy in buildings and the potentials that lies ahead, however, the knowledge of circular economy in buildings is low and it is yet to be common placed. Furthermore, the growing number of publications is a positive indication of a growing awareness. The research gaps identified above would foster a holistic solution for a resource and energy efficiency in buildings. This systematic review has also been able to put together and analyse major recommended circular economy interventions for a holistic application of circular economy in buildings which is a major novelty of this study. To sum up, the major contributions and significance of this paper include:

1. Articulation of proposed strategies for the application of circular economy in buildings.
2. Identification of research gap in this field of research.
3. Exploration of the recent advancements in the application of circular economy in buildings.
4. Exploration of Circular Economy awareness and benefits.
5. Identification of relevant studies and interventions.

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