Journal of Cleaner Production 446 (2024) 141429

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Taxonomy of circularity indicators for the built environment: Integrating circularity through the Royal Institute of British architects (RIBA) plan of work

Savanna Segara[a], Qian (Jan) Li[a,*], Alberto Gallotta[b], Yingli Wang[a], Jonathan Gosling[a], Yacine Rezgui[c]

[a] Cardiff Business School, Cardiff University, Colum Drive, Cardiff, CF10 3EU, UK
[b] WSP, 1 Capital Quarter, Tyndall Street, Cardiff, CF10 4BZ, UK
[c] School of Engineering, BRE Trust Centre on Sustainable Engineering, Cardiff University, Cardiff, CF24 3AB, UK

ARTICLE INFO

Handling Editor: Xin Tong

Keywords:
Circularity indicators
Royal institute of british architects (RIBA) plan of work
Taxonomy
Systematic literature review
Built environment
Circular economy

ABSTRACT

In the process of implementing circular economy within the built environment, quantifying progress and performance towards this effort has posed a substantial challenge. In response, this paper reviews the current state of building-specific circularity indicators, creates a taxonomy, and integrates them within the Royal Institute of British Architects (RIBA) Plan of Work, a commonly employed framework within the UK's built environment. Through a systematic literature review considering both academic and grey literature, 32 building circularity indicators, developed by academia, consulting agencies, and governments, are identified. The first contribution of this study is the creation of a taxonomy of building circularity indicators, which classifies the identified indicators into 8 categories, such as basic characteristics of indicators, circularity level, and sustainability pillars. The second contribution of this study is the alignment of circularity within the stages of Plan of Work framework. It is revealed that the framework does not currently incorporate circularity, resulting in the proposal of a new Stage 8: End of Life to encompass demolition, disassembly, and deconstruction activities. Alignment of the taxonomy to Plan of Work framework provides a guide in utilization of building circularity indicators throughout the process of designing, constructing and operating building projects.

1. Introduction

Construction and demolition waste constitutes over a third of all waste in the EU (Damgaard, 2022), and in the UK, it accounts for over 60% of total waste (Department for Environment Food & Rural Affairs (DEFRA), 2023). Policymakers recognize the urgency for the built environment to mitigate resource depletion and greenhouse gas emissions by shifting away from current linear economy approaches and embracing alternatives like the circular economy (CE) (Braakman et al., 2021). However, a major challenge in applying CE within the built environment lies in effectively tracking the progress towards this transition (Khadim et al., 2022).

To facilitate this transition, it's crucial to implement monitoring and evaluation tools for quantifying and assessing progress (Saidani et al., 2019). Circularity indicators (CIs) are a widely acknowledged tool essential in the CE transition, playing a pivotal role in simplifying information exchange and enhancing understanding, fundamental aspects of aiding the shift to a CE (Verberne, 2016). Furthermore, CI can support policymakers and practitioners in achieving circularity by helping set targets and measuring the effectiveness of diverse CE strategies (Blomsma and Brennan, 2017).

The unique characteristics of the construction industry pose a challenge when utilizing generic CIs to evaluate circularity in buildings. This has led to the development of specific indicators for the built environment, known as building-specific CIs (Khadim et al., 2022). These indicators vary, encompassing measurements for all buildings or specific types (e.g., schools, residential, commercial), components (e.g., façade, foundation, envelope), or phases (e.g., design, use, refurbishment) of building construction (Khadim et al., 2022). With 7% of indicators tailored for the built environment (OECD, 2020), a substantial number of building CIs are available.

The abundance of CIs emerging in recent years have led to numerous

* Corresponding author.
E-mail address: liq50@cardiff.ac.uk (Q.(J. Li).

https://doi.org/10.1016/j.jclepro.2024.141429
Received 25 October 2023; Received in revised form 15 February 2024; Accepted 23 February 2024
Available online 23 February 2024

studies attempting to review, understand and categorize these indicators. One of the most prominent studies which comprehensively review existing CIs is Saidani et al. (2019), in which 55 indicators for different sectors with differing degrees of complexity, coverage, and applicability were reviewed. The study concluded that continuous improvement and refinement of existing indicators are necessary to enhance stakeholders' trust and confidence in using CIs. Through a review of 74 micro level indicators, Kristensen and Mosgaard (2020) found a lack of standardized measurement for CE at the micro-level, with most indicators predominantly focusing on economic aspects and giving less attention to environmental and social aspects. Similarly, de Oliveira et al. (2021) examined 58 nano and micro-level indicators and concluded that the indicators reviewed were not comprehensive enough to fully address the complexities of CE practices.

The above studies highlight the lack of a uniform assessment methodology for CIs. The lack of consensus has led to a continuous influx of new indicators to bridge these gaps (Peña et al., 2021). The increasing number of indicators should be coupled with a guidance to understand and clarify their functions, to facilitate proper usage of these indicators. Despite previous efforts to classify circularity indicators, we believe no study has yet proposed a comprehensive classification of building-specific circularity indicators. This study intends to fill this gap by providing a comprehensive analysis of Building CIs to better understand their scope and functions, and contributing through the creation of a detailed taxonomy.

This study will identify the most recent existing tools and indicators used to measure circularity within the built environment, and analyse, examine and extract the features, principles and possible applications of the identified Building CIs. The extracted features will then be used to propose a taxonomy, where it is hoped the classification will clarify the objectives and potential applications of CIs in the built environment. In addition, this study contributes to the alignment of building CIs with the widely used RIBA PoW Framework. The PoW is a tool that organizes the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages (RIBA, 2020).[1] Understanding the framework through a circularity point of view will serve as a facilitative tool to allow seamless implementation of CE strategies within the construction process, to assist the design and operation of a new or existing building. To the author's knowledge, this is the first study to create a framework which maps building CIs to the PoW, focusing on the following three research questions:

RQ1: What is the current state of building CIs, and how can we better understand them through taxonomy?
RQ2: How can circularity be integrated within the built environment using the RIBA PoW framework while considering life cycle and supply chains?
RQ3: What building CIs should be used at each RIBA PoW stage to ensure the circularity of the design and operation of buildings?

This article is organised as follows. Section 2 reviews recent literatures in the CE and CI field as well as major frameworks used in the built environment to measure circularity. Section 3 will elaborate the methodology and data sources used. Section 4 presents the state-of-the-art analysis, and each sub-section investigates the findings related to the questions above. Section 5 provides further research directions. Section 6 draws the conclusions.

2. Circularity indicators and the built environment

This section provides an overview of circularity indicators as well as related taxonomies with a focus on the built environment.

2.1. Circularity indicators: purposes and the uses for the built environment

The definition of the term "indicator" has been debated by several scholars and organizations (OECD, 2020; A. Singh et al., 2011), with no one set definition (Saidani et al., 2019). Indicators being acknowledged as a useful tool in setting targets to achieve circularity through quantifying the performance of various strategies (Blomsma and Brennan, 2017). To ensure a successful transition to CE, the usage of indicators are essential (Bilal et al., 2020). However, there is a lack of consensus regarding methodology to assess CE strategies, and as a response a large variety of CI have been developed (Peña et al., 2021). This may be a result of the unclear and diverse understanding of the concept of CE itself by stakeholders (Corona et al., 2019).

It is widely accepted (Corona et al., 2019; Cottafava and Ritzen, 2021; Ghisellini et al., 2016; Kirchherr et al., 2017) that CI can be grouped into 4 levels: macro, meso, micro and nano. The division of CI to these levels are based on the levels which CE strategies are implemented (Kirchherr et al., 2017), in which it is appropriate that the indicators also be used to measure each level. Macro indicators can be applied to cities, regions and nations, meso indicators for businesses and industrial parks, whereas micro indicators can be applied to buildings and products (Banaitė, 2016).

Though the latter three levels have been acknowledged from relatively long ago, the term "nano" indicator was first coined by Saidani et al. (2017, p. 5) describing it as "*the circularity of products, components, and materials, included in three wider systemic levels, all along the value chain and throughout their entire lifecycle*". Due to the broad scope of the micro level, indicators identified as micro-level sometimes often fail to encompass the intricacies of a CE at the product level, which can result in diverse interpretations of what this specific level is targeting during circularity assessments (Lindgreen et al., 2020). Separating nano and micro indicators allows us to differentiate the impact of specific products and design options from the company's overall circularity. By emphasizing the circularity level in products, decision-makers can create strategies to enhance their production processes, which in turn will positively impact their higher circularity levels (de Oliveira et al., 2021).

A multitude of studies have endeavoured to formulate indicators specifically tailored for the construction industry. Khadim et al. (2022) identified 22 studies dedicated to this pursuit. While a significant portion of these indicators originates from academic sources, others are provided by companies or consulting firms. Additionally, governmental bodies have also played a role in issuing indicators (Dodd et al., 2021). One of the most comprehensive CI tools was considered to be the Building Circularity Indicator (BCI) proposed by Verberne (2016). BCI can determine the overall circularity performance of a building and associated parts by assessing individual products of the building such as doors, windows, tiles, etc. To enhance its accuracy, design factors which affect the environment (low reusability of product, etc) are incorporated to assign appropriate weights when evaluating the overall sustainability of the building.

As BCI has become one of the most widely accepted indicators for the construction industry, scholars have built on BCI to produce newer improved versions, such as calculating the disassembly or reusability potential more accurately (Vliet, 2018), or considering the recyclability of materials within the formula (van Schaik, 2019). The improvements on BCI continue as Zhai (2020) integrated the BCI with Building Information Modelling (BIM) software, a technology that has become more popular and widely used in the built environment. Though very rare, some indicators were built on an original framework, such as Núñez-Cacho et al. (2018)'s framework to measure circularity of construction companies on a company level.

The large amount of building CIs come with a wide range of applicability. While many indicators can be used on all types of buildings, some indicators such as Cottafava and Ritzen (2021)'s PBCI can only be

[1] See details of the RIBA PoW: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work.

used on existing buildings, making it unapplicable to measure circularity of a building during the design stage. Other indicators can only be utilized to measure a certain part of the building's circularity, such as Akanbi et al. (2018)'s BIM-based Whole-life Performance Estimator (BWPE) which evaluates the salvageability of building structural components.

Though many papers have reviewed CIs (e.g., Saidani et al., 2019), only a few have specifically conducted research on building CIs (Khadim et al., 2022). Furthermore, these studies, such as the one by Khadim et al. (2022), have generally not conducted a thorough review of CIs using a whole life cycle perspective. A more comprehensive review would be ideal to provide insights into the practicality and function of these indicators, enabling readers to immediately utilize them.

2.2. Taxonomy for circularity indicators within the built environment

Taxonomies facilitate the sharing of organized knowledge and advance the degree of understanding of a certain idea. Vegas et al. (2009) described 4 benefits of a taxonomy: (i) Provide a set of unifying constructs that characterize the field of research, which will help the sharing of knowledge; (ii) Allow a better understanding of the interrelationship of the many factors in a specific knowledge area; (iii) Help identify knowledge gaps; and (iv) Assist in the decision-making process.

The growing amount of sustainability related indicators have resulted in attempts to classify them (Saidani et al., 2019). However, the classification of these indicators itself seems to be fragmented through the variety of categorization by the authors. Some authors (Ruiz-Mercado et al., 2012) have classified indicators into three dimensions: Environment, Economic, and Society. The European Environment Agency (2003) classified sustainability-related indicators into five groups: (i) descriptive indicators (including state, pressure or impact variables, expressed in absolute scale); (ii) performance indicators; (iii) efficiency indicators; (iv) policy effectiveness indicators; and (v) total welfare indicators. R. Singh et al. (2009) provides an overview of various Sustainable Development Indices (SDI), categorizing them into several groups, and discuss the dimensions for classifying and evaluating these indices. A variety of CI and associated framework have been reviewed, characterized and classified by several authors in the past literature, with a summary of these studies available in Appendix A.

Almost all previous reviews have classified CI based on their relation to the CE, mapping them into the CE paradigm such as the 3Rs of Reduce, Reuse and Recycle, inspired by and rooted in the waste management hierarchy (Ghisellini et al., 2016). In their study, De Pascale et al. (2021) even classified CI into 6R, adding Recover, Remanufacture and Redesign, which was based on Reike et al. (2018)'s study finding that 6Rs are heavily present in Closed Loop Supply Chain Management field and design-oriented products. Kirchherr et al. (2017) and Potting et al. (2017) further extended the discussions of 9Rs by introducing concepts of Refuse, Rethink and Repurpose. Kristensen and Mosgaard (2020) notes that some indicators prioritize certain principles more than others, such as the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation (2015), which gives a higher score to products which can be Reused as opposed to Recycle.

Another popular way indicators have been classified is to map them according to alignment with the three sustainability pillars. This is understandable as CE can be seen as means to achieve sustainability (Geissdoerfer et al., 2017). Banaitė (2016) classifies CI in this way for policymakers to understand which indicators convey information on a country's performance towards their specific goals within the three pillars. There is an overall consensus on measuring the economic dimension through costs and revenue, the environmental dimension through CO_2 emissions, and the social dimension through job creation and safe working environment (Kristensen and Mosgaard, 2020).

A taxonomy was proposed to the type of measurement approach used such as single indicators or multiple indicators, and the specific parameters considered such as material and energy flow, land use, consumption, and life cycle-based factors. However, as micro level indicators for CE are largely targeted at companies, the usability of the indicators may outweigh the desired CE coverage, thus presenting a trade-off between CE coverage and practical usability (Kristensen and Mosgaard, 2020).

Though many literary studies have been conducted regarding CI, Merli et al. (2018) found none of the 30 CE and environmental assessment methodologies analysed could assess all the CE requirements. Ghisellini et al. (2016) found only 10 of 155 reviewed studies focused on the indicators for the assessment of CE strategies, despite the strategic importance of evaluation and monitoring tools. As CI is essential to assist policymakers and industry experts, further development of existing indicators is necessary (Saidani et al., 2019). Studies regarding CI are usually followed by the proposal of another new CI itself to fill the gaps (Elia et al., 2017). This proves the gap where a constant increase in the CI developed indicate a strong basis in the need to understand their characterization to classify within an appropriate taxonomy of CIs.

Very few papers have focused on a taxonomy for the Built Environment. Khadim et al. (2022) analysed and classified 35 building specific micro-indicators and found that most building specific indicators are still in the developing stage, primarily focusing on material loops while other CE pillars are ignored. As a result, the large amount and diversity of sustainability indicators leads decision and policy-makers to have difficulty in understand their meaning and relevance (Saidani et al., 2019). While recognizing previous studies which attempt to classify circularity indicators, to the best of our knowledge there have been no studies proposing a comprehensive classification of building specific circularity indicators.

3. Research design

Currently, there is an abundance of Building CIs with no clear guidance or classification system on how to appropriately use them. If the transition to the CE within the built environment's supply chain is to be expected, there is a necessity for a comprehensive guide regarding the selection and utilization of Building CIs. This study will build on a previous study by Khadim et al. (2022), where a list of building specific CI has been produced. By employing the systematic literature review (SLR) methodology, we update and extend the list of indicators since a large number of new indicators have emerged in the past year since Khadim et al. (2022)'s study. These indicators will then be analysed and examined to extract the features, principles and possible applications of the identified building specific CI, which will be used to propose a taxonomy.

Due to the UK context of the study, the author will rely on the RIBA Plan of Work (PoW) as the main framework used in UK's built environment. We will analyse the relationship between the widely used design framework RIBA PoW and circularity, followed by an analysis of stakeholders within the PoW framework.[2] This is essential to understand how to best integrate circularity within the framework. After the understanding is established, the study will then extract the features, principles, and applications of the building CIs, which will then be used to create a taxonomy. This taxonomy will then be used to align the Building CIs found from the SLR and industry partner validations to the PoW framework, which will then be a guide to answer research questions 2 and 3 (see Introduction section) how to integrate circularity within the PoW framework as well as which indicators should be used at each PoW life cycle stages. The process of the methodology is summarized in Fig. 1 below.

A transparent and effective systematic literature review can be conducted by considering the following vital points: keyword selection, database choice, and a thorough description of the practical and

[2] See stakeholders within the PoW framework: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work.

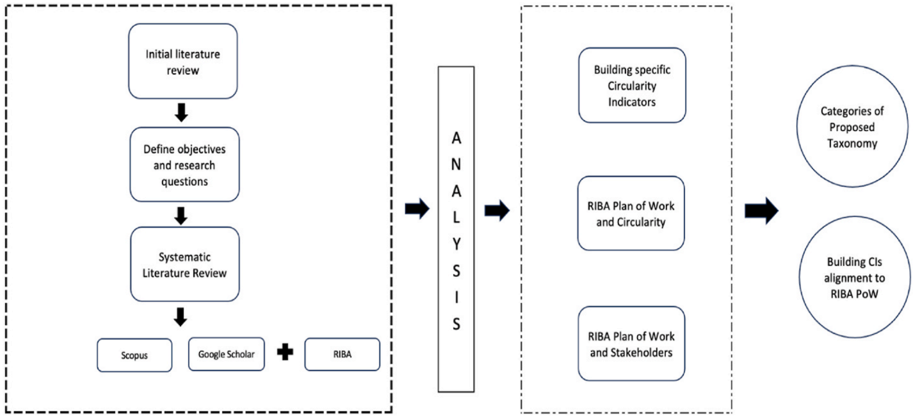

Fig. 1. Flowchart of research methodology.

methodological screening such as time and language (Fisch and Block, 2018). Guided by the research questions, a set of the following keywords were selected and searched in the chosen databases:

"("construction" OR "built environment" OR "building" OR "AEC" OR "architectur*") AND ("circularity indicator*" OR "circularity indice*" OR "circularity index" OR "circularity metric*" OR (circular PRE/2 (indicator* OR "indice*" OR "index" or "metric*")) OR ((assess* OR measur* OR test*) PRE/2 circularity) OR "circularity assessment*" OR "circularity measurement*")"*

In this field of research, peer-reviewed literature have as much importance as grey literature (reports, policy communications, etc.) because many circularity assessment tools are developed from non-academic institutions and organizations (Geissdoerfer et al., 2017; Lindgreen et al., 2020; Saidani et al., 2019). Grey literature, including dissertations (e.g. Verberne, 2016; Vliet, 2018; Zhai, 2020), conference papers and industry reports, was identified and included to provide a more holistic view of the subject matter. Such literature can provide valuable insights, particularly in emerging or practice driven research areas (Mahood et al., 2014). These sources were selected based on their relevance to the study's focus (i.e. did they help to answer the study research questions) and their contribution to a deeper understanding of

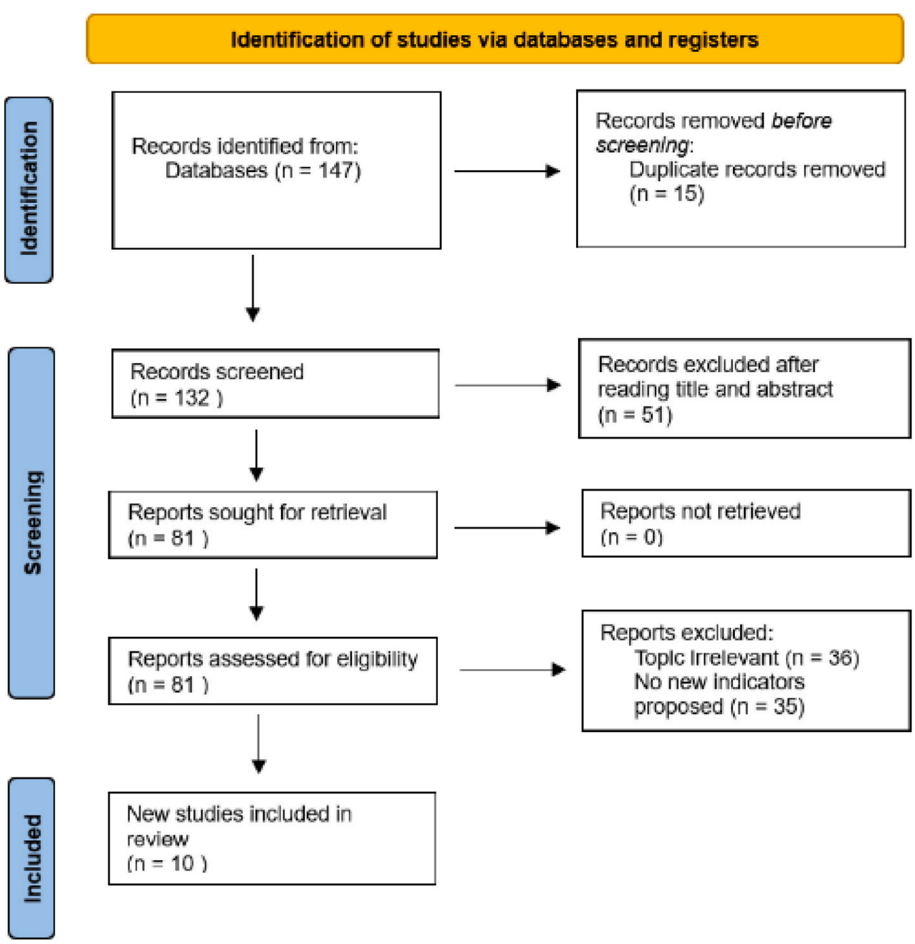

Fig. 2. Literature Review procedure as per PRISMA guidelines.

the topic. Therefore, we reply on both academic and non-academic databases. Two databases renowned for their broad coverage of peer-reviewed articles were selected: Scopus and Google Scholar. In addition, the PoW document, along with official website documents, serves as essential references used by British architects, making it a vital source for this study.

The systematic literature review was conducted based on the Preferred Reporting Items for Systematic Reviews and meta-Analyses (PRISMA) guidelines (Moher et al., 2009) (See Fig. 2 below). After searching the databases with the keywords, other limitations are also applied in the search. The age of the materials is limited to the time frame of 2010 onwards, since the term Circularity Indicators itself only emerged in 2010 (Saidani et al., 2019). This study will be limited to only materials in English. In total 147 articles were found through Scopus. Skimming through the abstract and title led to the selection of 96 relevant articles. After removing duplicates from within the list as well as Khadim et al. (2022) BCI table, 81 articles were left. Articles which target measuring CE or circularity in buildings or the built environment using a new proposed indicator were shortlisted. A full-text reading further excluded 71 articles, leaving us a final total 10 new studies.

The exclusion of many articles can be explained by the following factors: first, since the focus of this review is on the built environment, all indicators targeting higher levels of buildings such as industrial parks and cities were excluded. Structures such as bridges and roads were also excluded, narrowing the study scope to buildings only. Second, studies which conducted reviews of the current state of CIs but did not propose any new indicators or frameworks that provides a measurable result were also excluded.

In this study, we based our analysis on a table initially compiled by Khadim et al. (2022), which included 32 Building CIs gathered through an extended SLR from 2015 to 2021. Upon review, indicators measuring circularity of non-building structures (such as bridges and heritage buildings) and those not in English were excluded to align with this study's scope, resulting in the retention of 22 indicators. Additionally, the SLR identified 10 new indicators not previously included in Khadim et al. (2022)'s Building CI table. These indicators were then combined with the filtered table, resulting in a total of 32 Building CIs.

4. State of the art analysis

This section addresses the three research questions (RQ1-3) and elaborates on ways of integrating and aligning circularity concepts with the RIBA Plan of Work (PoW).

4.1. RQ1: The taxonomy of building CIs

In an effort to supplement the first reviews and taxonomies of CIs (Elia et al., 2017; Saidani et al., 2019), a taxonomy of building CIs is proposed and elaborated based on the 32 building CIs. With the increasing number of recently developed CIs serving various purposes, the main goal is to bring clarity to these indicators. This clarification helps practitioners in building projects choose the most suitable indicators for their needs.

To extract their features, principles and applications, these Building CIs were classified into 8 categories inspired by CE principles and indicator characteristics. The 8 categories are summarized in Table 1 below. Categories #1 and #2 were taken directly from Khadim et al. (2022). Categories #3 to #5 are linked to basic characteristics of indicators. Categories #6 to #8 are directly linked to CE principles. In addition, we elaborate the advantages and limitations of each indicator, with a comparative review of each indicator. The full taxonomy and a comparative review of the 32 CIs are available in Appendix B.

4.1.1. Issuer

This category indicates the development background and origins of the Building CIs: academia, government, consulting companies, and charities. Specification of the issuer is important due to a difference in requirements of creating an indicator in terms of scientific validity (e.g., peer-reviewed or not). Majority (77%) of building CIs originate from academia, indicating that many of them are still in a theoretical phase, awaiting peer review, or yet to undergo pilot testing on real buildings.

Table 1
Categories for the proposed taxonomy of Building CIs.

Categories	#1 - Issuer	#2 - Applicability	#3 - Base framework of indicator	#4 - Units
	Government	All kinds of buildings	MCI/BCI	Quantitative
	Academia	Residential buildings	Original	Semi-Quantitative
	Consulting Company	Materials	BIM	Qualitative
	Charity	Structure/ Envelope	LCA	
	#5 - Dimension	**#6 - Circularity level**	**#7 - Sustainability Pillars**	**#8 - Life Cycle Stages**
	Single	Nano	Environmental	Product
	Multiple	Micro	Economic	Construction
		Nano & Micro	Social	Use
				EOL

4.1.2. Applicability

Different indicators are specifically designed for various products, systems, or building components, leading to a spectrum of applicability across different aspects of building design, construction, and operation. While a majority (19 out of 32) of the listed indicators possess the versatility to be applied to all building types, there exists a subset of CIs that are tailored to assess specific parts of a building. For instance, certain indicators are exclusively designed to evaluate the sustainability of building façades or structural components. These specialized indicators are vital for a detailed and targeted assessment of these specific aspects, which may have unique material, energy, or lifecycle considerations compared to the building as a whole.

4.1.3. Base framework

Many of the CIs are created from the base of existing indicators and tools (Cottafava and Ritzen, 2021). Approximately 50% indicators were based on either MCI (Ellen MacArthur Foundation, 2015) or BCI (Verberne, 2016), the latter being a building specific indicator inspired by MCI that has now become a prominent metric, and has inspired the creation of other indicators. Some indicators are developed with the goal to leverage capability of BIM software, such as Biccari et al. (2019). Indicators were also categorized to understand the logic behind the formulas and methods of calculations.

4.1.4. Units

The choice of units utilized to calculate circularity is a fundamental element for any indicator (Linder et al., 2017). Moreover, the complexity of calculation methods directly relate to whether an indicator is easy to use or not. A qualitative KPI within an indicator can be translated to a quantitative score, which gives chance for subjectivity to be involved and therefore not "fully quantitative" (Khadim et al., 2022). Therefore, these indicators are classified as semi-quantitative, e.g., Circulytics (Ellen MacArthur Foundation, 2020) assesses a company's CE performance across its entire operations using multiple indicators with both qualitative and quantitative values.

4.1.5. Dimension

Understanding CI comprehensibility is important for selecting the most appropriate indicators for the intended users (Saidani et al., 2019). Single dimension indicators are easier to understand, however the simplicity may be a trade-off between CE coverage and practical usability (Kristensen and Mosgaard, 2020). Though single dimension indicators are simplified measures, they may be useful for managerial decision making (Linder et al., 2017). In contrast, building CIs with multiple dimension indicators provide in-depth analysis which may be suitable for multiple stakeholders who require more nuanced information.

4.1.6. Circularity levels

Different levels of CE implementation require different indicators to gauge the performance within those specific degrees (Saidani et al., 2019). Indicators that can only be used to assess materials are classified as nano, whereas those used parts of a building (envelope, façade) or the building is classified as micro. Some indicators can be applied to the whole life cycle of the building from sourcing the materials to when it becomes the end product, classifying the indicator as both nano and micro. The division between nano and micro circularity levels is crucial at the current development pace of CE related studies(de Oliveira et al., 2021)

4.1.7. Sustainability pillars

Many previous studies have grouped CIs based on their connection to specific sustainability pillars, as CIs are directly related to achieving sustainability (Geissdoerfer et al., 2017). Most indicators focus on the economic and environmental pillars of sustainability, while those addressing the social aspect of circularity remain scarce. One such indicator is the Circularity Assessment Methodology by Gonzalez et al. (2021), which measures the ratio of social impacts addressed in a new building to total potential addressable impacts. Categorizing this way helps users choose indicators aligned with their sustainability goals, e.g. those prioritizing the Economic pillar over the Social pillar.

4.1.8. Life cycle stages

Whole-Life Carbon Assessment (WLC Assessment) is a framework used to measure the emissions of a building throughout the stages of its life. To fully understand the emissions over a building's lifespan, one must consider the whole picture – from embodied carbon of procured material, the installation process, and day-to-day energy consumption, as well as lifetime emissions from maintenance, repair, replacement, and eventual demolition and disposal of the building (Keyhani et al., 2023). The most commonly used methodology for calculating embodied carbon of building projects is the Whole Life Carbon Assessment professional statement released by the Royal Institute of Chartered Surveyors (RICS) in 2017. The document uses the life cycle stages defined in EN 15978, which breaks down the built asset's life cycle into different stages, introducing a modular approach (RICS, 2017). Following the WLCA life stages, indicators were classified based on the five life cycle stages of A1-A5 Product stage, A4-A5 Construction stage, B1–B7 Use stage, C1–C4 EOL and D Beyond the life cycle stage. Classification based on these stages can be used as a benchmark to see which indicators cover what process of the carbon assessment. For instance, the Material Recovery Potential Index by Mayer and Bechthold (2017) can only be used throughout the design phase, whereas the Whole Building Circularity Indicator has the ability to cover the whole carbon assessment process.

4.2. RQ2: integrating circularity concept within the RIBA PoW framework

The RIBA Plan of Work (RIBA, 2020) was first developed by The Royal Institute of British Architects (RIBA) in 1963 in order to provide a framework for architects and bring clarity when communicating the different phases of building projects. The RIBA Plan of Work (PoW) has continued evolving to accommodate the everchanging demand of incorporating sustainability into the built environment. The PoW consists of 8 stages in total, which generally will be undertaken one after the other, though some will overlap such as stage 4 and 5 (RIBA, 2020). The PoW provides extensive information regarding the expected outcomes, stakeholders, and strategies of each stage. For example, in the Stage 0 strategic definition (see Fig. 3 below), the main outcome of this stage is to understand the best means of achieving the Client Requirements, a statement or document which defines the project outcomes and sets out what the client is seeking to achieve (RIBA, 2020). This stage focuses on making the right strategic decisions and capturing them in a Business Case, considering the pros and cons, project risks and project budget.

The PoW is open to interpretation and available for clients to set their own overlay of tasks or documents (RIBA, 2020). Some overlay templates that are commonly used can be found on the RIBA website [3] available for download, including technology overlays like BIM, or design overlays such as Design for Manufacture and Assembly and Passivhaus. Other official documents are also available on the website to guide the usage of the PoW such as the RIBA Plan for Use, RIBA Job Book, RIBA Sustainable Outcomes, and others.

The supplementary document (RIBA, 2019) outlines eight sustainable goals for projects, and includes details regarding the sustainability targets. Though sustainability is tied closely to circularity, it is two different things. There are similarities in the two concepts, where sustainability is more comprehensive in scope and encompasses social, economic and environmental dimensions as long-term goals, whereas in contrast the circular economy is more focused on resource efficiency, closed-loop systems, and short-term actions that can lead to long-term benefits (Geissdoerfer et al., 2017).

Though RIBA attempts to incorporate sustainability, the PoW is yet to include circularity within its framework. The document does not consider the life of buildings beyond construction as an official stage within the PoW. The document states that when the client is considering what to do when a building no longer fulfils the client's needs or at the end of a building's life, "*it is in essence commencing a new Stage 0 process, eliminating the need for an extra stage after stage 7*" (RIBA, 2020, p. 28). The options of which a building can go through at the end-of-life stage such as demolition or disassembly does not even exist within the PoW, and nothing ties the framework to closed-loop systems or other resource efficiency values contained in circularity thinking. The same thinking is echoed by Charef (2022), which suggests that end-of-life is not integrated within the PoW because the document was built on the concept of a linear economy. As a point of comparison, the Architect's Council of Europe (ACE), a similar organization to RIBA which jurisdiction lies in Europe, incorporates the end-of-phase within a building project's stages (AEC, 2013).

Integrating circularity within a framework requires consideration from the early design phase of the project to avoid risks of circular performance issues found in later phases (van der Zwaag et al., 2023). Acknowledging this, we propose an enhancement to the PoW framework by introducing a new stage, "Stage 8: End-of-Life" as in Fig. 3 below. This stage will focus on post-usage activities after the building's intended life span, such as demolition, disassembly, and deconstruction. However, to align with the principles of circularity, we emphasize the significance of integrating these considerations at the project's inception. This means actively evaluating options like refurbishing or converting existing structures before deciding to build anew. The option of disassembly and deconstruction will seal the loop of the building's lifecycle to establish a connection between the end-of-life, design, manufacture, and in-use phases of the asset. This new stage integrates the circular economy concept where deconstruction will be the new norm, in time replacing demolition as the main course of action taken at the end-of-life stage, which is no longer acceptable as the only option for buildings.

The proposed Stage 8: Deconstruction phase is envisioned to be directly connected with Stage 1: Preparation and Brief. This connection

[3] See details of the overlay templates of the RIBA PoW: https://www.architecture.com/knowledge-and-resources/resources-landing-page?singleSelection=true&Format=Advice.

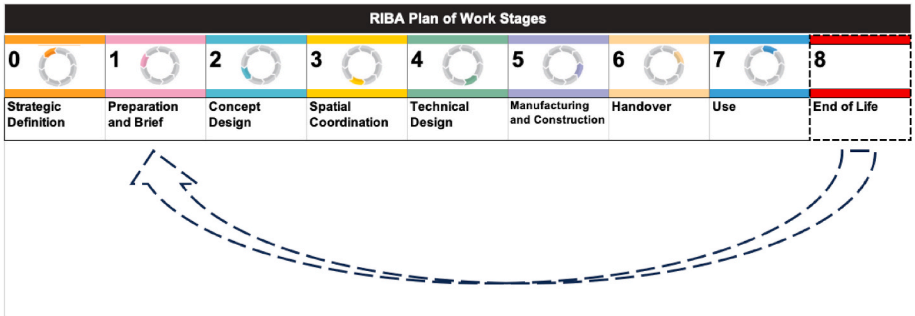

Fig. 3. RIBA PoW proposed stages.

symbolizes the closing loop of the PoW stages, forming a circular construction supply chain. The connection of these stages is in line with the concept of Design for Deconstruction (DfD), where a building is designed with the main goal of reutilizing the materials (Akinade et al., 2017). The concept of DfD and the use of reusable materials, as suggested by sources like Arup's Circular Buildings Toolkit, will be integral from Stage 1 to Stage 8 to prompt a holistic circular approach.[4] The decision to create a project that maximizes the utilization of reusable materials is usually taken by the client team during Stage 1 and underlines the importance of early-stage decisions by the client team in setting a project brief that prioritizes circularity (RIBA, 2020). These decisions are further developed in the Architectural Concept during stage 2, where stakeholders start to put a shape of the image decided through a rough design as well as the selection of materials and rough design align with the ultimate goal of a circular economy. In a perfect circular economy, demolition becomes a less favored option-however, it is understood that some existing buildings are still not designed for proper disassembly and deconstruction-therefore, demolition will be included as a course of action within Stage 8. The proposal of a stage 8 is essential in the context of measuring circularity in this study. In the following section, the alignment of building CIs with PoW framework will be discussed.

4.3. RQ3: The alignment of building CIs with RIBA PoW stages

Next, we align building CIs with the PoW to create a framework, which is vital for assisting a seamless implementation of these indicators throughout the PoW stages. This alignment is based on the taxonomy of building CIs established through a systematic literature review and industry partner validations. The framework can be found in Fig. 4 below.

We employ a "traffic light approach" to recommend the most suitable indicators. This approach considers the readiness, applicability, and complexity of these indicators, as determined by the analysis findings. Green indicates that the indicator is ready for use, whereas yellow indicates usage of the indicator is possible though caution is advised, and red indicates that the indicator is still immature and utilization is not advised.

The criteria for yellow is as follows: First, as this study is UK focused, all indicators developed based on laws and regulations from another country is yellow flagged. Except for indicators developed by the European Union, as the UK still relies on European Standards in its sustainability assessments, like EN 15978 (BSI, 2011). Second, if the indicator is yet to be pilot tested in a case study or peer-reviewed by any party other than the authors, it is yellow flagged. Third, the indicator will be yellow flagged if it is still relatively new; in the context of this study, an indicator is considered new if it has been introduced within the past 2 years. A combination of two or more yellow flags leads to a red flag.

Firstly, there is no certainty whether undertaking a new construction project will the right step to fulfil the client's needs, which will be confirmed in stage 0: Strategic Definition. Only after the necessity for a new building project is confirmed will the project move on to the creation of the Architectural Concept, where the design concept will be aligned with the client's needs and vision, as well as the assembly of a rough budget. Within the list of building CIs, Núñez-Cacho et al. (2018)'s Circular Economy Measurement Scale and Ellen MacArthur Foundation (2020)'s Circulytics are the only indicators that can be used during the first 2 stages of the PoW. due to the applicability of these indicators being company level, these indicators are not limited by the PoW stages and can be used at any stage.

Indicators can be grouped into 2 according to their degree of influence: action-oriented indicators, which help decision makers formulate clear targets and strategies; and information-oriented indicators, which help decision makers understand the current situation (Lützkendorf and Balouktsi, 2017). The handful of indicators which can be used from Stage 2: Concept Design are classified as action-oriented indicators. Utilization of indicators from this stage will help to understand early in the project planning stage how the basic designs created in this stage will precisely affect circularity, and take action if necessary such as applying modifications to the designs.

Moreover, most indicators which can be used from stage 2 are BIM based. A further analysis of the indicators' characteristics reveals a tendency that BIM-based indicators are created with designers and architects as the main users. The advantage of these indicators is that they can be used earlier in the design process, enabling designers to assess designs and concepts as well as alter them as necessary after measuring the circularity level of these designs. Since BIM software has advantages such as authoring tools to produce precise bills of quantity using the automation of volume estimation, these indicators are easy to use providing the right plugin is installed to the BIM software. However, these indicators can only be used and understood by a limited pool of people who are able to utilize BIM software, which may prove a disadvantage to some stakeholders which need the indicators to be widely comprehended.

Other than BIM based indicators, indicators which can be applied to materials can also be used from Stage 2. This is because these indicators measure circularity from the material and product level, and specifications regarding materials are usually decided in Stage 2 of the PoW.

A majority of indicators can be used during Stage 3: Developed Design and Stage 4: Technical Design. Information such as such as material weight and building measurements are necessary for the formulas of these indicators. With all final details of the design finalized during this stage, the availability of information enables utilization of most indicators. The exception for this general rule would be certain indicators that can only be used for existing buildings, such as Cottafava and Ritzen (2021)'s Predictive Building Circularity Indicator (PBCI), which calculates potential recyclability for existing buildings, and therefore can only be used from stage 6 and beyond.

[4] See details of the Arup Circular Buildings Toolkit: https://www.arup.com/services/climate-and-sustainability-services/circular-economy-services/circular-buildings-toolkit.

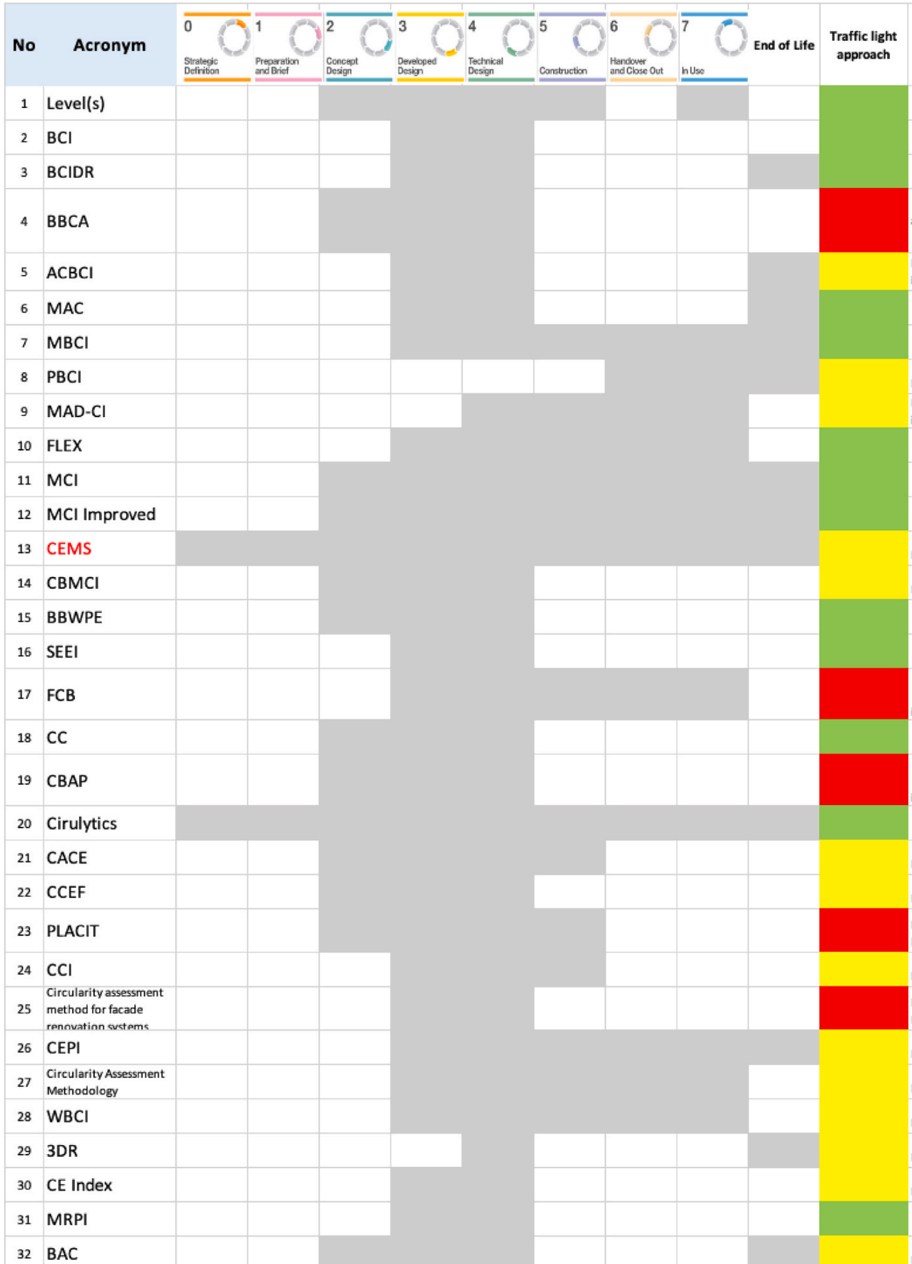

Fig. 4. Building CIs alignment to RIBA PoW Stages.

Arguably, most indicators cannot be used during the construction and handover phase. A further analysis of the characteristics and formulas of the indicators reveal that most indicators do not take into account activities during the process of construction when assessing the circularity of buildings. In the RIBA PoW, all information necessary to start construction of the building is acquired prior to stages 5–6. This marks the point at which modifications to the design can be made to attain the best possible circularity outcome. Calculating circularity during Stage 5 and 6 may prove pointless given that there is no new information to be obtained in these stages. This also ties up with the findings of alignment of RIBA, where it was found that the beginning design stages/product stages affects carbon emissions of a building.

In short, we conclude that BCI determines the overall circularity of a building by assesses a building's overall circularity by evaluating the circularity of its materials alone, without taking into consideration emissions during the construction process of the building. In contrast, the indicator Level(s) (Dodd et al., 2021) clearly includes the construction process as a measure of circularity, construction & demolition waste and materials, with kg of waste and materials as a core indicator, measured by kg of waste produced per m2 of total useful floor area as the unit of measurement.

5. Directions for further research

This section will discuss some of the further research directions related to the analysis above.

5.1. Real-world application and testing

In order to enhance the maturity and credibility of building circular indicators (CIs), future research should prioritize conducting real-world applications and testing of these indicators across a diverse range of construction projects. This involves implementing the identified indicators in actual construction scenarios and evaluating their practicality, effectiveness, and relevance. Researchers could collaborate with construction projects and stakeholders to apply these indicators, gather data on their performance, and assess how well they contribute to circularity in the built environment.

5.2. Pilot testing beyond creators

To address the observed lack of maturity and pilot testing of building CIs, future studies should emphasize encouraging pilot testing by a wider array of stakeholders beyond the creators of the indicators. This involves promoting collaboration with multiple organizations, construction firms, or industry associations to pilot test the identified indicators in various projects. It's important to involve stakeholders with different expertise, geographical locations, and project types to assess the applicability, accuracy, and reliability of these indicators. Comprehensive pilot testing will provide valuable feedback and data on the real-world performance of these indicators and guide their further refinement.

5.3. Traffic light approach refinement

The traffic light approach analysis, which assesses the readiness, applicability, and complexity of each indicator, should be refined and made more nuanced. Future research should aim to provide a detailed and nuanced evaluation of indicators by considering additional factors such as cost-effectiveness, environmental impact, and scalability. This refined approach will offer more specific recommendations on which indicators are most suitable for different project types, sizes, or contexts. Additionally, it should account for the dynamic nature of projects and evolving technology to ensure the recommendations stay relevant and up-to-date.

5.4. Life cycle assessment (LCA), circularity and the considerations of social aspects

The integration of Lifecycle Assessment (LCA) and circularity principles should be aligned within existing frameworks like the RIBA Plan of Work. Simultaneously, there's a need to incorporate social considerations, such as labor practices, human rights, health and wellbeing. These aspects are often overlooked in current research, which tends to focus primarily on environmental and economic dimensions. Therefore, it's crucial for the LCA and circularity communities to work together to address these interconnected challenges through a unified research and development strategy that encompasses environmental, economic, and social dimensions of sustainability. Research should also aim to conduct a comprehensive assessment of the long-term impact of implementing building CIs on construction projects and the built environment.

5.5. Stakeholder engagement and interdisciplinary collaboration

Understanding the perspectives, concerns, and levels of understanding of various stakeholders in the built environment concerning building circular indicators (CIs) is a critical avenue for future research. This can be achieved through stakeholder engagement involving architects, engineers, contractors, policymakers, environmentalists, and the public. Concurrently, interdisciplinary collaboration is vital for gaining a holistic understanding of the challenges and opportunities in building circularity. Bringing together experts from diverse disciplines such as construction, environmental science, economics, sociology, and policymaking can lead to the development of integrated approaches, innovative solutions, and well-rounded policy recommendations.

6. Conclusion

To support the adoption of a circular economy, this study provides a comprehensive review of the current state of Building CIs. Through a systematic literature review, a total of 32 indicators were analysed for their characteristics and notable features to create a taxonomy of 8 categories. However, differing methods of calculation and levels of applicability of these indicators lead to a conclusion that the available building CIs are disseminated. Many of the indicators lack maturity, being published in academia but have yet to be pilot tested by stakeholders other than their creators. This leads to confusion on how to fully utilize these indicators, which may contribute to hindering the implementation of CE.

As a widely accepted of design method, the RIBA PoW was analysed to gain the understanding of circularity within the built environment. Though there are an abundance of building CIs to help implement CE principles, we found that the PoW framework does not include circularity. Incorporating circularity within a framework that does not even consider circularity is impossible, therefore the addition of a new Stage 8: End of Life which encompasses demolition, disassembly and deconstruction to the framework is vital to incorporate circularity into the PoW.

The paper makes a twofold contribution to the body of knowledge in that (a) it proposes a taxonomy of building CIs, which classifies the identified CIs into 8 categories such as basic characteristics of indicators, circularity level, and sustainability pillars; and (b) it aligns the taxonomy of building CIs with the stages of PoW. The resulting framework, developed using extensive data from a research portfolio fuelled by Scopus, Google Scholar and PoW, offers valuable insights into the integration of Building CIs by showing which indicators can be used during what stage of the PoW. Ultimately, it provides guidance for stakeholders involved in building projects, enabling them to effectively leverage building CIs and implement CE principles within the industry's standard operating framework. A traffic light approach analysis based on the readiness, applicability, and complexity of each indicator was conducted to provide a recommendation of which indicators are most suitable to be utilized.

However, there are several limitations. First, due to the specific databases selected, some indicators may have not been identified. Additionally, some indicators applicable to the broader built environment but not explicitly designed for buildings, such as those for roads and foundations, were excluded. These indicators may have great potential for building circularity assessment, therefore future research should expand its scope to encompass these indicators for a more holistic view. Second, some parts of the analysis might be biased towards the UK. While our analysis might lean towards the UK context, the core principles of circularity and sustainable construction we discuss are universally applicable. Challenges and solutions related to Circularity Indicators (CIs) resonate across the global construction industry. Moreover, the frameworks we have utilized, including alignment with the RIBA PoW Framework, are inherently adaptable. They are designed to be modified according to local contexts and regulations in different countries, making them valuable tools for global practitioners. Additionally, the life cycle dimension of circularity proposed in our paper, using the RIBA PoW, adds a comprehensive perspective. While other countries may have their distinct process models, the total lifecycle perspective of our study is scalable and can be adapted to incorporate these various models. Therefore, while acknowledging some geographical bias in our current analysis, we emphasize that our insights and methodologies have significant global relevance and can inform sustainable construction practices in different countries.

For future research, our study suggests the need for a 'Middle-Out Approach' that combines both top-down and bottom-up perspectives, depending on the specific use cases addressed. This approach enables a more rounded analysis of building circularity, balancing the detailed focus on individual components and materials (as seen in the micro and nano levels) with a broader, systemic perspective (typical of the top-down approach). By integrating these perspectives, we can better understand the interplay between different levels of circularity and how they collectively contribute to the overall sustainability of the built environment. This 'Middle-Out Approach' is identified as a crucial area for future research, offering potential to deepen our understanding of circularity in the built environment and providing a more holistic framework for practitioners and researchers alike. Furthermore, we acknowledge the importance of CIs in the early stages (0–3) and 4 of the PoW. These stages, involving setting outcomes including sustainability and environmental objectives, are critical for impactful resource and carbon savings. Our research suggests a significant opportunity for future studies to develop and identify specific CIs tailored for these initial stages. Potential indicators, such as a mandatory requirement for using a certain percentage of recycled materials, could be key to driving circularity from the onset of building projects. Therefore, while our study has laid a foundational understanding of Building CIs and their alignment with the PoW, it also highlights the need for continued research and development of CIs, particularly for the early stages of building projects, to fully realize the potential of a circular economy in the built environment.

CRediT authorship contribution statement

Savanna Segara: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Qian (Jan) Li:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Alberto Gallotta:** Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Yingli Wang:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Jonathan Gosling:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Conceptualization. **Yacine Rezgui:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We acknowledge funding from the Engineering and Physical Sciences Research Council (EPSRC) (Grant No. EP/V042521/1) for interdisciplinary research on the project "Scalable Circular Supply Chain for the Built Environment" and funding for a public value engagement project on "Net Zero Neighbourhoods in South Wales" from Cardiff Business School. All remaining errors are solely our responsibility. We have no conflicts of interest regarding the presented analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141429.

References

Akanbi, L., Oyedele, L., Akinade, O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S. A., 2018. Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. Resour. Conserv. Recycl. 129, 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026.

Akinade, O., Oyedele, L., Ajayi, S., Bilal, M., Alaka, H.A., Owolabi, H.A., Kadiri, K.O., 2017. Design for Deconstruction (DfD): critical success factors for diverting end-of-life waste from landfills. Waste Manag. 60, 3–13. https://doi.org/10.1016/j.wasman.2016.08.017.

Banaitė, D., 2016. Towards circular economy: analysis of indicators in the context of sustainable development. In: Paper Presented at the Social Transformations in Contemporary Society.

Biccari, C., Abualdenien, J., Borrmann, A., Corallo, A., 2019. A BIM-based framework to visually evaluate circularity and life cycle cost of buildings. In: Paper Presented at the IOP Conf. Series: Earth and Environmental Science.

Bilal, M., Khan, K.I.A., Thaheem, M.J., Nasir, A.R., 2020. Current state and barriers to the circular economy in the building sector: towards a mitigation framework. J. Clean. Prod. 276 https://doi.org/10.1016/j.jclepro.2020.123250.

Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 (3), 603–614. https://doi.org/10.1111/jiec.12603.

Braakman, L., Bhochhibhoya, S., de Graaf, R., 2021. Exploring the relationship between the level of circularity and the life cycle costs of a one-family house. Resour. Conserv. Recycl. 164 https://doi.org/10.1016/j.resconrec.2020.105149.

BSI, 2011. EN 15978: 2011 Sustainability of Construction Works-Assessment of Environmental Performance of Buildings-Calculation Method".

Charef, R., 2022. Supporting construction stakeholders with the circular economy: a trans-scaler framework to understand the holistic approach. Cleaner Engineering and Technology 8. https://doi.org/10.1016/j.clet.2022.100454.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151 https://doi.org/10.1016/j.resconrec.2019.104498.

Cottafava, D., Ritzen, M., 2021. Circularity indicator for residential buildings: addressing the gap between embodied impacts and design aspects. Resour. Conserv. Recycl. 164 https://doi.org/10.1016/j.resconrec.2020.105120.

Damgaard, A., Lodato, C., Butera, S., Fruergaard, T.A., Kamps, M., Corbin, L., Tonini, D., Astrup, T.F., 2022. Background Data Collection and Life Cycle Assessment for Construction and Demolition Waste (CDW) Management. Retrieved from Publications Office of the European Union, 10.2760/772724.

de Oliveira, C.T., Dantas, T.E.T., Soares, S.R., 2021. Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments. Sustain. Prod. Consum. 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024.

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: the 61 indicators. J. Clean. Prod. 281 https://doi.org/10.1016/j.jclepro.2020.124942.

Department for Environment Food & Rural Affairs (DEFRA), 2023. UK Statistics on Waste. Retrieved from. https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste#key-points.

Dodd, N., Donatello, S., Cordella, M., 2021. Level(s) – a common EU framework of core sustainability indicators for office and residential buildings. Retrieved from European Commission Joint Research Centre. https://publications.jrc.ec.europa.eu/repository/handle/JRC109285.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.

Ellen MacArthur Foundation, 2015. Towards a Circular Economy: Business Rationale for an Accelerated Transition. Retrieved from. https://kidv.nl/media/rapportages/towards_a_circular_economy.pdf?1.2.1.

Ellen MacArthur Foundation, 2020. Circulytics. Retrieved from. https://www.ellenmacarthurfoundation.org/resources/circulytics/overview.

European Environment Agency, 2003. Environmental Indicators: Typology and Use in Reporting. Retrieved from. http://costabalearsostenible.es/PDFs/AMYKey%20References_Indicators/EEA%202003.pdf.

Fisch, C., Block, J., 2018. Six tips for your (systematic) literature review in business and management research. Management Review Quarterly 68 (2), 103–106. https://doi.org/10.1007/s11301-018-0142-x.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Gonzalez, A., Sendra, C., Herena, A., Rosquillas, M., Vaz, D., 2021. Methodology to assess the circularity in building construction and refurbishment activities. Resour Conserv Recycl Adv 12. https://doi.org/10.1016/j.rcradv.2021.200051. None.

Keyhani, M., Abbaspour, A., Bahadori-Jahromi, A., Mylona, A., Janbey, A., Godfrey, P., Zhang, H., 2023. Whole life carbon assessment of a typical UK residential building using different embodied carbon data sources. Sustainability 15 (6). https://doi.org/10.3390/su15065115.

Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. J. Clean. Prod. 357 https://doi.org/10.1016/j.jclepro.2022.131859.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243 https://doi.org/10.1016/j.jclepro.2019.118531.

Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. J. Ind. Ecol. 21 (3), 545–558. https://doi.org/10.1111/jiec.12552.

Lindgreen, E.R., Salomone, R., Reyes, T., 2020. A critical review of academic approaches, methods and tools to assess circular economy at the micro level. Sustainability 12 (12). https://doi.org/10.3390/su12124973.
Lützkendorf, T., Balouktsi, M., 2017. Assessing a sustainable urban development: typology of indicators and sources of information. Procedia Environmental Sciences 38, 546–553. https://doi.org/10.1016/j.proenv.2017.03.122.
Mahood, Q., Van Eerd, D., Irvin, E., 2014. Searching for grey literature for systematic reviews: challenges and benefits. Res. Synth. Methods 5 (3), 221–234. https://doi.org/10.1002/jrsm.1106.
Mayer, M., Bechthold, M., 2017. Development of policy metrics for circularity assessment in building assemblies. Econ. Pol. Energy Environ. (1), 57–84. https://doi.org/10.3280/efe2017-001005.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 339, b2535. https://doi.org/10.1136/bmj.b2535.
Núñez-Cacho, P., Górecki, J., Molina, V., Corpas-Iglesias, F.A., 2018. New measures of circular economy thinking in construction companies. J. E. U. Res. Bus. 2018, 1–16. https://doi.org/10.5171/2018.909360.
OECD, 2020. OECD Inventory Circular Economy Indicators. Retrieved from. https://www.oecd.org/cfe/cities/InventoryCircularEconomyIndicators.pdf.
Peña, C., Civit, B., Gallego-Schmid, A., Druckman, A., Pires, A.C., Weidema, B., Motta, W., 2021. Using life cycle assessment to achieve a circular economy. Int. J. Life Cycle Assess. 26 (2), 215–220. https://doi.org/10.1007/s11367-020-01856-z.
Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product Chain. Retrieved from. https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf.
Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? — Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.
RIBA, 2019. RIBA Sustainable Outcomes Guide 2019. Retrieved from. https://www.engc.org.uk/engcdocuments/internet/website/RIBA%20Sustainable%20Outcomes%20Guide%202019.pdf.
RIBA, 2020. RIBA Plan of Work Overview. Retrieved from. https://www.architecture.com/-/media/GatherContent/Test-resources-page/Additional-Documents/2020RIBAPlanofWorkoverviewpdf.pdf.
RICS, 2017. Whole Life Carbon Assessment for the Built Environment: RICS Professional Statement. Retrieved from. Royal Institution of Chartered Surveyors. https://www.rics.org/content/dam/ricsglobal/documents/standards/whole_life_carbon_assessment_for_the_built_environment_1st_edition_rics.pdf.
Ruiz-Mercado, G.J., Smith, R.L., Gonzalez, M.A., 2012. Sustainability indicators for chemical processes: I. Taxonomy. Ind. Eng. Chem. Res. 51 (5), 2309–2328. https://doi.org/10.1021/ie102116e.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2 (1). https://doi.org/10.3390/recycling2010006.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.
Singh, A., Berghorn, G., Joshi, S., Syal, M., 2011. Review of life-cycle assessment applications in building construction. J. Architect. Eng. 17 (1), 15–23. https://doi.org/10.1061/(asce)ae.1943-5568.0000026.
Singh, R., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indicat. 9 (2), 189–212. https://doi.org/10.1016/j.ecolind.2008.05.011.
van der Zwaag, M., Wang, T., Bakker, H., van Nederveen, S., Schuurman, A.C.B., Bosma, D., 2023. Evaluating building circularity in the early design phase. Autom. ConStruct. 152 https://doi.org/10.1016/j.autcon.2023.104941.
van Schaik, C., 2019. Circular Building Foundations: A Structural Exploration of the Possibilities for Making Building Foundations Contribute to a Circular Economy. Delft University of Technology.
Vegas, S., Juristo, N., Basili, V.R., 2009. Maturing software engineering knowledge through classifications: a case study on unit testing techniques. IEEE Trans. Software Eng. 35 (4), 551–565. https://doi.org/10.1109/tse.2009.13.
Verberne, J., 2016. Building Circularity Indicators - an Approach for Measuring Circularity of a Building. Eindhoven University of Technology.
Vliet, M.v., 2018. Disassembling the Steps towards Building Circularity. Eindhoven University of Technology.
Zhai, J., 2020. BIM-Based Building Circularity Assessment from the Early Design Stages. Eindhoven University of Technology.