TECHNICAL REPORT ON MULTI-CYCLE CIRCULARITY ASSESSMENT

Deliverable D1.3

June 27, 2024

VITO

This project has received funding from the European Union's Horizon Europe research and innovation programme, under grant agreement No. 101091749

Co-funded by the European Union

Grant Agreement No.	101091749
Start date of Project	1 January 2023
Duration of the Project	48 months
Deliverable Number	D1.3
Deliverable Leader	VITO
Dissemination Level (PU, SEN, Cl)	PU

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HaDEA. Neither the European Union nor the granting authority can be held responsible for them.

PU=Public, CO=Confidential, only for members of the consortium (including the Commission Services), CI=Classified, as referred to in Commission Decision 2001/844/EC.

Authors, Co-authors and contributors

Author	Organization
Joana Gonçalves	VITO
Steven Claes	VITO
Michiel Ritzen	VITO

Quality Control

Author	Name	Date
WP leader	Steven Claes	07 JUN 2024
Internal reviewer(s)	Sultan Çetin	11 JUN 2024
Internal reviewer(s)	Simon Duindam	14 JUN 2024
Internal reviewer(s)	Sriraj Gokarakonda	19 JUN 2024

History of Changes

Version	Change made	Date
V1	1st Draft	04 JUN 2024
V2	Submitted version	27 JUN 2024

Table of Contents

List of Figures

List of Tables:

Abbreviations

Acronym	Meaning
AEC	Architecture, Engineering, and Construction
API	Application Programming Interface
B2B	Business to Business
B2C	Business to Consumer
BCI	Building Circularity Indicator
BAMB	Buildings as Material Banks
BIM	Building Information Modeling
CDW	Construction and Demolition Waste
CC	Circularity Calculator
DBL	Digital Building Logbook
DPP	Digital Product Passport
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
IEQ	Indoor Environmental Quality
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LFI	Linear Flow Indicator
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
MP	Material Passport
RLBA	Residential Logbook Association
TPB	Theory of Planned Behavior
WLC	Whole Lifecycle

Executive Summary

The HEU project Demo-BLog: Development and Demonstration of Digital Building Logbooks (DBLs) is a four-year initiative aimed at showcasing the potential of DBLs in managing and integrating building-related data. Deliverable D1.3, the Technical Report on Multi-cycle Circularity Assessment, is part of Work Package 1, focusing on functionalities and user experience methodology, particularly multi-cycle circularity to enhance reused marketplaces.

This report, structured into five main chapters, presents the findings of three subtasks: mapping current practices, co-creation processes, and defining specifications for multi-cycle circularity. It identifies the existing gaps and future requirements for DBLs to support circularity, integrating data across three scales: materials, components, and whole buildings. Key indicators for circularity, such as reusability, recyclability, and disassembly potential, are emphasized alongside environmental impacts for a holistic sustainability approach.

The current state of DBLs predominantly focuses on operational energy efficiency, lacking comprehensive lifecycle coverage, particularly in material inventories and reuse potential. Future DBL developments must align with European policies like the Renovation Wave and the updated Energy Performance of Buildings Directive (EPBD), emphasizing the need for detailed lifecycle data and compatibility with the Level(s) framework for sustainability assessment.

Challenges remain in the diversity and lack of harmonization among existing circularity assessment frameworks (such as Level(s), Material Circularity Indicator, Building Circularity Indicator, among others), causing confusion and hindering adoption. Existing methods often overlook adaptability, repairability, and multi-cycle considerations. Integrating circularity assessments with technologies like BIM and material passports, and involving a broader range of stakeholders, could enhance the consistency, accuracy, and adoption of these assessments.

Stakeholder engagement through co-creation workshops highlighted the need to align circularity assessments with designers' values and to integrate smoothly with existing tools to avoid additional burdens. The proposed specifications for data requirements in DBLs are structured into four priority levels, ensuring a progressive and comprehensive approach to multi-cycle circularity.

In conclusion, this report sets a foundational framework for developing DBLs as circularity enablers in the built environment. By addressing identified gaps and aligning with policy and stakeholder needs, DBLs can significantly contribute to closing, slowing, and narrowing resource loops, ultimately driving the transition towards a circular economy.

1 Introduction

1.1 Objectives and scope

The HEU project Demo-BLog: Development and Demonstration of Digital Building Logbooks is a four-year project that aims to demonstrate the potential of Digital Building Logbooks (DBLs) as tools for integrating and managing building-related data, addressing key challenges in design, construction, operation, and financing. Demo-BLog brings together five different DBL demonstrators, addressing diverse stakeholders and functionalities. This deliverable *D1.3 Technical report Multi-cycle Circularity Assessment* is developed as part of WP1 on functionalities and user experience methodology and is specifically focused on the research pursued in task 1.4 multi-cycle circularity as a driver for enhanced reused marketplaces. This deliverable contributes to achieve the specific objectives of the project, in particular objective 2: demonstrate multi-cycle approaches and fostering the marketplace for the reuse of construction materials, to contribute to showcase the potential of DBLs as circularity enablers and reflect a whole lifecycle approach to the built environment.

This report presents the results of *Subtask 1.4.1 Mapping of the functionality, 1.4.2. Co-creation processes for a user-centric multi-cycle circularity approach*, and *1.4.3 Define specification for multi-cycle circularity*. It maps the current landscape of circularity assessment in the built environment, starting from the current practice in Digital Building Logbooks, followed by policy trends and future requirements. To identify the most common indicators to measure circularity, a systematic literature review is presented, identifying the most common assessment frameworks and quantitative indicators. The focus of this mapping is on three main scales: 1) building materials, 2) building components, and 3) whole building level. The subsequent chapters present the results in detail, emphasising a selection of key indicators for the future. These include reusability, recyclability, disassembly potential, recycled input, and reused input. However, to achieve maximum sustainability benefits, it is crucial to consider circularity aspects along with environmental impacts based on life cycle assessment.

The mapping of the functionality researched in *Subtask 1.4.1* also identified barriers to the adoption of circularity and the reuse of materials. On the one hand, the growing interest in the topic has generated a plethora of assessment frameworks, many of which are not harmonised, which has led to confusion among practitioners. On the other hand, the large supply of guidance methods, assessment frameworks, digital tools, and policy requirements, threatens to overwhelm practitioners, adding effort and time-consuming tasks to already resource-limited ongoing processes. To better understand these issues and the potential of Digital Building Logbooks to support practitioners in a reuse marketplace, a workshop was organised with AEC (architecture, engineering, and construction) professionals as part of subtask 1.4.2. The results of this co-creation process were integrated with the mapping results and contribute to the prioritisation of indicators and data specifications for a multi-cycle circularity assessment to enhance reuse marketplaces connection via Digital Building Logbooks.

This report is structured in five main chapters. Each chapter may be read independently, with a specific research question, but collectively they contribute to a holistic understanding of circularity integration in DBLs, as illustrated in the diagram in figure 1.

1. State of the practice: integration of circularity in Demo-BLog Digital Building Logbooks, introduces the context of circularity in Digital Building Logbooks and inventories current data fields that contribute to circularity in the built environment.
2. Policy context: the future of Digital Building Logbooks, analyses European policies that can influence the future development of DBLs in relation to circularity, and identifies key requirements that need to be addressed by DBLs in the near future.
3. State of the art: systematic review of circularity indicators for buildings, inventories circularity assessment frameworks and indicators to measure circularity at multiple scales (material, component, and building).
4. Co-creation: practitioners' attitudes towards reuse of material, presents the results of the co-creation workshop identifying behavioural drivers and barriers to reuse marketplaces.
5. Specifications for multi-cycle circularity, presents the final conclusions and technical specifications to consider in future DBL developments.

The results will be further implemented in the project in *Subtask 1.4.4* focusing on the IT developments at demonstrator level in the CIRDAX DBL, and tested in *task 3.6 Demo of circularity and material functionality* within CIRDAX DBL. However, the results of this report extend beyond the project's scope and provide insights for future developments in the field of Digital Building Logbooks.

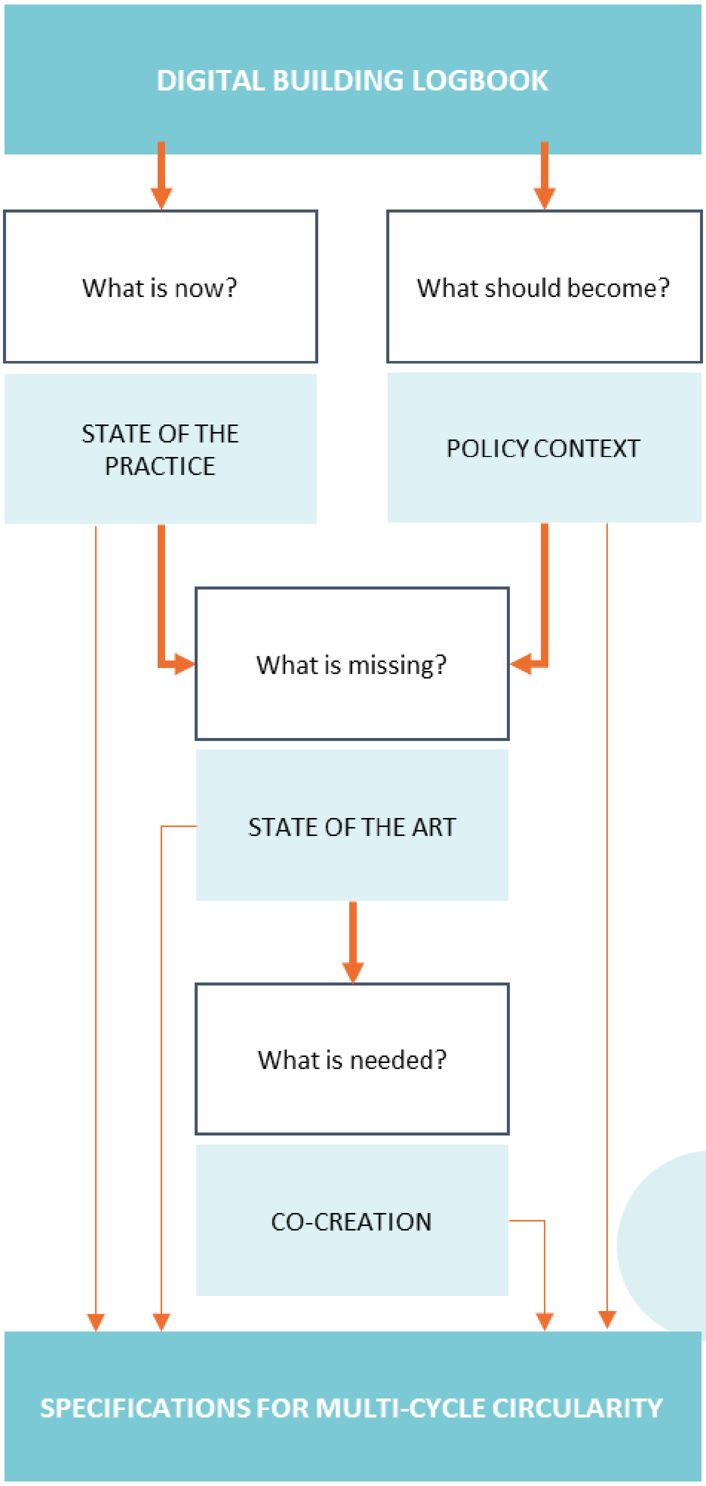

Figure 1 Outline of the report

2 State of Practice: Integration of circularity in Demo-BLog Digital Building Logbooks

The results of this chapter were first published as "The role of Digital Building Logbooks for a circular built environment" in the open access book Circular Economy in the Digital Age, *available under the CC BY 4.0 license*: ***Gonçalves, J.D.S., Lam, W.C., Ritzen, M. (2024). The Role of Digital Building Logbooks for a Circular Built Environment. In: De Wolf, C., Çetin, S., Bocken, N.M.P. (eds) A Circular Built Environment in the Digital Age. Circular Economy and Sustainability. Springer, Cham. https://doi.org/10.1007/978-3-031-39675-5_13***

2.1 Introduction to Digital Building Logbooks (DBLs)

Building logbooks are repositories of building-related information. They are also commonly referred to as building passports, electronic building files, and, in specific cases, building renovation passports. They provide a single source for inputting, accessing, and visualising all the information associated with a building that can be continuously monitored and updated (Hartenberger et al., 2021). As data is captured and managed throughout a building's whole life cycle, DBLs facilitate transparency, trust and informed decision-making in the construction sector and are considered enablers of a circular built environment (Dourlens-Quaranta et al., 2020). While material passports (MPs) focus on the material-related data of a product and its underlying components, such as life cycle impacts or circular characteristics (van Capelleveen et al., 2023), Digital Building Logbooks (DBLs) can include technical, spatial, and functional characteristics as well as environmental, social, and financial performance data of a building.

A DBL is intended to be a flexible repository of building-related information that can be accessed and managed in different ways by different stakeholders. These stakeholders should be able to manually enter, upload and update information, import data from external sources, or link to external databases. DBLs have the potential to cover a wide range of building-related information: static data (such as administrative documents, building plans, bills of materials, etc.) and dynamic data (such as maintenance logs, operational energy consumption, etc.) (Hartenberger et al., 2021). DBLs allow centralised access to information and can cluster digital product passports (DPPs) and MPs at the component and material level, including information on energy performance certificates and renovation roadmaps towards minimum energy performance requirements.

2.1.1 DBLs in the European built environment

In 2020, the European Commission commissioned a study on the development of a European Union framework for the DBLs (Dourlens-Quaranta et al., 2020). In several European countries, DBLs are already in use or in the process of being introduced (Gómez-Gil et al., 2022; Jansen et al., 2022). Some of these can be identified as a DPP or MP. The differences in scope between these digital tools are still a topic of discussion, as they can be related to the scale of implementation (from material and product to building), life cycle stages coverage, and scope of the contents. All three - DBLs, DPPs and MPs - are intended to be useful throughout the whole life cycle of a product. However, they have different focus: DPPs are created in the moment of production; MPs can be created during design and construction or at the end-of-life stage of a product or a building (Honic et al., 2021), but their most essential contribution lies at the beginning and at the end-of-life and next-use stages, enabling reuse and recovery of materials; and the main focus of DBLs is the use stage, as represented in Figure 2. DBLs might 'nest' lower-level passports (such as DPPs or MPs), so that information can be inherited at a higher (building) level from underlying levels (components or materials) (Platform CB'23, 2020). Furthermore, DBLs can be seen as 'living' logbooks that can be updated, automatically or not, during the life cycle stages, and they can include information related to energy performance, health and comfort, and operational management, while DPPs and MPs tend to be more static.

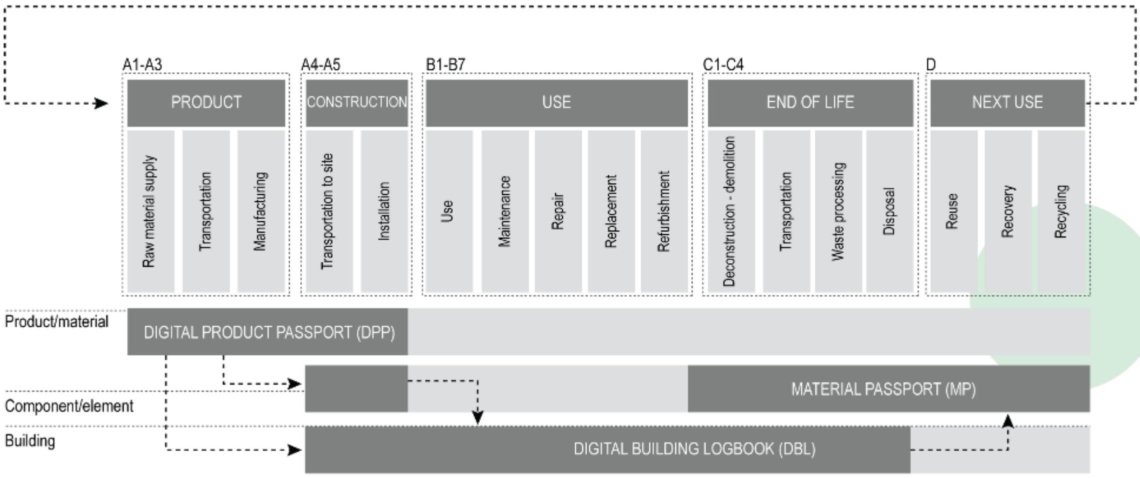

Figure 2 Relation of DPPs, MPs, and DBLs across scales and life cycle stages, with the darker shade highlighting the focus life cycle stages

2.1.2 DBLs for a circular economy

The EU Parliament's Strategy for a Sustainable Built Environment, aiming to set the legislative priorities for the built environment regarding the implementation of the European Green Deal, refers to the importance of DBLs to increase material efficiency and to reduce the climate impact of the built environment, in particular by promoting circularity principles throughout the life cycle of buildings (European Parliament, 2023). DBLs are an 'important means to achieve a more circular construction sector, as they promote reuse at the material, product, element, and building scale' (Platform CB'23, 2020). In addition, DBLs can promote the principles of durability, adaptability, and circularity principles throughout the life cycle of a building (Hartenberger et al., 2021). As with DBLs, information on the installed construction elements, components and materials, their lifespan, and the possibilities for dismantling, reuse, and recycling can be systematically collected, organised, and updated. In this way, DBLs can improve the overall transparency, trust, and cooperation between different stakeholders and support sustainable decision-making when it comes to modifying actions during the life cycle of a building, ultimately preserving the value of the materials. DBLs can help maintain the value of the building throughout its lifecycle and contribute to smarter use of materials and products (narrowing the loop), extending the life of buildings and components (slowing the loop) and ensuring beneficial end of life (closing the loop).

2.2 Circularity in Demo-BLog DBLs

This section presents examples of DBLs developed in five geographical contexts with different local drivers and normative frameworks: France (CLÉA), the UK (Residential Logbook Association/Chimni), Germany (CAPSA), Belgium (De Woningpas), and the Netherlands (CIRDAX). These DBLs were chosen to showcase the wide variety of legal and market backgrounds, level of maturity, functionalities, and target audiences. The DBLs are analysed in terms of functionalities, data management, data fields, and contribution to circularity strategies.

2.2.1 DBL Descriptions

CLÉA, France

Since January 2023, French regulations have made the 'Carnet d'Information du Logement' (dwelling information file) mandatory for all new buildings; however, digitalisation is not mandatory. In this context, Qualitel, a French certification body, has developed CLÉA – a DBL that was launched to the market in October 2020. Currently, CLÉA is used in 50,000 dwellings (45,000 privately-owned multi-family homes and 5,000 single-family homes). This business to consumer (B2C) DBL is intended for building owners and tenants, either directly or through real estate managers. The CLÉA DBL is divided into different information categories, namely: general dwelling information (cadastre information); documents (repository of pdf files with invoices, rules, or minutes of residents' association); equipment (user guides and maintenance alerts for heating, ventilation, and air conditioning (HVAC) equipment); news (blog); and energy monitoring (connected to smart meters).

Residential Logbook Association, the United Kingdom

In the UK, there is no specific building logbook legislation. In 2021, the Coalition for the Energy Efficiency of Buildings (CEEB) developed a standardised framework for Building Renovation Passports in the UK to help finance a net-zero carbon built environment. In this context, the Residential Logbook Association brings together several DBL companies to contribute to the regulatory process. Approximately 250,000 homes have a DBL verified by the RLBA. Chimni is one of these business to business (B2B) and B2C DBLs. It is tailored for homeowners, estate agents, and house builders for existing and new buildings. Information categories currently included in this DBL are pictures and floor plans; geolocation; document storage (deeds, certificates, etc.); utility dashboard (connecting to gas, electricity, and water companies); and property history timeline.

De Woningpas, Belgium

The Woningpas (De Woningpas, 2023) is a DBL owned and developed by the Flemish government as part of the implementation trajectory for the renovation wave and the regional decree on building passports (Vlaams Overheid, 2018). It makes building passports available for all building units in Flanders. The Woningpas was launched in December 2018 as a B2C DBL for residential building units, and an extension of the DBL to all non-residential buildings is planned for the end of 2023. The DBL data is linked to external platforms via Application Programming Interfaces (APIs), connecting all available information from public authorities or other institutions (e.g., inspection organisations of energy network operators). In this way, the Woningpas is automatically fed with data and made freely available to the building owners of all four million individual building units in Flanders. A building owner can add information about work carried out and certificates (pdf files) in a digital environment, and also can share the information in this DBL with the public. The information categories currently offered by this DBL include building information (cadastre information); energy (energy performance certificate, renovation advice, renovations work); insulation, glazing and installations characterisation; soil characterisation; building permits; dwelling quality; mobility; water and sewage; flood sensitivity; biodiversity level; and asbestos.

CAPSA, Germany

Chillservices is a commercial company that has been providing building logbooks for large food retailers since 2016. In 2021, the company launched a new variant for office and residential buildings – CAPSA, which is currently applied to 50,000 apartments in Germany, but also in smaller test cases in Scotland, the Netherlands, and Italy. CAPSA is a B2B DBL to support housing owners and facility managers. It consists of a smartphone app to collect primary data, supported by geo-positioning and image recognition. The collected data is stored in a cloud-based platform and interpreted with the support of external data sources. Functionalities currently offered by this DBL includes the following information categories: calculation of energy performance; surface area; material catalogue and embodied carbon; asset management (condition assessment, monitoring, and maintenance advice); and semi-automated calculation of decarbonisation roadmaps.

CIRDAX, the Netherlands

CIRDAX (*CIRDAX*, 2023) is a commercial materials management system launched in 2016 in the Netherlands by the company Re-Use Materials. As the focus of this DBL is mostly on materials, it can be considered as an MP (see Chapter 5 by Honic et al. on material passports). However, CIRDAX is also an example of an integrative approach of digitalisation, as it combines the inventory of materials and components in a building scale with a digital twin and includes building management functionalities, and should therefore be considered as a DBL. The data collected by 3D-scanning or manual inputs is aggregated in a DBL, linked to a blockchain to provide verifiable information about the ownership of materials for future transactions. CIRDAX is a B2B DBL, currently used by governmental organisations and real estate organisations for in-depth digitalisation of existing real estate portfolios. This DBL currently includes material passport; 3D Digital Twin; CO_2 balance calculator; management and maintenance (condition assessment and maintenance alerts); performance dashboards (circular potential, financial value, and CO_2 emissions); and material marketplace.

2.2.2 Data fields supporting circular strategies

Table 1 presents a summary of the most relevant data fields enabling circularity in the built environment present in the analysed DBLs. All analysed DBLs include geolocation of the building, a data field that can be linked to GIS to optimise distances in the construction and end of use stages, encourage smart use of available space, track and trace available resources (from materials to energy, including space), and encourage excess resource exchange.

Most DBLs focus on operational energy consumption in buildings (i.e., during the use phase). This includes information on the maintenance and use of HVAC equipment (CLÉA, Chimni, Woningpas, CAPSA), links to energy certificates (Woningpas), invoices and consumption data from utilities (Woningpas, Chimni), and live monitoring through smart meters (CLÉA, CAPSA). Thus, they support the narrowing of resource loops in the use stage, by improving and tracing energy efficiency in buildings, with energy renovation roadmaps (such as Woningpas and CAPSA) and encouraging the reduction of primary energy inputs, by integrating renewable energy sources and analysing solar potential (Woningpas).

Slowing resource loops is also an important aspect tackled by the analysed DBLs. By integrating data about the heritage values of the building, tools like Chimni and Woningpas reinforce the emotional connection with the users so that the users feel attached to their buildings (Çetin et al., 2021). Together with information about user guidance, condition assessment, and maintenance (for instance in CAPSA and CIRDAX), these strategies facilitate the development of redesign strategies that extend the service life of the building.

Table 1 Data fields related to circularity strategies

			Digital Building Logbook				
Category	Data field	Strategy	CLÉA	CHIMNI	WONINGPAS	CAPSA	CIRDAX
Plot	Geolocation	ALL	x	x	x	x	
	Soil characterisation	Regenerate			x		
	Flood sensitivity	Regenerate			x		
	Water & sewage	Narrow/Regenerate			x		
	Blue-green level	Regenerate			x		
	Solar potential	Narrow			x		
	Mobility	Narrow/Regenerate			x		
Building	Construction Date	Slow	x	x	x		
	Heritage listing	Slow		x	x		
	Building timeline	Slow		x			
	Home quality	Regenerate			x		
	Surface area	Slow		x		x	x
	Architectural characteristics	Slow/Close		x	x	x	x
Services	HVAC systems	Narrow	x	x	x	x	
	HVAC user guides	Slow	x	x			
	HVAC maintenance alerts	Slow	x	x		x	
	Energy performance	Narrow	x	x	x	x	
	Energy consumption	Narrow	x	x	x		
	Energy monitoring	Narrow	x			x	

Components and materials	Characterisation	Slow/Close				x	x
	Embodied carbon	Narrow/Close				x	x
	Circular potential	Close					x
	Marketplace	Close					x
	Residual financial value	Close					x
Maintenance	Condition assessment	Slow				x	x
	Monitoring hotspots	Slow				x	
	Maintenance strategies	Slow		x		x	x
Roadmaps	Energy renovation	Narrow			x	x	
	Project templates	Slow		x			

By including modules related to materials, such as an inventory of materials and components and analysis of embodied carbon, CIRDAX and CAPSA show the potential of DBLs to contribute to closing resource loops, avoiding waste and bringing resources back into the economic cycle. CIRDAX links to a circular potential analysis (Potting et al., 2017) and the residual value of the building, and connects supply and demand for material reuse with blockchain technology. Woningpas is the only DBL analysed to include information on the plot and city level, such as soil characterisation, mobility, and blue-green levels (combining natural vegetation and water management strategies). It also includes information related to the indoor environmental quality (IEQ) (home quality assessment), making this the only analysed DBL already targeting the regeneration of natural and human systems, promoting biodiversity, healthy environment, and exchange of resources at community level.

2.3 Discussion and conclusions

2.3.1 Evolution of data requirements in DBLs

The potential for developing DBLs and increasing the contribution to a circular built environment varies considerably depending on the current level of complexity and the stakeholders targeted. Most of the current DBLs still have a one-dimensional focus on the use phase and operational energy consumption, with little coverage of the whole cycle (Hartenberger et al., 2021). DBLs such as Woningpas are aiming to integrate external data from smart meters to monitor real performance, and CAPSA has already implemented this functionality. Some of the DBLs presented already provide users with automated renovation advice

(Woningpas) or detailed decarbonisation roadmaps (CAPSA), which can support the renovation of the building stock, investment decision-making, and access to EU funding, green financing, and insurance products.

According to the European Commission, the automatic input of data from a BIM model (see Chapter 1 by Koutamanis) is considered important for the majority of stakeholders (Dourlens-Quaranta et al., 2020), as it would contribute to speed up the processes and reduce costs – two major barriers to the implementation of DBLs (Dourlens-Quaranta et al., 2020). This is not yet a common practice, as the analysis of cases demonstrated. Only CIRDAX offers this possibility, and Chimni is actively working on integrating it with the DBL.

Collaboration is an essential strategy in the transition towards a circular built environment (Çetin et al., 2021), which will require integrating needs and expectations of multiple stakeholders at multiple scales. Understanding the building as a part of a larger complex system shaped by social, economic, and environmental forces is important for identifying flows of material products and waste across different scales. DBLs contribute to a better overview of the existing building stock and can enhance collective approaches that significantly reduce impacts at the neighbourhood and urban levels. The integration of DBs and GIS technologies can support community-driven decarbonisation and the decentralisation of water, energy, and waste flows. Simultaneously, it can establish urban mining networks, which would provide information on the location and availability of materials.

To improve the contribution towards a circular built environment, the next generation of DBLs needs to go beyond operational energy and provide support for sustainable flows throughout the entire life cycle of the building and beyond. In the study of the European Commission, participating stakeholders identified the building material inventory as one of the most important features (Dourlens-Quaranta et al., 2020). However, the analysis of the practical cases presented in this chapter shows that DBLs integrating this feature remain the exception rather than the norm. Requiring a bill of materials could increase the completeness and accuracy of the DBLs (Platform CB'23, 2020) in the early stages and, later on, facilitate the traceability of embodied carbon and life cycle costing (Hartenberger et al., 2021). It also would offer an opportunity to integrate DBLs with current policy frameworks, such as LEVEL(s), by providing the necessary information to assess resource efficiency and material life cycles (European Commission, 2021), currently required by the new EPBD (European Commission 2024).

2.3.2 Challenges in the development of DBLs

To ensure that DBLs are effectively useful tools, a more systematic and aligned approach to data collection, storage, and exchange is needed. DBLs should facilitate the comparison and interchange of information, and 'it is important that everyone uses the same technical terms and uses the same definitions' (Platform CB'23, 2020). The five practical cases analysed show that the same functionalities may have different meanings in the different DBLs. This was clear in the data fields related to general cadastre information and building characterisations, for instance, and in the integration of maintenance advice or environmental product declarations (EPDs). Future developments need to establish protocols and tools to ensure the interoperability and compatibility of information so that DBLs are effective tools for information sharing and not obstacles to access. A harmonised framework of minimum requirements and protocols for DBLs is essential to ensure the availability of accurate and correct data, while still allowing for a diverse range of DBLs to meet different market needs and local drivers. The standardisation of minimum requirements goes hand in hand with the financing of the development of DBLs (Dourlens-Quaranta et al. 2021): certain mandatory aspects can be developed by the public sector (such as the Woningpas), ensuring transparency and harmonisation. Meanwhile, more advanced features can be developed with commercial purposes, targeting stakeholders' specific needs (such as CIRDAX). The highest value for the end-users will be achieved when both approaches can be integrated.

User-friendliness is a key factor determining the success of DBLs. Greater market uptake depends on the extent to which governments impose obligations (Platform CB'23, 2020), but also on a better understanding of users' needs, attitudes, and personal motivations (J. D. S. Gonçalves et al., 2021). It is important to recognise that there is no 'one-size-fits-all' solution for DBLs. Despite the overarching benefits of implementing DBLs identified in the findings, not all levels of information are relevant to all stakeholders. Therefore, DBLs, despite their role as an information hub, need to allow for different levels of granularity and user roles to avoid overburdening stakeholders with additional work and costs for data storage and management (Hartenberger et al., 2021). A significant challenge for the successful development and large-scale application of DBLs will depend on the business model. Some will be based on a business-to-business (B2B) model, business-to-consumer (B2C) model, or will be fully supported by governments. For the B2B and B2C models, it will be key to define clear unique selling propositions that generate value for the customer.

2.3.3 DBLs as enablers of circular economy

DBLs have the potential to contribute to three main circularity goals: 1) measuring achieved circularity; 2) management and maintenance in the use phase; and 3) facilitating future reuse and value retention (Platform CB'23, 2020). Despite the differing levels of complexity and detail, all the five DBLs presented in this chapter contribute to the second goal, facilitating the maintenance of the existing building stock; CAPSA and CIRDAX include some functionalities that contribute to the first goal, namely the material inventory and calculation of embodied carbon, but only CIRDAX actively aims at future circularity, value retention and circular potential. Future developments should integrate renovation advice with MPs and reuse marketplaces with blockchain technology. This would allow to balance achievements on operational and embodied carbon and make the most of the resources already present in the building or its surroundings, avoiding disposal and loss of value and enabling multiple life cycles.

Despite the challenges to their development, the analysed cases of DBLs already demonstrate the potential of DBLs to enable a circular economy in the four strategies proposed by (Çetin et al., 2021): 1) they facilitate the upgrade and improvement of energy efficiency in buildings in the use phase (narrowing resource loops); 2) contribute to extending buildings' lifetime through maintenance and repair, and enabling smart reuse of space (slowing resource loops); 3) enable tracking, tracing, and bringing material resources back into the economic cycle in the next-use phase (closing resource loops); and 4) contribute to a net positive impact when including indicators on biodiversity, surplus resources, and environmental quality (regenerating resource loops).

3 Policy context: the future of Digital Building Logbooks

3.1 Introduction

This section frames circularity requirements in Digital Building Logbooks in the context of European policies and long-term ambitions. Starting from the European Green Deal's ambitions towards 2050, a series of strategy documents (such as the renovation wave or the circular economy action plan) were traced to be implemented through directives (Ecodesign and energy performance in buildings) and European regulations (such as the climate law, or the construction product regulation). A content analysis was conducted to identify themes, criteria, and priorities that can affect the future development of Digital Building Logbooks.

The European Green Deal is an umbrella document that outlines the EU's climate-neutrality goals by 2050 in several sectors, including construction and the built environment (European Commission 2019). It is transposed in regulatory measures such as the climate law, the EU taxonomy (European Union 2020), the Construction Product regulation (European Commission 2022a), the revised EPBD (European Commission 2024) and the Ecodesign recast proposal (European Commission 2022b), naming a few with more relevance to the built environment. It is accompanied by more specific strategy documents on the industrial strategy, circular economy action plan (European Commission 2020a), decarbonization (European Commission 2021a), and renovation of the built environment (European Commission 2020b). All documents analysed focus on climate objectives, and greenhouse gas emissions. Despite the emphasis on "energy efficiency first" principle, there is a clear tendency towards the inclusion of embodied greenhouse gas (GHG) emissions and whole lifecycle carbon (WLC). The Level(s) framework is often recommended as a baseline methodology to assess lifecycle GHG emissions (Energy Performance of Buildings, 2024) and resource efficiency, which makes bills of materials an important instrument to collect relevant data (Nugent, Audrey et al., 2022).

3.2 Digital Building Logbooks and passports

The concept of Digital Building Logbooks is frequently associated with the concept of a "passport" and it is sometimes designated by different terms according to the context and scale. For example, Digital Building Logbooks (DBLs) (European Commission 2020b; European Parliament 2023a), renovation passports (European Commission 2021b), digital product passports (European Commission 2022b), and declaration of performance (DoP) (European

Commission 2022a). These concepts refer to digital tools that support traceability, transparency, and access to information across the building (or product) lifecycle.

2024 EPBD recast introduces a common framework for renovation passports, which EU countries are encouraged to implement as a voluntary tool to support homeowners. A Renovation Passports are defined as "tailored roadmaps for the deep renovation of a specific building" with the goal of transforming the building into a zero-emission building by 2050 at the latest (European Parliament 2023a). The Renovation Passports should outline a roadmap to achieve the minimum energy performance standards (MEPs), measures to reduce the whole life cycle GHG emissions, an indication of benefits in terms of energy savings and savings on energy bills, information regarding the potential connection to district heating network and renewable energy, an estimated cost, and details on the financial and technical support available for renovation. Beyond the scope of energy renovation, Renovation Passports should also include bill of materials, information on construction products circularity, and aspects related to the health, comfort, IEQ, safety, and adaptive capacity of the building to climate change.

Digital Building Logbooks are referred by the Renovation Wave, the Strategy for a Sustainable Built Environment Legislative train (European Parliament 2023b) and the EPBD. The Renovation Wave defines Digital Building Logbooks as "repositories for data on individual buildings and facilitate information sharing within the construction sector, and between building owners and tenants, financial institutions and public authorities" (European Commission 2020b). This key strategy document for the built environment envisions DBLs to integrate data from building renovation passports, smart readiness indicators, Level(s) assessments, and Energy Performance Certificates, to ensure compatibility and integration of data. The revised EPBD (2024) adds to the definition of Digital Building Logbook from the Renovation Wave, to highlight the importance of DBLs to include data on the life cycle GWP and smart readiness indicators. DBLs will allow to centralize access to information and can cluster digital product passports at component and material level, include information on energy performance certificates and renovation roadmaps towards minimum energy performance requirements. DBLs can also facilitate the connection of homeowners with incentives and financing schemes for renovation, affordability, and cost-benefit analysis, bringing together information requirements from the different thematic categories (from climate to actors and manufacturers).

3.3 Policy themes and requirements

Figure 3 shows the key emerging themes. The theme Climate includes criteria such as carbon targets, operational GHG, embodied carbon, Life Cycle Assessment, etc.; the theme Energy refers to primary energy use, energy performance, and renewable energy generation, distribution, and consumption. Resource Efficiency includes, for example, material recovery targets, secondary markets, sustainably sourced materials; Design for longevity includes aspects more related to durability, maintenance, and repairability were included; End of life handling refers to the aspects related to the material at the end of its life, including dismantling and disassembly, or pre-demolition audits; Technical performance is a theme that includes criteria related to quality, structural integrity and descriptive aspects of materials and product characteristics; the Health and environment theme refers to traceability of hazardous substances and Indoor Environmental Quality (IEQ) monitoring; the theme Actors and manufactures includes criteria related to services, technical support, or financing; finally, the theme Tools includes references to digital product passports, renovation passports, Digital Building Logbooks, and associated methodologies. Some of these themes are particularly relevant for the integration of reuse marketplaces and multi-cycle circularity in Digital Building Logbooks, namely: resource efficiency, design for longevity, and end-of-life handling.

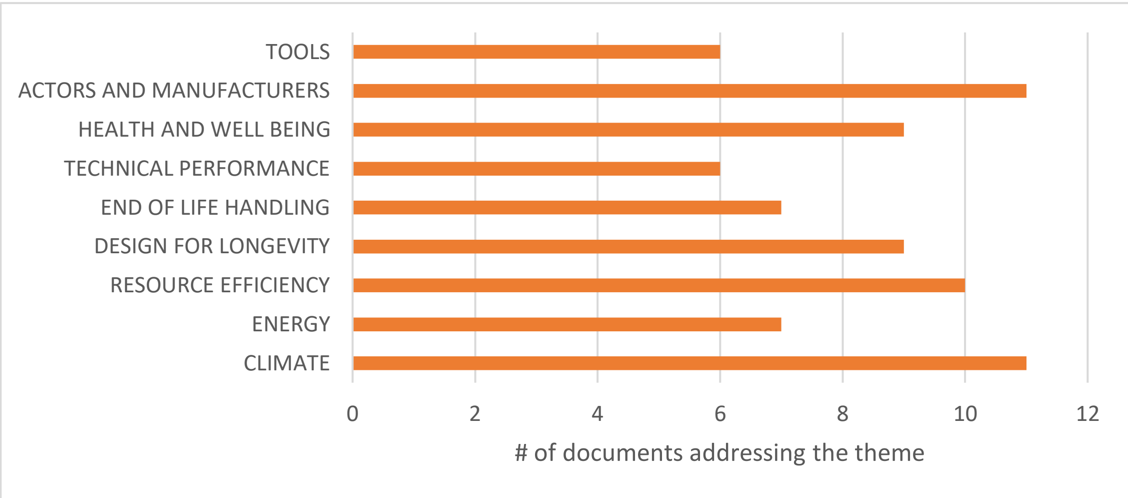

Figure 3 Key themes identified in European policies

The analysed policies frequently mention resource efficiency, design for longevity, and circularity principles. However, the level of ambition and measurement methodologies are not clear as they may vary according to product categories and the implementation in national legislation. Indicators that are more frequently mentioned include **durability and product/material/components lifespans**, **reparability** (including repairability scoring, access to spare parts, technical assistance, and repair instructions), and **reusability**. **Dismantling and disassembly** processes are also important criteria and may include instructions and ease of scoring, as well as energy efficiency quantification on the process.

The reduction in the consumption of primary materials implies an **easier access to a secondary market** for recovered materials and the provision of technical guidance to circular supply chains. The identification and **traceability of products origin**, quality, and the actors and manufacturers are essential for the transition to a circular economy. Extended producer responsibility and take-back schemes are recommended by experts such as the World Green Building Council (Nugent, Audrey et al. 2022). At a product level, the integration of traceability of materials and substances used is a priority, together with the **environmental indicators according to the LCA methodology**. Material recovery targets will be gradually integrated according to product categories. These are inextricably linked with **reducing whole lifecycle GWP** and collecting information on the **bill of materials**.

3.4 Circularity assessment at EU level

While specific measurements and indicators for circulatory assessment are not defined for all the priority themes and requirements, reporting and assessment according to the LEVEL(s) framework is often referenced across the policy documents analysed, including (but not limited to) the Energy Performance of Buildings Directive, the Renovation Wave, and the Circular Economy Action Plan.

The Level(s) framework is a European initiative aiming at providing stakeholders with a common language for sustainability performance assessment in a life cycle context. It is a reporting tool and not a rating system with specified benchmarks, which contributes to the harmonisation of definitions and methodologies (Directorate-General for Environment (European Commission), 2021). Level(s) framework addresses six macro-objectives for sustainability performance. Macro-objective 2 – Ensuring resource efficient and circular material lifecycles – focuses on 4 indicators for improving circularity in the built environment:

- Bills of quantities, materials, and lifespans
- Construction and demolition waste
- Design for adaptability and renovation
- Design for deconstruction.

The indicator bill of quantities, materials, and lifespans, requires information regarding the total **mass of construction products and materials** necessary for the construction, renovation, and demolition activities. This information must be reported in tons and as a percentage of the total mass, split by building element, and including the **expected lifetime in years**. The data gathered in this indicator serves as a data inventory for the **Life Cycle Assessment (LCA**) and the Life Cycle

Cost (LCC) analysis. The second indicator, construction and demolition waste (CDW), builds upon the bills of materials to define end-of-life scenarios for the output material of the construction activities, focusing solely on CDW. The indicator measures the quantity of waste in kilograms per square meter, considering both the best possible and probable outcomes. The results present the percentage **split of materials for reuse, recycling, backfill, energy recovery, and landfill/disposal** and, also, the amounts of **hazardous waste** materials. The third indicator, design for adaptability and renovation focuses on the long-term capacity for adaptation of the spatial configuration to accommodate changing needs. This is a semi-quantitative assessment, in which adaptability design aspects are scored on a checklist (internal space distribution, building servicing, and changes to façade and structure), with a dimensionless score. Finally, the indicator on **design for deconstruction** focuses on future circularity and opportunities for harvesting and reusing building parts and materials. As in the indicator Construction and Demolition Waste, this indicator starts from the data collected in the **bill of quantities** but considers end-of-life scenarios beyond CDW, considering potential renovation cycles throughout the intended service life of the building. This indicator provides a semi-quantitative assessment, scoring disassembly aspects in a checklist, with a dimensionless score based on the best outcome scenario (landfill, recovery, recycling, reuse). A checklist can be used to qualitatively assess the best outcome scenario, considering three main aspects: the **ease of disassembly** (identification of connections, nature of connections, access, and complexity of disassembly); the **ease of reuse** (standardised dimensions, modularity, and adaptability to future changes); and the **ease of recycling** (homogenous materials; easily separated; established recycling options).

The two first Level(s) indicators are quantitative in nature, whereas the indicators for adaptability and deconstruction are primarily qualitative checklists. The data requirements for completing the Level(s) indicators are not aligned with current practice and are not easily available, resulting in a time-consuming process that is dependent on subjective assumptions (e.g., split construction products by material type; or determining probable outcomes for CDW).

The European Commission study on measuring the application of circular approaches in the construction industry ecosystem (2023) recommends a limited set of indicators for the construction ecosystem, considering data (availability, accuracy, and timeliness), the availability of standard measurements, the ease of measurements, relevance, and drivers and barriers to data acquisition. The study differentiates four levels for the assessment:

- Product or material level – materials and products within construction
- Building or infrastructure level – whole asset level
- Organizational level – organization and company’s activities
- Urban level – city level

Table 2 Top priority indicators identified at policy level

Priority requirements	Level(s)	European Commission, 2023	Strategy
Reusability	Probable/best outcome (2.2, 2.4); Circularity score (2.4)	Realistic EOL scenarios (P8), CDW reused, recycled, recovered, landfilled (B10, B16)	Slow
Recyclability	Probable/best outcome (2.2, 2.4); Circularity score (2.4)	Realistic EOL scenarios (P8), CDW reused, recycled, recovered, landfilled (B10, B16)	Close
Disassembly potential	Circularity score (2.4)	Design for disassembly score (B7)	Close
Percentage recycled input	-	Recycled content (P3, B5)	Close
Percentage reused input	-	Reused content (P1, B4)	Slow
Toxicity	Amount of hazardous waste (2.2)	Hazardous waste (P7)	Regenerate
Life cycle environmental impact	(Warming potential (1.2) based on Bill of Materials (2.1))	Comparison of life cycle assessment (B2)	ALL
Design for longevity	Expected lifetime in years (2.1)	Predicted service life (P6)	Slow
Sustainability certificates and environmental product declaration	-	(Required for the calculations)	ALL
Disassembly – assembly instructions	-	-	Narrow/Close
Contractual agreements (e.g.: material-as-service; take-back services)	-	-	Close
Energy performance	(Use stage energy performance (1.1))	-	Narrow

In the context of future developments for digital building logbooks, levels 1 and 2 (product and building) were identified as the most pertinent. It is possible to aggregate data available in DBLs to provide information at urban level. In these two levels, the study recommends 14 indicators and related measures, which range from life cycle assessment to design for deconstruction. In contrast to the focus on Level(s) on future circularity, the indicators recommended in the European Commission study (European Innovation Council and SMEs Executive Agency., 2023) integrate the assessment of current circularity of the construction work. This includes the inclusion of **reused products, reused and recycled content**. Most indicators are measured in weight or relative percentage by mass, with data sourced from the **bill of materials**, the **environmental product declarations**, and **pre-/post-demolition audits**.

3.4 Conclusions

Table 2 presents a summary of the findings of the policy analysis, listing the priority requirements identified in European policies and potential indicators to monitor and assess them according to the Level(s) framework and the European Commission recommendations to measure circularity. The results highlight the overlaps between the two methodologies, with regard to factors such as the expected lifetime and amount of hazardous materials. Furthermore, the European Commission recommendations extend beyond Level(s) framework, addressing gaps in the current circularity assessment (e.g.: reused input, recycled input). Certain priority requirements identified do not directly link to circularity assessment indicators. However, they provide data and evidence to ensure accuracy and substantiate assumptions, including sustainability certificates, EPDs, energy performance certificates, disassembly instructions, ownership agreements). These should thus be included in digital building logbooks to facilitate traceability and data availability. Additionally, the importance of the bill of materials is emphasised in both frameworks as a fundamental data source for circularity assessment.

4 State of the Art: Systematic review on measuring circularity in the built environment

4.1 Introduction

The transition towards a circular economy in the built environment is widely recognized as a critical strategy to address the significant environmental and resource challenges facing the construction sector. The circular economy approach emphasizes the need to maintain the value of materials, components, and buildings for as long as possible, through strategies such as reuse, repair, refurbishment, and recycling. A variety of R-hierarchies can be identified in the literature (from 3Rs to 9Rs). These hierarchies allow for the categorisation of core strategies towards circularity, from recovery to refuse. Recovery is the lowest R-level, representing the most environmentally impactful strategy and the closest alignment with a linear economy. In contrast, refuse is the highest R-level, offering the greatest potential for environmental benefits and a higher level of circularity (Potting et al., 2017). This contrasts with the traditional linear "take-make-waste" model, which has dominated the construction industry and which contributes to high levels of resource extraction, waste generation, and greenhouse gas emissions.

Rahla et al. (2019) highlight the diversity and vagueness of circular economy definitions, the overlap between the concepts of circularity and sustainability, the lack of social measurements, and the ambiguity in the aggregation of assessment results as main obstacles for monitoring circularity. A systematic review of 114 circular economy definitions of (Kirchherr et al., 2017) revealed that most definitions are reductive in nature, failing to consider the concept in a systemic perspective that integrated environmental, economic prosperity and social equity. Furthermore, many definitions subvert the concept by failing to integrate waste hierarchies (R-hierarchy). In the scope of this research, the term “circular economy” is defined according to Van Buren et al. (2016): “the focus point in a circular economy is to not unnecessarily destroy resources. This implies far more than the reduction of waste through recycling, stresses the following focal points: reducing the consumption of raw materials, designing products in such a manner that they can easily be taken apart and reused after use (eco-design), prolonging the lifespan of products through maintenance and repair, and the use of recyclables in products and recovering raw materials from waste flows”.

The scientometric analysis of literature on circularity indicators in the construction and built environment sector (Gomis et al., 2023) provides a global overview of the trends in the field. Although it does not provide a comprehensive inventory of measuring frameworks and indicators, the analysis demonstrates a growing interest in the topic, with research output raising exponentially between 2019 and 2022. This research also identifies life cycle assessment (LCA) as a prominent tool to evaluate the circularity in the literature. Nevertheless, LCA alone is not sufficient to measure circularity, as it focuses primarily on environmental impacts and does not fully capture the complexity of circular economy principles, such as resource loops, lifetime extension, and material reuse.

According to Cambier et al. (2020) the prevalence of uncoordinated developments can lead to confusion among designers and slow down their adoption by stakeholders in practice. The study concludes that there is an oversupply of tools and a need for a clearer workflow to transfer information between stakeholders. Furthermore, there is a necessity for the facilitation of guidance for the effective use of the tools, which should provide guidance and user-friendly environments.

To address these challenges and drive the adoption of circular economy principles in the built environment, the development of effective circularity assessment tools and indicators is of paramount importance. This implies working towards harmonization of existing indicators and bringing together current knowledge about measuring circularity to support decision-making throughout the construction life cycle. This systematic review aims to critically analyse the existing literature on circularity indicators and assessment methods for the built environment, with the goal of identifying commonalities and future research directions. By synthesizing the current state of knowledge, this review can contribute to the development of more robust, comprehensive, and user-friendly circularity assessment frameworks that can drive the transition towards a circular built environment.

4.2 Methodology

A comprehensive literature review was conducted to identify and analyse indicators used to measure circularity in the built environment. Data was collected on July 4, 2023, from Web of Science, Scopus, Science Direct, and Google Scholar, yielding a total of 20,482 records. After removing duplicates, 15,228 records were screened using Rayyan, an app for systematic reviews (Ouzzani et al., 2016). The review followed PRISMA guidelines for transparency and replicability (Page et al., 2021)..

Articles were included if they focused on circularity in the built environment, proposed or evaluated indicators, and were peer-reviewed. Exclusion criteria were non-English articles, studies not related to the built environment, and articles not addressing circularity indicators. VOS Viewer (van Eck & Waltman, 2014) was used for visualizing bibliometric networks and thematic analysis, while content analysis of selected full texts focused on quantitative frameworks for measuring circularity from material to building scale.

4.3 Thematic analysis

4.3.1 Circularity definitions and measures

The most common topics identified in the scope of circular economy in the built environment are life cycle assessment, materials, and management of construction and demolition waste. These are linked with recycling and the production of new materials using recycled and natural aggregates, mostly in mortars, concrete, and bricks (e.g., (W. Chen et al., 2019; Marrocchino et al., 2021). Although these studies are often of quantitative nature, they are not aimed at measuring circularity but rather to assess the performance of these building materials in terms of their impact on the environmental (Suttie et al., 2017), energy consumption (Carbonaro et al., 2016), quality and physical-chemical behaviour (Piña Ramírez et al., 2018).

LCA is the most frequently mentioned methodology in the publications analysed in this stage (n=645) in the context of assessing circularity in the built environment. However, as pointed out by Antwi-Afari et al.(2021), this approach comes with challenges in terms of accounting for potential reuse possibilities and its applicability in the design stage. Furthermore, Futas et al.(2019) identify limitations in current measuring methodologies, including those based on cradle-to-cradle, and LCA approaches. These limitations are attributed to the lack of availability and accuracy of information, reliance on assumptions, and the lack of comparability of results. While LCA remains as the most accepted methodology for assessing environmental impacts, it is often applied in a linear perspective, considering one functional cycle in a static way. This is due to the lack of a widely accepted allocation approach and consistent system boundaries to assess circularity in a multi-cycle perspective (S. C. Andersen et al., 2022; Lei et al., 2021; van Stijn et al., 2021). Overall, the review highlights the need for the development of complementary indicators to assess circularity in conjunction with environmental impacts. This would enhance transparency and facilitate decision-making.

4.3.3 Circularity assessment: enabling reuse of building components

The analysis of the selected results, which focused on indicators or indicator frameworks to measure circularity (n=253), revealed a growing interesting on the recent topic of circularity assessment in the building sector. The majority of the publications in this area were concentrated after 2020 (figure 4). The top 10 countries (in figure 5) represent 66% of publications. Italy, Belgium, and United Kingdom are the countries with more publications on the topic of measuring circularity in the built environment.

Figure 4 Distribution per year

Figure 5 Distribution per country

Only 23.3% of the publications assess circularity at multiple scales, with the vast majority (76.7%) focusing on a single scale. From the single scale publications, a third (33.5%) are focused on the whole building scale, around 17% on building materials scale, and 23% on building components or products and building elements. Less than 20% addresses circularity at urban and regional scale (e.g.: Foster & Saleh, 2021; Sala Benites et al., 2023) and only about 9% of publications focus on organizational indicators (e.g.: Nußholz et al., 2020; Yi & Liu, 2016). In the scope of the Demo-BLog project only publications about buildings, components, materials, and the ones addressing multiple scales are reported.

Circularity at building scale

In the publications related to the building scale, the design stage is of particular importance, as it is linked to BIM parametric tools (Akanbi et al., 2019; Atik et al., 2023; Cavalliere et al., 2019) and decision-making support tools (e.g.: (Abadi & Moore, 2022; Antwi-Afari et al., 2022).

Adaptive reuse of existing buildings (Berardi et al., 2020; Bosone et al., 2021; Foster & Kreinin, 2020), design for disassembly (Nemeth et al., 2022), and reversibility (Andrade et al., 2019; Cheirchanteri, 2020) are the most frequently referred circularity strategies. A limited number of papers address the topic of adaptability (e.g., (Geraedts, 2016; Hamida et al., 2022)), and even fewer refer to the role of maintainability for circularity. Regarding reuse of the existing building stock, Zatta & Condotta (2023) have develop a decision-making tool to support designers in the adoption of reclaimed building elements and materials, considering environmental, social, and economic aspects. Despite referring to the whole building scale, circularity strategies focus on deconstruction, harvesting, and reuse of building components.

Circularity at element and component scale

The terms component and element scale are often used interchangeably, with structural elements and components being used as synonyms. Common elements addressed by the literature are internal walls (Buyle et al., 2019a), façade systems (Gulck et al., 2021), and structural elements (Joensuu et al., 2022; Rakhshan et al., 2021).

The research of Buyle (Buyle et al., 2019b, 2019a) uses consequential LCA and LCC assessments to compare different demountable and reusable internal wall alternatives. Van Gulck's research develops a method for assessing circularity on façade systems for the early design stage (Gulck et al., 2021) and for integrating multi-cycling in the life cycle assessment (Van Gulck et al., 2022). Considering multiple life cycles, the research of Eberhardt et al. (2019b, 2019a; 2020; 2020, 2022) applies to multiple elements (for instance columns, rooftops, or façade systems) and is focused on the development of a life cycle allocation approach for LCA of circular building components. Also based on LCA calculations, the study of Schaubroeck et al. (2022) discusses a methodology to assess cascade potential of in-use construction products, and predict cascade of material pathways overtime, using the concept of multi-functionality (the multiple uses of a product) instead of multi-cycling (the multiple life cycles of the same product). Focusing on the potential for reversibility and ease of disassembly, the research of Androsevic et al. (2019) and Lam et al. (2022) analyse the impact of the type of connections to determine the reuse potential and a semi-quantified circularity indicator.

Circularity at material scale

At the material scale, construction and demolition waste (CDW) and end-of-life management are the most common topics, focusing on recycling and recyclability. With the ambition of achieving a more integrated assessment, combining environmental and economic aspects the study by Tseng et al. (2021) performs a cost-benefit analysis of recycling of CDW, while Di Maria et al. (2018) compares downcycling and recycling scenarios combining LCA and LCC. The assessment of the environmental impacts and circularity of composite materials with aggregated recycled content is a common topic of investigation (for instance (Kadawo et al., 2023). Concrete and cement are materials often addressed in the identified studies (Sobotka & Sagan, 2021), with a minority of publications specifically addressing timber (Roithner et al., 2022) or earth construction (Pelicaen et al., 2021).

Circularity at multiple scales

Fifty-nine (59) publications were identified with a multi-scale approach. A frequent relationship emerges between the urban scale and the material scale, particularly in the context of material stock assessment and the potential for urban mining (Ajayebi et al., 2020; Arora et al., 2021; Tirado et al., 2021). Research on collaboration between stakeholders frequently targets both the building scale and the organisational scale (Abadi & Moore, 2022) (Abadi, 2022). Similarly, research on business models often considers both scales (de Carvalho Araújo et al., 2022; Villaizän Marïn, 2022). Research at the component level often relates to specific material choices. For instance, Ali et al. (2020) investigate the potential of metal waste streams to be reused in building facades, while Balasbaneh et al. (2022) assess the circularity of alternative timber walls.

A few publications have addressed the role of material passports for circularity. Kovacic & Honic (2021) present and discuss a methodology for linking BIM-based material passports with laser scanning and data capturing to assess geometry and material composition. (Heisel & Rau-Oberhuber, 2020) assess the circularity of a case study using Madaster's material passports and circularity indicator, emphasising the potential of these tools to support circular design. The research of Atta et al. (2021), integrates an assessment method with a material passport linked to BIM, including a deconstructability score, a recovery score, and an environmental score. This provides decision-makers with qualitative and quantitative information.

4.4 Content analysis

4.4.1 Quantitative circularity assessment frameworks

The content analysis excludes publications that focus on the organisational and urban scales. A full paper screening was performed to select the studies that employed a quantitative methodology to measure circularity. Studies referring to life cycle assessment for circularity and comparing allocation approaches (S. C. Andersen et al., 2022; L. C. M. Eberhardt et al., 2020; Van Gulck et al., 2022) were excluded from the present analysis. A total of 64 publications were identified matching these criteria. Of these, four were literature reviews and 12 were case study applications. In the scope of the Demo-BLog project, this content analysis addresses the key circularity assessment frameworks identified in the literature reviews and case studies.

Table 8 presents a comprehensive overview four extensive literatures on circularity assessment frameworks that have been identified. These were published between 2020 and 2022 and, despite the common methodology, they address different research questions. The research of Khadim et al. (2022) employs a systematic methodology to standardise existing measurement frameworks and provides an overview of the key circularity assessment frameworks and derivative works until 2021. This represents an important steppingstone for the current research. Similarly systematic is the research of Zhang et al. (2021), which builds on the existing literature on circularity indicators to develop a new Building Circularity assessment linking a material flow model, a material passport, and circularity calculation. In Belgium, Cambier et al. (2020)

focus on the design stage, reviewing the tools available in practice to support the circular building process. They also contrast the existing functionalities with the needs and priorities of the relevant stakeholders. The review by Askar et al. (2022) addresses the role of design for adaptability in existing assessment frameworks, providing a detailed overview of categories, criteria, and weighting methods.

A total of 87 circularity support tools were identified in the four reviews. The analysis shows that, despite having similar search queries and timeframes, the results vary largely between the five reviews, due to their specific research questions. The research of Askar et al. (2022) includes indicators addressing building adaptability, while the review of Cambier et al. (2020) includes tools to support circularity in buildings, in addition to measuring indicators, such as design guidelines and reuse marketplaces. The review by Khadim et al. (2022) focuses primarily on indicator frameworks in the built environment. In contrast, Zhang et al. (2021) includes LCA-based methodologies and multi-sector frameworks.

A total of 41 frameworks were identified that met the research criteria set out in the present review. These frameworks were designed to measure circularity in buildings at different scales, from material to whole-building scale, and are presented in Table 9. Some frameworks are mentioned by three or more reviews, namely: **Building Circularity Indicator** (Verbene, 2016)**; Material Circularity Indicator (Ellen MacArthur Foundation, 2015); MAD-CI (Madaster, 2018); Platform CB'23 Core method for circularity assessment** (Platform CB'23, 2020)**; Circularity Calculator (IDEAL & Co Explore, 2017); and the Circular building assessment prototype (BAMB, 2012).** In addition, MCI and BCI are also the two frameworks with the greatest number of derivative frameworks, including the Building Circularity Indicator – Disassembly reconsidered, the Alba Concepts BCI, the Modified Alba Concepts for Foundations, the modified building circularity indicator, and the predictive building circularity model (all derived from BCI); and the MAD-CI, the MCI' by Jiang (2020), and the GaBi circularity toolkit (derived from MCI).

Table 3 Literature reviews on Circularity measuring frameworks and tools

Author	**Year**	**Scale**	**Aim**	**Outcome**	**Time frame**
Khadim et al.	2022	Multi-scale	Standardize existing measurement frameworks	Identification of key circularity assessment tools and derivative works	2015-2021
Zhang et al.	2021	building	CE economy assessment methods for architecture, engineering, and construction	Building Circularity assessment framework including material flow, material passport, and circularity calculation	n.d.
Askar et al.	2022	building	How can adaptability be integrated circularity assessment frameworks	Detailed Overview of categories, criteria, and weighting methods	n.d.
Cambier et al.	2020	building	Comparing the functionalities of available tools with the needs identified by designers	Classification of existing tools according to design phase and design need	n.d.

In addition to the literature reviews, twelve publications were identified as case studies testing the application of assessment frameworks in different contexts (products, BIM applications, etc.). However, these case studies do not develop an original framework. The case studies identified were published between 2019 and 2023 and address the same main tools identified in the literature reviews, thereby confirming the BCI and MCI as the most recognised frameworks to assess circularity internationally (Androsevic et al., 2019; Christian et al., 2021; Dräger et al., 2022; Giama et al., 2019; Göswein et al., 2022; Heisel & Rau-

Oberhuber, 2020; Honarvar et al., 2022; Kadawo et al., 2023; Kayaçetin et al., 2022; Lukianova et al., 2022; Ollár et al., 2022; Poolsawad et al., 2023).

Table 9. Circularity measuring frameworks identified in the literature reviews

Table 4 Circularity measuring frameworks identified in the literature reviews (dark grey colour highlights more frequent frameworks, and light grey colour highlights derivative frameworks)

Acronym	**Framework**	**Source**	**Khadim**	**Askar**	**Zhang**	**Cambier**	**Case studies**
Level(s)	Level(s)	European Commission	x	x		x	
BREEAM	Building Research Establishment's Environmental Assessment Method	BREEAM		x			
LEED	Leadership in Energy and Environmental Design – materials and resources	LEED		x			
GRO	GRO	Het Facilitair Bedrijf, 2020				x	
BCI	Building circularity indicator	Verbene, 2016	x	x			x
BCIDR	building circularity indicator – disassembly recosidered	Van Vliet, 2018	x	x			x
BBCA	BIM-based building circularity assessment	Zhai, 2020	x				

MAC	modified alba concept (for foundations)	van schaik 2019	x	x				
ACBCI	Alba concepts BCI	Alba, 2019	x	x		x	x
MBCI	Modified Building circularity indicator	Braakman et al. 2021	x					
PBCI	Predictive building circularity model	Cottafava and Ritzen, 2021	x					
ARCHCEIF	ARCH Circular environmental indicator framework	Foster et al. 2020	x					
MAD-CI	MADASTER circularity indicator	Madaster, 2018	x		x	x	x
FLEX	FLEX	Prins and Geraedts, 2015	x	x				
MCI	Material Circularity Indicator	Ellen MacArthur Foundation and Granta Design, 2015	x	x	x		x
MCI*	Material Circularity Indicator for construction	Jiang, 2020	x					
IEPC	Integrated energy performance and circularity	Sreekumar, 2019	x					
BBWPE	BIM-based whole-life	Akanbi et al. 2018	x					

	performance estimator							
SEEI	Synthetic economic environmental indicator	Fregonara et al., 2017	x					
GEOLMI	Gypsum end of life measurement indicator	Jimenez-Rivero and Garcia-Navarro, 2016	x					
RIPAT 1.0	RIPAT 1.0	Valdebenito et al, 2021	x					
FCB	Framework for circular buildings	Kubbinga et al. 2018	x					
PCB	core measuring method	Platform CB223, 2020	x		x	x	x
CC	Circularity calculator	IDEAL and CO Explore, 2017	x	x		x	
CBAP	Circular building assessment prototype	BAMB, 2012	x	x		x	
C-CALC	C-CALC	CENERGIE, 2020	x			x	
CACE	Circular Asessment criteria for Envelope	Finch et. Al, 2021	x				
CCEF	Circular Construction Evaluation Framework	Dams et al. 2021	x	x			
CTI	circular transition indicators	Circular IQ				x	

GaBi	GaBi circularity toolkit	Sphera				x	
MRS	Material Reutilization Score	Cradle2Cradle		x			
CE Meter	CE Meter	Geraedts and Prins, 2015		x			
D-DAS	Disassembly and deconstruction analytics system	Akanbi, 2019		x			
SAGA	Spatial Assessment of Generality and Adaptability	Herthogs et al, 2019					
PAAM	Preliminary Assessment Adaptation Model	Wilkinson, 2014		x			
AdaptSTAR	AdaptSTAR Model	Conejos et al. 2013		x			
IconCUR	IconCUR	Langston et a. 2012		x			
ABD	Adaptable Building Design	Allahaim et al. 2010		x			
ARP	Adaptive Reuse Potential Model	Langston et al. 2007		x			
CEI	Circular Economy Index	Di Maio and Rem, 2015			x		
RDI	Resource duration indicator	Franklin-Johnson et al., 2016		x	x		

Material Circularity Indicator (MCI)

Khadim et al. (2022), Askar et al. (2022), and Zhang et al. (2021) reviews strongly emphasize the use of MCI framework developed by the Ellen MacArthur Foundation. This framework was not specifically developed for construction. Instead, it assesses the circularity of materials and products by summing the results of the constituent materials. Askar et al. (2022) propose that MCI can be used at the building scale, although it requires the integration of complementary methods to assess the hierarchical composition of building elements and other design aspects (e.g., design for disassembly or adaptability, for instance). According to Zhang et al. (2021) the MCI is one of the few available tools that allows for the consideration of both technical and the biological cycles. The MCI assesses circularity considering two indicators: the linear flow index (LFI) and the Material Utility (U). The LFI considers the mass of input material (virgin or reused) and output (recyclable, landfill, etc.). The Material Utility penalises products with poor use and short lifetimes, by considering longevity and intensity of use in comparison to an average product of the same type (Khadim et al., 2022). Zhang et al. (2021) is the only source that provides a detailed explanation of the calculation method for the MCI. This is achieved by multiplying the LFI by the material utility, with the latter calculated by considering the lifetime of the product in relation to the average lifetime of a product of the same type, and the average number of functional units. However, the functional units are not easily defined in the scope of construction projects. The calculation of the MCI requires collation of data pertaining to the quantity of virgin, recycled, and reused content; the mass of unrecoverable waste; and data concerning the utility of the product (Askar et al., 2022).

The MCI methodology is limited in that it does not consider material losses incurred during extraction, transportation, and manufacturing. Additionally, it does not consider loss of quality of salvaged materials nor the actual possibility of recovering materials (based on the type of connections). Furthermore, it excludes the economic cycle (Zhang et al., 2021; Khadim et al., 2022).

Derivative works such as Jiang et al.'s MCI' (2022) integrate the economic value by introducing a residual value factor to estimate value loss after each cycle and linking MCI with design for disassembly calculations. However, the necessity for additional data renders this framework more challenging in practice than the original model (Khadim et al, 2022). Madaster's Circularity Indicator (MAD-CI) also builds on the MCI but focuses exclusively on the technical cycle (Zhang et al., 2021). This circularity indicator is implemented in Madaster's material passports, thereby allowing the centralisation of a database of available building stocks for reused or recycling. This database is linked to material quality and location in the building. Unlike MCI, the MAD-CI does not consider the functional units achieved (material utility indicator). Furthermore, the design for disassembly, which is integrated in BCI, is also not included in the MAD-CI framework (Zhang et al., 2021). The review papers do not report on the data collected or the assessment methodology employed.

Building Circularity Indicator (BCI)

The BCI is addressed by the review of Khadim et al. (2022), Askar et al. (2022), and Cambier et al. (2020), the latter of which is presented in the Alba Concepts version. Verbene's BCI (Verbene, 2016) builds upon the MCI framework, extending it to the building scale according to the shearing layers of Brand. In the BCI design, for disassembly is considered and calculated according to the Disassembly Determining factors (Durmisevic, 2006), in the product circularity indicator (Askar et al., 2022; Khadim et al., 2022). The BCI employs hierarchical approach, with product circularity indicator being calculated on the basis of material and disassembly factors. This indicator is subsequently used to calculate the system circularity indicator, and finally, the BCI for the whole building (Askar et al., 2022). Khadim et al. (2022) identified several limitations in the BCI method. Firtsly, it is mass-dependent calculation method, which creates a bias towards heavy materials. Secondly, the disassembly calculations are highly subjective, and thirdly, it does not consider materials used during operation and maintenance. Derivative works have addressed some of these limitations, but no version has created an overall solution: Cottafava and Ritzen (2021) propose an adaptation of the BCI method that employs embodied energy and embodied carbon as a normalizing factor, instead of mass; Van Vliet develops rational patterns to assess disassembly of connections with a detailed weighting system; and Braakman's (2021) version of BCI factors in the maintenance repairs and the efficiency of recycling processes. The Alba Concepts adapts the BCI for industry and integrates scenarios to differentiate inputs types (new, reused, recycled, bio-based) and outputs categories (landfill, combustion, recycle, reuse) (Khadim et al., 2022).

Other frameworks

Other frameworks are frequently references in the literature reviews, including Platform CB23, the Circularity Calculator, and the Resource Duration Indicator. However, the review papers analysed does not provide sufficient information regarding the indicators, data collected, and calculation.

The Platform CB'23 core measurement method (Platform CB'23, 2020) is also frequently reviewed in the literature. As indicated by the name, this is not a direct assessment tool, but a methodological recommendation on how to assess circularity at multiple scales (material, product, structure, and area) (Zhang et al., 2021). The Platform CB23 method comprises three main indicators: the existing material stock, an environmental assessment, and the retention of material value (Khadim et al., 2022). Other socio-economic and technical aspects are considered, such as quality and degradation, adaptive capacity, and availability. One of the main limitations identified is that assessment is not aggregated, resulting in the absence of a single circularity score for decision making purposes.

The Circularity Calculator, developed by IDEAL and CO Explore BV (Khadim et al., 2022), is an online decision tree tool that enables users to input data from the bill of materials to calculate a circularity score. In sequential steps, users input data such as product mass, material and production costs, and percentages of recycled or reused content, for instance (Ideal &Co, 2024). This data is then processed to generate scores for four quantitative indicators: the circularity indicator, value capture indicator, recycled content indicator, and reuse index. This facilitates the comparison of various circularity scenarios—including reuse, refurbishment, remanufacture, and recycling—enabling users to identify optimal design choices for improving product sustainability (Askar et al., 2022).

The Circular Building Assessment Platform (CBAP) is a semi-automated tool developed within the BAMB project (reference). The online platform utilises BIM data and allows users to upload files from common 3D modelling software. The CBAP calculates the reuse potential considering material selection, design parameters, and the building's lifecycle (Khadim). The CBAP facilitates decision-making by assessing resource productivity and reuse potential for both new and existing buildings. It is connected with Reversible Building Design strategies, which are also developed in the BAMB project. It should be noted that CBAP is still a prototype and is not yet an open-access tool for CE practitioners (Askar et al., 2022).

4.4.2 Indicators to measure circularity

The studies previously identified present an overview of existing frameworks for circularity assessment and their coverage. As concluded by Khadim et al. (2022), circularity indicators are dispersed across multiple frameworks and lack maturity and confidence from practitioners. However existing reviews do not systemically identify what data is collected to assess what and how, nor do they identify data requirements and measures. They remain at the category/strategy level. This section presents a mapping of the data requirements of the key circularity assessment frameworks identified in the literature review, and their relationship with scales, R-levels and circularity strategies.

The results demonstrate that, despite the diversity of frameworks, there is a degree of redundancy in data requirements. Furthermore, a limited number of indicators can be identified across the five key frameworks analysed (32). These redundancies are related to the different units considered in the assessment (e.g., amount in mass or amount in percentage) and the breakdown of indicators (e.g., ease of reuse instead of detachability and accessibility of connection, for instance). Table 5 inventories the indicators identified across methodologies.

Most indicators focus on closing resource loops (37.5%), which involves reintroduction of resources into the economic system through recycling or on slowing resource loops, which keeps resources in the system without major transformation through reuse (40.6%). Narrowing resource loops is associated with efficiency improvements in production processes, reducing water and energy demand, the mass of virgin materials and waste (12.5%). Regenerating is linked to the avoidance of toxic materials and potential of renewable materials (6.5%). Consequently, most indicators are related to material efficiency, which entails reducing the consumption of raw materials by shifting towards bio-based and secondary materials. Of these, less than a third (29%) relate to current circularity (the input of secondary materials from the design stage), while the majority (about 70%) address future circularity in the end-of-life phase (potential harvesting, reuse, or recycling scenarios). The second largest category of indicators is those pertaining to design for disassembly. These indicators are intended to assess the viability of a product for reuse at the end of its useful life. In addition to this, the majority of common assessment frameworks fail to adequately address adaptability (with no additional material use) and maintainability in order to extend the longevity of construction products.

Material is the scale more commonly assessed, however the distinction between material and component scale is not always clear. While mass of virgin material or amount of renewable materials refer to raw materials, other indicators such as percentage of reused materials tend to refer to transformed construction products and should thus be considered at component scale. This is an important distinction as it has implications on the interpretation of the R-levels and possible cascading throughout the life cycle. By definition, reuse refers to the use of a product in good condition and in its original function, which is only possible considering the product level. The act of "reusing" a material in a new product with a similar or different function implies a higher level of transformation and resource consumption. Consequently, this would thus be, by definition, repurposing or manufacturing (using the material to create new products). Most indicator frameworks do not consider the differences between R-levels in their circularity assessment. Furthermore, they often aggregate these levels under a common indicator for "secondary materials", despite the potential for significant differences in environmental impact.

Table 5 Inventory of indicators across methodologies

Indicator	Scale	R-level	Strategy	Source
Mass of virgin material	Material	Reduce	Narrow	MCI MAD-CI
Amount of scarce materials	Material	Reduce	Narrow	MCI
Amount of toxic materials	Material	Refuse	Regenerate	MCI
Amount of non-renewable primary materials	Material	-	Narrow	PCB23
Amount of renewable primary materials	Material	-	Regenerate	PCB23 MAD-CI
Percentage of secondary materials used	Material	Reuse-Recycle	Close	MAD-CI
Percentage of recycled input	Material	Recycle	Close	CC
Amount of secondary materials from recycling	Material	Recycle	Close	PCB23
Percentage of materials viable for secondary used	Material	Reuse-Recycle	Close	MAD-CI
Amount of unrecoverable waste	Material	Reduce	Narrow	MCI
Amount of materials viable for recycling	Material	Recycle	Close	PCB23
Amount of materials used for energy recovery	Material	Recovery	Close	PCB23

Percentage of waste stream downcycled	Material	Recycle-Recovery	Close	CC
Ease of recycling	Material	Recycle	Close	MAD-CI
Percentage actualy recycled after use	Material	Recycle	Close	CC
Percentage actually collected after use	Material	Reuse-Recycle	Close	CC
Ease of recovery (harvesting)	Component	Reuse-Recycle	Slow	PCB23
Ease of reuse	Component	Reuse	Slow	PCB23
Detachability of connection type	Component	Reuse-Recycle	Slow	MAD-CI
Accessibility of connection	Component	Reuse-Recycle	Slow	MAD-CI
Amount of secondary materials from reuse	Material/Component	Reuse	Slow	PCB23
Amount of materials viable for reuse	Material/Component	Reuse	Slow	PCB23
Percentage of actual refurbished after use	Component	Refurbish	Slow	CC
Percentage of actual remanufactured after use	Component	Remanufacture	Slow	CC
Length of use phase	Component	-	Slow	MCI, BCI, MAD-CI
Number of maintenance cycles	Component	Repair	Slow	CC
Techno-functional quality	Component	Repair	Slow	PCB23
Intensity of use	Component/building	Rethink	Slow	MCI

Spatio-functional adaptive capacity	Building	Rethink	Slow	PCB23
Environmental impact according to LCA	Component,	Reduce	ALL	MAD-CI PCB23 MCI
Energy use	Component, Building	Reduce	Narrow	MCI
Water use	Component, Building	Reduce	Narrow	MCI
Economic value loss	Component, building	-	Close	PCB23
Financial residual value	Component, building	-	Close	MAD-CI

4.5 Discussion and conclusions

The key literature reviews and case studies on the assessment of circularity in buildings analysed allow the identification of the main existing frameworks and a growing trend of research on the topic. The existing literature does not provide details on the actual indicators (here understood as measures) and data requirements. This gap that was addressed in the present research. By focusing the review of the literature on the existing reviews, this research contributes to harmonisation and integration of the existing knowledge. Furthermore, this approach also contributed to improve research results by including building sustainability assessments and grey literature that would not otherwise be identified through the search query.

One of the key issues identified is the lack of a systematic approach to data collection and assessment across the different circularity assessment methods. As observed by Khadim (2022), the indicators, data collected, units and scoring methods vary considerably between the different frameworks, making it challenging to compare and evaluate their effectiveness. Nevertheless, these indicators refer to a limited set of measures that frequently overlap, thereby underscoring the potential for developing a more standardized approach to data collection and assessment. Such an approach could improve the consistency and reliability of circularity measurements.

Another important gap in the existing methods is the tendency to focus primarily on material flows and disassembly, while neglecting other important aspects of circularity such as adaptability, repairability and maintainability (Askar et al., 2022; Zhang et al., 2021). This means that existing frameworks tend to focus on future circularity, and potential optimistic scenarios, and do not assess the current circularity achieved, for instance through adaptive reuse. Future frameworks should aim to address this imbalance and provide a more holistic assessment of circularity that considers the full range of strategies and their interconnections.

The literature review reveals that most of the frameworks fail to consider multiple lifecycles and the integration of a R-hierarchy, thereby risking the subversion of the circular economy concept and limiting its potential benefits (Kirchherr et al., 2017). This represents a significant gap, as the ability to maintain and extend the useful life of building components and materials through various R-strategies (Reuse, Repair, Refurbish, Remanufacture) is a fundamental principle of the circular economy and goes far beyond than closing loops by recycling (Van Buren et al., 2016). By incorporating multi-cycle considerations into circularity assessments, researchers and practitioners can more accurately assess the long-term value and environmental benefits of building components and materials, and potentially consider cascading scenarios throughout the lifecycle of a product. This cascading approach acknowledges the interdependence and hierarchy of the different R-strategies. Consequently higher-value strategies (e.g., repair, reuse) should be prioritized over lower-value ones (e.g., recycling). Integrating these multi-cycle perspectives would provide a more accurate and comprehensive understanding of the circularity of a building or building component. In the analysed assessment tools, only the Circularity Calculator accounts separately for percentages of recycled, reused, refurbished, or remanufactured materials. In the literature review, only the research of Zhang et al. (2021) proposes to factor the R-hierarchy in the assessment, without, however, detailing how these factors can be determined and quantified.

The analysis of the literature reveals that there is a growing emphasis on the integration of circularity assessment with other emerging technologies and frameworks, such as building information modelling (BIM) and material passports (Khadim et al., 2022). The integration of circularity assessment and material passports is particularly promising, as they can provide detailed information on the composition, origin, and potential for reuse or recycling of building materials and components, as well as ensuring traceability of end-of-life scenarios. This integration could significantly enhance the accuracy and applicability of circularity assessments, as well as facilitate the transfer of information between different stakeholders and systems, thereby facilitating more informed decision-making.

Closely related to this is the need to enhance the integration of the various stakeholders and their respective needs and roles in the design and evaluation of circularity (Cambier et al., 2020). By involving a broader range of stakeholders, researchers can develop more comprehensive and user-friendly assessment tools that are better aligned with the practical realities of the built environment. By actively engaging with practitioners and incorporating their feedback, researchers can ensure that the tools are responsive to the needs and concerns of the industry, and thus more widely adopted.

5 Co-creation: Practitioners' attitudes towards reuse of materials

5.1 Introduction

The success of digital tools to increase the circular resource use depends on a large market uptake of these solutions and their ability to add added value rather than create additional burdens for users. Involving users in the identification of information and functionality they need is fundamental to enabling a wider uptake of these tools. For this to happen "the situation should change from: 'what do we think should be in it?' to: 'where do we find the value?'" (Platform CB'23, 2020).

In the context of digital tools for circularity in construction, Takacs et al. (2022) emphasizes that maturity of technological solutions is a minor barrier, as many technical solutions exist but are not available where they are needed. Technological path dependencies associated with prevailing societal values and consumer behaviours can impede the replacement of old, inefficient technologies and processes (Takacs et al., 2022).

In their study on design tools, Weytjens et al. (2009) surveyed 319 architects in Flanders and found that experience is the most important factor in the design process (47%) and decision-making (86%), followed by clients' demands (76%). Only 21% of architects considered decision support tools to be significant for decision-making, and 20% for the design process. Among those who use design support tools, 70% believe that they should improve design quality, while 30% consider them to be effective means of enhancing the designer's knowledge. Similarly, Cambier et al. (2020) interviewed building designers in Flanders regarding the use of design support tools for circular buildings, revealing an oversupply of tools and a lack of clear workflow for information sharing and collaboration. The findings of this study corroborate those of Weytjens et al. (2009) in that they demonstrate the crucial role of experience, particularly in the context of time and resource constraints and increased design complexity.

It is insufficient to focus exclusively on technological solutions to drive more circular practices. A better understanding of designers' attitudes towards reuse of materials is fundamental to unlock the full potential of a reuse marketplace. The aim of this chapter was to investigate the role of tacit knowledge in shaping building designers' perceptions of "reuse of materials" and influencing their attitudes towards circularity.

5.2 Theoretical background

According to the theory of planned behaviour (TPB), attitudes are a fundamental determinant of behaviour (Ajzen, 1991). The likelihood of behaviour implementation depends on the alignment of attitudes, subjective norms, and perceived behavioural control. When these factors are aligned, intentions are more likely to translate into behaviour; otherwise, cognitive dissonance occurs, preventing implementation. Sheeran et al. (1999) propose that intentions driven by internal motivations and, attitudinally control have a higher likelihood of being performed than those controlled by external pressures. In the last decade this theoretical model of behaviour has been used to analyse designers' decisions regarding sustainable materials (Lee et al., 2013; Markström et al., 2016), construction waste minimisation (Li et al., 2015), and sustainable heritage conservation (J. Gonçalves et al., 2021), highlighting the significant role of attitudes as predictors of designers' behaviours.

In psychology, attitudes are defined as an individual's evaluative response to an object or entity, which may range from favour to disfavour (Eagly & Chaiken, 1998). Attitudes are formed as a result of direct and indirect experiences, and can have three distinct components: affective (feelings), behavioural (actions), and cognitive (thoughts). This model is knows as the ABC model of attitude (Eagly & Chaiken, 1998).

Recent studies emphasize the central role of emotions in sustainable behaviour, particularly as predictors of climate change risk perception, willingness to engage in mitigation actions, policy support, and technology acceptance. Emotional responses serve to highlight individuals' values and have intrinsic motivational value, as people strive to increase positive emotions and reduce negative ones (Brosch & Steg, 2021). Plutchik's emotion wheel (1980) identifies eight primary emotions: anger, anticipation, joy, trust, fear, surprise, sadness, and disgust.

The formation of an attitude is deeply rooted in individual's values, which are stable guiding principles that transcend specific situations (Bouman et al., 2018). Values and perceived self-identity are key motivators of pro-environmental behaviours (Bouman et al., 2021). Individuals tend to favour options that align with their prioritised values and consider the implications supporting those values (Steg, 2016). Steg (2016) identifies four fundamental values that influence environmental beliefs and actions. Self-transcending values are focused on the interests and well-being of others (altruistic) and the environment (biospheric). iN contrast, self-enhancing values are focused on self-interests, such as pleasure (hedonic) or status (egoistic). Self-transcending values tend to encourage climate action; conversely, self-enhancing values often inhibit it due to associated costs (Bouman et al., 2021). These costs may be monetary, but they may also be related to effort required. De Vries (2020) identifies the "hassle factor"—the perceived effort and inconvenience—as a significant psychological barrier to adopting pro-environmental behaviours.

The objective of this research is to describe designers' attitudes towards the reuse of materials. To this end, it analyses generative objects created in an interactive workshop supported by the theoretical framework presented. It is expected that understanding the determinants of behaviour will contribute to the identification of opportunities for the development of digital tools and marketplaces that effectively encourage practitioners to adopt more reused materials and components, with the ultimate objective of achieving a more circular built environment.

5.3 Methodology

An interactive workshop was organised with a sample of 11 architecture professionals from Belgium. The workshop took place in Brussels, on 5 October 2023 at the facilities of the Flemish Research Foundation (FWO). Participation was voluntary and the event was disseminated through the online networks of EnergyVille/VITO, the Horizon Europe Demo-BLog project, and the Belgian architecture platform architectura.be.

The research employed fenerative techniques to access participants' unconscious knowledge, thereby circumventing the limitations of conscious logical thinking and social desirability biases. The participants were asked to individually express "what does reuse of materials mean" to them by using collages and then they described the results in a short 3-minutes pitch. Qualitative content and thematic analysis were performed, coding keywords and images. Frequencies were also quantified to identify patterns and the most common beliefs. The data was analysed in accordance with the ABC model of attitudes, as defined by Eagly & Chaiken (1998), which has three components: affective, behavioural, and cognitive. To this framework an additional level variable was added, which analysed the participants' expressed values according to the framework of Steg (2019) for measuring values in environmental research.

5.4 Results

5.4.2 Values: drivers behind reuse of materials

The results show that **Biospheric values** have the most references, including references to ecosystem and sustainability. Despite the frequency of references to nature, only one participant refers to climate change when describing the meaning of reuse: "it is more of a way of life, reducing global warming is not just about materials". **Hedonic values** are consistently identified across images, text, and narrative, thus making it the second most frequently mentioned value. One participant uses an image of a plate repaired with the kintsugi technique – bonding with gold, with the words "seeing the beauty of the imperfect" to emphasize that repair can make products or materials reusable again but also be "charming" (Figure 6). References to **Egoistic values** were also identified, mostly linked to consumption patterns. However, these values were only a minority of and were not self-identified by the participants. Rather, they were identified as barriers to reuse. Through the collage, one participant reflected "we have tendency towards buying new things; Project developers want new facade after 20 years just because this sells better" (Figure 7).

Figure 6 Hedonic values expressed by the kintsugi technique.

Figure 7 Egoistic values related to luxury consumption patterns.

5.4.3 Affective component: emotions associated with reuse

The emotional responses of the participants were analysed according to Plutchik's wheel of emotions (1980). The results show that participants do not express sadness, disgust, or surprise regarding reuse of materials. Joy and optimism are the emotions most frequently expressed. Optimism is closely related to the emotions of **anticipation,** as participants express the feeling of looking forward to the future with **interest** and **curiosity,** a willingness to *try*, *experiment*, and l*ook for alternative ways*, but also with **vigilance** and a sense of urgency: "we need to do it now and don't push it any further". **Apprehension** is also expressed, which is connected with **trust** – or the lack thereof. Participants show apprehension regarding *uncertainties* associated with reuse, *unknown* pathways to successfully achieve it, and need for more *safety* and *control*.

5.4.4 Behavioral component: actions associated with reuse

The analysis of the behavioral component identifies the actions that architects most identify with the reuse of materials. **Reuse** is in itself the action most mentioned, framed by the scope of the workshop.

Demolition actions are identified as the ones that are avoided by reuse: "demolition is design failure" declares one participant, while other refers "some materials are just used once and then thrown away". **To make** appears associated with choice – represented by a participant with a *paper fortune teller*– in relation to policies and decisions. However, it is more often associated with a creation concept – *to make something*, *to make more sustainable*, *to make better* and in that sense overlapping with the action **to create** (the second most mentioned action). Reuse is a creative action that, according to one participant, requires designers to "try, experiment and see what or can work and cannot work". As asserted by another participant "if you make something that is beautiful and honest it will be used longer, and better, and more"".

While the workshop was focused on the reuse of materials participants addressed reuse at multiple scales, from the landscape to the material and including space. Designers have emphasized that reuse contributes to the limitation of expansion of the built environment, it is about "not building further and further in the landscape" and has the potential to connect and integrate urban areas to the surrounding **landscape**. Reuse is about "questioning the mortality or immortality of building materials". The **building** scale is often mentioned, as reuse goes beyond reusing parts to reuse *whole* structures or even *series of buildings* is "reflecting about the existing structures and trying to identify all buildings to be reused". **Space** emerges, thus, as a key concept, represented by the section of a building in a collage: "is about how to really use the spaces of existing heavy building and maybe reinterpret them".

5.4.5 Cognitive component: barriers and enablers

The cognitive component analysis identifies participants believes regarding barriers and enablers of reuse. Seven main believes about barriers to reuse of materials were identified:

- **Knowledge** (e.g.: "we don't know the exact route");
- **Uncertainty** (e.g.: "how are we dealing with these uncertainties?");
- **Complexity** (e.g.: "it's a very curvy and bumpy road");
- **Financial** (e.g.: "today we are in a system where everything is financially based");
- **Time** (e.g.: "it is possible you will have to wait a few months for something to come up");

- **Mindset** (e.g.: “project developers want new because it sells better”);
- **Inaction** (e.g.: “blah blah blah blah and but we're not doing it yet”).

Beliefs about barriers are often interrelated, for instance the barriers related to **financial** and **time** constraints require different **mindsets**: reuse “resembles slowing down a bit”, and questions existing ideas on *repairability, beauty,* and *value*. For participants, reuse is about “valuing more the products we use”, making them *last longer* and embracing its character and *history*: “every material has a history that we should think about”.

Participants identify the complexity of the challenge participants but also propose solutions to drive reuse materials. Seven enablers were found in the analysis:

- **Different values** (e.g.: “valuing more the products we use”);
- **Quality data** (e.g.: “data to get more safety”);
- **Transparency** (e.g: “the process should be really transparent and honest”);
- **Collaboration** (e.g.: “we need to work together”);
- **Affordability** (e.g.: “has to be affordable”);
- **Marketplaces** (e.g.: “a place to harvest and bring materials back”);
- **Policies** (e.g.: “we need quicker shifts in policy”);
- **Technology** (e.g.: “the technology already exists”).

Technology, quality data, and **transparency** are closely related as they can bridge **knowledge** gaps and provide *safety* and *control* to deal with **uncertainties**. While one participant highlights that reuse “it is not rocket science, the technology already exists”, others emphasize the need for more *analytic* tools and additional *data* that will allow to *measure impact of reuse*,. One participant places several *QR codes* on different components of a *building* and these are then connected to a hand drawn *industrial building*, representing **marketplaces** as a fundamental enabler of material reuse. **Transparency** is not always used in relation to information but is linked to beauty and the creative process instead. Using “honest materials, pure materials” will enable *easier deconstruction* processes and contribute *to long lasting* solutions; *showing* the imperfect and assuming the appearance of reused materials “should be a really transparent and really honest process, in the image of the building”, is a common topic across collages.

Overall, the results indicate that designers tend to adopt solution-oriented approach. Of the cognitive component factors coded, only 21% were identified as barriers, while the remaining 79% were enablers. From the enablers, *data* was the most mentioned one, followed by *policies* – identified as key to have a significant impact in changing reuse practices. Despite the focus on solutions, participants also display a strong external locus of control (Rotter, 1954), perceiving these solutions to be outside of their own control and dependent on external influences or circumstances. Only 19% of the references to enablers or reuse were perceived as the responsibility of the architects themselves, namely through their own design choices.

5.4.6 Designers' attitudes towards reuse of materials

The analysis suggests that designers' attitudes towards reuse are rooted on self-transcending values, with predominance of biospheric and altruistic values. The latter are linked to the important focus on collaboration as an enabler of reuse, ensuring inclusivity and multidisciplinary approaches. While the reuse of materials is triggered by the designers' engagement with nature and the environment, greenhouse gas emissions and carbon are barely mentioned, suggesting that other aspects may be more influential in driving reuse. Hedonic values, which relate to beauty, enjoyment, and aesthetic fruition, are consistently identified across scales of analysis, and play an important role in designers decision-making. The Incorporation of reused materials represents a creative challenge that is seen as an opportunity for transformation and value creation. Designers design from reuse, not the other way around. This means that reused materials are more than one-on-one replacements for new materials and that the availability, appearance, and story of reused materials will influence and even guide the design process.

Designers approach the challenge of reusing materials with optimism and positive emotions, although there is apprehension regarding the lack of trust in the quality and reliability of reused materials. They express a sense of urgency and interest in the topic but, yet despite their solution-oriented approach, they seem to believe that the solutions lie beyond their responsibility. Egoistic values, associated with personal gain, profit and prestige, can hinder the adoption of sustainable practices. While these pose a significant barrier, they are not self-identified. The participants believed that external factors, such as regulations, market demand, and availability of data on reuse materials, have a significant impact on their ability to reuse materials.

5.5 Discussion

5.5.1 Behavioural change does not (need to) change values

Behaviours are rooted in culture, experience, education, norms, values, and other psychological determinants and, as such they are hard to change. Interventions aimed at changing behaviours do not directly change behaviours (van Valkengoed et al., 2022). Instead, they target the variables that are inhibiting or enabling the behaviour in the first place. Individuals with higher biospheric and altruistic values are more likely to engage in pro-environmental behaviours than individuals with stronger egoistic and hedonic values (Steg, 2016). However, the present research suggests that often these values not only coexist but can also be competing. The participants emphasised biospheric values through situational factors and symbolic images (e.g., nature, tree, mountain). In contrast, hedonic values were more persistently identified, showing the importance of paying attention to aspects related to beauty, pleasure, fruition, or comfort when developing tools aimed at empowering designers to reuse materials. Highlighting the consequences of options that align with the values that users prioritize, is an important strategy that can contribute to change the perceptions of the costs and benefits of a behaviour (Steg, 2016). While CO2 emissions were hardly mentioned by the participants of the workshop, reinforcing positive actions already in place such as the adaptive reuse of existing buildings (historic feedback) or featuring information regarding the materials story, history, and heritage values of reused materials and components (information provision), can achieve the same goal (reduction of CO2 emissions) by triggering different values.

5.5.2 Everyone is doing something

The results of the workshop are aligned with the self-reported value endorsement observed in Belgium reported by Bouman et al. (2021). Participants perceptions of their own values and others' values differ considerably: while designers refer to their biospheric values and ambition to create in harmony with nature, they identify "others" egoistic values as a major barrier to reuse (from project developers to society in general). This corroborates the findings of Bouman et al. (2021), participants in the workshop "believe that most others care considerably less about the environment than they do themselves".

At the same time, the expressed altruistic values appear as manifestations of the dominant external locus of control: by emphasizing the need to collaborate, participants express the allocation of responsibility to others, as they feel the solution does not depend on them alone. Together, these two factors may pose a significant barrier to adoption of reused materials and circular design practices, as by underestimating other's biospheric values and environmental action designers may regard their own individual actions as inefficacious and feel demotivated (Bouman et al., 2021). Interventions that strengthen perceived values of the group, emphasizing that others are also taking action, can have a significant role in encouraging adoption. In the case of reused materials marketplaces this could mean, for instance, accounting for CO2 saved together by using the platform (group-based feedback) or benchmarking the user's reuse material score against other designers in the area (social comparison feedback).

5.5.3 Avoiding the hassle factor

The workshop shows that affective attitudes of designers regarding reuse oscillate between optimism and fear/apprehension. Fear can make people more aware of the risks and uncertainties associated with environmental problems, but it can also lead to avoidance, denial, or helplessness if the problems seem too large and uncontrollable (Brosch & Steg, 2021). This emphasizes the importance of dealing with the trust issues that have been identified, providing reliable data, transparency, and credible information regarding the quality, safety, and technical performance of reused materials. Conversely, positive emotions, such as pride, pleasure, or hope, can enhance pro-environmental intentions and actions.

Emotional responses are also related to the hassle factor identified by De Vries (de Vries et al., 2020) as a psychological barrier. When anticipating stress and unpleasant uncomfortable processes, people will tend to avoid the behaviour. This seems to be the case also with reuse of materials. In the open discussion following the collage exercise, participants expressed concerns regarding the additional hassle of calculating the impacts associated with reused materials, integrated in an already complex and time-limited process. To facilitate the adoption of reused materials in practice, the process has to be easier and more convenient than the status quo. Certain strategies can contribute to mitigate the hassle factor, for instance, reduce cognitive effort by making reused materials the default scenario in calculation and design tools, or avoiding information overload by providing information tailored to the values of the user – not necessarily about environmental consequences of the action (information provision).

5.6 Conclusions

In conclusion, this study reveals that designers' attitudes towards the reuse of materials are influenced by a combination of self-transcending values, predominantly biospheric and altruistic, but also a significant role of hedonic values. These attitudes are further shaped by the perceived opportunities for creativity, transformation, and value creation that reused materials present. Despite the challenges and apprehensions regarding the quality and reliability of reused materials, designers adopt an optimistic and a solution-oriented mindset in addressing these concerns. However, they also acknowledge that the responsibility for solutions extends beyond their individual roles, indicating the influence of external factors such as regulations, market demand, cooperation with others, and data availability.

This research also identifies a number of key strategies to empower designers to reuse materials, considering the values and attitudes identified, namely: information provision tailored to users' values (in particular hedonic values), historical feedback, with positive reinforcement of actions already in place (such as adaptive reuse), group-based feedback, and social comparison feedback, which emphasises the contribution of the individual to the bigger picture. Interventions that reduce cognitive effort, such as making reused materials the default scenario in design tools, providing tailored information to the determinants of behaviour and integrating reuse in already ongoing processes, can help overcome barriers to adoption.

Overall, the findings underscore the importance of understanding designers' attitudes and the role of tacit knowledge in promoting the reuse of materials and achieving a more sustainable built environment. The small size of the sample is a limitation of the present study. Future efforts should validate the results presented with a survey disseminated with a representative sample of the study population, which would allow to develop user profiles that are inclusive and representative of the larger professional population and substantiate tailored approaches to encourage more circular practices in the built environment.

6 Specifications for integration of multi-cycle circularity in DBLs

6.1 What is now?

The analysis of the State of Practice in the specific five DBLs demonstrated in the Demo-BLog project, presented in chapter 2, provides an overview of the current state of DBLs and their coverage of circularity-related data fields. The national context, scope, level of complexity, and target audience varies considerably between the five demonstrators, which illustrates the diversity of ongoing DBL developments. Nevertheless, the results show that most DBLs have a one-dimensional focus on the use phase and operational energy consumption, with a lack of comprehensive coverage of the whole life cycle of the building.

The current functionalities have an emphasis on facilitating the improvement of energy efficiency in buildings, and thus contribute to narrowing energy resource loops. By facilitating condition assessment and integrating maintenance and repair functionalities, some of the analysed DBLs contribute to extend the buildings' lifetime in the use phase, slowing resource loops. But overall, a major gap can be identified in the relation of the potential of DBLs to contribute to closing resource loops. DBLs have the potential to enable tracking, tracing, and exchange of resources in the economic cycle. However, material inventories and/or bill of materials at the whole building scale (beyond energy systems) are rarely integrated into current practice.

6.2 What should become?

Chapter 3 presents an overview of the European policy landscape and its potential impact on the future developments of DBLs. These are specifically addressed by the Renovation Wave, the Strategy for a Sustainable Built Environment Legislative train and in the EPBD, defined as repositories of data on individual buildings that facilitate information sharing between stakeholders. While the focus is currently on energy performance, the new EPBD highlights the importance of including life cycle GWP data, pointing in the direction of a stronger integration of whole life cycle data, including material resources. Compatibility with the Level(s) assessment framework is a key priority for assessing and reporting on the sustainability performance of buildings, including circularity.

Future DBL developments need to consider a rising importance of closing and slowing resource loops. The integration of a detailed bill of materials will increase traceability of resources and EOL scenarios and ensure data availability for LCA and Leve(s) assessments. Providing information to estimate potential ease of disassembly, ease of reuse, and ease of recycling is increasingly important.

6.3 What is missing?

The policy requirements identified highlight key priorities towards the integration of circularity in DBLs, but these are still far from offering a comprehensive coverage of circularity strategies. At the same time, some of the indicators rely on assumptions (e.g., best possible outcomes) and subjective assessment checklists (e.g., ease of reuse). To bridge this gap, the State of the Art presented in chapter 4, maps existing circularity assessment frameworks and inventories indicators to measure circularity at multiple scales (material, component, and building).

The results show the abundance and diversity of frameworks, with a lack of harmonised calculation methods and definitions. However, a limited set of indicators has been identified that have the potential to cover blind spots in current DBLs and policy requirements related to economic aspects, material scarcity and sustainable sourcing, quality and maintenance, adaptability, and actual quantification and hierarchisation of EOL scenarios based on the R-hierarchy, supporting a multi-cycle approach.

6.4 What is needed?

The research results suggest that the integration of multi-cycle circularity into DBLs will come at the cost of increased complexity, with additional data requirements and assessment indicators. Ideally, a holistic circularity assessment framework should include a whole life cycle approach, covering present and future circularity, factoring differences between different R-levels, and integrating environmental, economic aspects, and social aspects. However, ensuring higher adoption requires less time consuming and less complex processes, that prioritise stakeholders' values. Chapter 5 presents the results of the co-creation workshop with practitioners, conducted to better understand the potential of DBLs to improve multi-cycle circularity by supporting a reuse marketplace.

Three key aspects are highlighted: changing the behaviours towards higher adoption of circular practices (and in particular reused materials) needs to be aligned with designers' values; circularity assessments should emphasize current circularity and valorise ongoing circular practices, gradually nudging towards more ambitious goals. The success of DBLs will depend on their capacity to avoid the hassle factor, and smoothly integrate with existing assessment and design tools, making fulfilling legal requirements easier and more convenient.

6.4 DBLs for enhanced multi-cycle circularity

The answers to the four questions above inform the development of a set of specifications for integration of multi-cycle circularity in DBLs. The specifications for data requirements are divided in four levels of priority, as presented below.

Minimum requirements:

The minimum requirements (table 6) form the baseline that ensures DBLs aggregate sufficient information to ensure traceability throughout the whole life cycle. These minimum requirements do not provide circularity or sustainability assessments by themselves but provide the information for these assessments to be performed outside the DBL environment, according to the European policy analysis.

Table 6 Indicators to fulfil minimum requirements

Indicator	Unit	Scale	Strategy
Bill of materials	Mass in kg	Materials - Building	ALL
Traceability of end of-life outcomes	-	Materials/ Components	Close
Traceability of contractual agreements *(take back schemes, producer responsibility)*	-	Materials / Components	Slow/Close
Certifications *(EPD, EPC, etc.)*	-	Component/Building	ALL

Priority 1

By integrating the indicators in this priority level (table 7), DBLs can anticipate and ensure compatibility with European policies, including whole life cycle assessment (LCA) and the Level(s) framework, while reducing the hassle factor for practitioners. These focus mostly on closing resource loops.

Table 7 Priority 1 indicators

Indicator	Unit	Scale	Strategy
Amount of toxic materials	Mass in kg	Materials	Regenerate
Split f CDW EOL Scenarios *(reused, recycled, recovery, landfilled)*	Mass in kg	Materials	Close
Expected service life	Years	Component	Slow
Global Warming Potential *(according to LCA methodology)*	kg CO2 eq.	Component/Building	ALL
Ease of reuse, recycling, disassembly *(options, instructions, information)*	-	Component	Slow/Close

Priority 2

The indicators in this level address (table 8) the priorities identified in co-creation with the stakeholders; these are, thus, specific to the scope of the Demo-BLog project and its target audience (architects in Flanders). As a general recommendation, priority 2 requirements should be defined in co-creation with target stakeholders, ensuring that they are aligned with their needs and values. The requirements in these priority level focus mostly on slowing resource loops.

Table 8 Priority 2 indicators

Indicator	**Unit**	**Scale**	**Strategy**
Split of input material *(renewable, reused, recycled…)*	Mass in kg	Material	Narrow
Disassembly score *(detachability and accessibility)*	-	Component	Slow/Close
Realistic output in end-of-use *(split by R-levels)*	Mass in kg	Material/Component	Slow/Close
Techno-functional value *(condition, performance)*	(depends on product)	Component	Slow
Spatio-functional adaptive capacity	-	Building	Slow
Aesthetic aspects *(color, texture, shape, size and proportion, etc.)*	-	Material/Component	Slow
Heritage values and narratives	-	Component/Building	Slow
Price *(and saving in comparison to new product)*	Euros	Component	Slow
Automated environmental impacts *(according to LCA methodology)*	(depending on indicator)	Component/Building	ALL
Connection to BIM *(automated bill of materials)*	-	Materials - Building	ALL

Priority 3

The indicators in this priority level (table 9) include complementary indicators for a more complete contribution towards circularity, including strategies to narrow, slow, close, and regenerate the loops. Some of these indicators are already integrated in Demo-BLog demonstrators, while not specifically showcase by their contribution to circularity.

Table 9 Priority 3 indicators

Indicator	Unit	Scale	Strategy
Amount of scarce materials	Mass in kg	Materials	Narrow
Number of maintenance cycles	n.	Component	Slow
Intensity of use	(depending on product)	Component/Building	Slow
Energy use	kWh/yr	Component/Building	Narrow
Water use	$m^3/o/a$	Component/Building	Narrow
Economic value loss	Euro	Component/Building	Slow
Financial residual value	Euro	Component/Building	Slow/Close

6.4 Recommendations for future research

The set of data requirements provided is not intended to generate a circularity assessment score, as these scores can vary depending on the methodology and are not yet consistent, standardised, or widely accepted. Instead, the integrated data requirements provide the essential information needed to input data for circularity assessments that are compatible with different methodologies.

Future research should address the need for harmonised calculation methods. Design for disassembly and deconstruction scores exist today, but they are not comparable between frameworks. The Level(s) circularity score attributes a circularity score based on the “best possible outcome” defined by the user (reuse, recycle, landfill, etc.). The design for disassembly indicator proposed in the European Commission (2023) considers only the percentage of reuse potential by mass. The disassembly determining factors by Durmisevic (2006) is the most frequently cited methodology, although not all of the proposed indicators are applied, focusing mainly on the type of connection and accessibility to fixing and not considering among others, morphology and geometry, or assembly sequences. Although it provides a numerical score, this method depends on subjective assessments.

The systematic literature review identified some frameworks that address spatial adaptive capacity within the context of circularity. However, the results suggest that these frameworks are not yet widely adopted, despite being recognised as a key priority by practitioners. Additionally, techno-functional value, which involves ensuring technical quality and measuring degradation, needs to be considered to achieve holistic circularity assessments.

Conclusions

A comprehensive analysis of current practices, policy landscapes, and co-creation processes with stakeholders was conducted to identify both the existing gaps and the future requirements necessary to enhance the functionality of DBLs in supporting multi-cycle circularity.

The current state of DBLs, as highlighted in this report, reveals a predominant focus on the operational phase of buildings, particularly energy efficiency. While this is an important aspect, it underscores a critical gap in addressing the whole life cycle of buildings, especially regarding material inventories and their reuse potential. The findings indicate that to achieve the full benefits of circularity, DBLs must evolve to include detailed information on materials and ensure traceability of end-of-use scenarios.

Future developments in DBLs are expected to be significantly influenced by European policies, such as the Renovation Wave and the updated Energy Performance of Buildings Directive (EPBD). These policies emphasise the need for comprehensive life cycle data, in alignment with frameworks, such as like Level(s) to ensure the consistency and reliability of sustainability assessments. Therefore, incorporating these requirements into DBLs will be crucial for their future relevance and effectiveness.

Despite the progress made, several challenges remain. The diversity and lack of harmonisation among existing circularity assessment frameworks create confusion and hinder the broader adoption of circular practices. Existing methods often focus on material flows and disassembly, neglecting adaptability, repairability, and multi-cycle considerations, which are crucial for a holistic assessment of circularity. Integrating circularity assessments with emerging technologies like BIM and material passports, and involving a broader range of stakeholders, could improve the consistency, accuracy, and adoption of these assessments.

To integrate multi-cycle circularity effectively, DBLs need to balance the increasing complexity with user-friendly approaches. Stakeholder engagement through co-creation workshops has highlighted the importance of aligning circularity assessments with the values of designers and practitioners. Emphasising current circularity practices and gradually introducing more ambitious goals can facilitate higher adoption rates. Moreover, DBLs must integrate smoothly with existing tools and processes, minimising additional burdens on users.

The proposed specifications for data requirements in DBLs are structured into four priority levels, ensuring a progressive and comprehensive approach to multi-cycle circularity. The minimum requirements form the baseline for traceability, while higher priority levels address policy compatibility, stakeholder needs, and a holistic approach to circularity. The set of data requirements provided do not aim to provide a circularity assessment score, as these may vary according to methodology and these are not yet consistent, standardised, and widely accepted. The integrated data requirements provide the necessary information to input data for circularity assessment compatible with multiple methodologies.

In conclusion, this report establishes a baseline framework for the future development of DBLs as enablers of circularity in the built environment. By addressing the identified gaps and aligning with policy and stakeholder needs, DBLs can make a significant contribution to closing, slowing, and narrowing resource loops, and ultimately drive the transition towards a circular economy.

References

State of Practice: Integration of circularity in Demo-BLog Digital Building Logbooks

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Bouman, T., Steg, L., & Kiers, H. A. L. (2018). Measuring Values in Environmental Research: A Test of an Environmental Portrait Value Questionnaire. *Frontiers in Psychology*, *9*, 564. https://doi.org/10.3389/fpsyg.2018.00564

Bouman, T., van der Werff, E., Perlaviciute, G., & Steg, L. (2021). Environmental values and identities at the personal and group level. *Current Opinion in Behavioral Sciences*, *42*, 47–53. https://doi.org/10.1016/j.cobeha.2021.02.022

Brosch, T., & Steg, L. (2021). Leveraging emotion for sustainable action. *One Earth*, *4*(12), 1693–1703. https://doi.org/10.1016/j.oneear.2021.11.006

Cambier, C., Galle, W., & De Temmerman, N. (2020). Research and Development Directions for Design Support Tools for Circular Building. *Buildings*, *10*(8), Article 8. https://doi.org/10.3390/buildings10080142

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. *Sustainability*, *13*(11), Article 11. https://doi.org/10.3390/su13116348

CIRDAX. (2023). Vastgoed Digitalisering. https://www.cirdax.com/

CLÉA. (2023). CLÉA, l'espace Numérique Du Logement. https://clea.qualitel.org/

de Vries, G. (2020, July 16). Habit and hassle: Psychological barriers to sustainable behaviour. *LSE Business Review*. https://blogs.lse.ac.uk/businessreview/2020/07/16/habit-and-hassle-psychological-barriers-to-sustainable-behaviour/

de Vries, G., Rietkerk, M., & Kooger, R. (2020). The Hassle Factor as a Psychological Barrier to a Green Home. *Journal of Consumer Policy*, *43*(2), 345–352. https://doi.org/10.1007/s10603-019-09410-7

Dourlens-Quaranta, S., Carbonari, G., Groote, M. D., Borragán, G., Regel, S. D., Toth, Z., Volt, J., Glicker, J., Lodigiani, A., Calderoni, M., Loureiro, T., Sterling, R., Vandevelde, B., Spirinckx, C., Kondratenko, I., Rajagopalan, N., & Rapf, O. (2020). *Study on the Development of a European Union Framework for Digital Building Logbooks* (Final; Study on the Development of a European Union Framework for Digital Building Logbooks). Executive Agency for Small and Medium-sized Enterprises (European Commission). https://doi.org/10.2826/493576

Eagly, A. H., & Chaiken, S. (1998). Attitude structure and function. In *The handbook of social psychology, Vols. 1-2, 4th ed* (pp. 269–322). McGraw-Hill. https://books.google.be/books?hl=en&lr=&id=-4InWCsra7IC&oi=fnd&pg=PA269&dq=%5B8:16+AM%5D+Joana+Gon%C3%A7alves+Eagly,+A.+H.,+%26+Chaiken,+S.+(1998).+Attitude+structure+and+function.+In+D.+T.+Gilbert,+S.+T.+Fiske,+%26+G.+Lindzey+(Eds.),+The+handbook+of+social+psychology+(pp.+269%E2%80%93322).+McGraw-Hill.&ots=hciBWL-qmb&sig=_AYnkcRdqN18YytTrXYNcMME8TY&redir_esc=y#v=onepage&q&f=false

EEA. (2022). *Circular economy country profile – Belgium* (ETC CE Report 2022/5). European Environmental AGency.

European Commission. (2021). *Level(s), Putting whole life carbon into practice*. Directorate-General for the Environment (European Commission). https://doi.org/10.2779/284030

European Innovation Council and SMEs Executive Agency. (2023). *Study on measuring the application of circular approaches in the construction industry ecosystem: Final study*. Publications Office. https://data.europa.eu/doi/10.2826/488711

European Parliament. (2023). *Strategy for a Sustainable Built Environment*. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-strategy-for-a-sustainable-built-environment

Gómez-Gil, M., Espinosa-Fernández, A., & López-Mesa, B. (2022). Review and Analysis of Models for a European Digital Building Logbook. *Energies*, *15*(6), 1994. https://doi.org/10.3390/en15061994

Gonçalves, J. D. S., Mateus, R., Silvestre, J. D., & Roders, A. R. P. (2021). Beyond good intentions: The role of the building passport for the sustainable conservation of built heritage to behavioural change. *Sustainability (Switzerland)*, *13*(15). https://doi.org/10.3390/su13158280

Gonçalves, J., Mateus, R., Silvestre, J. D., Roders, A. P., & Bragança, L. (2021). Attitudes matter: Measuring the intention-behaviour gap in built heritage conservation. *Sustainable Cities and Society*, *70*. https://doi.org/10.1016/j.scs.2021.102913

Hartenberger, U., Ostermeyer, Y., & Lützkendorf, T. (2021). *The Building Passport: A tool for capturing and managing whole life data and information in construction an real estate—Practical guideline*. Global Alliance for Buildings and Construction, UNEP. https://globalabc.org/resources/publications/building-passport-tool-capturing-and-managing-whole-life-data-and

Honic, M., Kovacic, I., Aschenbrenner, P., & Ragossnig, A. (2021). Material Passports for the end-of-life stage of buildings: Challenges and potentials. *Journal of Cleaner Production*, *319*, 128702. https://doi.org/10.1016/j.jclepro.2021.128702

Jansen, M., Gerstenberger, B., Bitter-Krahe, J., Berg, H., Sebestyén, J., & Schneider, J. (2022). *Current approaches to the digital product passport for a circular economy: An overview of projects and initiatives* (Vol. 198). Wuppertal Institut für Klima, Umwelt, Energie. https://doi.org/10.48506/opus-8042

Lee, E., Allen, A., & Kim, B. (2013). Interior Design Practitioner Motivations for Specifying Sustainable Materials: Applying the Theory of Planned Behavior to Residential Design. *Journal of Interior Design*, *38*(4), 1–16. https://doi.org/10.1111/joid.12017

Li, J., Tam, V. W. Y., Zuo, J., & Zhu, J. (2015). Designers' attitude and behaviour towards construction waste minimization by design: A study in Shenzhen, China. *Resources, Conservation and Recycling*, *105*, 29–35. https://doi.org/10.1016/j.resconrec.2015.10.009

Markström, E., Bystedt, A., Fredriksson, M., & Sandberg, D. (2016). *Perceptions of Swedish architects and contractors for the use of bio-based building materials*. https://www.semanticscholar.org/paper/Perceptions-of-Swedish-architects-and-contractors-Markstr%C3%B6m-Bystedt/7c9a45ccfd60da9000a25c6ecc7fd8b68558373d

Nugent, Audrey, Montano-Owen, Carolina, Pallares, Laura, Richardson, Stephen, & Rowland, Miles. (2022). *EU Policy Whole life carbon roadmap*. World Green Building Council. https://viewer.ipaper.io/worldgbc/eu-roadmap/?page=1

Platform CB'23. (2020). *Guide for Passports for the Construction Sector 2.0*. Platform CB'23. https://platformcb23.nl/english

Plutchik, R. (1980). Chapter 1—A GENERAL PSYCHOEVOLUTIONARY THEORY OF EMOTION. In R. Plutchik & H. Kellerman (Eds.), *Theories of Emotion* (pp. 3–33). Academic Press. https://doi.org/10.1016/B978-0-12-558701-3.50007-7

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain* [Policy Report]. PBL Netherlands Environmental Assessment Agency.

Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Energy Performance of Buildings (Recast), COM/2021/802, European Commision, COM(2021) 802 final (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

Sheeran, P., Norman, P., & Orbell, S. (1999). Evidence that intentions based on attitudes better predict behaviour than intentions based on subjective norms. *European Journal of Social Psychology*, *29*(2–3), 403–406. https://doi.org/10.1002/(SICI)1099-0992(199903/05)29:2/3<403::AID-EJSP942>3.0.CO;2-A

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T., & T. Garofano, N. (2023). Circular economy in the Australian AEC industry: Investigation of barriers and enablers. *Building Research & Information*, *51*(1), 56–68. https://doi.org/10.1080/09613218.2022.2099788

Steg, L. (2016). Values, Norms, and Intrinsic Motivation to Act Proenvironmentally. *Annual Review of Environment and Resources*, *41*(1), 277–292. https://doi.org/10.1146/annurev-environ-110615-085947

Takacs, F., Brunner, D., & Frankenberger, K. (2022). Barriers to a circular economy in small- and medium-sized enterprises and their integration in a sustainable strategic management framework. *Journal of Cleaner Production*, *362*, 132227. https://doi.org/10.1016/j.jclepro.2022.132227

van Capelleveen, G., Vegter, D., Olthaar, M., & van Hillegersberg, J. (2023). The anatomy of a passport for the circular economy: A conceptual definition, vision and structured literature review. *Resources, Conservation & Recycling Advances*, *17*, 200131. https://doi.org/10.1016/j.rcradv.2023.200131

van Valkengoed, A. M., Abrahamse, W., & Steg, L. (2022). To select effective interventions for pro-environmental behaviour change, we need to consider determinants of behaviour. *Nature Human Behaviour*, 6(11), Article 11. https://doi.org/10.1038/s41562-022-01473-w

Weytjens, L., Verdonck, E., & Verbeeck, G. (2009). Classification and Use of Design Tools: The Roles of Tools in the Architectural Design Process. *Design Principles and Practices: An International Journal—Annual Review*, *3*(1), 289–302. https://doi.org/10.18848/1833-1874/CGP/v03i01/37572

Policy context: the future of Digital Building Logbooks

PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal

European Commission (2021a) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS “Fit for 55”: delivering the EU’s 2030 Climate Target on the way to climate neutrality

European Commission (2020a) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A new Circular Economy Action Plan For a cleaner and more competitive Europe

European Commission (2022a) Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011

European Commission (2021b) Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast)

European Commission (2022b) Proposal for a Regulation establishing a framework for setting ecodesign requirements for sustainable products, amending Regulation (EU) 2019/1020 and repealing Directive 2009/125/EC

European Commission (2023) Types of EU law. In: Types EU Law. https://commission.europa.eu/law/law-making-process/types-eu-law_en. Accessed 15 Jun 2023

European Commission (2020b) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives

European Parliament (2023a) Energy performance of buildings (recast) Amendments adopted by the European Parliament on 14 March 2023 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast) (COM(2021)0802 – C9-0469/2021 – 2021/0426(COD))1

European Parliament (2023b) Strategy for a Sustainable Built Environment

European Union (2020) Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance)

Nugent, Audrey, Montano-Owen, Carolina, Pallares, Laura, et al (2022) EU Policy Whole life carbon roadmap. World Green Building Council

Directorate-General for Environment (European Commission). (2021). *Level(s): Putting circularity into practice*. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/19010

European Innovation Council and SMEs Executive Agency (European Commission), Brincat, C., Graaf, I. de, León Vargas, C., Mitsios, A., Neubauer, N., Adams, K., & Hobbs, G. (2023). *Study on measuring the application of circular approaches in the construction industry ecosystem: Final study*. Publications Office of the European Union. https://data.europa.eu/doi/10.2826/488711

German Sustainable Building Council (DGNB). (2020). *Ease of Recovery and recycling TEC1.6* (DGNB System - New Buildings Criteria Set). German Sustainable Building Council (DGNB).

State of the Art: Systematic review on measuring circularity in the built environment

Abadi, M., & Moore, D. R. (2022). Selection of Circular Proposals in Building Projects: An MCDM Model for Lifecycle Circularity Assessments Using AHP. *Buildings*, *12*(8), Article 8. https://doi.org/10.3390/buildings12081110

Abruzzini, A., & Abrishami, S. (2021). Integration of BIM and advanced digital technologies to the end of life decision-making process: A paradigm of future opportunities. *Journal of Engineering, Design and Technology*, *20*(2), 388–413. https://doi.org/10.1108/JEDT-12-2020-0524

Ajayebi, A., Hopkinson, P., Zhou, K., Lam, D., Chen, H.-M., & Wang, Y. (2020). Spatiotemporal model to quantify stocks of building structural products for a prospective circular economy. *Resources, Conservation and Recycling*, *162*, 105026. https://doi.org/10.1016/j.resconrec.2020.105026

Akanbi, L. A., Oyedele, L. O., Akinade, O. 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. *Resources, Conservation and Recycling*, *129*, 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, *223*, 386–396. https://doi.org/10.1016/j.jclepro.2019.03.172

Akinade, O. O., & Oyedele, L. O. (2019). Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS). *Journal of Cleaner Production*, *229*, 863–873. https://doi.org/10.1016/j.jclepro.2019.04.232

Alberto López Ruiz, L., Roca Ramon, X., Melissa Lara Mercedes, C., & Gasso Domingo, S. (2022). Multicriteria analysis of the environmental and economic performance of circularity strategies for concrete waste recycling in Spain. *Waste Management*, *144*, 387–400. https://doi.org/10.1016/j.wasman.2022.04.008

Al-Hamrani, A., Kim, D., Kucukvar, M., & Onat, N. C. (2021). Circular economy application for a Green Stadium construction towards sustainable FIFA world cup Qatar 2022™. *Environmental Impact Assessment Review*, *87*, 106543. https://doi.org/10.1016/j.eiar.2020.106543

Ali, A. K., Kio, P. N., Alvarado, J., & Wang, Y. (2020). Symbiotic Circularity in Buildings: An Alternative Path for Valorizing Sheet Metal Waste Stream as Metal Building Facades.

Waste and Biomass Valorization, *11*(12), 7127–7145. https://doi.org/10.1007/s12649-020-01060-y

Andersen, C. E., Kanafani, K., Zimmermann, R. K., Rasmussen, F. N., & Birgisdóttir, H. (2020). *Comparison of GHG emissions from circular and conventional building components* (1). *1*(1), Article 1. https://doi.org/10.5334/bc.55

Andersen, S. C., Birgisdottir, H., & Birkved, M. (2022). Life Cycle Assessments of Circular Economy in the Built Environment—A Scoping Review. *Sustainability*, *14*(11), Article 11. https://doi.org/10.3390/su14116887

Andrade, J., Araújo, C., Castro, M. F., & Bragança, L. (2019). New Methods for Sustainable Circular Buildings. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012037. https://doi.org/10.1088/1755-1315/225/1/012037

Androsevic, R., Durmisevic, E., & Brocato, M. (2019). Measuring reuse potential and waste creation of wooden façades. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012017. https://doi.org/10.1088/1755-1315/225/1/012017

Antwi-Afari, P., Ng, S. T., & Chen, J. (2022). Developing an integrative method and design guidelines for achieving systemic circularity in the construction industry. *Journal of Cleaner Production*, *354*, 131752. https://doi.org/10.1016/j.jclepro.2022.131752

Antwi-Afari, P., Ng, S. T., & Hossain, Md. U. (2021). A review of the circularity gap in the construction industry through scientometric analysis. *Journal of Cleaner Production*, *298*, 126870. https://doi.org/10.1016/j.jclepro.2021.126870

Arora, M., Raspall, F., Fearnley, L., & Silva, A. (2021). Urban mining in buildings for a circular economy: Planning, process and feasibility prospects. *Resources, Conservation and Recycling*, *174*, 105754. https://doi.org/10.1016/j.resconrec.2021.105754

Asante, R., Faibil, D., Agyemang, M., & Khan, S. A. (2022). Life cycle stage practices and strategies for circular economy: Assessment in construction and demolition industry of an emerging economy. *Environmental Science and Pollution Research*, *29*(54), 82110–82121. https://doi.org/10.1007/s11356-022-21470-w

Askar, R., Bragança, L., & Gervásio, H. (2021). Adaptability of Buildings: A Critical Review on the Concept Evolution. *Applied Sciences*, *11*(10), Article 10. https://doi.org/10.3390/app11104483

Askar, R., Bragança, L., & Gervásio, H. (2022). Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings. *Applied System Innovation*, *5*(1), Article 1. https://doi.org/10.3390/asi5010024

Atik, S., Domenech, T., & Raslan, R. (2023). *The Opportunities and Challenges of Using LCA-Based BIM Plugins in Early-Stage Building Design: An Industry Expert Perspective* (pp. 401–408). https://doi.org/10.1007/978-981-19-4293-8_42

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, *43*, 103233. https://doi.org/10.1016/j.jobe.2021.103233

Azcarate-Aguerre, J. F., Klein, T., Konstantinou, T., & Veerman, M. (2022). Facades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope. *Applied Sciences*, *12*(3), Article 3. https://doi.org/10.3390/app12031267

Backes, J. G., Del Rosario, P., Luthin, A., & Traverso, M. (2022). Comparative Life Cycle Assessment of End-of-Life Scenarios of Carbon-Reinforced Concrete: A Case Study. *Applied Sciences*, *12*(18), Article 18. https://doi.org/10.3390/app12189255

Balasbaneh, A. T., & Sher, W. (2022). Economic and environmental life cycle assessment of alternative mass timber walls to evaluate circular economy in building: MCDM method. *Environment, Development and Sustainability*, *26*(1), 239–268. https://doi.org/10.1007/s10668-022-02707-7

Bayram, B., & Greiff, K. (2023). Life cycle assessment on construction and demolition waste recycling: A systematic review analyzing three important quality aspects. *The International Journal of Life Cycle Assessment*, *28*(8), 967–989. https://doi.org/10.1007/s11367-023-02145-1

Benedetti, A. C., Costantino, C., Gulli, R., & Predari, G. (2022). The Process of Digitalization of the Urban Environment for the Development of Sustainable and Circular Cities: A Case Study of Bologna, Italy. *Sustainability*, *14*(21), Article 21. https://doi.org/10.3390/su142113740

Berardi, U., Alfaro Garrido, L. J., Procházkova, Z., Pich-aguilera Baurier, F., & Manca, M. (2020). *Building circular economy: A case study designed and built following a BIM-based life cycle assessment approach*. 1–8. https://doi.org/10.23967/dbmc.2020.179

Bosone, M., De Toro, P., Fusco Girard, L., Gravagnuolo, A., & Iodice, S. (2021). Indicators for Ex-Post Evaluation of Cultural Heritage Adaptive Reuse Impacts in the Perspective of the Circular Economy. *Sustainability*, *13*(9), Article 9. https://doi.org/10.3390/su13094759

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. *Resources, Conservation and Recycling*, *164*, 105149. https://doi.org/10.1016/j.resconrec.2020.105149

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019a). Consequential LCA of demountable and reusable internal wall assemblies: A case study in a Belgian context. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012057. https://doi.org/10.1088/1755-1315/323/1/012057

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019b). Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, *218*, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306

Cambier, C., Galle, W., & De Temmerman, N. (2020). Research and Development Directions for Design Support Tools for Circular Building. *Buildings*, *10*(8), Article 8. https://doi.org/10.3390/buildings10080142

Capua, S. E. D., Paolotti, L., Moretti, E., Rocchi, L., & Boggia, A. (2021). Evaluation of the Environmental Sustainability of Hemp as a Building Material, through Life Cycle Assessment. *Environmental and Climate Technologies*, *25*(1), 1215–1228. https://doi.org/10.2478/rtuect-2021-0092

Carbonaro, C., Tedesco, S., Thiebat, F., Fantucci, S., Serra, V., & Dutto, M. (2016). An integrated design approach to the development of a vegetal-based thermal plaster for the energy retrofit of buildings. *Energy and Buildings*, *124*, 46–59. https://doi.org/10.1016/j.enbuild.2016.03.063

Cavalliere, C., Dell'Osso, G. R., Favia, F., & Lovicario, M. (2019). BIM-based assessment metrics for the functional flexibility of building designs. *Automation in Construction*, *107*, 102925. https://doi.org/10.1016/j.autcon.2019.102925

Cerreta, M., & Savino, V. (2020). Circular Enhancement of the Cultural Heritage: An Adaptive Reuse Strategy for Ercolano Heritagescape. In O. Gervasi, B. Murgante, S. Misra, C. Garau, I. Blečić, D. Taniar, B. O. Apduhan, A. M. A. C. Rocha, E. Tarantino, C. M. Torre, & Y. Karaca (Eds.), *Computational Science and Its Applications – ICCSA 2020* (pp. 1016–1033). Springer International Publishing. https://doi.org/10.1007/978-3-030-58808-3_72

Cheirchanteri. (2020). The new model of circular economy gor sustainable constructions. *Sustainable Mediterranean Construction*, *N.12 2020*. https://www.sustainablemediterraneanconstruction.eu/en/rivista/2020-12/2020-12-067/

Chen, K., Wang, J., Yu, B., Wu, H., & Zhang, J. (2021). Critical evaluation of construction and demolition waste and associated environmental impacts: A scientometric analysis. *Journal of Cleaner Production*, *287*, 125071. https://doi.org/10.1016/j.jclepro.2020.125071

Chen, W., Jin, R., Xu, Y., Wanatowski, D., Li, B., Yan, L., Pan, Z., & Yang, Y. (2019). Adopting recycled aggregates as sustainable construction materials: A review of the scientific literature. *Construction and Building Materials*, *218*, 483–496. https://doi.org/10.1016/j.conbuildmat.2019.05.130

Christian, Chang, Y.-T., & Hsieh, S.-H. (2021, August 30). *BIM-based assessment of building circularity and embodied carbon for a circular built environment*.

Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resources, Conservation and Recycling*, *164*. https://doi.org/10.1016/j.resconrec.2020.105120

de Carvalho Araújo, C. K., Bigarelli Ferreira, M., Salvador, R., de Carvalho Araújo, C. K. C., Camargo, B. S., de Carvalho Araújo Camargo, S. K., de Campos, C. I., & Piekarski, C. M. (2022). Life cycle assessment as a guide for designing circular business models in the wood panel industry: A critical review. *Journal of Cleaner Production*, *355*, 131729. https://doi.org/10.1016/j.jclepro.2022.131729

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Management*, *75*, 3–21. https://doi.org/10.1016/j.wasman.2018.01.028

Díaz-López, C., Carpio, M., Martín-Morales, M., & Zamorano, M. (2019). Analysis of the scientific evolution of sustainable building assessment methods. *Sustainable Cities and Society*, *49*, 101610. https://doi.org/10.1016/j.scs.2019.101610

Díaz-López, C., Carpio, M., Martín-Morales, M., & Zamorano, M. (2021). Defining strategies to adopt Level(s) for bringing buildings into the circular economy. A case study of Spain. *Journal of Cleaner Production*, *287*, 125048. https://doi.org/10.1016/j.jclepro.2020.125048

Dräger, P., Letmathe, P., Reinhart, L., & Robineck, F. (2022). Measuring circularity: Evaluation of the circularity of construction products using the ÖKOBAUDAT database. *Environmental Sciences Europe*, *34*(1), 13. https://doi.org/10.1186/s12302-022-00589-0

Durmisevic, E. (2006). *Transformable building structures: Design for dissassembly as a way to introduce sustainable engineering to building design & construction*. https://repository.tudelft.nl/islandora/object/uuid%3A9d2406e5-0cce-4788-8ee0-c19cbf38ea9a

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019a). Comparing life cycle assessment modelling of linear vs. Circular building components. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012039. https://doi.org/10.1088/1755-1315/225/1/012039

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019b). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027

Eberhardt, L. C. M. (2020). *Qualifying Circular Economy in Building Design Practice: Developing Life Cycle Assessment Design Concepts that Support Implementation of Circular Economy in the Building Sector*. https://doi.org/10.5278/vbn.phd.eng.00084

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *18*(2), 93–113. https://doi.org/10.1080/17452007.2020.1781588

Eberhardt, L. C. M., Stijn, A. van, Rasmussen, F. N., Birkved, M., & Birgisdottir, H. (2020). Towards circular life cycle assessment for the built environment: A comparison of allocation approaches. *IOP Conference Series: Earth and Environmental Science*, *588*(3), 032026. https://doi.org/10.1088/1755-1315/588/3/032026

Elghaish, F., Hosseini, M. R., Kocaturk, T., Arashpour, M., & Bararzadeh Ledari, M. (2023). Digitalised circular construction supply chain: An integrated BIM-Blockchain solution. *Automation in Construction*, *148*, 104746. https://doi.org/10.1016/j.autcon.2023.104746

Foster, G., & Kreinin, H. (2020). A review of environmental impact indicators of cultural heritage buildings: A circular economy perspective. *Environmental Research Letters*, *15*(4), 043003. https://doi.org/10.1088/1748-9326/ab751e

Foster, G., & Saleh, R. (2021). The Circular City and Adaptive Reuse of Cultural Heritage Index: Measuring the investment opportunity in Europe. *Resources, Conservation and Recycling*, *175*, 105880. https://doi.org/10.1016/j.resconrec.2021.105880

Futas, N., Rajput, K., & Schiano-Phan, R. (2019). Cradle to Cradle and Whole-Life Carbon assessment – Barriers and opportunities towards a circular economic building sector. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012036. https://doi.org/10.1088/1755-1315/225/1/012036

Geraedts, R. (2016). FLEX 4.0, A Practical Instrument to Assess the Adaptive Capacity of Buildings. *Energy Procedia*, *96*, 568–579. https://doi.org/10.1016/j.egypro.2016.09.102

Ghisellini, P., Passaro, R., & Ulgiati, S. (2022). The Role of Product Certification in the Transition towards the Circular Economy for the Construction Sector. *Key Engineering Materials*, *919*, 248–259. https://doi.org/10.4028/p-5582x4

Ghisellini, P., & Ulgiati, S. (2020). 3—Economic assessment of circular patterns and business models for reuse and recycling of construction and demolition waste. In F. Pacheco-Torgal, Y. Ding, F. Colangelo, R. Tuladhar, & A. Koutamanis (Eds.), *Advances in Construction and Demolition Waste Recycling* (pp. 31–50). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-819055-5.00003-6

Giama, E., Mamaloukakis, M., & Papadopoulos, A. M. (2019). Circularity in production process as a tool to reduce energy, environmental impacts and operational cost: The case of insulation materials. *2019 4th International Conference on Smart and Sustainable Technologies (SpliTech)*, 1–5. https://doi.org/10.23919/SpliTech.2019.8783007

Girard, L. F. (2021). The evolutionary circular and human centered city: Towards an ecological and humanistic "re-generation" of the current city governance. *Human Systems Management*, *40*(6), 753–775. https://doi.org/10.3233/HSM-211218

Gomis, K., Kahandawa, R., & Jayasinghe, R. S. (2023). Scientometric Analysis of the Global Scientific Literature on Circularity Indicators in the Construction and Built Environment Sector. *Sustainability*, *15*(1), Article 1. https://doi.org/10.3390/su15010728

Göswein, V., Carvalho, S., Lorena, A., Fernandes, J., & Ferrão, P. (2022). Bridging the gap – A database tool for BIM-based circularity assessment. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012099. https://doi.org/10.1088/1755-1315/1078/1/012099

Gulck, L. V., Leenknecht, E., Debusseré, E., Steenkiste, J. V., Steeman, M., & Bossche, N. V. D. (2021). Development of a circularity assessment method for facade systems. *IOP Conference Series: Earth and Environmental Science*, *855*(1), 012008. https://doi.org/10.1088/1755-1315/855/1/012008

Hamida, M. B., Jylhä, T., Remøy, H., & Gruis, V. (2022). Circular building adaptability and its determinants – A literature review. *International Journal of Building Pathology and Adaptation*, *41*(6), 47–69. https://doi.org/10.1108/IJBPA-11-2021-0150

Han, D., Kalantari, M., & Rajabifard, A. (2021). Building Information Modeling (BIM) for Construction and Demolition Waste Management in Australia: A Research Agenda. *Sustainability*, *13*(23), Article 23. https://doi.org/10.3390/su132312983

Heisel, F., & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *Journal of Cleaner Production*, *243*, 118482. https://doi.org/10.1016/j.jclepro.2019.118482

Honarvar, S. M. H., Golabchi, M., & Ledari, M. B. (2022). Building circularity as a measure of sustainability in the old and modern architecture: A case study of architecture development in the hot and dry climate. *Energy and Buildings*, *275*, 112469. https://doi.org/10.1016/j.enbuild.2022.112469

Honic, M., Kovacic, I., & Rechberger, H. (2019). Concept for a BIM-based Material Passport for buildings. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012073. https://doi.org/10.1088/1755-1315/225/1/012073

Huang, H., Bi, J., Li, X., Zhang, B., & Yang, J. (2008). Material flow analysis (MFA) of an eco-economic system: A case study of Wujin District, Changzhou, China. *Frontiers of Biology in China*, *3*(3), 367–374. https://doi.org/10.1007/s11515-008-0045-7

Huuhka, S., & Vestergaard, I. (2019). Building conservation and the circular economy: A theoretical consideration. *Journal of Cultural Heritage Management and Sustainable Development*, *10*(1), 29–40. https://doi.org/10.1108/JCHMSD-06-2019-0081

Incelli, F., & Cardellicchio, L. (2021). Designing a steel connection with a high degree of disassembly: A practice-based experience. *TECHNE - Journal of Technology for Architecture and Environment*, 104–113. https://doi.org/10.36253/techne-10574

Ingrao, C., Arcidiacono, C., Bezama, A., Ioppolo, G., Winans, K., Koutinas, A., & Gallego-Schmid, A. (2019). Sustainability issues of by-product and waste management systems, to produce building material commodities: A comprehensive review of findings from a virtual special issue. *Resources, Conservation and Recycling*, *146*, 358–365. https://doi.org/10.1016/j.resconrec.2019.04.001

Jayasinghe, L. B., & Waldmann, D. (2020). Development of a BIM-Based Web Tool as a Material and Component Bank for a Sustainable Construction Industry. *Sustainability*, *12*(5), Article 5. https://doi.org/10.3390/su12051766

Jiang, L., Bhochhibhoya, S., Slot, N., & de Graaf, R. (2022). Measuring product-level circularity performance: An economic value-based metric with the indicator of residual value. *Resources, Conservation and Recycling*, *186*, 106541. https://doi.org/10.1016/j.resconrec.2022.106541

Joensuu, T., Leino, R., Heinonen, J., & Saari, A. (2022). Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components. *Sustainable Cities and Society*, *77*, 103499. https://doi.org/10.1016/j.scs.2021.103499

Kadawo, A., Sadagopan, M., During, O., Bolton, K., & Nagy, A. (2023). Combination of LCA and circularity index for assessment of environmental impact of recycled aggregate concrete. *Journal of Sustainable Cement-Based Materials*, *12*(1), 1–12. https://doi.org/10.1080/21650373.2021.2004562

Kayaçetin, N. C., Verdoodt, S., Leferve, L., & Versele, A. (2022). Evaluation of Circular Construction Works During Design Phase: An Overview of Valuation Tools. In J. R. Littlewood, R. J. Howlett, & L. C. Jain (Eds.), *Sustainability in Energy and Buildings 2021* (pp. 89–100). Springer Nature. https://doi.org/10.1007/978-981-16-6269-0_8

Khadim, N., Agliata, R., Marino, A., Thaheem, M. J., & Mollo, L. (2022). Critical review of nano and micro-level building circularity indicators and frameworks. *Journal of Cleaner Production*, *357*, 131859. 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* (SSRN Scholarly Paper 3037579). https://doi.org/10.2139/ssrn.3037579

Kovacic, I., & Honic, M. (2021). Scanning and data capturing for BIM-supported resources assessment: A case study. *Journal of Information Technology in Construction (ITcon)*, *26*(32), 624–638. https://doi.org/10.36680/j.itcon.2021.032

Lam, W. C., Claes, S., & Ritzen, M. (2022). Exploring the Missing Link between Life Cycle Assessment and Circularity Assessment in the Built Environment. *Buildings*, *12*(12), Article 12. https://doi.org/10.3390/buildings12122152

Lei, H., Li, L., Yang, W., Bian, Y., & Li, C.-Q. (2021). An analytical review on application of life cycle assessment in circular economy for built environment. *Journal of Building Engineering*, *44*, 103374. https://doi.org/10.1016/j.jobe.2021.103374

López-García, A. B., Cotes-Palomino, T., Uceda-Rodríguez, M., Moreno-Maroto, J. M., Cobo-Ceacero, C. J., Andreola, N. M. F., & Martínez-García, C. (2021). Application of Life Cycle Assessment in the Environmental Study of Sustainable Ceramic Bricks Made with 'alperujo' (Olive Pomace). *Applied Sciences*, *11*(5), Article 5. https://doi.org/10.3390/app11052278

Lukianova, T., Kayaçetin, C., Lefevre, L., Versele, A., & Klein, R. (2022). BIM-based circular building assessment and design for demountability. *CLIMA 2022 Conference*. https://doi.org/10.34641/clima.2022.291

Marichova, A. (2021). Circular Economy and Strategic Management of the Construction Company. *Ovidius University Annals of Constanta - Series Civil Engineering*, *23*(1), 35–44. https://doi.org/10.2478/ouacsce-2021-0004

Marrocchino, E., Zanelli, C., Guarini, G., & Dondi, M. (2021). Recycling mining and construction wastes as temper in clay bricks. *Applied Clay Science*, *209*, 106152. https://doi.org/10.1016/j.clay.2021.106152

Merli, R., Preziosi, M., Acampora, A., Lucchetti, M., & Petrucci, E. (2019). Recycled Fibers in Reinforced Concrete: A systematic literature review. *Journal of Cleaner Production*, *248*, 119207. https://doi.org/10.1016/j.jclepro.2019.119207

Mrad, C., & Frölén Ribeiro, L. (2022). A Review of Europe's Circular Economy in the Building Sector. *Sustainability*, *14*(21), Article 21. https://doi.org/10.3390/su142114211

Naneva, A. (2022). greenBIM, a BIM-based LCA integration using a circular approach based on the example of the Swiss sustainability standard Minergie-ECO. *E3S Web of Conferences*, *349*, 10002. https://doi.org/10.1051/e3sconf/202234910002

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, *183*, 443–457. https://doi.org/10.1016/j.ijpe.2016.06.008

Nemeth, I., Schneider-Marin, P., Figl, H., Fellner, M., & Asam, C. (2022). Circularity evaluation as guidance for building design. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012082. https://doi.org/10.1088/1755-1315/1078/1/012082

Nocca, F., & Angrisano, M. (2022). The Multidimensional Evaluation of Cultural Heritage Regeneration Projects: A Proposal for Integrating Level(s) Tool—The Case Study of Villa Vannucchi in San Giorgio a Cremano (Italy). *Land*, *11*(9), Article 9. https://doi.org/10.3390/land11091568

Nußholz, J. L. K., Nygaard Rasmussen, F., & Milios, L. (2019). Circular building materials: Carbon saving potential and the role of business model innovation and public policy. *Resources, Conservation and Recycling*, *141*, 308–316. https://doi.org/10.1016/j.resconrec.2018.10.036

Nußholz, J. L. K., Rasmussen, F. N., Whalen, K., & Plepys, A. (2020). Material reuse in buildings: Implications of a circular business model for sustainable value creation. *Journal of Cleaner Production*, *245*, 118546. https://doi.org/10.1016/j.jclepro.2019.118546

Ollár, A., Granath, K., Femenías, P., & Rahe, U. (2022). Is there a need for new kitchen design? Assessing the adaptative capacity of space to enable circularity in multiresidential buildings. *Frontiers of Architectural Research*, *11*(5), 891–916. https://doi.org/10.1016/j.foar.2022.03.009

Orsini, F., & Marrone, P. (2019). Approaches for a low-carbon production of building materials: A review. *Journal of Cleaner Production*, *241*, 118380. https://doi.org/10.1016/j.jclepro.2019.118380

Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan—A web and mobile app for systematic reviews. *Systematic Reviews*, *5*(1), 210. https://doi.org/10.1186/s13643-016-0384-4

Owojori, O. M., Okoro, C. S., & Chileshe, N. (2021). Current Status and Emerging Trends on the Adaptive Reuse of Buildings: A Bibliometric Analysis. *Sustainability*, *13*(21), Article 21. https://doi.org/10.3390/su132111646

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Pelicaen, E., Janssens, B., & Knapen, E. (2021). Circular building with raw earth: A qualitative assessment of two cases in Belgium. *IOP Conference Series: Earth and Environmental Science*, *855*(1), 012002. https://doi.org/10.1088/1755-1315/855/1/012002

Piña Ramírez, C., Atanes Sánchez, E., del Río Merino, M., Viñas Arrebola, C., & Vidales Barriguete, A. (2018). Feasibility of the use of mineral wool fibres recovered from CDW for the reinforcement of conglomerates by study of their porosity. *Construction and Building Materials*, *191*, 460–468. https://doi.org/10.1016/j.conbuildmat.2018.10.026

Platform CB'23. (2020). *Guide Measuring Circularity 2.0* (Working Agreements for Circular Construction). Platform CB'23.

Poolsawad, N., Chom-in, T., Samneangngam, J., Suksatit, P., Songma, K., Thamnawat, S., Kanoksirirath, S., & Mungcharoen, T. (2023). Material circularity indicator for accelerating low-carbon circular economy in Thailand's building and construction sector. *Environmental Progress & Sustainable Energy*, *42*(4), e14105. https://doi.org/10.1002/ep.14105

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain* [Policy Report]. PBL Netherlands Environmental Assessment Agency.

Rahla, K. M., Bragança, L., & Mateus, R. (2019). Obstacles and barriers for measuring building's circularity. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012058. https://doi.org/10.1088/1755-1315/225/1/012058

Rakhshan, K., Morel, J.-C., & Daneshkhah, A. (2021). A probabilistic predictive model for assessing the economic reusability of load-bearing building components: Developing a Circular Economy framework. *Sustainable Production and Consumption*, *27*, 630–642. https://doi.org/10.1016/j.spc.2021.01.031

Roithner, C., Cencic, O., Honic, M., & Rechberger, H. (2022). Recyclability assessment at the building design stage based on statistical entropy: A case study on timber and concrete building. *Resources, Conservation and Recycling*, *184*, 106407. https://doi.org/10.1016/j.resconrec.2022.106407

Sala Benites, H., Osmond, P., & Prasad, D. (2023). A Future-Proof Built Environment through Regenerative and Circular Lenses—Delphi Approach for Criteria Selection. *Sustainability*, *15*(1), Article 1. https://doi.org/10.3390/su15010616

Sanchez, B., Rausch, C., & Haas, C. (2019). "Deconstruction programming for adaptive reuse of buildings". *Automation in Construction*, *107*, 102921. https://doi.org/10.1016/j.autcon.2019.102921

Schaubroeck, S., Dewil, R., & Allacker, K. (2022). Circularity and LCA - material pathways: Cascade potential and cascade environmental impact of an in-use building product. *IOP Conference Series: Earth and Environmental Science*, *1122*(1), 012041. https://doi.org/10.1088/1755-1315/1122/1/012041

Sobotka, A., & Sagan, J. (2021). Decision support system in management of concrete demolition waste. *Automation in Construction*, *128*, 103734. https://doi.org/10.1016/j.autcon.2021.103734

Sorin, E., Tirado, R., Gully, E., Louërat, M., & Laurenceau, S. (2022). BTPFlux: A building material flow analysis model to enhance the urban metabolism on French territories. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012027. https://doi.org/10.1088/1755-1315/1078/1/012027

Su, Y., Si, H., Chen, J., & Wu, G. (2020). Promoting the sustainable development of the recycling market of construction and demolition waste: A stakeholder game perspective. *Journal of Cleaner Production*, *277*, 122281. https://doi.org/10.1016/j.jclepro.2020.122281

Suttie, E., Hill, C., Sandin, G., Kutnar, A., Ganne-Chédeville, C., Lowres, F., & Dias, A. C. (2017). 9—Environmental assessment of bio-based building materials. In D. Jones & C. Brischke (Eds.), *Performance of Bio-based Building Materials* (pp. 547–591). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100982-6.00009-4

Tirado, R., Aublet, A., Laurenceau, S., Thorel, M., Louërat, M., & Habert, G. (2021). Component-Based Model for Building Material Stock and Waste-Flow Characterization: A Case in the Île-de-France Region. *Sustainability*, *13*(23), Article 23. https://doi.org/10.3390/su132313159

Tseng, M.-L., Jeng, S.-Y., Lin, C.-W., & Lim, M. K. (2021). Recycled construction and demolition waste material: A cost–benefit analysis under uncertainty. *Management of Environmental Quality: An International Journal*, *32*(3), 665–680. https://doi.org/10.1108/MEQ-08-2020-0175

Van Buren, N., Demmers, M., Van der Heijden, R., & Witlox, F. (2016). Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments. *Sustainability*, *8*(7), Article 7. https://doi.org/10.3390/su8070647

van Eck, N. J., & Waltman, L. (2014). Visualizing Bibliometric Networks. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), *Measuring Scholarly Impact: Methods and Practice* (pp. 285–320). Springer International Publishing. https://doi.org/10.1007/978-3-319-10377-8_13

Van Gulck, L., Wastiels, L., & Steeman, M. (2022). How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978. *The International Journal of Life Cycle Assessment*, *27*, 1–18. https://doi.org/10.1007/s11367-022-02099-w

van Stijn, A., Malabi Eberhardt, L. C., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling*, *174*, 105683. https://doi.org/10.1016/j.resconrec.2021.105683

Véliz, K. D., Ramírez-Rodríguez, G., & Ossio, F. (2022). Willingness to pay for construction and demolition waste from buildings in Chile. *Waste Management*, *137*, 222–230. https://doi.org/10.1016/j.wasman.2021.11.008

Verbene. (2016). *Building circularity indicators* [Eindhoven University of Technology]. https://research.tue.nl/en/studentTheses/building-circularity-indicators

Villaizän Marïn, P. (2022). *Study and analysis of the transition towards a circular economy in the construction sector.Business models, indicators and assessment methods. Covering a case study for the economic evaluation as a design parameter in collaboration with Arkitema* [Universitat Politècnica de València]. https://riunet.upv.es/handle/10251/189446

Villoria Sáez, P., & Osmani, M. (2019). A diagnosis of construction and demolition waste generation and recovery practice in the European Union. *Journal of Cleaner Production*, *241*, 118400. https://doi.org/10.1016/j.jclepro.2019.118400

Yi, L., & Liu, Z. (2016). *Establishment of Evaluation Index System on Construction Enterprise's Circular Economy and Empirical Study*. 695–698. https://doi.org/10.2991/ieesasm-16.2016.145

Yılmaz, Y., & Seyis, S. (2021). Mapping the scientific research of the life cycle assessment in the construction industry: A scientometric analysis. *Building and Environment*, *204*, 108086. https://doi.org/10.1016/j.buildenv.2021.108086

Zaman, A. U., Arnott, J., McIntyre, K., & Hannon, J. (2018). Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. *Sustainability*, *10*(10), Article 10. https://doi.org/10.3390/su10103430

Zatta, E., & Condotta, M. (2023). Assessing the sustainability of architectural reclamation processes: An evaluation procedure for the early design phase. *Building Research & Information*, *51*(1), 21–38. https://doi.org/10.1080/09613218.2022.2093153

Zhang, N., Han, Q., & de Vries, B. (2021). Building Circularity Assessment in the Architecture, Engineering, and Construction Industry: A New Framework. *Sustainability*, *13*(22), Article 22. https://doi.org/10.3390/su132212466

Co-creation: Practitioners' attitudes towards reuse of materials

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Bouman, T., Steg, L., & Kiers, H. A. L. (2018). Measuring Values in Environmental Research: A Test of an Environmental Portrait Value Questionnaire. *Frontiers in Psychology*, *9*, 564. https://doi.org/10.3389/fpsyg.2018.00564

Bouman, T., van der Werff, E., Perlaviciute, G., & Steg, L. (2021). Environmental values and identities at the personal and group level. *Current Opinion in Behavioral Sciences*, *42*, 47–53. https://doi.org/10.1016/j.cobeha.2021.02.022

Brosch, T., & Steg, L. (2021). Leveraging emotion for sustainable action. *One Earth*, *4*(12), 1693–1703. https://doi.org/10.1016/j.oneear.2021.11.006

Cambier, C., Galle, W., & De Temmerman, N. (2020). Research and Development Directions for Design Support Tools for Circular Building. *Buildings*, *10*(8), Article 8. https://doi.org/10.3390/buildings10080142

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. *Sustainability*, *13*(11), Article 11. https://doi.org/10.3390/su13116348

CIRDAX. (2023). Vastgoed Digitalisering. https://www.cirdax.com/

CLÉA. (2023). CLÉA, l'espace Numérique Du Logement. https://clea.qualitel.org/

de Vries, G. (2020, July 16). Habit and hassle: Psychological barriers to sustainable behaviour. *LSE Business Review*. https://blogs.lse.ac.uk/businessreview/2020/07/16/habit-and-hassle-psychological-barriers-to-sustainable-behaviour/

de Vries, G., Rietkerk, M., & Kooger, R. (2020). The Hassle Factor as a Psychological Barrier to a Green Home. *Journal of Consumer Policy*, *43*(2), 345–352. https://doi.org/10.1007/s10603-019-09410-7

Dourlens-Quaranta, S., Carbonari, G., Groote, M. D., Borragán, G., Regel, S. D., Toth, Z., Volt, J., Glicker, J., Lodigiani, A., Calderoni, M., Loureiro, T., Sterling, R., Vandevelde, B., Spirinckx, C., Kondratenko, I., Rajagopalan, N., & Rapf, O. (2020). *Study on the Development of a European Union Framework for Digital Building Logbooks* (Final; Study on the Development of a European Union Framework for Digital Building Logbooks). Executive Agency for Small and Medium-sized Enterprises (European Commission). https://doi.org/10.2826/493576

Eagly, A. H., & Chaiken, S. (1998). Attitude structure and function. In *The handbook of social psychology, Vols. 1-2, 4th ed* (pp. 269–322). McGraw-Hill. https://books.google.be/books?hl=en&lr=&id=-4InWCsra7IC&oi=fnd&pg=PA269&dq=%5B8:16+AM%5D+Joana+Gon%C3%A7alves+Eagly,+A.+H.,+%26+Chaiken,+S.+(1998).+Attitude+structure+and+function.+In+D.+T.+Gilbert,+S.+T.+Fiske,+%26+G.+Lindzey+(Eds.),+The+handbook+of+social+psychology+(pp.+269%E2%80%93322).+McGraw-Hill.&ots=hciBWL-qmb&sig=_AYnkcRdqN18YytTrXYNcMME8TY&redir_esc=y#v=onepage&q&f=false

EEA. (2022). *Circular economy country profile – Belgium* (ETC CE Report 2022/5). European Environmental AGency.

European Commission. (2021). *Level(s), Putting whole life carbon into practice*. Directorate-General for the Environment (European Commission). https://doi.org/10.2779/284030

European Innovation Council and SMEs Executive Agency. (2023). *Study on measuring the application of circular approaches in the construction industry ecosystem: Final study*. Publications Office. https://data.europa.eu/doi/10.2826/488711

European Parliament. (2023). *Strategy for a Sustainable Built Environment*. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-strategy-for-a-sustainable-built-environment

Gómez-Gil, M., Espinosa-Fernández, A., & López-Mesa, B. (2022). Review and Analysis of Models for a European Digital Building Logbook. *Energies*, *15*(6), 1994. https://doi.org/10.3390/en15061994

Gonçalves, J. D. S., Mateus, R., Silvestre, J. D., & Roders, A. R. P. (2021). Beyond good intentions: The role of the building passport for the sustainable conservation of built heritage to behavioural change. *Sustainability (Switzerland)*, *13*(15). https://doi.org/10.3390/su13158280

Gonçalves, J., Mateus, R., Silvestre, J. D., Roders, A. P., & Bragança, L. (2021). Attitudes matter: Measuring the intention-behaviour gap in built heritage conservation. *Sustainable Cities and Society*, *70*. https://doi.org/10.1016/j.scs.2021.102913

Hartenberger, U., Ostermeyer, Y., & Lützkendorf, T. (2021). *The Building Passport: A tool for capturing and managing whole life data and information in construction an real estate—Practical guideline*. Global Alliance for Buildings and Construction, UNEP. https://globalabc.org/resources/publications/building-passport-tool-capturing-and-managing-whole-life-data-and

Honic, M., Kovacic, I., Aschenbrenner, P., & Ragossnig, A. (2021). Material Passports for the end-of-life stage of buildings: Challenges and potentials. *Journal of Cleaner Production*, *319*, 128702. https://doi.org/10.1016/j.jclepro.2021.128702

Jansen, M., Gerstenberger, B., Bitter-Krahe, J., Berg, H., Sebestyén, J., & Schneider, J. (2022). *Current approaches to the digital product passport for a circular economy: An overview of projects and initiatives* (Vol. 198). Wuppertal Institut für Klima, Umwelt, Energie. https://doi.org/10.48506/opus-8042

Lee, E., Allen, A., & Kim, B. (2013). Interior Design Practitioner Motivations for Specifying Sustainable Materials: Applying the Theory of Planned Behavior to Residential Design. *Journal of Interior Design*, *38*(4), 1–16. https://doi.org/10.1111/joid.12017

Li, J., Tam, V. W. Y., Zuo, J., & Zhu, J. (2015). Designers' attitude and behaviour towards construction waste minimization by design: A study in Shenzhen, China. *Resources, Conservation and Recycling*, *105*, 29–35. https://doi.org/10.1016/j.resconrec.2015.10.009

Markström, E., Bystedt, A., Fredriksson, M., & Sandberg, D. (2016). *Perceptions of Swedish architects and contractors for the use of bio-based building materials*. https://www.semanticscholar.org/paper/Perceptions-of-Swedish-architects-and-contractors-Markstr%C3%B6m-Bystedt/7c9a45ccfd60da9000a25c6ecc7fd8b68558373d

Nugent, Audrey, Montano-Owen, Carolina, Pallares, Laura, Richardson, Stephen, & Rowland, Miles. (2022). *EU Policy Whole life carbon roadmap*. World Green Building Council. https://viewer.ipaper.io/worldgbc/eu-roadmap/?page=1

Platform CB'23. (2020). *Guide for Passports for the Construction Sector 2.0*. Platform CB'23. https://platformcb23.nl/english

Plutchik, R. (1980). Chapter 1—A GENERAL PSYCHOEVOLUTIONARY THEORY OF EMOTION. In R. Plutchik & H. Kellerman (Eds.), *Theories of Emotion* (pp. 3–33). Academic Press. https://doi.org/10.1016/B978-0-12-558701-3.50007-7

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain* [Policy Report]. PBL Netherlands Environmental Assessment Agency.

Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Energy Performance of Buildings (Recast), COM/2021/802, European Commision, COM(2021) 802 final (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

Sheeran, P., Norman, P., & Orbell, S. (1999). Evidence that intentions based on attitudes better predict behaviour than intentions based on subjective norms. *European Journal of Social Psychology*, *29*(2–3), 403–406. https://doi.org/10.1002/(SICI)1099-0992(199903/05)29:2/3<403::AID-EJSP942>3.0.CO;2-A

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T., & T. Garofano, N. (2023). Circular economy in the Australian AEC industry: Investigation of barriers and enablers. *Building Research & Information*, *51*(1), 56–68. https://doi.org/10.1080/09613218.2022.2099788

Steg, L. (2016). Values, Norms, and Intrinsic Motivation to Act Proenvironmentally. *Annual Review of Environment and Resources*, *41*(1), 277–292. https://doi.org/10.1146/annurev-environ-110615-085947

Takacs, F., Brunner, D., & Frankenberger, K. (2022). Barriers to a circular economy in small- and medium-sized enterprises and their integration in a sustainable strategic management framework. *Journal of Cleaner Production*, *362*, 132227. https://doi.org/10.1016/j.jclepro.2022.132227 van Capelleveen, G., Vegter, D., Olthaar, M., & van Hillegersberg, J. (2023). The anatomy of a passport for the circular economy: A conceptual definition, vision and structured literature review. *Resources, Conservation & Recycling Advances*, *17*, 200131. https://doi.org/10.1016/j.rcradv.2023.200131

van Valkengoed, A. M., Abrahamse, W., & Steg, L. (2022). To select effective interventions for pro-environmental behaviour change, we need to consider determinants of behaviour. *Nature Human Behaviour*, *6*(11), Article 11. https://doi.org/10.1038/s41562-022-01473-w

Weytjens, L., Verdonck, E., & Verbeeck, G. (2009). Classification and Use of Design Tools: The Roles of Tools in the Architectural Design Process. *Design Principles and Practices: An International Journal—Annual Review*, *3*(1), 289–302. https://doi.org/10.18848/1833-1874/CGP/v03i01/37572