Integration of Building Information Modelling into Building Circularity Assessment: A Systematic Review

Abstract

Purpose - Despite several attempts to integrate Building Information Modelling (BIM) with Building Circularity Assessment (BCA), no systematic review has yet been carried out on this topic to the best knowledge of the authors. The objective of this review is to fill this gap by reviewing the current attempts, identifying the tools, and exploring the state-of-the-art in BIM and BCA.

Design/methodology/approach - A systematic literature review methodology was employed. 30 documents published between 2015 and 2023 were selected and analysed across the concept, methodology, and value dimensions.

Findings - There has been an increase in the development of BIM-based BCA tools in recent years, with the Netherlands taking the lead. Most tools developed were based on the material circularity indicator (MCI) and by using Autodesk Revit as BIM software. Three integration approaches for BIM with BCA were identified: (i) using an external platform; (ii) linking an external database to BIM; and (iii) within the BIM environment. The review has revealed that still there is no standard for BCA, and interoperability and lack of circularity databases are the major challenges.

Originality - This study contributes to providing a comprehensive up-to-date overview of recent advancements in BIM-BCA integration, as well as a framework for understanding its concept, methodology, and value dimensions. It also highlights significant areas where practitioners and researchers can identify knowledge gaps and future research directions.

Keywords Building Information Modelling; Circularity Assessment; Circularity Indicators; Circular Economy; Sustainability; Materials Passport; Life Cycle Assessment.

Paper type Review Paper

1. Introduction

The construction sector consumes around 30% of raw materials and generates nearly 25% of waste globally (Benachio *et al.*, 2020). This implies that, to tackle these issues there is a need in the construction industry for a transition from a linear toward a circular economy paradigm. As measuring is critically important for managing, one of the main questions and barriers to the implementation of a circular economy (CE) concept is how to assess and monitor the progress of such a transition (Saidani et al., 2019; Khadim et al., 2022). Zhai (2020) defined Building Circularity Assessment (BCA) as “measuring the value of the building’s circularity that is affected by various circular building design principles”. These results are then used to assess the performance of circular building design principles and determine the progress towards achieving circularity in buildings (Zhai, 2020).

The emergence of Building Information Modelling (BIM) facilitated the design process enabling improved analysis and control compared to manual methods. Typically, BCA requires a significant amount of information, so a supplementary tool is needed to conduct the assessment and BIM tools can facilitate this process (Rahla et al., 2019). Charef and Emmitt (2021) identified seven new uses for BIM to implement the principles of CE, one of which is circularity assessment. Charef (2022) suggested allocating a new dimension, termed the eighth dimension (8D), to sustainable end-of-life management. The 8D enables the design team to assess circularity during the design process (Charef, 2022). However, it is reported that there is a lack of information within the BIM model to conduct BCA.

To date, there have been only a few review studies conducted in this area, which in turn have some limitations. Muñoz et al. (2022) conducted a scoping review of software tools for measuring the environmental performance of CE. However, the study looked at product and material level, not at building level, and BIM integration was not addressed. Khadim et al. (2022) reviewed building circularity indicators and mentioned some of them were integrated into some BIM-based tools. Similarly, Almeida et al. (2023) reviewed the assessment methodologies for measuring building circularity. However, both studies did not focus on BIM-BCA integration, and many tools were not included in the analysis. Considering these limitations, previous review articles do not offer a comprehensive representation of the state-of-the-art research on BIM-BCA integration. Indeed, a comprehensive review of the BIM-BCA body of knowledge is still lacking, despite the increasing number of studies on BIM-BCA integration. Such a review is needed to better understand the state of the art and is crucial to avoid rework and ensure the right direction when advancing research in a particular field.

This review study, to the best knowledge of authors, is one of the first attempts to examine the body of knowledge on BIM-BCA integration comprehensively. The study contributes to the field of research by providing a framework for the systematic review of BIM-BCA integration across dimensions such as concept, methodology, and value, providing valuable insights into the state-of-the-art, and identifying the gaps and directions for future research. In practical terms, this review serves as a reference point for practitioners to enhance their knowledge of using BIM for BCA. Through discussions, awareness will be raised about the BIM-based tools available for BCA in construction projects. To achieve the aim of this review, the following research questions need to be addressed: “what indicators and assessment models are used in BIM-based BCA?”, “how to integrate BIM with BCA?” and “what are the applications of BIM-BCA integration?”. In responding to these questions, the uniqueness of this paper is the content analysis based on the analysis framework for understanding its concept, methodology, and value dimensions presented in section 2.2.

The reminder of this paper is structured as follows: Section 2 presents the research methodology; Section 3 presents the results; Section 4 discusses the results and provides recommendations for future research, and Section 5 concludes the study.

2. Research Methodology

2.1 Systematic literature review

This study employed a systematic literature review (SLR) approach to map, assess and accumulate literature to develop the existing body of knowledge (Tranfield et al., 2003). The key steps adopted in this study, shown in Figure 1, were adopted from Page et al. (2021).

Insert Figure 1

2.1.1 Identification

First, to find academic articles, the relevant keywords and the criteria for inclusion and exclusion were defined following the research questions. A preliminary search is conducted in two databases: Scopus and Web of Science. (Morioka and de Carvalho, 2016)(Carvalho et al., 2013). The search string used were “Building Information Modelling” OR “Building Information Modeling” OR "BIM" AND "Circularity" OR "Circular Economy" OR “Circularity assessment” OR “BCA” within the titles, keywords, and abstracts of the documents. Since only a few papers were published in peer-reviewed journals, a manual search was conducted for other sources such as theses, conference proceedings and grey literature (Tranfield et al., 2003).It is worth noting that many of the circularity assessment models used in peer-reviewed articles were proposed in theses (Verberne, 2016) and reports (EMF, 2015). To ensure that all relevant research was included, the citations and references of the selected papers were also examined. After checking the references of the selected articles by snowballing approach (Wohlin, 2014), the data was extracted from the included documents.

2.1.2 Screening

The findings of the previous step were filtered in two stages: (1) based on the title, keywords, and abstract reading, and (2) the full paper reading according to the inclusion and exclusion criteria to select eligible documents. To include all relevant documents, the period from 2015 to 2023 was selected since the material circularity indicator (MCI) was proposed in 2015 (EMF, 2015). Additionally, research that solely focused on BCA without utilising BIM tools was excluded. Only publications in English and documents with full text were considered.

2.1.3 Inclusion

Following the selection process, the total number of documents included for content analysis was 30, as shown in Table I.

Insert Table I

2.2 Analysis framework

The 30 selected documents were analysed in more detail through content analysis guided by the analysis framework shown in Figure 2, as described in the following sections. This framework has been adopted from BIM-Life cycle assessment (LCA) integration research (Safari and AzariJafari, 2021; Teng et al., 2022). The concept dimension identifies the data input process. This dimension includes the circularity assessment models and indicators. The methodology dimension investigates how to integrate BIM with BCA. The value dimension investigates the application, which mirrors the data output process. It includes the use after the assessment results are obtained. This framework was developed to answer all three of the research questions listed in the introduction.

Insert Figure 2

3. Results

Results are presented based on the analysis framework in Figure 2. This review benefited significantly from sources beyond just journal articles. BIM-based BCA has seen a significant rise in publications in recent years particularly in the last three years. Europe, especially the Netherlands, makes the largest contribution. It is worth noting that some identified tools have resulted in multiple papers. Twenty-two BCA tools were identified from selected documents, as shown in Table II.

Insert Table II

3.1 Concept: data input

Studies conducted on building circularity assessment have documented a need to digitalise the process due to its requirement for a large amount of data and its complexity. The data for BCA tools include geometric and semantic information on materials and products.

3.1.1 Circularity model input

The BCA methods can be divided into two categories, represented by indicators of circularity such as the building circularity indicator (BCI) proposed by Verberne (2016) and the measuring adaptability capacity (Cambier et al., 2020). The ISO 20887:2020 (ISO, 2020) and Level(s) framework (Dodd and Donatello, 2021) also separate the principles of design into the design for disassembly (DfD) and the design for adaptability (DfA). Most authors linked their tools to a particular principle and key performance indicators (KPIs), while neglecting the others, as shown in Table III.

Insert Table III

3.1.1.1 The circularity assessment model

Most identified tools utilised established circularity assessment models using the Material Circularity Indicator (MCI) proposed by the Ellen MacArthur Foundation (EMF, 2015; EMF, 2019) as shown in Table II. This is followed by the Deconstructability Assessment Score (DAS) proposed by Akinade et al. (2015) and the transformation capacity (TC) model proposed by Durmisevic (2006). However, a few authors designed their tools using their proposed indicators (Di Biccari et al., 2019; Jiang et al., 2022).

It is worth mentioning that there is still no standardisation to assess building circularity, and the existing assessment models and indicators are still under development with many versions developed. However, developing BIM tools based on traditional indicators (such as BCI) is more reliable than proposed ones that are based on a limited number of factors (Khadim *et al.*, 2022). The existing circularity indicators (BCI) and existing platforms like Madaster require improvements by incorporating design criteria to quantify the recovery potential (Cottafava and Ritzen, 2021). However, the latest version of BCI proposed by (Khadim *et al.*, 2023), does not employ the DfD to quantify the recovery potential.

While only MCI-based tools consider material flow and utility (lifetime), most tools assess disassembly, particularly the type of connection. Most tools adopt four DfDs factors (Detachability Index DI) (van Vliet, 2021) a simplified version of TC (Durmisevic, 2006), but Zhang et al. (2021) and Karabınar (2021) ignore disassembly. The disassembly functionality in One Click LCA does not affect the circularity (Gillott *et al.*, 2023). Only some BCI tools adopted building layers (Brand, 1994). Although most tools cover the structure, skin, and space plan layers, only two studies focus on the services layer (Lukianova et al., 2022;) (Sebastian et al., 2022). Some assess the whole building without considering circularity at different composition levels such as DAS tools. Limiting circularity assessment to the building level makes it hard for decision-makers to implement changes and communicate (Zhai, 2020). DAS tools consider factors influencing material recovery such as avoidance of toxic and secondary finish while BCI tools do not consider them. However, all the tools do not consider other component reusability factors such as transportability and standardisation (Coenen *et al.*, 2021).

3.1.1.2 Circularity database

Conducting BCA requires data on materials and products. However, there is a lack of databases that contain circularity information such as the materials source and future scenario. The circularity database is the main obstacle in the implementation of the BIM-based BCA as circularity databases are still in their infancy (Khadim *et al.*, 2022). The information in commercial databases (Alba Concepts, Madaster and One Click LCA) is not structured in a way that allows direct links for automated assessment and is not open source. Therefore, the researchers manually collected data to build their databases, with Excel (CSV file) (Zhai, 2020; Zhang et al., 2021; Christian et al., 2021; Karabınar, 2021; van der Zwaag et al., 2023). Göswein et al. (2022) developed a relational database in the Circular EcoBIM project. However, this database focuses primarily on Portugal and includes Portuguese Environmental Product Declarations (EPDs). If specific data is not available across databases and manufacturers, it is possible to use the average data, particularly in the early design stages. Heisel and Nelson (2020) have compiled a dataset for their generic database (Heisel *et al.*, 2023).

3.1.2 Sustainability Model

Sustainability aspects must be assessed before implementing CE activities to deliver on their promises (Blum *et al.*, 2020). The European Commission's Level(s) framework and Platform CB'23's measurement method exemplify this approach (Dodd and Donatello, 2021; Platform CB’23, 2022). Moreover, various researchers have suggested integrating circularity with sustainability in building design assessments (Akanbi et al., 2018; Zhai, 2020; Zhang et al., 2021). However, circularity and sustainability assessments are often conducted separately, and most tools assess only the technical circularity and ignore the sustainability aspects. Most tools also focus on the environmental impact more than the economic value, and there is no tool to assess the social aspect.

3.1.2.1 Environmental impact

Most tools assessed the environmental impact in terms of embodied carbon. Shivakumar (2021) assessed eleven environmental impacts. However, non-specialists may find it difficult to understand some of the impact categories such as Acidification Potential (Atta *et al.*, 2021). One Click LCA deals only with recycling materials and does not deal with reusing building components for module D of EN 15978 (Al-Obaidy *et al.*, 2022). Karabınar (2021) consider only the production stage, while most authors do not define their LCA system boundary and scope.

3.1.2.2 Economic value

Di Biccari et al. (2019) calculated life cycle costing (LCC) but did not distinguish between different building end-of-life scenarios. Karabınar (2021) calculated only manufacturing and construction costs. However, all tools do not consider the uncertainty in their LCC calculations.

3.2 Methodology: BIM and BCA Integration Approaches

Different methods and tools were utilized in the literature, which differ in terms of information exchange approaches and the platforms used to conduct assessment calculation and results visualisation:

1. Online platforms: Developed by companies because they require advanced programming skills, examples include Madaster and One Click LCA.
2. Third-party applications: Utilize existing software like Microsoft Power BI, Excel, Java, or MATLAB for calculations and results visualisation.
3. Standalone applications: They are less commonly used. The sole tool of this type was developed by Jiang et al. (2022). Additional procedures are required to export Industry Foundation Classes (IFC) files, and real-time design assessment capability is lacking.
4. Visual Programming Languages (VPLs): Like Dynamo and Grasshopper, while it is easier to learn compared to programming languages, VPLs may have limitations because they require technical knowledge of Revit, which deals with nodes and runs the Dynamo player, mostly without a graphical user interface (GUI). Additionally, plugins built with C# perform faster than Dynamo-built tools, particularly for large project files (Karabınar, 2021). Even some researchers who have used VPL recommend developing direct plugins (Lukianova *et al.*, 2022).
5. Plugins: Created using programming languages like C# and Application Programming Interface (API) to add specific functionalities.

Some authors employed multiple tools such as Van der Zwaag et al. (2023) and Akanbi et al. (2018). Notably, most authors developed their tools using Autodesk Revit.

Zhai (2020) described two BIM-BCA integration approaches (online external platform and within the BIM environment) derived from a literature review and was the first study that implemented the integration approach linked BIM to an external database. However, the study reviewed only five tools, and several tools were developed subsequently. Van der Zwaag et al. (2023) also mentioned these approaches; however, no tools are categorised into them.

3.2.1 External platform

The first approach is processing an exchange file such as Industry Foundation Classes (IFC) and processing it in the external platform for assessment. The Building as Material Banks (BAMB), a project funded by the European Commission, has developed tools for Materials Passports (MP) and circular building assessment (CBA). The platform is still undergoing validation using pilot projects (BAMB, 2018). CBA has some limitations, such as considering reuse only (Gillott *et al.*, 2023). The Madaster Foundation developed an online platform for MPs (Madaster, 2018). However, registration in the platform is available only for some European countries. One Click LCA is an online platform for LCA, LCC, and building circularity assessment (One Click LCA, 2019). To obtain the results, it is required to conduct three separate assessments independently. Even using the Revit plugin is still time-consuming; the user must manually map each material, and at the end, the user will return to the online platform to see the results (Karabınar, 2021).

The main limitation of this type of integration is the procedure done manually to upload data to the online platform. These procedures are time-consuming and interrupt the design stage, decreasing work efficiency and wasting time, especially in design phases that require multiple circularity assessments (Zhang et al., 2021; Zhai, 2020). In addition, the interoperability issues, require a high level of detail (LOD) and are data-intensive and need a detailed design, unable to perform real-time design assessment (Zhai, 2020). They are not applicable for use in the early stages of building design (Gillott *et al.*, 2023). The platforms require a paid subscription.

BCA is more effective when used during the early design stage of construction projects, where crucial decisions are made as opposed to the late design stages, in which changes are more costly and complex. LOD 300 is found to be appropriate for integrating BCA into BIM. During the design phases, designers may not have the time to check the circularity of every modification. Designers need a simplified approach for assessing circularity continuously throughout the design phase. Hence, there is a need for a tool that works within BIM software and enables a quick assessment of the building's circularity. Moreover, by creating a plugin in Revit, interoperability weaknesses and errors that occur while transferring BIM files to IFC files during import and export processes, are eliminated and any potential complications that may arise as a result can be avoided (Bertin *et al.*, 2020). The goal is to ensure a smoother and more efficient process. Finally, even some researchers who have used external platforms (Heisel and Rau-Oberhuber, 2020), then developed tools inside the BIM environment (Heisel and Nelson, 2020).

3.2.2 External database linked to BIM

This type of integration approach automates the linkage between the BIM model and an external database that includes data required for the assessment by using a unique ID. This ID should be assigned to all BIM elements using Assembly Code for calculation and matching between both BIM and the database. Due to most of the reviewed tools having been developed in the Netherlands, they adopt the NL-SfB, a standard for a classification system that is applied in Dutch construction, which is not commonly used outside the Netherlands. However, only Fernandes et al., (2022) used the Uniclass 2015 classification system. Most tools calculate MCI in Excel outside of BIM.

- **Third-party applications**

Van der Zwaag et al. (2023) developed a decision support dashboard based on the BCI Gebouw. However, the main limitation is that the results are outside the BIM environment in a third-party commercial application (Microsoft Power BI).

- **VPL**

Zhai (2020) developed BCAS based on BCI, and then Zhang et al. (2021) developed a tool using the nodes arranged in Zhai's (2020) previous study but ignored the disassembly potential.

- **Plugins**

Karabınar (2021) developed a plug-in based on MCI but neglected the disassembly potential and is limited to walls and floors.

The limitation of this type of integration lies in the fact that BCA data is not stored in the BIM model, which is supposed to be a data repository (Santos *et al.*, 2019). This approach considers BIM only for geometric information and quantity take-off to extract the bill of quantities. A manual database file is required to be created. Moreover, including circularity information within the BIM will facilitate the generation of material passports and data traceability for the material bank.

3.2.3 Within the BIM environment

In the third approach, users are required to create parameters for each building element containing the required information to conduct the assessment. The assessment is conducted using embedded geometric and semantic information within the BIM environment.

- **Third-party application**

Akinade et al. (2015) and Janani et al. (2022) developed BIM-DAS tools to assess deconstructability using Excel and Java respectively. Both studies recommended integrating the tools as Revit plugins.

- **VPL**

Atta et al., (2021) developed a MP tool to assess deconstructability, recovery, and environmental score. However, the circularity is limited to qualitative information.

- **Plugins**

Akanbi et al., (2018) developed an add-in for the parameters influencing recycling and reusability. However, it is for the whole building level. Fernandes et al., (2022) developed a plugin based on BCI and Portuguese building archetypes, part of the Circular EcoBIM project and Product Data Template (Göswein et al., 2022). However, similar to the previous tools it is also required to assign an assembly code for each element. The addition of information in objects is limited only to the elements (thus, not materials). The LCA is handled in a separate plug-in and the LCC is restricted to (A1–A5) modules (Alves Ferreira et al. 2022).

One of the main challenges for BCA within BIM is that the current IFC schema does not include all the necessary properties to store information required to assess circularity. Table IV compares integration approaches and their advantages and disadvantages.

Insert Table IV

3.3 Value: Data output and result

BIM-BCA should have more applications as a design tool than being a scoring and checking app (Jiang *et al.*, 2022). However, the development of design-supporting tools for circular buildings is still lacking (Cambier *et al.*, 2020).

3.3.1 Optimisation

The final building design and material selection decision-making depends on implementing both circularity and sustainability, which may conflict. Thus, there is a need for the utilization of decision support systems. Only Shivakumar (2021) implemented the multiple-criteria decision-making (MCDM) to identify the most suitable alternative products based on circularity and environmental impact. However, the process is not integrated within BIM and is conducted in Excel. Van der Zwaag et al. (2023) developed a decision support dashboard, but it can not assign weight factors that allow the designer to prioritize certain aspects over others.

3.3.2 Uncertainty analysis

Uncertainty analysis is crucial for LCA and LCC due to various factors such as the uncertainty of the database, potential risks, and parameter settings (Lu *et al.*, 2021). Moreover, as the life span of buildings may reach 50 years, uncertainties in end-of-life scenarios could potentially pose a risk of unsatisfactory CE performance (Lei *et al.*, 2022). However, there is no identified tool to consider the uncertainty analysis and the probabilistic calculations for circularity, LCA and LCC.

3.3.3 Material passport and material bank

Online platforms such as BAMB and the Madaster have limitations for application, such as not documenting the early design stage, which is crucial for making new buildings material banks rather than urban mines (Heisel and Nelson, 2020). Madaster lacks a mechanism for remotely monitoring and managing building components (Xing *et al.*, 2020). Few authors generated MP in their tools (Van der Zwaag et al., 2023; Atta et al., 2021), but these lack all the required information for a circular material passport (Zhang et al., 2021; Göswein et al., 2022). Additionally, they were lacking in connecting building components through tracking technologies such as quick-response (QR) codes. Karabınar (2021) highlighted connecting BCA tools with a material bank enabling designers to access and utilize existing reusable materials and components directly within the design process to improve circularity. However, this connection is still missing.

4 Discussion

This paper identified the existing gaps in BIM-BCA integration and provides recommendations for future research based on the dimensions of the analysis framework. First, for concept dimension, there is a lack of standardization for building circularity assessment even the same assessment model for example BCI, there are several versions such as (Zhai, 2020; Zhang et al., 2021; Fernandes *et al.*, 2022). There is a need to standardise the building circularity assessment models based on comprehensive existing indicators rather than creating new ones from scratch and aligning them with the Level(s) framework and ISO 20887:2020. This will enhance consistency and comparability in the assessment. Another gap identified is the lack of BIM tools that assess circularity in terms of design for adaptability (DfA) as most tools focus on design for disassembly (DfD) as shown in Table II and exclude DfA. This may be back that their assessment model does not consider it. However, it is worth mentioning that recently Khadim et al. (2023) proposed the last version of BCI, the whole building circularity indicator (WBCI), and considered DfA at the system level.

Furthermore, there is a lack of circularity databases (Shivakumar, 2021) that include all the information needed for circularity assessment poses a challenge. Göswein et al., (2022) and Heisel et al., (2023) developed their custom databases. It is worth noting that Cottafava & Ritzen (2021) proposed the Predictive Building Circularity Indicator (PBCI) that quantifies the recovery potential based on DfD criteria. However, none of the tools adopted it.

Moreover, there is a lack of tools for a sustainable circular economy. Most existing tools do not consider the sustainability aspect (Akanbi et al., 2018; Zhang et al., 2021). Circularity and sustainability assessments are often conducted separately. For example, Circular Eco BIM project tools (Fernandes *et al.*, 2022). Integrating LCA and LCC simultaneously with circularity is crucial for a comprehensive assessment (Zhang et al., 2021). In addition, there is a lack of consideration of the whole life cycle for sustainability aspects (Karabınar, 2021). Considering the whole life cycle modules is crucial, particularly Module D (reuse and recycling impact). The whole life cycle is not just for sustainability but also for circularity (Khadim *et al.*, 2023). However, none of the tools consider all material flows from a life cycle perspective.

Second, for the methodology dimension, interoperability is the major challenge. Integrating circularity within the BIM environment requires extending the IFC information schema to leverage BIM. In the Circular EcoBIM project, develop a product data template and include information to element level, not material (Fernandes et al., 2022). There is a need to Extend IFC by developing an information schema for BCA within the BIM environment. Furthermore, there is a lack of data structure that allows a direct link to BIM (van der Zwaag et al., 2023). There is a need to develop circularity databases that allow direct links with BIM to avoid manual procedures and users can add new materials to the database or edit already existing ones.

Finally, for value dimension, current tools are checking apps rather than “a design tool” (Jiang et al., 2022). Current tools often lack integration of multi-criteria methods with BIM to support designers in trade-off aspects and conflicting objectives. Future studies should focus on integrating multi-criteria decision-making methods within BIM tools (Shivakumar, 2021). Additionally, there is a notable absence of studies and tools addressing uncertainty in circularity calculations (Lei et al., 2022), highlighting the need for the development of tools incorporating uncertainty analysis. Moreover, there is a lack of tools that automate circularity improvement and automatic design optimization. Developing tools to provide suggestions. Such tools could compare various assessment results straightforwardly (Zhai, 2020) and provide users with suggestions (Zhang et al., 2021) for design materials and components with higher circularity and/or lower embodied carbon or cost (Karabınar, 2021).

Furthermore, there is a lack of BIM-based circular material passports (Göswein et al., 2022) and a lack of a mechanism for remotely monitoring and managing building components (Xing et al., 2020). The absence of integration with material banks presents a gap (Karabınar, 2021), emphasizing the need to link the tools to a material bank, allowing designers to browse for reused materials and reclaimed components to improve building circularity.

5 Conclusions and directions for future research

This review examined 30 documents on BIM-BCA integration published from 2015 to 2023. This review has found the most recent information about BIM-based tools used to assess circularity in buildings. It has identified tools, specifically focusing on evaluating circular economy aspects for buildings. The novelty of this study stands out due to its focus on BIM-based tools specific to the building and its in-depth analysis of the concept, methodology, and value dimensions. The analysis revealed an increase in publications within the past few years. However, more research is still needed in some areas. The Netherlands is in the lead in pioneering the development of BIM tools for BCA. Autodesk Revit is the most-used BIM software and databases in the form of spreadsheets are widely used.

Most tools are based on existing circularity assessment models. Several indicators and assessment models were found confirming the scattering currently happening and emphasizing the missing standard framework for the BCA. The MCI-Based tools were widely used to assess the circularity of buildings. The integration framework considering both circularity with LCC and LCA is still missing. A comprehensive and standardized assessment method is crucial to selecting the best circular and sustainable alternative, as current BIM tools focus on a specific aspect. In addition, the lack of this method means that results from these tools are not comparable. Three types of approaches for the integration of BIM with BCA were identified, (i) External platform; (ii) External database linked to BIM; and (iii) Within the BIM environment. By comparing their advantages and disadvantages, interoperability and lack of circularity databases are the major challenges for BIM-BCA integration.

Future research should focus on developing tools that simultaneously consider circularity and sustainability from a life cycle perspective. These tools should integrate MCDM methods to compare various design alternatives straightforwardly and provide suggestions. Additionally, future tools should quantify recovery potential based on DfD criteria and other reusability factors, incorporating uncertainty analysis and probabilistic assessment. Enhancing interoperability by extending the IFC schema and the buildingSMART Data Dictionary (bSDD) is crucial to support open BIM. Develop BIM-based circular material passports that connect to material banks and building components through tracking technologies such as QR codes.

The contribution of this review is to identify and document the latest advancement developments and what has already been done in BIM-BCA integration, emphasizing their features and limitations. This review study can be used as a launch point to develop a robust and comprehensive BIM-based framework and tool for BCA toward a circular and sustainable built environment. The research offers practitioners a reference point and raises awareness within the industry regarding the BIM-based tools currently available for dealing with BCA.

Although the paper has made contributions, it is important to recognize certain limitations. One of these is the inability to explore all the tools in depth as some of them are not available or accessible. Another limitation is the relatively small number of studies that were reviewed, primarily because there is a lack of research in this area due to the BIM-based BCA is still in its infancy compared to the BIM-based LCA.

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Table II Summary of analysis framework for the identified tools

No	**Reference**	**Tool name**	**Concept (Input)**				**Methodology (Process)**		**Value (Output)**
			Circularity model		**Sustainability Model**				
			Circularity Assessment model	**Circularity Database**	**Environmental impact**	**Economic value**	**Integration approach**	**Assessment platform**	**MCDM / MP**
1	(BAMB, 2018)	CBA	Reuse potential	Materials Passport Platform Prototype	✓	✓	1	Online platform	MP
2	(Madaster, 2018) (Heisel and Rau-Oberhuber, 2020) (Sebastian *et al.*, 2022)	Madaster	Madaster CI	Madaster (NIBE and NMD)	✓	✓	1	Online platform	MP
3	(One Click LCA, 2019) (Feng *et al.*, 2022) (Honarvar *et al.*, 2022)	One Click LCA	Custom (building circularity) calculations' formulas unpublished	One Click LCA	✓	✓	1	Online platform and plugin	-
4	(van der Zwaag *et al.*, 2023)	Dashboard	BCI Gebouw (Alba Concepts)	Excel (NMD and NIBE)	✓	-	2	3rd party app Power BI	MP
5	(Zhai, 2020) (Zhang *et al.*, 2021)	BCAS	BCI (two DfD & without DfD)	Excel (Alba Concepts)	-	-	2	VPL Dynamo	-
6	(Christian *et al.*, 2021)	BIM tool	Madaster CI	Excel Literature review	✓	-	2	VPL Dynamo	MP
7	(di Biccari et al., 2019)	CBMCI	Circular Indicator	LCA database	✓	✓	-	Revit Plugin	-
8	(Jiang *et al.*, 2022)	B-CAT	Circular project model	Excel	-	-	-	Standalone app	-
9	(Atta *et al.*, 2021)	MP	DAS	-	✓	-	3	VPL Dynamo	MP
10	(Yüksel, 2023)	BIM-based BCA Tool	DAS	Excel (EPD)	✓	-	3	VPL Dynamo	-

11	(Shivakumar, 2021)	CEI	MCI and Detachability Index	Excel (NMD)	✓	-	2	VPL Dynamo	MCDM
12	(Heisel and Nelson, 2020)	RhinoCircular	Madaster CI	Generic custom database	✓	-	-	VPL Grasshopper	MP
13	(Karabınar, 2021)	CECC	MCI	Excel (NIBE)	✓	✓	2	Revit Plugin C#	-
14	(Akanbi *et al.*, 2019) (Akanbi *et al.*, 2018) (Akinade *et al.*, 2015)	D-DAS BWPE	DAS, reusability, and recyclability	-	-	-	3	Revit Plugin C#, MATLAB 3rd party Excel	-
15	(Fernandes *et al.*, 2022) (Göswein *et al.*, 2022)	Level(s) Circularity	BCI	SQL Specific custom database	-	-	3	Revit Plugin C#	-
16	(Basta *et al.*, 2020)	SS-DAS	DAS	-	-	-	3	VPL Dynamo	-
17	(Janani *et al.*, 2022)	BIM based DAS tool	DAS	-	-	-	3	3rd party Java	-
18	(Kim and Kim, 2023)	Design support tool for DfD	DAS	-	✓	✓	3	Rhinoceros, Python3 & NetworkX	-
19	(Lukianova *et al.*, 2022)	CBCI	Detachability Index				-	VPL Dynamo	-
20	(Ogunjinmi, 2022)	BIM-based Building Detachability Assessment	Detachability Index	-	-	-	3	VPL Dynamo	-
21	(Durmisevic *et al.*, 2021)	RBIM	Reuse potential		✓	✓	-	Revit Plugin	MP
22	(Mercado Siles, 2020)	Steel Deconstruction	DAS	-	-	-	3	Tekla Structures Plugin C#	MP

Table III Circularity assessment model of identified tools and its key performance indicators

Assessment model		**Evaluation**	**Technical circularity indicators**					
			Material flows	**Building layers**	**Disassembly**	**Recovery**	**Lifetime**	**Prefabrication**
MCI-based	BCI	• Assess circularity on different levels of building composition • Does not consider recovery • Require improvements by incorporating design criteria to quantify the recovery potential (Cottafava and Ritzen, 2021)	✓	✓	✓		✓	
MCI-based	Madaster CI	• Does not assess circularity on different levels of building composition (Zhai, 2020) • Score for the construction phase, use phase, and end of life phase • Disassembly potential in the first version was based on three questions • Require improvements by incorporating design criteria to quantify the recovery potential (Cottafava and Ritzen, 2021)	✓	✓	✓			
MCI-based	MCI	• Product level • Generic (Not for buildings-specific) • Theoretical value (Verberne, 2016)	✓				✓	
DAS	DAS	• Focus on the whole building level and does not assess circularity on different levels of building composition (Zhai, 2020) • Ignore differences in the building's component life • Does not consider the material flow			✓	✓		✓
Transformation Capacity (TC)	Reuse potential and Detachability Index	• Consider only disassembly			✓			
Proposed by authors	Circular Indicator	• Less reliable for detailed analysis (Khadim *et al.*, 2022) • Does not assess circularity on different levels of building composition (Zhai, 2020)			✓			
	Circular Project Model	• Limited to the materials flow in and out of the site, rather than encompassing the entire life cycle • Only reuse or unrecoverable waste scenarios	✓		✓			

Table IV Comparison of three BIM-BCA Integration approaches

Type	**Integration approach**	**Assessment Platform**	**Advantage**	**Disadvantage**
1	External platform	Eternal online platform Standalone software	• Applicable for all BIM software (Zhai, 2020) • Professional	High LOD, data-intensive, only applicable during detailed design Manual procedures and time-consuming (Zhai, 2020) Unable real-time assessment (Zhai, 2020) Requires a paid annual subscription with a license Requires high programming skills (Zhai, 2020)
2	External database linked to BIM	Plugin Dynamo Third-party app Standalone software	• Early design stages • Real-time assessment (Zhai, 2020) • 3D visualisation by colour override (Zhai, 2020) • Simple	BCA data is not stored in the BIM model, which is supposed to be a data repository (Santos *et al.*, 2019). A manual database file is required to be created.
3	Within the BIM environment	Plugin Dynamo Third-party app	• Early design stages • The BIM model is a data repository (Santos *et al.*, 2019) • Real-time assessment (Zhai, 2020) • 3D visualisation by colour override • Simple	Need to create parameters and a suitable environment (Santos *et al.*, 2019) (Zhang *et al.*, 2021)

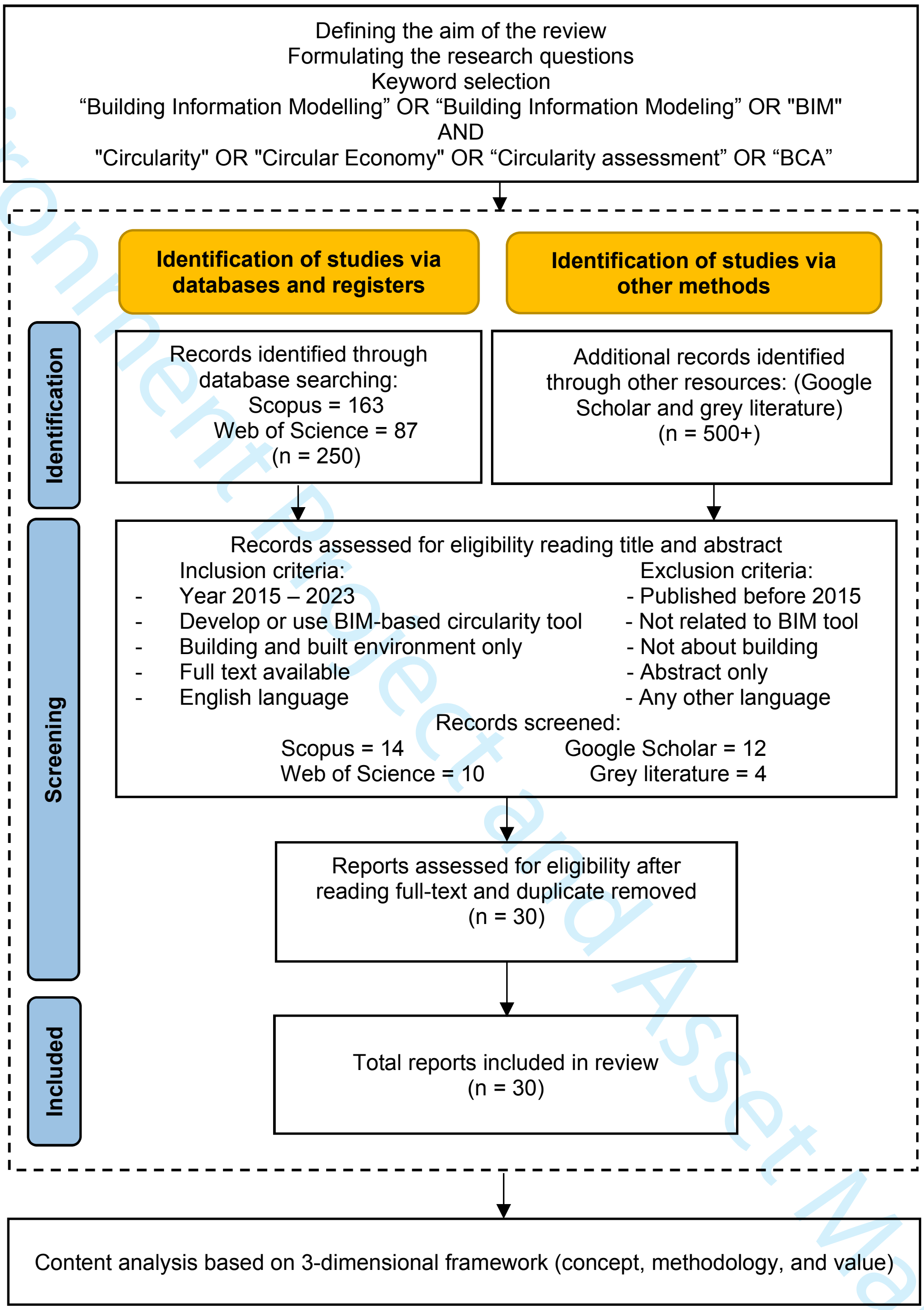

Figure 1 The review methodology (review date: November 2023)

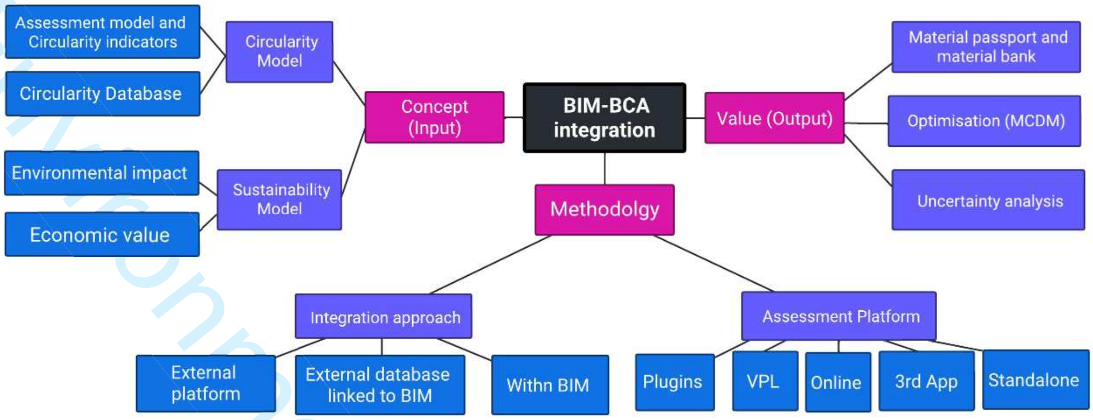

Figure 2 Analysis Framework