The Role of BIM in Supporting Circularity: A Conceptual Framework for Developing BIM-Based Circularity Assessment Models in Buildings

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Abstract. The simultaneous evolution of the construction sector towards the circular economy and digitalization is widely recognized and endorsed by both policy initiatives and academic discourse. In this dynamic landscape, research efforts are focused on creating automated tools and models to facilitate the implementation and monitoring of circularity in buildings, thereby enhancing efficiency and effectiveness of decision-making processes. Building Information Modelling (BIM) stands out for its acknowledged capabilities in data storage and process automation, making it a compelling platform for achieving these objectives. This paper aims to establish a conceptual framework that addresses the challenge of developing BIM-supported tools and models for promoting circularity in buildings. The primary goal of the proposed framework is to assist tool developers and professionals in the construction sector, providing them with a systematic approach to integrate circularity aspects into BIM for efficient and automated assessment processes. To achieve this, the study critically analyzes five existing BIM-based circularity tools and models from previous studies, elucidating the key stages and providing detailed steps for their development. The paper concludes by emphasizing the main barriers hindering the development and automation of circularity tools within the BIM framework. This comprehensive exploration contributes to the ongoing discourse on sustainable construction practices, offering valuable insights for practitioners, researchers, and policymakers striving to advance the integration of circular and digital principles in the construction industry.

Keywords: BIM · Circular Economy · BIM-based Circularity Assessment · Conceptual Framework · Circular Buildings

1 Introduction

The construction industry faces numerous challenges, as it stands as one of the major contributors to natural resource consumption and environmental impact. Additionally, the issue of construction and demolition waste (CDW) resulting from demolition activities

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during the end-of-life stage exacerbates the industry's resource, energy, and greenhouse gas (GHG) intensity. Consequently, there is an urgent need to explore more sustainable approaches to transform the industry, making it a top priority on both International and European agendas for achieving sustainable development.

The European Green Deal, part of the sustainable growth agenda, has spearheaded a green transition, leveraging the challenge of climate change to create a unique opportunity. According to the European Commission, this transition is crucial for two primary objectives: firstly, mitigating the consequences of climate change and environmental degradation, and secondly, enhancing the European Union's (EU) energy self-sufficiency [1]. At the core of the European Green Deal's roadmap lies the Circular Economy (CE), a critical policy area designed to promote the efficient use of resources and stimulate sustainable economic growth. This initiative places particular emphasis on seven resource-intensive sectors, including construction and building [2].

Within the construction industry context, numerous studies advocate for the development of indicators to measure the implementation of CE principles, especially in expressing the circularity of individual buildings [3]. Decision-makers in the industry, including architects, engineers, and contractors, require tools that can assist them in harnessing the value of CE approaches. These tools should provide a systemic view of the effects of material circularity specifications and circular design aspects.

On the other hand, Industry 4.0 marks the world's fourth industrial revolution, aspiring to bring about a significant transition. This transition encompasses profound changes in the design, production, operation, and servicing of manufacturing systems and products [4]. Termed as the digital transition, this transformation relies on various innovative technological advancements. These include strategic information and communication approaches, Cyber-physical systems (which involve additive manufacturing supported by sensors and robots), network communications, simulation, modeling, and virtualization techniques (such as BIM, Virtual and Augmented Reality), as well as data collection and management through big data analytics and cloud computing. Additionally, this transition aims to support human workers by integrating robots and other intelligent tools.

The EU's commitment to fostering a sustainable yet competitive economy has gained significant importance through its embrace of the objectives of Industry 4.0 and the CE, recognizing their pivotal influence on the economy [5], environment, and society. The tandem of green and digital shifts is acknowledged as the twin transition, highlighted by the EU agendas as pivotal for shaping the EU's future, encapsulating both green and digital objectives. The synergies between these transitions amplify their individual impacts. The digital shift holds promise in bolstering the green transition by transforming current business models into new approaches that actively pursue sustainable development across environmental, economic, and social pillars. This is achieved by supporting efficient processes, fostering a deeper understanding, and facilitating comparisons among alternatives to effectively and efficiently identify optimal solutions.

This paper aims to demonstrate the synergistic alignment of twin transition objectives, explicitly focusing on the application of BIM to facilitate circularity implementation and monitoring. The study unfolds in a structured manner, providing readers with a cohesive and clear understanding of the study's objectives, methodologies, outcomes, and challenges. The first section delves into a comprehensive background overview, exploring the motivations behind the research. The second section outlines the methodology employed to meet the study's objectives. The third section presents analysis results and introduces the conceptual model's structure for seamlessly integrating circularity assessment into BIM. Finally, the fourth section addresses challenges, highlighting barriers encountered in the process of circularity assessment and integration into BIM.

2 Methodology

The study endeavors to elucidate the pivotal role of BIM in facilitating the implementation and evaluation of circularity principles within the construction sector. Its primary aim is to establish a conceptual framework tailored for stakeholders keen on harnessing BIM and digital technologies to streamline their thought processes.

The methodology employed to attain this objective involves an in-depth analysis of five pre-existing studies that have effectively utilized BIM capabilities to craft functionalities supporting the integration and assessment of circular practices in construction. Building upon this analytical foundation, a comprehensive conceptual framework delineating intricate steps is proposed to develop models for assessing circularity. The framework accentuates and illustrates essential steps while addressing potential barriers and challenges inherent in the process.

In essence, the study furnishes a roadmap for stakeholders seeking to capitalize on the capabilities of digital technologies and tools for supporting circular practices. It serves as a brief guide to inform decision-making processes aligning with their overarching goals.

3 Results

3.1 BIM for Circularity Assessment

The recent paradigm shift toward a design-centric and information-centric approach in building construction has led to the widespread adoption of BIM [6]. BIM can be defined as an integrated process involving collaborative efforts from stakeholders to create a parametric virtual model representing a building with the aim of facilitating effective management throughout the building lifecycle, from planning and design through operation and maintenance to end-of-life decommissioning [6].

Parametric representation within BIM ensures bi-directional connectivity with reality, supporting changes that occur along the building's lifecycle. This connectivity is crucial, as alterations to one element can influence connected elements, ultimately impacting the overall building integrity [7]. The increasing implementation of BIM for various purposes, such as 3D building visualization, building performance analysis, cost estimation, and facility management, underscores the necessity for genuine innovation within the construction industry to be BIM compliant [6].

In the context of BIM, a building model is portrayed as a database, creating opportunities for incorporating diverse sustainability analyses [8, 9]. BIM serves as a valuable instrument for conducting environmental or economic assessments considering the entire lifecycle of a building. These assessments may be required multiple times over the building's lifespan [8]. Various tools have been developed to integrate sustainability objectives into BIM, enhancing calculation processes and supporting decision-making. An example is the IMPACT (Integrated Material Profile And Costing Tool) tool by the Building Research Establishment (BRE), designed to integrate Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) into BIM [10]. Models compliant with IMPACT, such as One Click LCA, conduct assessments in accordance with sustainability standards. Numerous studies have highlighted BIM's use in addressing environmental and economic sustainability concerns during different lifecycle stages of buildings [6]. Other BIM-based tools developed to improve sustainability include the BIM-based design optimization method for improving building sustainability [11].

Utilizing BIM for evaluating circularity in buildings represents a relatively novel area, with limited literature offering insights into BIM's potential in this context. Nonetheless, the significance of this research direction is widely recognized among scholars, researchers, stakeholders, and professionals. Notably, there is a noticeable gap in existing studies that specifically address circularity objectives, particularly during the deconstruction stage and the planning of circular paths from the early design phase. This gap may be attributed to the recent attention to the CE concept. However, there is a growing interest in exploring this research direction to create tools for assessing circularity in buildings. The incorporation of BIM is seen as a pivotal element to enhance efficiency in information accumulation and calculation across different lifecycle stages and for various assessment purposes. To fulfill the objectives of this study, this section delves into five prominent BIM-based tools that have been developed to evaluate and guide the implementation of circularity in buildings.

BIM-DAS, 2015. In a study by Akinade et al., the BIM-based De-constructability Assessment Score (BIM-DAS) was introduced as a tool to evaluate a building's deconstructability, starting from the design stage [12]. The model employs a mathematical approach, incorporating efficient material requirement planning and Design for Deconstruction (DfD) principles. The BIM-DAS model was integrated into Autodesk Revit software to facilitate the comparison of deconstructability potential alternatives during the design phase. The combination of the Deconstruction Score and Recovery Score determines the DAS Score. BIM played a critical role in this model by facilitating circularity data storage within project elements through custom parameters. Additionally, it aided in the generation of bills of quantities and automated the calculation processes. This use of BIM technology ensures an inclusive assessment of deconstructability factors, enabling informed decision-making early in the project lifecycle.

BWPE, 2018. In 2018, Akanbi et al. introduced the BIM-based Whole-life Performance Estimator (BWPE) as a valuable tool for construction practitioners [6]. This innovative system facilitates informed decision-making by assessing the salvage performance of structural components, including reusability and recyclability. Importantly, it provides insights right from the design phase and at any stage throughout the building lifecycle. The BWPE employs a mathematical modeling approach, grounded in the principles of Weibull reliability distribution for manufactured products. Its functionality leverages various BIM capabilities, such as modeling, visualization, and material databases. The model has been seamlessly integrated into the Autodesk Revit BIM software as an add-in, utilizing multiple programming languages and the Revit Application Programming Interface (API). To enhance user experience, the BWPE visualizes data through a 2D line chart embedded in the Revit interface. The model's efficacy was rigorously evaluated using three structural design specifications derived from a real-life building case study. This comprehensive assessment underscores the practicality and reliability of the BWPE in supporting decision-making processes within the construction industry.

D-DAS, 2019. In a study be Akanbi et al. [13], a BIM-based Disassembly and Deconstruction Analytics System (D-DAS) was developed, drawing inspiration from earlier tools such as BIM-DAS [12] and BWPE [6]. The purpose of D-DAS is to offer an end-of-life performance assessment for buildings, starting from the design stage. The system is designed with a four-layer architecture, each layer interconnected to form a cohesive system that integrates their relationships and interactions. These layers include (i) the Data Storage Layer, (ii) the Semantic Layer facilitating data exchange and provisioning to the application layer, (iii) the Analytics and Functional Models Layer where the system's functionalities are developed, and (iv) the Application Layer enabling user interaction with the system. D-DAS, implemented as a Revit plug-in, provides three key functionalities supporting end-of-life circularity. These functionalities are: (i) Building Whole Life Performance Analytics (BWLPA), (ii) Building Element Deconstruction Analytics (BEDA), and (iii) Design for Deconstruction Advisor (DfDA). Leveraging both mathematical approaches and BIM capabilities, the D-DAS model incorporates machine learning in its data storage layer. This allows the system to be trained with historical data on deconstruction practices, enabling it to predict material destinations such as reusable, recyclable, or disposal. Functioning as a decision-support tool for construction industry practitioners and professionals, D-DAS facilitates the comparison of design alternatives. It enables the appraisal of the preferred option based on project circularity objectives.

A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of Buildings, 2019. In this work, Biccari et al. employed BIM to create a methodological framework for assessing the circularity and total life cycle cost (LCC) of building projects at various stages of their lifecycle [8]. The aim was to identify optimal solutions by comparing alternatives. To implement their framework, the scholars utilized multiple BIM capabilities, developing an Autodesk Revit add-in that automated volume estimations for bills of quantities (BoQ) generation. They also employed Product Breakdown Structures (PBS) to define the Work Breakdown Structure (WBS) and established links with other software tools for Cost Breakdown Structure (CBS). Additionally, custom parameters were introduced, complementing the standard ones offered by BIM software. The add-in facilitated the visualization of circularity levels for different groups of components, along with their associated life cycle costs. This visualization aimed to evaluate the Circular Business Model (CBM) using a straightforward mathematical approach based on the CBM's circularity value, recyclable volume, and Life Cycle Assessment (LCA) performance in terms of CO_2 emissions. Components were grouped based on their circularity characteristics, such as the share of their recyclable volume. The LCC was calculated using the CBS, applying net present value for each component. The resulting visualization, employing different colors to represent various levels of circularity and LCC values, allowed users to make informed decisions about the desired solution and understand the trade-offs involved between these two variables.

BCA, 2020. In 2020, Zhai introduced a BIM-based circularity assessment (BCA) framework [14], with automated circularity assessments spanning various building composition levels. This innovative approach adopted a bottom-up progression, starting from the material level, progressing through the product then system levels, and culminating in a comprehensive assessment of the entire building level. After delineating key indicators, informed by a literature review focusing on disassembly potential and circular material flow, the BCA framework was established and subsequently automated using Dynamo—a visual programming software compatible as a plug-in for BIM platforms like Autodesk Revit. Dynamo's prototyping capabilities were instrumental in creating an automatic connection between Revit and an external database. This connection facilitated the calculation of BCA metrics and the visual representation of results in Revit through charts, along with the application of colour overrides to elements. The development of the BCA model harnessed various BIM capabilities, including the creation of element families with shared parameters, customization of parameters, effective data storage, and automated calculations. These functionalities were further enhanced by seamless integration with an external database, emphasizing the model's efficiency and accuracy in circularity assessments.

3.2 A Conceptual Framework/Structure of Integrating Building Circularity Assessment into BIM

Expanding on the analysis of the preceding five BIM-based tools, a conceptual framework has been formulated for the development of a circularity implementation and assessment tool, specifically designed for seamless integration within the BIM environment. This framework encompasses crucial steps for constructing a comprehensive circularity model, encompassing the necessary requirements and facilitating their digitization, as well as the automation of indicators and variables for calculation purposes. The conceptual structure is briefly summarized in Fig. 1, and the necessary steps are elaborated upon in detail as follows.

To effectively develop a circularity assessment tool or model and seamlessly integrate it into BIM, a systematic approach must be adhered to. This process commences with Stage 1, wherein the primary focus lies in defining the objectives and motivations underlying the integration of the chosen method or tool. This entails a meticulous articulation of the problem or challenge at hand, outlining the desired outcomes, and elucidating the expected results in terms of the tool's utility for potential users such as practitioners, contractors, and end-users. Emphasis should be placed on how the tool facilitates decision-making concerning the assessed subject.

Equally crucial at this stage is a comprehensive understanding of the background, aim, and scope of the subject earmarked for digitization and automation. This entails defining the concepts, principles, and circularity aspects to be assessed and measured by critically analyzing existing models and building upon prior work to identify influential factors. This step serves as a foundation for selecting the most appropriate method to achieve the defined goals.

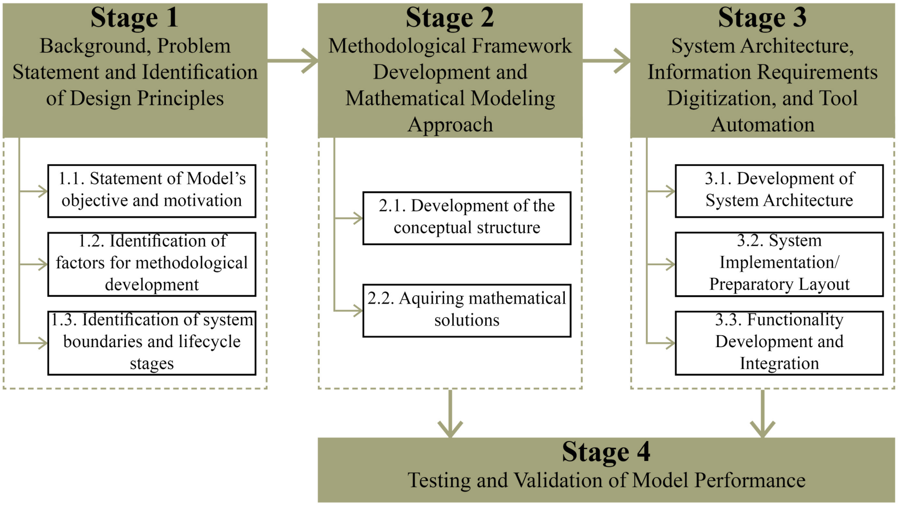

Fig. 1. A Conceptual Framework of BIM-based Circularity Assessment Tools. Source: Authors' own elaboration.

Ultimately, it is imperative to delineate the system boundaries of the subject under assessment, clearly specifying the lifecycle stage or stages to be considered. Details should encompass the extent of circularity of materials, indicating its commencement (e.g., former use of materials, number of previous uses, supply chain) and termination (destination of materials leaving the building loop and the subsequent loops to be integrated, considering the next use or multiple next uses). Other boundaries should also be distinctly outlined, specifying the particular aspects to be addressed without veering into unrelated considerations.

Stage 2 of the framework is dedicated to the development of the methodological framework and mathematical modeling approach. This phase entails creating the conceptual structure of the methodology, which includes formulating a mathematical modeling approach. The process involves defining essential variables and indicators based on factors and parameters identified in the initial stage. This includes establishing relationships and specifying equations. Furthermore, articulating key assumptions is a crucial part of this stage.

Once the conceptual structure is established, mathematical and computational solutions are derived for the model using algorithms. These solutions are then interpreted in relation to the defined variables, parameters, and assumptions. It is important to highlight that, in many instances, tools are constructed on the foundations of prior ones incorporating existing indicators in newly proposed models.

Stage 3 focuses on the development of the system architecture, digitization of information requirements, and tool automation. During this phase, the system is seamlessly integrated into BIM software by identifying the necessary additional software, programming languages, and skills. This integration ensures a smooth data flow, exchange, and access. BIM software such as Revit is carefully chosen and assessed for its capabilities. Tools for programming, mathematical simulation, and assessments are incorporated, while connectivity with tools like Life Cycle Assessment (LCA) is considered to enhance integration. Custom parameters are defined to tailor the system to specific needs and augment BIM model elements.

In the System Implementation/Preparatory Layout phase, the BIM model undergoes development or enhancement for seamless integration. This involves achieving an appropriate Level of Detail (LOD) and considering standard parameters like parametric elements. Additional information, such as custom parameters covering material specifications, dimensions, and lifecycle data, is integrated into the 3D geometric model. Information requirements for calculations, including BoQ, are prepared, alongside the setup of external databases for efficient data management.

The Functionality Development and Integration step involves creating system functionalities that can serve as add-ins to BIM software. Relevant programming languages and tools, including the Application Programming Interface (API), are utilized to establish an application interface that facilitates user interaction with the system. Various activities within this step include establishing connections with external databases (if applicable) to enhance data integration and developing visualization forms for presenting results. These forms may include charts, tables, graphics, and element overrides with colors, all aimed at ensuring effective communication of information.

Stage 4 in the model development process focuses on the Testing and Validation of Model Performance, representing the final phase. The primary objective at this stage is to conduct comprehensive testing and validation to ensure that the developed model meets the desired performance standards. Employing a case study, the model is simulated, and its results are meticulously examined. Conclusions are drawn based on the findings of this evaluation, which plays a crucial role in identifying any shortcomings or areas for improvement. Necessary modifications are then incorporated to enhance the model as needed. It is essential to note that Stage 4 can also occur after Stage 2, where the mathematical approach of the model is simulated using a typical dataset to validate functionality and interpret results. However, the timing of this stage depends on the project plan and whether there is a decision to test the model tool after its development but before full automation.

4 Discussion and Conclusions

This study presents a conceptual framework for the development of BIM-based circularity implementation and assessment tools. The proposed conceptual structure is derived from a critical review of five existing BIM-supported models for circularity. The framework outlined in this work offers valuable insights and guidance for tool developers and CE practitioners in the construction sector. It provides necessary steps and considerations for the development of circularity tools with automated functionality utilizing the BIM. This is crucial because, while the automation of traditional dimensions of sustainability (particularly environmental and economic aspects) has been extensively explored in previous studies, the integration of CE principles into BIM is still evolving. Numerous initiatives are underway to support this research direction, aiming to bring key benefits to the industry. However, a more in-depth analysis of more BIM-based tools is essential for refining the proposed framework.

Developing circularity tools in the BIM context is a complex task, presenting challenges in methodological development and automation. Effective CE implementation in construction requires knowledge of the status and quality of building materials, especially for pre-existing buildings where material information may not be readily accessible. Incorporating circularity throughout the lifecycle of building materials is complicated by their previous loops, making it uncertain to predict their destinations after leaving the assessed building loop. Assumptions are necessary in the tool's development process to address this uncertainty. Similarly, planning the full lifecycle of buildings requires assumptions due to changing circularity factors influenced by market conditions, policies, and other factors.

Regarding BIM integration, it is noteworthy that the automation and digitalization of circularity processes' evaluation in BIM environments demand thorough preparatory and well-structured work, which takes time. However, once the process is automated, it can be applied repeatedly, providing efficiency and real-time assessment capabilities, contributing to efficient and effective decision-making processes.

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