

Assessment of Existing BIM Tools and Solutions Supporting Circular
Economy Indicators in Construction by literature-based analysis using
AI tool

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DECLARATION

I hereby, declare that this manuscript, entitled “Assessment of Existing BIM Tools and Solutions Supporting Circular Economy Indicators in Construction by literature-based analysis using AI tool”, is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Abstract

The construction industry is shifting towards a circular economy from a linear economy, in which buildings are designed with considerations of reusing materials, reducing waste, and carbon dioxide emissions. However, it is unknown how advanced BIM-based tools are in providing data for the circular economy. This research aims to assess the current state of BIM-based tools that claim to enable a circular economy.

Firstly, in accordance with the latest literature, a list of the most relevant indicators of the circular economy in construction has been compiled (for example, the potential for reusing materials, waste generation, and adaptability of design). Scientific articles are analyzed using artificial intelligence-based search tools such as Undermind AI and Elicit Pro. Each of the found tools is tested for its ability to calculate at least one of the selected indicators.

The BIM Maturity Matrix (BIMMI) developed by Succar was used for the comparison of the tools. The BIM Maturity Matrix assesses the solution on a scale of 0 to 50, with 5 levels of maturity from "initial" to "optimized" levels, divided into 3 groups of competence: "technology," "process," and "policy." The majority of the tools score between 10 and 30 points, which means they can retrieve information about the circular economy from BIM models (destruction indices, quantification of waste, life cycle analysis, etc.), but only at the "technological" level, in the early stages of development (object-oriented modeling, collaboration on the basic model, etc.). Some of them have begun to connect the BIM models with cost management systems or facilities, but none of them have reached the level of "optimization."

The data indicate that the overall maturity of BIM tools for assessing the circular economy is low to intermediate. The main difficulties that prevent the development of the overall degree of maturity of BIM tools in the assessment of the circular economy are the unavailability of fragmented data, the low standard set of objects in IFC files, and the low level of integration with organizational aspects. The study also demonstrates that applying a literature review with the help of artificial intelligence can be used to gather data on new topics, such as BIM-enabled cycling. The application of the search criteria and the verification process can be repeated by any graduate student or researcher who wants to evaluate and select BIM tools for the implementation of the circular economy project.

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Chapter 1 – Introduction

1.1 Overview

This thesis proposal has been developed for a master's degree program and includes the initial literature review, research aims, significance, methods, and future actions for the project. It evolves through an introduction to the concept of circular economy and key indicators relevant to the construction industry. The role of Building Information Modeling (BIM) in integrating these indicators into the design of buildings is further developed. However, since the BIM adoption is still at an early stage in applying the concept of a circular economy (CE) in-built environment, the focus of the thesis is mainly on the prioritization of circular economy indicators and assessment of existing tools and solutions supporting CE indicators through doing the relevant literature review using Deep Search AI tools. It also includes how BIM is reported in the context of a circular economy in construction.

1.2 Thesis Statement

This study aims to assess existing digital tools and conduct literature-based analysis using AI tools: BIM implementation for circularity in construction. The assessment will be conducted through analyses of Deep Search AI tools: Undermind AI and Elicit Pro.

1.2 Objectives

The main objectives of the thesis proposal are listed below and might be updated later:

- Introduction of the circular economy concepts in construction
- Evaluation and prioritizing the main indicators of the CE
- Explaining definition to each chosen CE indicator to clarify their purpose
- Learning to effectively use AI tools in the literature review
- Assessing the challenges of digital tools integration into CE
- Assessing the reputation of the existing BIM tools and solutions supporting CE indicators
- Modelling the assessment framework for available BIM tools

Chapter 2 – Literature Review

2.1 Circular Economy in Construction

2.1.1 Introduction

The construction industry emits the maximum greenhouse gases into the atmosphere, accounting for at least 37% of total global emissions every year. Companies now are focusing majorly on reducing what they refer to as 'operational carbon' of buildings—that is emissions due to heating, cooling, and lighting. Over the past 30 to 40 years, thus, operational carbon has been reduced by nearly 75% to 25% (United Nations Environment Programme & Yale Center for Ecosystems + Architecture, 2023). However, this solution tackles the factors of climate change in the short term. Instead, it is recommended to give importance to the sustainability of the building materials and their life cycle stages.

2.1.2 Concept of Circular Economy in Construction

The circular economy is system of the framework which deal with the global issues like climate change, pollution of the Earth and the biodiversity loss. It follows the principles eliminate issue, circulate it and redevelops or extend product lifecycle. For construction industry, the CE is about maintaining the building process within the parameters of sustainability. Circular economy have 5 key parts of targeting application across sectors, such as efficiency, recycling, recovery, design, and reduction. All these factors are interrelated; for instance, recycling of any waste material such as basic oxygen furnace slag (BOFs) or waste glass provides a means for replacing natural aggregates, like river sand, in geopolymer concrete. Thus, by this treatment, both waste reduction and recovery targets are achieved with enhanced resource efficiency because natural resources replaced are with industrial byproducts. Circularity in construction is more a research-driven mode of action, expected to be improved continually so that there can be data on the amount consumed of a natural resource and control over the carbon dioxide emissions for further growth in the sustainability endeavor.

It is possible to reduce carbon emissions to net zero levels in 2060 under CE concepts. Achieving this will involve reducing the use of natural resources by optimally putting to application data-drive design while also incorporating low-carbon earth and bio-based construction materials like bamboo, timber, and agricultural debris. These materials are renewable and greener because they can be produced yearly instead of finite natural resources like steel, aluminum, and coal. Furthermore, it would develop ways to radically

decarbonize conventional materials such as concrete, petroleum-based plastics, and glass, using alternatives such as industrial by-products to replace them or reducing overall material consumption.

There are several international bodies dedicated to pushing circularity and raising awareness among the public because stopping climate change begins with the awareness and actions of people. The Ellen MacArthur Foundation (EMF) is one such body whose primary mission is building a pioneering world community that inspires system change. Of interest here is that circularity in construction extends beyond the sector into other industries as well. For instance, replacing cement with waste materials not only reduces carbon dioxide emissions associated with cement production, but also lowers the cost of operation. The MacArthur Foundation collaborates closely with companies, policy makers, and investors to develop sustainable solutions for the industry in the next few decades (Ellen MacArthur Foundation, 2024). This trend represents a revolutionary transformation in the construction industry, like the fast development of urban areas in previous industrial revolutions.

Based on the publication by Ellen MacArthur Foundation in 2024 regarding the building prosperity in Europe, innovations in policy and technology are driving the shift to circular construction strategies. The European Union is battling actively against material inefficiencies and land development, having shown through research that the construction sector has the highest material footprint in the region—5.5 tonnes per citizen annually. The sector still remains incredibly wasteful, with 8% of office space vacant in 2023 and over 20,000 km² of brownfield land lying unused, as urban sprawl continues unabated.

Digital technology will be at the forefront of scaling circular construction. AI, IoT, and blockchain technologies are being increasingly used to speed up material tracing, lifecycle assessment, and resource optimization (Ellen MacArthur Foundation, 2024). They track supply chains more efficiently, make them more transparent, and facilitate efficient reuse and

At the same time the European Commission is reinforcing its digital and sustainability policy in order to ensure the built environment is contributing to climate targets. The EU construction sector will run out of its carbon budget for keeping global warming below 1.5 degrees Celsius by 2026, according to the Circular Buildings Coalition. In turn, new initiatives are encouraging the use of alternative materials such as bio-based building materials and low-carbon alternatives to concrete and steel. Thus, this is a good outcome of

the effort of the round tables, that resulted in a clear definition of the main indicators of the CE in construction and the introduction of digital tools to speed up this process.

2.1.3 Circularity Indicators in Construction

One of the key objectives of this study is to identify the performance indicators that for tracking progress towards circular building practice and to compare their effectiveness in terms of source data and application to different layers of buildings.

As there is no international standard that can be utilized, there is a need to carry out literature review to determine the average number of the indicators and have priorities based on the initial plan of this research study. For the sake of clear comprehension of the scale of the number of the indicators and its essence, it is advised to reconsider the former review that is already in place. Consequently, it is acquired the 45 CE indicators are targeted towards construction products: 66% of which were mentioned only in academic papers, 23% mentioned only in non-academic papers, and 11% were mentioned in both (Egerter et al., 2024), reflecting the more sophisticated nature of the academic research into CE, whereas industry reports condensed and summarized more categories. It is important to highlight that CE indicators assess the building and construction materials during the three stages starting from construction, use and ending with end-of-life. According to Bilal et al. (2020), their research interviewed 21 experts in construction from 14 different countries, as a result make list from 21 indicators that are the most important in evaluating the circularity of the building.

Therefore, this paper conducts a detailed literature review to highlight 22 Circular Economy indicators as in Table 2.1, subsequently, these indicators are categorized and prioritized at the Material Level and Building Component and System Level based on the research studies by Tleuken et al. (2024) and Pineda-Martos et al. (2024).

Table 2.1: Circular Economy Indicators

	CE Indicators	
<i>Nº</i>	<i>Building Component and System level</i>	<i>Material level</i>
1	Design for Adaptability (DfA)	Construction Materials Flow Analysis
2	Modular Construction and Prefabrication	Energy Flow Analysis

3	Design for Durability	Construction Material Usage
4	Adaptive Reuse of building elements (e.g. rooms)	Resource Potential Indicator (RPI)
5	Design for Disassembly (DfD)	Material Circularity
6	Easy Maintenance (Maintainability)	Material Longevity
7	Product Responsibility	Resource Productivity
8	Structural Component (e.g., prefabricated elements, dry walls, beams, columns, etc.) Recovery for Reuse and Recycling	Construction and Demolition Waste (C&DW) Management
9	Sharing and Exchange Opportunities	Water Consumption
10	Connections Conditions	Carbon Footprint Impact
11	Regulation and Documentation	
12	Stakeholder Involvement	

Material circularity indicators are a key attribute towards sustainability since materials are the raw materials which pass through various stages of maintenance, recycling, reuse, remanufacturing, and composting. If greenhouse gas emissions such as carbon dioxide must be lowered, the first step must be directed towards being able to assess and prolong the life of raw materials. A full understanding of materials, together with circularity indicators for measuring their quality, enables well-informed decision-making for future action. Other materials can be employed in subsequent stages as required to enhance sustainability in construction industry.

According to the Building Component and System Level indicators, they are significant in quantifying and developing the circularity of building. At the component level, building components such as windows, doors, and walls are taken into consideration for reuse value, recyclability, or refurbishment to achieve resource efficiency and reduce waste. At the system level, systems of these components—such as structural systems or HVAC systems—are analyzed based on their functionality, lifespan, and scope to be adapted (Tleuken et al., 2024). These indicators are responsible for improving the life of materials,

energy efficiency, and minimizing environmental impact. By applying circular economy principles, such as closing, slowing, and shrinking material loops, these indicators facilitate sustainable building activity, limiting carbon emissions, and enabling efficient use of resources during the building process. There are examples of the chosen indicators, what are their objectives and why we need them.

Table 2.2 shows the shortlisted 13 indicators that are employed in this study to identify and evaluate the relevant digital and BIM tools. Not all the indicators for the circular economy were taken into consideration, as some of them are more qualitative in nature. Specifically, nine indicators, such as regulation and documentation, connection conditions, and information sharing and exchange, were not taken into consideration because they are more based on narrative or procedural evaluations rather than calculations.

Because digital and BIM tools are meant to carry out calculations and provide quantifiable results and reports, this research aims to identify and evaluate the indicators that can be calculated or quantified. These indicators can be used to measure the efficiency of material use and other performance-related results that can be directly supported by digital tools.

Table 2.2: Chosen Circular Economy Indicators for further research

	CE Indicators	
№	Material level	Building Component and System level
1	Construction Materials Flow Analysis	Design for Adaptability (DfA)
2	Construction Material Usage	Modular Construction and Prefabrication
3	Resource Potential Indicator (RPI)	Design for Durability
4	Material Circularity	Adaptive Reuse of building elements (e.g. rooms)
5	Material Longevity	Design for Disassembly (DfD)
6	Resource Productivity	Easy Maintenance (Maintainability)
7	Construction and Demolition Waste (C&DW) Management	

Design for Adaptability (DfA): means introducing flexibility, convertibility, and expandability in design to prolong the functional life of a building and thereby postpone demolition. Thus, versatility refers to slight changes interior-wise, convertibility refers to change in function, and expandability enables a physical increase in the space.

Some core principles would be that related to the open-building, where structural and interior systems are separated. Adaptability also depends on demountable connections, allowing for disassembly and reconfiguration of assemblies at the scales of whole systems down to individual materials (Tleuken, A., 2024). DfA is indispensable in a Circular Economy to reduce material waste and carbon emissions through the reuse, transformation, and long-term usability of buildings.

Modular Construction and Prefabrication: modular building and prefabrication are instrumental in identifying the practices of the circular economy (CE) in the built environment since they are the main features that enable resource efficiency, waste minimization, and the enhanced adaptability throughout the building lifecycle. Several tasks are necessary to make this indicator work. The first of these is the development of Life Cycle Assessments (LCAs) which measure the environmental performance of modular and prefabricated systems and, thus, provide the means to decrease the energy embodied and emissions of carbon dioxide. The second measure should be the setting up of Circular Business Models (CBMs) in order to make sure that modular construction remains in harmony with the principles of reuse, refurbishment, and extended product lifespans. Besides, the implementation of Modern Methods of Construction (MMC) and prefabricated components open the way for precise manufacturing, the shorter construction period, and the more efficient use of materials. Moreover, the use of Building Information Modelling (BIM) in Building Circularity Assessment (BCA) facilitates digital monitoring, measurement, and management of circularity performance in the new modular design. All these tasks, when taken together, make modular construction and prefabrication more effective carriers of the idea of circularity as the most feasible routes for the construction sector to commit to the goal of sustainability (Tleuken et al., 2024).

Design for Durability: concentrates in inverting the lifetime of components in building by resistance against efforts, foreign environment, and use. It is slowing down material loops by keeping function, in order to make structures and materials remain usable over longer periods and delay their end-of-use phase. Larger importance includes structures as they must experience measurements of fill and load for adaptive changes in future and also

use over longer time. reducing frequency of repair and replacement maximally reduce consumption, waste, and cost (Tleuken et al., 2024).

Furthermore, that also contributes to not only the energy efficiency of a structure but especially on facades and handling systems. This has very close relations with principles of circular economy, where in components become much more generally applicable to use-reuse cycles. According to material circularity indicator with long service life compared to the average in the industry, they improve circular performance. Ideally, all materials forming an assembly should have equal lifetimes so that no premature collapse of assembly occurs because of the failure of one weak material. Design-for-disassembly (DfD) completes durability by allowing easy maintenance, repair, and recovery of materials damaged to surrounding elements. the two complement each other to an added advantage of sustainable construction through maximizing the material use and minimizing environmental impact.

Adaptive Reuse of building elements (e.g. rooms): one of the core principles of the circularity is adaptive reuse of the building. It is a process where an existing, historically old building may be rebranded and have the new functions. It is one of the brilliant ideas how to implement circularity goals as it conserves embodied energy and material used in its original construction (Baker et al., 2017). Moreover, when the purpose of usage of the building is changed, there is no need for new raw materials, energy expenditure and landfill waste. As a result, as there is no any demolition process, there is reduction of carbon dioxide, and greenhouse gas emissions and declining the demand on fossil fuels (Jorge-Ortiz et al., 2023).

Another key factor why it is the best solution is on protecting a city's cultural heritage and unique architecture. It provides a chance, for instance, for old church become a local library and save the cultural importance. Saving the original facades and decorative features may help the nations to continue their identity and become the place for tourist attractions. In addition, it may the historical legacy for future generations (Pan & Sidwell, 2011).

A good conversion outcome relies on carefully looking at how the building was originally designed and its current state to see if it can work. To help people make smart choices, different tools and models have been developed. Some popular ones include the adaptive reuse potential model (ARP) from Langston et al. in 2008, IconCUR by Langston and Smith in 2012, and the preliminary assessment adaptation model (PAAM) by Wilkinson in 2014.

Design for Disassembly (DfD): Design for Disassembly (DfD) is a mainstay indicator of the circular economy (CE) that keeps a construction sector clean and green by

demonstrating application, prolongation, and material recovery for the entire building life cycle. The integration of DfD calls for numerous tasks that are related to each other. First, "disassembly potential of connections" is a major assessment in which it is figured out whether or even in a set of components they can be separated without destruction so that they can be both reused and recycled. Second, the elements of the product and building should be easy to disassemble and be repaired to ensure that the materials and components have a certain value even after their first use. Besides that, recording the duration as well as the intensity of use allows for correct measuring of the remaining service life of materials, which is very important in planning reuse or replacement strategies. At the end of it all, DfD looks first at the design of accessible components, thus, maintenance, replacement, and even disassembly in the future can be carried out in an easy and quick manner. These measures collectively aid in the establishment of building systems that are not only more adaptable to change and efficient in resource utilization but also in sync with the idea of circularity (Tleuken et al., 2024).

Easy Maintenance (Maintainability): is one of the significant circular economy (CE) indicators, providing strategies for businesses and individuals to analyze the lifecycle assessment (LCA) and subsequently extend the functional usage of materials. As previously noted, the key advantages of this strategy extend beyond preserving historical significance to include substantial financial incentives. This is because policies often exist to actively support such projects financially. In addition, a significant volume of facilitating grants provides non-repayable capital for developers. Consequently, it becomes more economically viable to repurpose a building's functional objective rather than demolish it (Vanegas et al., 2018; World Green Building Council, 2023; Su et al., 2023).

However, following adaptive reuse may be time taking and expensive; in this way easy maintainability indicator can provide a brilliant strategy. The maintenance programme includes constantly screening products to extend their lifespan. In addition, making sure every part is easy to reach so it can be checked, fixed, or repaired whenever needed. Also, easy maintainability covers the designing of products that are made to last to longer time and can be easily disassembled for recycling and repairs. It is important to highlight that this indicator also includes choosing reusable products initially, which prevents spending an excessive amount of money on new raw materials. Consequently, there is a clear mindmap of what happened with the building after the usage and how to redesign it or reconstruct it if it is planned initially. At this point, waste materials from the construction should be mentioned

anyway (Vanegas et al., 2018; World Green Building Council, 2023; Su et al., 2023). As there is a huge amount of organic and inorganic waste that should be minimized, in the case of organic waste, used to create nutrient-rich soil that should be used to plant a new green area.

Despite the structural elements, it is necessary to employ predictive maintenance models. These help identify when equipment or building components require repair, allowing for proactive interventions. Finally, managing these processes is impractical without technology. Therefore, remote monitoring systems are recommended to control equipment remotely, allowing for the early detection of anomalies or failures within the buildings.

Product Responsibility: Nowadays, a lot of countries are trying to switch to a greener economy where they are trying to achieve net-zero in greenhouse gas emissions. However, it is important to highlight the significance of choosing product materials. Here is a new term and circular economy indicator named product responsibility; it is usually presented in documents and involves the development and management process of all products, and shows the percentage of environmentally friendly products (Kralj & Mirko Markič, 2008). This indicator not only concerns choosing environmentally friendly materials, but also designing products with minimal waste.

For example, Company A produces a car, and for the next 3 years, it is impossible to repair it, as it is impossible to replace the parts in the engine with those from the mass market. The seats need repair after one year of usage, and are impossible to replace or wash them because of their size and material types, respectively. Also, the car runs on petrol and therefore it produces a huge amount of carbon dioxide emissions. In contrast, Company B has an electric car which emits less carbon dioxide. The parts of the car can be easily changed if necessary, and the company can take the car back in order to give a second life to some parts. This directly shows what "product responsibility" is: it is when the company or the people who made the product care about the end-of-life of their products.

Connections Conditions: In the construction of a CE, interconnections between BC&S should be arranged as demountable units which can be quickly disconnected and detached without damage to connected elements or parts. For example, this may include being coupled in a reversible manner, such as bolted/screwed connections; "click" connectors; velcro-style connections; or the use of magnets contacting each other, rather than one surface to which is permanently attached (e.g. adhered with adhesive), welded, joined with special fixtures/hardware and/or the like. These links allow reused recovered parts and

components, and contribute to functional autonomy (Tleuken et al., 2024). Because standardized fasteners and connections allow for quick and easy assembly and disassembly, standardization of connections is also a key enabler of circularity. Furthermore, standardized connections make up for the requirement for standardized parts and components, streamlining the procedure and promoting circularity even more.

By making it simple to assemble and disassemble building components, the use of modular construction techniques improves the circularity process. Adaptability is greatly aided by modularity, which makes design simpler and makes it easier to change and transform spatial systems.

The identification, sorting, and tracking of BC&S during disassembly can be substantially facilitated by the use of standardized labeling systems with distinct identification tags or markings. This promotes circularity by guaranteeing that components are utilized as efficiently and fully as possible. The number of connections needed can be decreased by using fewer and different structural elements. The Eurostat monitoring framework for CE's Resource Productivity criterion is related to the effective use of structural components, reducing potential waste and permitting additional disassembly using circular construction techniques like modular structures and dry connections.

Regulation and Documentation: as the main enablers, are very important for the application of the circular economy (CE) in the construction sector since they provide procedures that are standardized, proper responsibilities, and incentives for the stakeholders. The work on the ground to bring to life this indicator revolves around several tasks. Developing disassembly sequences with recommended tools and safety standards is the first step to ensure that the elimination of the dismantling part is done in a safe way for the workers and at the required speed.

Moreover, the procurement processes in circularity lead to the priority of construction projects being materials that are reusable, recyclable, and sustainably produced. Besides that, resource efficiency in building materials through the creation of guides will not only lead to resource optimization but also to the reduction of waste that can be generated both from construction and operation. Also, designing of the protocols that facilitate CE practices will make the stakeholders that will be involved in the processes of reuse, recycling and resource management to be very active (Tleuken et al., 2024).

On top of that, the creation of voluntary agreements between stakeholders will not only lead to the collaboration but also to the shared responsibility in advancing the circularity. Practically, these actions combined become the regulatory and documentary framework which is a bridge between on-the-spot implementation and goal of long-term sustainability.

Stakeholder Involvement: Stakeholders have a significant role in sustainability, as the final decisions are always made by them. Therefore, if the Chief Executive Officer (CEO) has a clear vision of how to move to the circular economy from the linear economy, then it is much easier to speed up this process. The primary strategy should be written based on the concept of circular economy and checked against each indicator in this paper. The written report can give a clear vision on where to start.

First of all, if there is an objective to build a business centre, the service life of the building must be defined. Based on that, one should choose the proper materials which last more than the service life and can be easily replaced in case of any accidents. Also, there should be an action plan for what to do with the building after its service life. There should be at least 5-6 scenarios for that. As sometimes it can be chosen for adaptive reuse, or sometimes it is much easier to disassemble and use the materials for another purpose.

Construction Materials Flow Analysis: It is a systematic method for assessing the movement and transformation of resources, energy, and waste within a specific system, such as an industrial sector or a country's economy. Based on the law of conservation of mass, MFA covers the entire value chain: from raw material extraction and production to operation and waste disposal (CDW). In construction, it helps identify the potential for reuse of materials, reduce dependence on primary resources, and reduce greenhouse gas emissions. The use of combined approaches (for example, the bottom-up approach) makes it possible to improve national statistics by converting data on waste flows into strategies for sustainable development and effective resource management (Pineda-Martos et al., 2024).

Construction Material Usage: The consumption of building materials is an important indicator of resource efficiency, which shows how much total materials (by weight) are required for the construction and further operation of a building. The "Level(s)" system (Indicator 2.1) (Pineda-Martos et al., 2024). suggests measuring it in tons or percentages of the total weight of a building, tying it to specific structural elements. This indicator considers the entire life cycle of a building, including materials for construction, maintenance and repair. The analysis of these data makes it possible to assess the "cyclical

nature" of construction, determine the proportion of recycled materials, predict the volume of future waste and calculate the carbon footprint of the project.

Resource Potential Indicator (RPI): It is a numerical estimate of how feasible it is to reuse waste in a circular economy based on available technologies. The effectiveness of RPI depends on several factors. One of them is the level of technology development in a particular region: the better the circulating methods, the higher the resource potential. However, the RPI has limitations: it shows only a theoretical maximum, ignoring market prices and logistics. To make informed decisions, RPI should be complemented by market analysis.

Material Circularity: In order to move away from the conventional "produced-used-discarded" model, the Ellen MacArthur Foundation created the Material Circularity Indicator (MCI), a comprehensive tool for gauging how well a product or material complies with the principles of a closed-loop economy (Pineda-Martos et al., 2024). MCI is evaluated on a scale of 0 to 1, with 1 denoting full cycling—that is, using only recycled materials and having the potential to recycle the product 100% after use. The mass of raw materials, the quantity of trash that cannot be recycled, and the effectiveness of product use are all taken into consideration in the computation. This technique or technology aids engineering companies in introducing sustainable methods, lowering waste percentages, and improving resource management.

Material Longevity: It is intended to evaluate the efficiency of the resource in terms of protecting other resources via the measurement of the resource's lifespan. This lifespan consists of two components: the first one is the resource's useful life, and the second one is the resource's longevity due to maintenance and recycling. The primary purpose of this technique is to reduce the speed of utilization. Because the conventional Longevity Indicator (LI) cannot reflect the use frequency of the resource, more sophisticated LI models have been created (Pineda-Martos et al., 2024). The latter incorporate the ideas of durability and cyclicity, making the evaluation of the material efficiency more objective.

Resource Productivity: It is one of the major indicators which demonstrate the efficiency of using material resources in order to produce added value. This indicator demonstrates how much added value is produced from every kilogram, tons, or other units of used materials. Traditionally, the assessment of such an indicator consists in comparing GDP with the total amount of domestic material use (Pineda-Martos et al., 2024). Therefore, with this indicator, it is possible to estimate the efficiency of using raw materials and transforming them into goods.

Construction and Demolition Waste (C&DW) Management: This construction demolition waste involves the process of gathering, transportation, recycling, reusing as well as disposing of ordinary materials like steel, concrete, wood, and other construction waste. Key targets of C&DW Management are; reducing the volume of waste that is discarded in the landfills, encouraging recycling and reuse of material to save on the natural resources, minimizing the environmental factors such as pollution and depleting resources, making the building sector sustainably and boosting the economic efficiency through value creation out of the waste materials.

The circular economy (CE) of the construction industry is important because, to a large extent, C&DW Management reuses waste materials, which are normally discarded in a linear (take-make-dispose) approach, into an environmentally restorative one. Within a CE system, waste is considered as a resource that can be reused, recycled, or re-processed which will maintain the value of materials and minimise the requirement to mine new resources. C&DW management can be used to minimize the consumption of new raw materials by promoting reuse and recovering of materials. Moreover, it significantly minimizes environmental impacts such as resource extraction and waste disposal like pollution and carbon emissions, and it helps to bridge material loops, which promotes sustainable trends in production and consumption (Purchase et al., 2021).

Construction and demolition waste management indicators are quantitative tools to assess how construction and demolition waste is produced and managed. One of the main functions of these indicators is to facilitate a systemically planned system management process of C&DW. The key goal is to encourage reuse, recycling, or recovery of components, materials and wastes instead of their disposal. This high-value recovery is practically accomplished by dividing the collection of C&DW (on-site separation of materials like concrete, metal, wood etc.) during the whole life of the building into segments that are separated and stored in segregated spaces. These indicators are observed as a part of an even greater objective to achieve resource-saving and circular material life cycles.

These indicators are used to calculate and measure the total amount of waste produced. Besides being delivered as an aggregate sum, this data can be classified according to the primary categories of C&DW, often following the approaches developed by such frameworks as the European List of Waste entities. The data is normally expressed in kilograms (kg) or more importantly, the kilograms per unit area (kg/m²) so that they can be easily compared across projects. It is necessary to use this data at each phase of the project: during the conceptual design, it allows developing the outline of a Waste Management Plan

(WMP); (Pineda-Martos et al., 2024) during the detailed design and construction, it assists in developing a more detailed WMP; and during the as-built or in-use phase, actual inventory data is collected and used to perform a final performance analysis. Another example of a waste management measurable is CDW dumping. This measure distinguishes between the hazardous and non-hazardous waste depending on the ultimate fate of waste produced. It also relates to the ultimate destination of waste, which may be a material recovery, fill, incineration, or landfill to identify whether waste is being recycled or disposed of in a landfill.

Water Consumption: Water is one of the main critical sources that should be economically spent in every sphere of life. If we consider water consumption under the term of circular economy, it is inevitable to make some calculations on how much water is spent on the building.

Water consumption does not cover only the consumption of water by the residents of the house; on the contrary, it should cover how much water was used during the construction of the building and how much water was spent on the production of each raw material that is used in the construction. In this way, we can calculate the exact amount of water spent just on the construction of the building (Pineda-Martos et al., 2024).

There is a huge amount of water usage in construction site, and knowing the exact number of cubic metres of water used in construction can help to deal with this problem. It is difficult to decrease the amount of water used, but it is possible to optimize this process by using rainwater. Also, creating consumption monitoring systems helps to manage the situation in this field clearly.

According to Kakwani and Kalbar (2022) the system boundary and scope of the Water Circularity Indicator (WCI) underlines the fact that the evaluation is limited to the engineered water flows in urban water systems, where only water processes controlled by humans are considered. These are water supply, treatment, reuse, recycling, reclamation and restoration that are within the specified limit whereas the natural water flows like rainfall, groundwater recharge, and surface runoff are excluded unless they are incorporated into an engineered process.

The scope identified in the figure indicates that WCI is used to measure the efficiency and sustainability of water management in urban infrastructure, and within the system boundary that is fixed. This boundary encompasses the total water flows of urban water use, treatment and recovery which forms a clear framework in assessing circularity. The diagram, probably, illustrates the water flow passing through various phases of freshwater flow into the

system, treated wastewater, reuse, reclaimed water and ultimate restoration of water in the urban system.

Focusing on these designed flows, the diagram underlines that the WCI is designed to determine the efficiency of urban water systems in facilitating resource circularity and minimizing waste. It assists in explaining that this indicator is aimed to assess the operation of engineered processes in ensuring a sustainable and circular water cycle in the city or region, not to consider wider natural hydrological processes. This narrowed down boundary is to ensure that the assessment is relevant to the infrastructural management and optimization towards the sustainability objectives.

Carbon Footprint Impact: The carbon footprint has become a key tool for measuring greenhouse gas emissions and developing an environmentally friendly approach in the context of the circular economy. By mapping the environmental impact of a product, the companies are driven to optimize supply chain processes, simplifying operations and modernizing technologies that may be sources of emissions.

Furthermore, the growing spotlight given to carbon footprint analysis from global norms to local regulations underlines its function: fostering sustainable manufacturing and reduced-emission consumption. This attention itself is crucial to the success of the circular economy in as much as it drives industries and persons to behaviors that lessen the harm on the ecology. There are a lot of sources of carbon footprint, such as fabrics, construction, vehicles, chemical production, and so on.

There are some advantages and disadvantages in using the LCA to analyze the carbon footprint. First of all, when considering benefits, LCA uses comprehensive calculation stages: It provides a comprehensive view of the full life cycle of the product, from gathering resources to managing waste, using good and coherent consistency throughout the system. Secondly, it assists in identifying significant processes and elements, which enables focused mitigation strategies that support eco-conscious and sustainable development. Last but not least, LCA's flexibility allows for adjustment of both scale and detail to suit specific situations and may also enhance the resolution of results (Yu et al., 2024).

Among the drawbacks, LCA might not be uniformly conducted, and obtaining exact figures is sometimes difficult, which would hamper the credibility of the results, thereby influencing the decision-making process in carbon footprinting (Yu et al., 2024). Due to this, the process is time-consuming, involving a lot of effort, because it is complex, especially in complex systems, making it unsuitable for quick assessments. Some stages, such as the use

phase and post-use management, might also be left out, where most of the ecological footprint could occur.

2.1.4 Challenges in Implementing Circular Economy in Construction

The circular economy in construction makes it possible to make a building more environmentally friendly by reducing the percentage of greenhouse gas emissions, however, since there are no uniform standards for all buildings, this leads to challenges during implementation it. Then the question arises: what are the main barriers to the implementation of CE in the industrial sectors?

Based on the systematic review that was done by Tan et al. (2022), there are several limitations of introducing the CE. Firstly, researchers have observed an interesting behavioral phenomenon known as the "intention-action gap." This refers to the discrepancy between consumers' increasing awareness of environmental issues and what they do. That is, while individuals have expressed their intention to adopt sustainable living, their actions are less than the intention. For instance, even in attempting to reduce waste, most people still use disposable coffee cups because they are convenient. Similarly, the fact that a paper coffee cup would be preferable to one made of plastic is no answer to the problem at hand. Individuals know the long-term environmental and health negative consequences of the use of plastic, but effective solutions like using a reusable cup daily do not exist.

Second, risky behavior is not always an easy choice for consumers in putting circularity into their businesses. One of the reasons is decision-making psychology. Kahneman and Tversky (1979) believe that people like smaller, sure changes in their strategic plans more than riskier alternatives. However, when people faced with the threat of losing a lot of money, for instance, the high price of cement for ordinary concrete—customers may be inclined to take more risks. For instance, instead of purchasing ordinary cement, they can use geopolymers concrete made from industrial waste products like fly ash and ground granulated blast-furnace slag (without affecting the quality of the final product), which are considerably cheaper. In such circumstances, individuals are likely to be more dangerous, taking a risk instead of guaranteed lesser loss.

Lastly, another critical obstacle in advancing the circular economy is an understanding of the concept and access to the application of technology in enhancing capability within the CE (Tan et al., 2022). It entails comprehension of circular business models and capability in analyzing as well as employing them when appropriate. In addition, the unavailability of digital tools/software in advancing circularity remains the ultimate issue

whose resolve will provide maximized procedure. While current BIM tools can incorporate data tables, such as waste management plans or material estimates for a construction project, there are no precise digital tools designed to assess and manage projects based on key CE indicators. Moreover, existing tools do not provide recommendations such as, for minimizing carbon dioxide emissions and, consequently, reducing costs—an essential aspect of sustainable construction.

In conclusion, the challenge in the realization of circular economy in the industry is due to the absence of a clear framework backed with appropriate circularity indicators. This means few professionals get to learn work theoretically, while the other hindrance remains an absence of sophisticated digital tools. The implementation of the circularity is still be a tough call without precise digital solutions.

2.2 Digitalization in the Construction Industry

2.2.1 Role of Digitalization in Sustainable Construction

Sustainability in construction is improved by using new technologies in the fields of building design, construction, and entire lifecycle management through digitalization. Digital tools allow engineers to create a virtual model of a building so energy and waste may be minimized before the physical construction begins. Energy efficiency and cost savings are improved through the use of building information modeling (BIM), smart meters, and sensors, artificial intelligence (AI) and machine learning (ML), e.g.

It might be more accurate if the digital tools usage is split according to the full lifecycle of the building from Design Engineering to Renovation and Demolition. For example, for a new construction, sensors will be used to monitor the environmental conditions for energy optimization and comfort levels of the occupants. Thus, before construction, BIM will make it easier to find design flaws and improve energy efficiency by limiting material waste, while smart meters can give information about energy usage for efficient input management. Thus, 3D printing and robotic technologies are advantageous to all contractors by increasing process flow, decreasing material consumption and increasing precision (Asif et al., 2024). In this way, during operations digital twins and Building Management Systems (BMS) will collaborate to optimize buildings' performances and energy costs, thus satisfying the first indicators of the CE. Digitization creates an opportunity to continuously integrate new and emerging technologies to design and build buildings that meet adaptability, cost, and environmental requirements, thus directly supporting the global sustainability agenda.

2.2.2 Benefits of Digitalization for Circular Economy

Technology has become cheaper in the industry 4.0 because Big data, IoT and AI are the examples of modern "digital technology" operating in the network because of the Internet and create networks (Allen & Sarkis, 2021). The Internet is the digital economy (DE) centre and the platform for creating connectivity and productivity among consumers, workers, companies, and industries worldwide, especially in the rural regions. Thus, digital technologies can lead to a direct intervention in the circularity of construction by enabling to rethink business models, raw materials and consumption patterns (Kalogiannidis et al., 2022).

Hedberg et al. (2021) concluded that the digitalization of a circular economy increases resource efficiency due to the ability to connect stakeholders and make information more accessible. Material and hazardous substance tracking along the value chain makes recycling and reuse safer: traceability makes CE indicators easier to follow. Digitalization makes circular economy systems better and transforms the way they think by structuring themselves and by being able to modify the structures and understand more easily what these structures imply. The results from the SPSS (Statistical Package for the Social Sciences) analyses showed that 73.7% of the responses (200 participants including certificate-9, Diploma-22, Bachelor's degree-65, Master's degree-97, PhD-7) agreed with the statement "digitalization includes the promotion of current small enterprises and circular business methods of major firms." Meanwhile, 62.8% of respondents also agreed that "CE sustainability is enhanced by a broader use of the Internet of Things, big data and data analytics" (Kalogiannidis et al., 2022, p.11). This research findings indicate that CE has a very huge positive impact of the digital technology which may help in optimizing the process by making the process clear and safe for the consumers and stakeholders/contractors involved.

2.3 Building Information Modelling (BIM) for Circular Economy

2.3.1 BIM as a Tool for Circular Construction

Modeling Information Building (BIM) is an integrated process that enables many stakeholders to collaborate and work on a digital representation of a building. BIM enables the management of the stages of the building lifecycle, by storing detailed data parameters of the building from design to demolition. Although BIM offers improved data storage, automated procedures and management collaboration, it does not specify BIM levels from the most basic 2D CAD (Level 0) up to fully integrated 3D BIM (Level 3). Under design facilitation, early decisions are made, and changes of design will be reflected automatically in related components by coupling with relations in parametrical modeling under BIM. In

addition, material optimization with respect to the circularity principle during production will be supplemented by process simulation, cost calculations, and schedules. Once constructed, it becomes that dynamic database of effective and sustainable maintenance, life cycle, and upgrades. Such characteristics continue to promote circularity by means of material passports which hold information about the material origin, re-usability, and recyclability. It also supports life-cycle assessments (LCA) through automatic estimation of volumes on greenhouse gas emissions, recyclable content and sustainability assessments. It incorporates with real-time circularity assessments of deconstruction potential and material selection in combination with automatic decision support tools (Askar et al., 2024). As a result, BIM is a key driver in the development of sustainable and circular construction since it offers users the ability to make decision-making based on data while optimizing resources effectively.

Nowadays, as Askar et al. (2024) stated there are only few projects that demonstrate BIM in CE. One of them BIM-DAS automatically provides the deconstructability assessment from the design phase by automating material data storage and bill of quantities generation. Moreover, there is the Visual Circularity Assessment Framework which links lifecycle costs with circularity metrics, visually assessing sustainability across a building lifecycle within a deployment.

Also, one of the brightest example was the Accelerated Metallurgy project funded under H2020 which want to find eco-friendly metal alloys and create new materials using AI (Hedberg et al., 2020). In the focus of efforts is to tap into the capabilities of digital technologies to speed up the development of new materials. The digital technologies are meant to cut down time consumption and aid in discovering alternative materials. These BIM-based projects prove that it is possible to add functionality to ready-made programs or create a new one based on an existing structure with indicators.

2.3.2 Challenges in BIM Adoption for Circular Economy

Digitalization for a circular economy, facing some progress, still has several barriers. Firstly, although digitalization can lead to circularity, it is not developed for that end. There is little progress in encouragement of purpose-driven digitalization by policy or investments. Furthermore, many businesses do not have frameworks, as well as knowledge and motivation, to acquire digital tools. Secondly, limited access to data is caused by standards, trust, and data protection issues; hence data that is available is less actionable which slows down the process (Hedberg et al., 2020). The last but not least, the data can affect the sharing and the creation of valuable insight into the ideas more generally around a circular economy

if it is fragmented over different isolated databases. New software and older hardware incompatibilities would thus lead to an increased demand for faster hardware turnover and thereby increase e-waste.

2.4 Information Requirements and Data Standards for Circularity

This research paper is collaborating with the circular indicators on Material level and Building Component and System level. Thus, the literature review was mostly performed in this direction, one of the main barriers to the implementation of the BIM tools for compliance with circularity indicators in the construction process, is the absence of information on the construction materials and the BIM tools implementation procedure.

There are a couple of initiatives across Europe that have been in existence for some time for the purposes of collecting the digital data for circularity initiatives. Circular practices are also required by the European Taxonomy and the ISO 20887 standard on design for disassembly and adaptability (DfD/A), International Organization for Standardization, 2020. The standard provides general design guidelines for versatile buildings that can be created by using interchangeable building components. It also advocates the use of BIM in the management and analysis of relevant information although the digital implementation is not defined. According to the constructive research done by Tomczak et al. (2024), there is a demand to translate needs of circularity into machine-readable formats based on the new Information Delivery Specification (IDS) standard. While some data is not modifiable in BIM, such as inconsistent terminology and disassembly information, the research indicates that most of what we want to know about sustainability can be modeled in BIM, and it aligns sustainability data needs with what can actually be modeled. Indeed, if a database with all materials characteristics and related characteristics is generated and maintained accurately, frameworks can easily be matched with or generated, and such database can be made available as a library for all BIM tools.

In addition, while quantities and size of elements have very much support and standardization through the Industrial Foundation Classes (IFC) schemas, other very important items like disassembly instructions, material circularity, and environmental impacts have less schema support and rely heavily on custom nouns or external data references. This reflects the fact that circularity assessments require and seek information that is currently not embedded in BIM models. In addition, connection information and material safety data are not only in high demand but also have strict supply limits, so that they are rarely or provisionally provided within the digital model. The results support the conclusion that

further efforts are required to incorporate circularity indicators in meaningful ways into BIM workflows. By normalizing terminology across the used platforms and harmonizing information requirements through the creation of common tools (e.g. the IDS), the consistency and reusability of data could be further improved. As the prevalence of digital construction practices increases, it will be of utmost importance that the information on sustainability is machine readable and verifiable to accommodate the lifecycle thinking and circular economy principles from the design and planning phase onward.

Chapter 3 – Methodology

3.1 Research Approach

3.1.1 Introduction to the Methodology

This research paper intends to conduct an assessment on available existing digital tools, including mainly BIM tools, using Deep Search AI tools, to assess the level of digitalization in the circular economy in the construction sector. Taking into consideration the roles and issues that arise with BIM adoption with respect to the existing literature, there is a need to assess how current BIM tools for each CE indicator can adapt through artificial intelligence assistance. This area of research, which includes both systematic reviews and case studies, can provide a thorough, data-driven understanding of such an artificial intelligence-based assessment, thereby improving the overall understanding of BIM in circular construction.

It is important to highlight that generating reports with the list of digital tools for each indicator made by Elicit Pro, but the revision was done manually by the author of this research. Therefore, this paper does not use just generated answers from deep search. Every tool and source for each tool was double-checked. An AI research tool used only to sort the papers accurately and cover as possible number of papers

3.1.2 Data Collection Methods

Systematic literature reviews are downright time-consuming to perform, particularly when one works around a wide field of existing research or maps works of existing ones for further assessment. Traditionally, various platforms, such as Google Scholar, ResearchGate, and Elsevier, provide access to official research or conference papers. However, manually reviewing hundreds of articles with several keywords is impractical in the very first stages of finding research gaps. Digital technologies can make processes much faster than they used to be, but it's still important to choose the right and accurate AI tools for doing literature reviews. According to José de la Torre López et al. (2023), automating systematic literature reviews is still a new and growing field that needs more development. Although it is important to highlight that it allowed researchers to focus on the content of each research work and study them accurately and efficiently by speeding up the process of making a possible list of research outlines for the literature review. Here comes the most significant part: the paper selection. AI tools for doing literature review may have huge databases of research papers, but will always require an effective script. The short script helps the AI find the exact content quickly, and it's a good sign when the AI asks 5 - 6 questions, showing that

its work is accurate. However, it takes time to understand the workflows. In addition, it should be noted that it is impossible to make the same script while doing an academic literature review as writing the definition for each prompt may change things. Therefore, it is recommended to analyze and check instructions for columns. In conclusion, choosing the accurate AI tool that matches the goals of the project shows how precise the approach is.

This reaserch work used 2 AI tool such as Undermind AI and Elicit AI, as a result will choose the most appropriate Research AI tool for doing further literature review.

3.2 AI-Assisted Literature Discovery: Iterations

3.2.1 Initial Exploration using Undermind AI

This paper choose Undermind AI for doing the systematic literature review on BIM tools used for chosen 13 circular economy indicators as shown in Table 2.2 It is the AI-powered research assistant that promises to revolutionize the reading of scientific literature for making the procedure smooth yet fruitful. Beyond traditional research tools, Undermind offers many benefits such as fully automated formatting, collaboration functionalities, AI-oriented insights, and research paper publishing support and full list of references. The Undermind AI allows researchers to save time by focusing only on the most relevant papers and narrowing the scope, as in the past, literature review required considerable time and reduced the efficiency of authors. At present, however, authors can concentrate on identifying novelty, conducting experiments, and carrying out surveys by quickly understanding the content.

The Figure 3.1 shows the Undermind Research Assistant interface, which enables deep searching of scientific articles based on user-provided questions. One of the key advantages of this AI tool is its ability to enhance search accuracy by prompting users with 5–10 clarifying questions, while also enabling dialogue with the AI-powered search engine to achieve more precise results. This enhances the accuracy of search queries, which can be edited and defined by the user for narrowing down their queries, ultimately improving the quality of retrieved publications. As a result, the report will be done in 5 minutes.

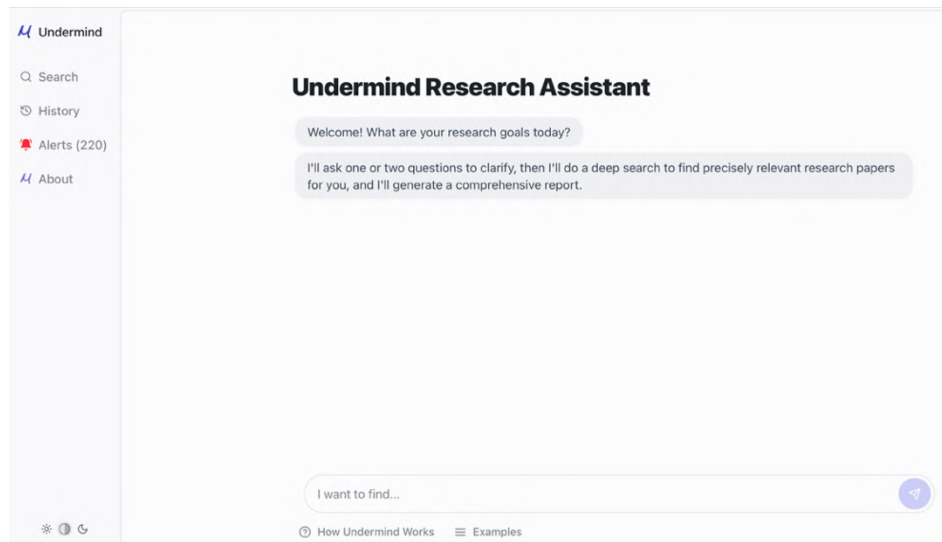


Figure 3.1: The main interface of SciSpace for Deep Search

Once a request has been made, the tool, as illustrated in Figure 6, generates a table of papers after scanning over 500 publications and picking the most relevant ones by giving relevance percentages for each of them. Users can further customize the table by adding various columns—such as year of publication, relevance level, keywords, and abstract scans—to facilitate effective paper comparison.

REFERENCES		Q	Sort	Filter	Export
1	100% 2022 10.5	Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings Rand Askar, ..., and H. Gervasio Applied System Innovation 15 февр. 2022 г. 37 Citations			
		Reviews BIM-based frameworks and tools for DfA assessment in circular buildings. Analyzes both theoretical frameworks and recent BIM-enabled assessment tools (CBA, D-DAS, material passports) and their functionalities/limitations. Highlights prototype status, methodological gaps, and challenges in BIM-DfA-circularity integration, with explicit discussion of metrics (LCA, LCC, reusability), interoperability, and tool maturity.			
2	98% 2019 27.8	Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy L. Ákánbí, ..., and H. Owolabi Journal of Cleaner Production 1 июня 2019 г. 174 Citations			
		No text available for this reference.			
3	98% 2024 0.8	Estimating the Circularity of Building Elements using Building Information Modelling O. Gbenga John, ..., and A. Borrmann IOP Conference Series: Earth and Environmental Science 1 июня 2024 г. 1 Citation			
		Proposes a BIM-based framework to assess building element detachability for circularity. Utilizes BPMN and attribute matrices to automate integration of detachability (a DfA aspect) within BIM circularity assessment workflows. Addresses measurable DfA/circularity indicators (detachability), BIM functionalities, some integration challenges, but focuses mainly on detachability—not the full maturity of BIM-DfA-CE integration.			
4	97% 2020 22.5	BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review Arghavan Akbarieh, ..., and F. N. Teferle Sustainability 28 марта 2020 г. 122 Citations			
		Reviews BIM-based tools and frameworks for end-of-lifecycle circularity and deconstruction. Maps existing research and measurable digital methods (e.g., BIM Deconstructability Scores, recycling/reuse estimation tools) for supporting circular-EoL decision-making. Highlights limited maturity, ad hoc implementations, lack of global circularity frameworks, major interoperability/IFC challenges, and briefly assesses integration depth for DfD/DfA in BIM.			

Figure 3.2: The results of the deep search in table for the first CE indicator - Design for Adaptability (DfA)

As shown in Figure 3.2, a list of papers with high relevance percentages is displayed. In practice, the Undermind Research Assistant identified 517 papers related to existing tools

and solutions supporting the Design for Adaptability (DfA) indicator in the circular economy. However, it is important to consider the relevance percentage when selecting materials. For example, although Undermind initially reviewed 517 papers and selected 80 that appeared related, only 11 of them ultimately had a relevance score above 50%.

Besides generating a list of scientific papers with relevance levels, this AI tool also offers short summaries with citations, helping users find relevant papers more quickly, as shown in Figure 3.3.



Figure 3.3: Options for creating columns

Another good thing about this tool is its search feature in the report. This lets users quickly find specific words, ideas, or mentions without having to sift through a lot of text by hand. Because of this, it's much easier and faster to go over and put together information. Also, this helps with detailed research by letting people check the same words or topics in different documents, which makes it easier to understand the whole body of work better, as in Figure 3.4.

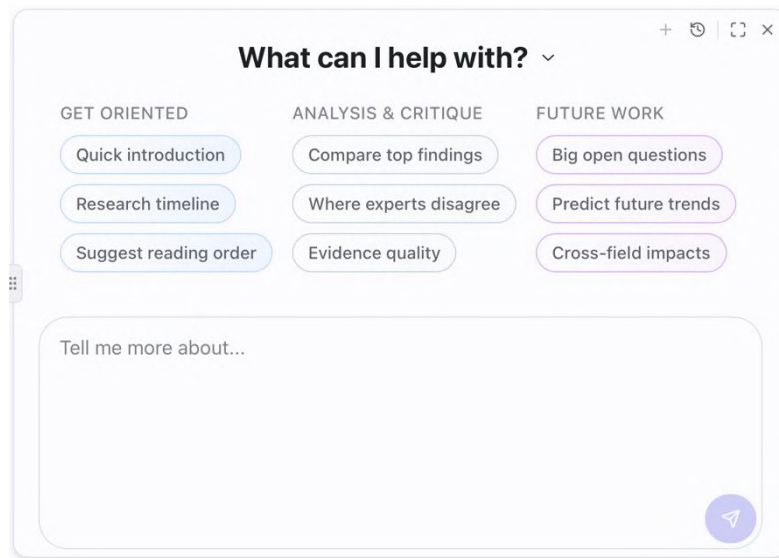


Figure 3.4: Searching point in the Undermind AI

Nonetheless, it must be clarified that the Undermind AI used in this study to extract information largely from the abstracts of scientific papers based on the Retrieval-Augmented Generation (RAG) method, as it does not always have constant full access to original papers ((Jain, Sibbu, Kuri, Sanmati, & Jain, 2023)). Some papers may require a direct request to the authors for full access. Accordingly, this study utilizes Elicit AI to analyze large datasets and assemble a collection of the most relevant sources for further in-depth analysis.

3.2.1 Critical Evaluation and Tool Selection: Transitioning to Elicit AI

Elicit is an AI (artificial intelligence) research assistance tool built with language models to partially automate the research workflow, particularly in evidence synthesis and literature search (Bernard et al., 2025). While retrieving published material from Semantic Scholar, Elicit can find relevant papers with no exact keyword match, summarise the major findings of each publication, and extract structured data from abstracts (Bernard et al., 2025). Based on the studies of Elicit's ability to assist with the systematic review process showed the value of comparing Elicit to traditional screening methods in terms of repeatability, reliability and accuracy providing proof that AI-assisted searching may provide a viable adjunct to traditional literature review methods (Bernard et al., 2025). Based on accuracy, relevance, and efficiency, they were able to identify the strengths and limitations of various search tools using a two-phase framework, with Elicit offering a new strategy for conducting structured literature searches, critical thinking about the use of AI-powered search engines (Fenske & Otts, 2024). The systematic review conducted using Elicit AI can generate up to 1,000 papers and extract relevant data by filtering the information. During the identification

of BIM tools for the selected 13 CE indicators, the required information was included in predefined columns, and specific instructions were provided for each column.

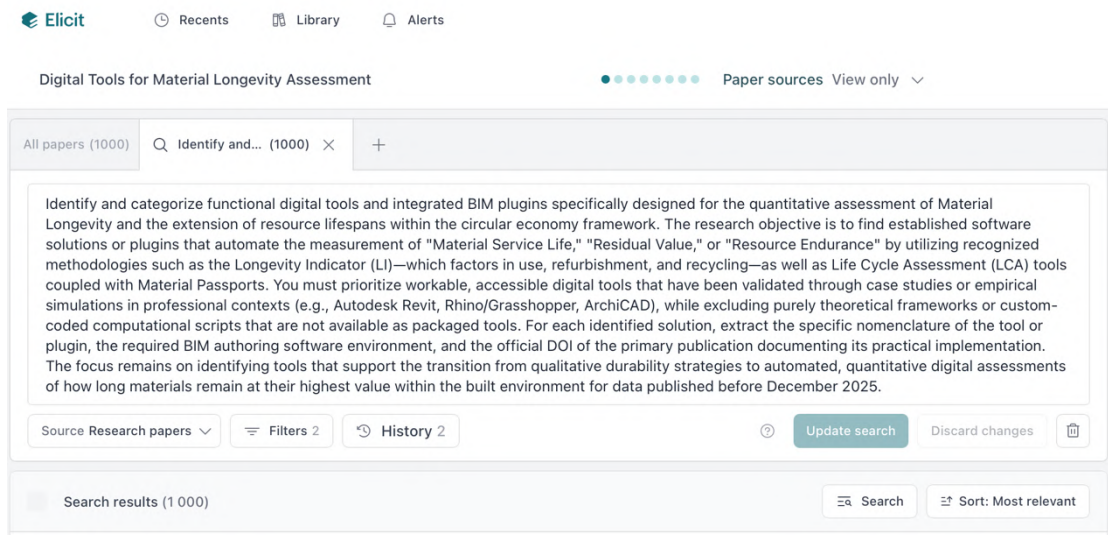


Figure 3.5: Entering initial script for systematic review in Elicit Pro

Initially, this study created individual scripts for 13 indicators, which were used in a systematic review in Elicit Pro. These scripts were developed and generated using an AI tool and then manually reviewed and validated by the author. The script contains the definition of each indicator and the requirements for searching the digital tool for the stated indicator name. All 13 scripts are listed in Appendix A.

The first step is to select the systematic review function in Elicit Pro and enter the initial script. As Figure 3.5 shows, the systematic review analyzed 1,000 papers using the initial script. However, relying solely on the initial script and waiting for accurate results is not the correct way to use an AI tool for research. Since Elicit is an AI research assistant, your task is to develop a model and train the AI tool to achieve the best results. Therefore, this research tried to use all functions of the Elicit Pro, as the systematic review involves abstract screening, full-text screening, data extraction, and the final report; these functions should be used in advance. The following questions, paired with column-specific instructions, were used to extract and organize accurate information from the selected papers, as shown in the tables below. These questions helped analyze the initially identified 1000 papers step by step and, as a result, yielded the most accurate answers.

The first stage involved entering the initial script and identifying 1000 relevant papers. Afterwards, the system uses a second filter called “Abstract Screening. ” Table 3.1

shows the two questions used in this stage. The second step analyzes papers based on whether the abstract mentions the BIM tool name and whether the paper provides quantitative analysis regarding the selected circular economy indicator. These questions help eliminate unnecessary papers in the second stage. Similar questions are recommended automatically based on the initial script. To get the most accurate and consistent results each time, the study created a list of questions for each filter stage. They are the same across all 13 indicators and are applied to each.

Table 3.1: Criteria for Abstract Screening during Systematic Review

Abstract screening	
BIM Tool Mentioned	Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
Circular Indicator	Does the paper claim to quantitatively measure [Indicator name: Design for Adaptability]? Answer 'No' if it is purely qualitative.

The third stage involves screening based on the full text of the papers. It is important to note that initially, it was decided that all papers must be open access for the full text and cover all publications before December 2025. Based on Table 3.2, there are three questions for this filter. First, it checks whether the tool demonstrated integration with other BIM tools. Second, the filter checks the practical validation of this tool, because the aim of the research is to find a workable tool. Third, it considers if there is a tool that can produce what kind of output regarding the chosen circular indicator.

Table 3.2: Criteria for Full-text Screening during Systematic Review

Full-text screening	
Tool Implementation	Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
Practical Validation	Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
Primary Output	Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

The fourth stage involves summarizing the information into a single table. It is important to note that creating the same table for each of the 13 reports was somewhat challenging. The possible reason might be the variety of papers and methods used. Therefore,

reports for the 13 indicators are saved in PDF files and analyzed manually for further discussion.

Table 3.3: Criteria for Standardized Data Extraction Report

Data extraction	
Exact Tool Name	Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'
Tool Type	BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on).
	Visual Programming Script: A script developed in Rhino or Dynamo.
	Cloud-based Platform/API: A web-based tool that processes BIM data.
	Standalone BIM Software: A separate software that imports IFC/BIM files for analysis.
	BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking.
	Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis.
BIM Software	State the host software required
Download & Access	Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?
Ease of Use	Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.
Focus area	Specifically, how does this tool support [Indicator Name]? What is its main automated output (e.g., Disassembly Index)?

The reports include information about the specific tool names based on the papers. Additionally, tool types are categorized into six groups, which include: BIM plugin, Visual Programming Script, Cloud-based Platform, Standalone BIM software, and BIM Integrated Database or Frameworks. The main reason for dividing the tool types in this way is that few BIM tools support CE indicators, and the initial aim of this work is to assess the maturity of existing solutions.

Figure 3.6 shows the list of columns that can be automatically selected based on the initial script and manually corrected based on the guidelines in Table 3.3.

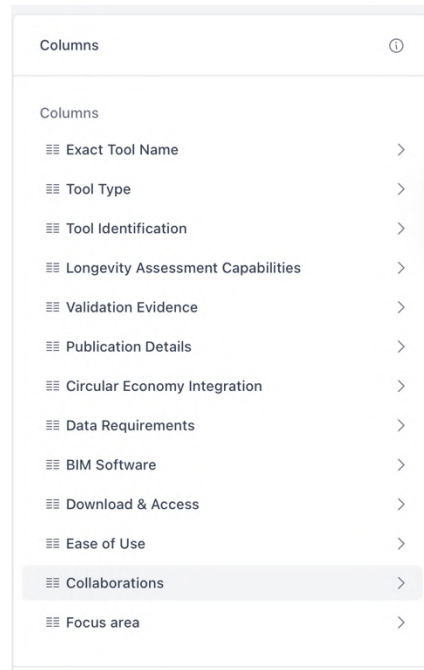


Figure 3.6: Columns in the extraction stage

Elicit Pro is an AI Research Assistant used in this paper. The main reason is that Elicit AI can process up to 1000 papers, whereas Undermind AI can only handle 500, allowing for broader comprehensive coverage. Additionally, based on the initial script for each of the 13 indicators, Elicit automatically generates a column to sort the papers, making it much easier to manually correct the list of columns. Later, the report will generate several tables based on the selected columns in the final stage. In contrast, Undermind AI can also generate reports, but because there is no option to sort step-by-step by columns, the results are less accurate and harder to verify. In addition, Elicit automates the full PRISMA workflow, which includes search with a script, abstract screening, full-text appraisal, and report generation, reducing manual errors.

While using the Pro version of Elicit AI, all literature reviews were conducted with the ‘systematic review’ function and included only papers that are open access and cover publications up to December 2025. The main drawback of using the AI Research Assistant is that it does not produce the same report with identical tables for each indicator. This may be due to differences in the styles of the papers and their accessibility. Additionally, to generate

an identical report for each indicator, connect coding would be needed to write a script with an “if” function.

3.3 BIM Tool Assessment Framework

3.3.1 Overview

With the help of Succar's BIM Maturity Index (BIMMI) and the associated BIM Maturity Matrix as the primary evaluation framework, this thesis looks at BIM tools and solutions supporting the thirteen circular economy indicators picked. The study chose Succar's BIM Maturity Matrix as the only BIM-focused maturity model, distinguishing between tool functionalities and effectiveness levels. First proposed as a peer-reviewed section in 2010 (Succar, 2010), the matrix afterward became the foundation for the BIME Initiative's useful self-evaluation package. The information about BIME website: the first document was published in November 2010, and the BIM matrix itself was given during workshops conducted in June 2016. Afterwards, it was updated and published on July 22, 2016, as part of the BIME Initiative (301 in the 2019 BIM Maturity Matrix). This information shows that this framework was reviewed academically and appropriate for usage.

3.3.2 The core elements of the BIMMI framework

The BIM Maturity Matrix consists of 3 interconnected components that describe how to characterize, measure, and improve BIM implementation. The first component is “BIM competency sets,” which group the skills supporting the stages and levels. Succar (2010) kind of splits these into three strange but logical areas, though they sometimes overlap a bit. The Technology area is like the machinery part—software, hardware, and the network things that make BIM breathe, or function, or however you’d call it. The Process area is more about people leading, designing workflows, and the outcomes that BIM produces (such as design-for-disassembly). The Policy area, on the other hand, deals with the rules, contracts, and training that somehow push or slow BIM’s acceptance and control (Succar, 2010). Mapping a tool to these three fields, it sorts of reveals if it’s more of a technological helper, a process improver, or something that leans toward policy.

The second is “BIM capability stages,” which define the functional level of a BIM tool or process (Succar, 2010). In its simplest form, “Stage 1 – Object-based modeling” refers to tools that operate on a single-discipline 3-D model; for example, a Revit plug-in that

extracts quantities for a life-cycle assessment. “Stage 2 – Model-based collaboration” extends beyond a single discipline, enabling the exchange of models, often using IFC. This means, for instance, that an LCA engine can use data from both architectural and structural models. The most advanced stage, “Stage 3 – Network-based integration”, describes a cloud environment where different stakeholders maintain a shared, federated model. Also, the stage number itself is used as the “score” ($S1 = 1$, $S2 = 2$, $S3 = 3$). This is the value you already have in the “Capability stage” column of your table. This allows the tool to function in a real-time, multi-user ecosystem that includes design, construction, and operations.

The third component of BIMMI is “Granularity levels,” which signify the degree of detail within the assessment process (Succar, 2010). It consists of 3 granularity levels:

- G1 – *Discovery* is more like a quick self-peek, kind of a rough guessing game about how mature or ready something might be, not very strict but still helpful.
- G2 – *Evaluation* asks for more serious evidence, like written samples or maybe a short story from a project, and it gives a number that looks more exact.
- G3 – *Certification* is a formal inspection that ends with a locked maturity tag, usually done by someone not in the project, which makes it official.

The main scoring system is “BIM maturity levels,” which measure the quality and reliability of BIM use at each capability stage (Succar, 2010). An “Initial” level indicates experimental use with limited documentation, relying heavily on individual expertise. The “Defined” level has a documented workflow, but monitoring and quality control are still limited. The “Managed” level shows a repeatable workflow where data exchanges are monitored. Case studies often support this with consistent results. At the “Integrated” level, outputs are linked to other project processes and data sources, such as cost, scheduling, or facilities management systems. The highest level, “Optimized”, demonstrates ongoing improvement, strategic use of BIM data, and a methodical approach to improving performance.

When integrated with 3 components — capability stages, competency sets, and granularity — the BIM maturity matrix provides a framework for evaluating any BIM-related artifact, including the digital tools discussed in this paper. The matrix gives what they call a “maturity score,” somewhere between 10 and 50, by linking each stage to a number—10 for Initial, 20 for Defined, 30 for Manageable, 40 for Integrated, and 50 for Optimized. It’s kind

of like a ladder but with numbers instead of steps. To get the score on Succar's BIM maturity matrix you just pick the level that actually fits what's been documented, or what the tool really shows, initial or defined or managed or whatever it is, and that's the number you take. No math gymnastics needed. But if you decide to add the three BIM competence bits—technology, process, policy—each goes from –10, so you add them up (max 30) and then stretch that to the –50 scale by multiplying by $5/3$, which sounds simple but somehow feels not simple at all.

The final figure, 0-50, can be indicated in the table as an indicator of the instrument's maturity. This assessment system, which supports the BIMe initiative self-assessment kit included in the BIM Maturity Matrix (2019), provides a quantitative framework for the comparative analysis presented later in the Results chapter.

In addition, there are tables with criteria specified in Succar (2010) to select the appropriate option, with full-fledged criteria for each BIM tool, which will be analyzed using this structure, provided in Appendix B (the Figures B. 1-B. 5 are the BIMMI framework taken from Succar's (2010) research work). It is important to emphasize that this article uses an existing framework, and the author expresses his opinion and evaluates BIM programs based on information from official documents and case studies, as well as his experience. This work requires further development by more experienced employees in the industry.

Chapter 4 –Results and Discussion

4.1. Overview of CE Indicators

This part of the study will analyze the identified BIM tools and solutions which were sorted using Elicit Pro AI Research Assistant for 13 selected Circular Economy indicators, such as: Design for Adaptability (DfA), Modular Construction and Prefabrication, Design for Durability, Adaptive Reuse of building elements, Design for Disassembly (DfD), Easy Maintenance (Maintainability), Construction Materials Flow Analysis, Construction Material Usage, Resource Potential Indicator (RPI), Material Circularity, Material Longevity, Resource Productivity, and Construction and Demolition Waste (C&DW) Management. In addition, all digital tools will be assessed using the BIM Maturity Matrix developed by Succar (2010).

This part of the study will examine each digital tool individually, highlighting the types of indicators they cover and conducting maturity assessments using BIMMI. Appendix C includes tables with digital tools corresponding to each of the 13 indicators. Appendix D includes the reports generated by Elicit AI for every 13 CE indicator, as it consists around 200 pages, this document should be added to thesis as a separate material.

4.2 Performance Analysis and Maturity Assessment of Digital Solutions for Circularity

Revit-based transformability-index tool (Diana et al., 2022): aimed for Design for Adaptability and identify "transformability index" which shows how this building can be redesigned or reused after the end of its lifespan. In this process plug-in helps to collect data on material, functional and geometric levels from the model in Revit. It is then puts information about the location of the building, how to get there and the nearby buildings into GIS. As a result, these collected database using plugin and GIS can calculate the transformability index. This approach has been empirically tested on a publicly available foundation of abandoned medical facilities in Campania, Italy, illustrating how this tool can be applied to a real portfolio of buildings to prioritize the most flexible facilities for reuse. Based on the results of this case study, the tool not only evaluates flexibility but also helps in decision-making to achieve the goals of a closed-loop economy in an artificial environment (Diana et al., 2022).

Table 4.1: Maturity assessment (BIMMI) for Revit-based transformability-index tool

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Revit-based transformability-index	Integrated BIM framework	S1	G1	Technology	Defined	20

Based on the information in table 4.1 the tool works on the basis of a single-dimensional Revit model, complemented by GIS data, without using a combination of interdisciplinary models or collaboration in the cloud. Thus, it belongs to capability stage S1 (Object-Oriented Modeling), where the stage number indicates capabilities. Since the data is based on a single regional case study, the level of detail is G1 (discovery), indicating limited but understandable documentation. Its main goal is to manage digital geometry and spatial data, with technology being the most important BIM skill. The workflow is systematic, repeatable, and documented in the literature according to the definition of a specific maturity level in the BIMMI matrix, which corresponds to 20 maturity points on a scale from 0 to 50. Although this tool is still in the early stages of broader certification and integration, the assessment suggests that it makes a significant technological contribution to DfA.

PMOOD (Parametric Multi-Purpose Optimization and Decision Support) (Julia et al., 2022): is an integrated BIM platform that combines Rhino 3D, Grasshopper, and Karamba3D to create alternative spatial layouts, structural systems, and material selection for an industrial facility, while improving indoor air quality, cost, and energy consumption. The pilot application at a hygiene products manufacturing facility demonstrates a fully parametric process in which design factors (floor plan geometry, structural elements, facade composition) are correlated with performance goals using a multi-purpose evolutionary algorithm. Designers can assess how quickly an enterprise can be converted to a different product line or a new functional program, which provides exactly the flexibility that DfA requires, since the optimization mechanism can quickly analyze several "what if" situations. A practical example shows that the tool can generate measurable flexibility indicators (for

example, less waste on the area, more possibilities for reuse of structures) without complex coding, which makes this approach accessible to architects and engineers.

Table 4.2: Maturity assessment (BIMMI) for PMOOD (Parametric Multi-Purpose Optimization and Decision Support)

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
PMOOD	Integrated BIM framework	S2	G2	Technology	Managed	30

The framework operates on three closely connected software platforms that let you exchange models for structural analysis (Karamba3D) and geometry (Rhino/Grasshopper). This multidisciplinary cooperation advances the framework to the S2 (model-based collaboration) level and assigns it a 2. Since the pilot project goes beyond a basic proof of concept, it provides a repeatable, well-documented procedure satisfying the level of detail necessary for the G2 grade. Its primary objective is the automated construction and evaluation of design capabilities, hence the primary ability of BIM is technology 1. The tool corresponds to the managed maturity level in the Succar matrix, rated at 30 points on a 0-50 scale, because it provides a systematic, repetitive decision-support process that increases design flexibility and efficiency. Although there is space for more integration and certification, PMOOD provides a mature, technologically sophisticated contribution to DfA, according to this review.

Building Automated Characterisation (BAC) (Fernandes et al., 2022): is a comprehensive BIM system developed and evaluated in a residential building in Lisbon, Portugal, using BIM software developed according to the Uniclass 2015 classification criteria. The workflow improves the BIM components by adding relevant data adapted for the material passports. This leads to a complete inventory of parts, materials, and their properties. By methodically describing the current building design, BAC ensures adaptability of design (highlighting which components can be changed or repurposed during renovation projects), durability of design (documenting construction methods and material characteristics applicable to long-term use), adaptive reuse (providing the necessary data to evaluate many approaches to reconstruction in terms of efficiency of existing design), as well as the durability of materials (by linking materials to passports that allow you to track the remaining

service life, reuse and recycling possibilities). The importance of a data-rich characteristic to support a renovation project focused on a closed-loop economy is demonstrated by this implementation, as shown in the case study.

Table 4.3: Maturity assessment (BIMMI) for Building Automated Characterisation (BAC)

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
BAC	Integrated BIM framework	S1	G1	Technology	Initial	10

As shown in Table 4.3, BAC operates in a single BIM environment complemented by a categorization system, in the absence of thorough documentation of an interdisciplinary federation of models or collaborative activities, so it corresponds to capability stage S1 (Object-oriented modeling) with capability assessment 1. The proposed material covers one housing case study and a general overview of the workflow presented in the document, according to G1 (Discovery) details. Its main goals are the digital organization and extraction of data related to buildings and materials, so technology is the most important focus in BIM. Since this approach is at an early stage of development, marked by weak validation and lack of documented tools, it belongs to the initial maturity level, which is rated on a 10 point scale from 0 to 50.

AdRem (Palma et al., 2020) is a visual programming system for adaptive remediative processes that can be applied using either Grasshopper for Rhino or Dynamo for Revit, and it has been presented at the polluted industrial site of Nitrastur in La Felguera, Spain. The workflow of this application combines 3D modeling in Rhinoceros with parametric modeling implemented through Python scripts in Grasshopper or Dynamo. Instead of a fixed initial state, it explores the evolution of the territory over time. This includes an analysis of various spatial configurations, step-by-step development plans, dynamic terrain changes, and construction integration. Special attention is paid to the flexibility of land use, reuse of existing structures and gradual adaptation to changing environmental and legal frameworks. This parametric, scenario-based approach makes it possible to achieve a high degree of adaptability of the project at the site level. Although the presented material demonstrates the use of a digital twin strategy for data integration, the full details of the implementation are not

disclosed. This indicates that the adaptive potential of the building is under active development, rather than being fully realized.

Table 4.4: Maturity assessment (BIMMI) for AdRem

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
AdRem	Visual-programming script / Integrated BIM workflow	S1	G1	Technology	Defined	20

AdRem works primarily within a single developer 3D world (using either Rhino or Revit), supplemented by scripts written in either Grasshopper or Dynamo. There is little evidence of multidisciplinary pooling of models or data exchange for collaborative work. This is consistent with Stage S1 Object Oriented Modelling and has a score of 1. There is a single case study (for a project called Nitrastur Industrial Area), but this has been implemented and documented to include a description of how it works; there are no official implementation instructions or general duplication, consistent with G1 – Discovery. The technology has its power within 3D and parametric modelling, scripting, and possibly digital doubles, rather than within organizational processes or rules. The process described is a regular and repetitive one, even though it is a research prototype and requires a high level of programming knowledge. Therefore, it has a certain level of maturity consistent with the data presented within Table 4.4 and has a score of 20 out of a possible 50.

MIVES (Integrated Value Model for Sustainable Evaluation) (Tan et al., 2024) is an autonomous multi-criteria decision platform (MCDM) that integrates with BIM to evaluate the sustainability of Design for Manufacture and Assembly (DfMA) solutions (modular construction and prefabrication) for modular facade retrofitting. In Wuhan, China, the frame has been used to assess 5 different prefabricated external panel configurations for a facade renovation project. Based on the data from the Revit model, for example, is used to generate a combined sustainability index and its correlation to social, environmental, and financial factors by MIVES. This helps designers to select the most sustainable modular facade design, which in turn enables them to make decisions while designing modular and factory-assembled construction.

Table 4.5: Maturity assessment (BIMMI) for MIVES (Modelo Integrado de Valor para una Evaluación Sostenible)

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
MIVES	Standalone MCDM framework integrated with BIM	S1	G1	Technology	Defined	20

Based on Table 4.5, MIVES is employed as a self-governing decision support system that communicates through a sole Revit model, without any noticeable evidence of any interdisciplinary model integration and management, thereby placing it in the S1 (Object Oriented Modeling) level of capability, where "1" is used for the assessment of the capabilities. This method has been validated through a comprehensive practical investigation of the renovation of facades in Wuhan, assessing five DfMA options, according to the level of detail of G1 - Discovery, as there is evident proof of concept, although there is a lack of widespread duplication and official standardization. The main strength of this method is its application in the technological domain, as it utilizes MCDM algorithms, as well as BIM, which operate based on model data as opposed to any changes in the processing rules. The level of the workflow is based on a particular level of maturity, equalling 20.

Revit API plugin (Fernández Mora et al., 2022): includes the structural strength index based on carbonation within Revit, allowing users to easily calculate the remaining service life of concrete components without programming. This allows users to instantly get data on which parts of a building are most vulnerable to destruction by importing data and automatically calculating a quantified measure of durability for each structural element. This feature might help structural engineers to do action plan regarding the building's lifespan and prevent some lossess in materials. The BIM model serves as the basis for quantifying durability, helping users develop strategies to improve it. This includes choosing durable materials, optimizing coatings, and planning maintenance to minimize the environmental footprint.

Table 4.6: Maturity assessment (BIMMI) for Revit API plugin

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Revit API plugin	BIM plugin	S1	G2	Technology	Defined	20

Based on the BIMMI assessment in Table 4.6, it is clearly seen that this plugin is in the S1 phase (extraction and analysis of basic data) but provides G2 level detail (evaluation) in terms of data on durability rather than simple data. The focus on the plugin's ability to process data in BIM terms positions it in terms of technological competence, while its focus on key performance indicators of durability suggests it is aligned with a specific maturity level defined by a score of 20 out of 0-50.

Eco2soft (Sun et al., 2022): BIM integrated platform includes an extensive lifecycle analysis engine that is directly integrated into the environment for Revit 2019, allowing designers to analyze recycling potential, global warming potential, and full cycle performance of materials used in bulk wood and concrete structures without requiring any coding. This directly impacts the durability of the structure by identifying the most elastic elements of the materials used in construction and opening avenues for protective elements in buildings.

These features directly impact the analysis of materials used in buildings because they allow users to analyze material flow in buildings and their cycling through transparent tracking of recyclable materials used in construction; they also impact material durability and resource-saving efficiencies because they identify carbon emissions and waste generation associated with materials used in construction with every design option; in addition, they impact waste management in buildings during construction and dismantling because they offer accurate forecasts of waste generation that can be used to plan waste management strategies in buildings.

Table 4.7: Maturity assessment (BIMMI) for Eco2soft

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Eco2soft	Integrated BIM framework	S2	G3	Technology	Managed	30

In Table 4.7 this falls under the umbrella of technological competencies, as it is primarily designed to automatically extract and analyze structural and environmental data in the Revit platform, with a focus on computerized quantification of impacts rather than management of socio-technical processes. The technology is currently being tested in Stage S2, as it uses parametric BIM objects to design and analyze options to materials such as solid wood and concrete in relation to coordinated design, even if it doesn't yet have the capacity to perform multi-platform and federated integrations necessary to reach Stage 3. As to the level of detail in the assessment, it is classified as G3, as it produces data-driven LCA results that allow for comparative analysis in relation to sustainable development decision-making, going beyond the scope of G1 and G2 tools. Lastly, the maturity level of this technology is considered to be manageable, as it earned 30 points and has a well-defined and controlled scope in relation to a documented case of a residential high-rise building. However, this tool has not yet demonstrated the interdisciplinary system integration or continuous iterative performance optimization required for integrated or optimized classification.

GeNie (via PyS-MILE/Dynamo) (Morgenstern & Raupach, 2023): which is accessible through the visual programming script of PyS-MILE/Dynamo, makes available Bayesian inference in Autodesk Revit for the probabilistic modeling of wear in concrete structures, and the plugin has the capability to receive results from wear simulation, update previous wear parameters in accordance with actual data, and visualize probabilities of subsequent failure. This makes it possible to set design objectives for the durability of structures and materials, in accordance with stochastic calculations for assessing durability.

Table 4.8: Maturity assessment (BIMMI) for GeNie

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
GeNie	Visual-programming script / BIM plugin	S2	G2	Technology	Defined	20

The evaluation of the plug-in indicates that it is a competency in BIM technology, as it primarily leverages the computational power of the Bayesian engine and information from

the BIM model. The level of detail of the evaluation is defined as G2, as it primarily assesses the detail of the reliability forecasts provided by the plugin, which are based on scenarios used to evaluate the structure's reliability as in shown Table 4.8.. The level of detail in the evaluation of the workflow is defined as S2, as it utilizes the object-level Revit models, enriching the information in the model with the probabilistic performance information without combining the information in the network level, as is required in the S3 level. The degree of readiness of the workflow is defined according to the provided definition and is rated as 20, as it is clearly show and repeatable for the purposes of the study, although it has not been systematically applied for several projects.

BIM3LCA (Bernardette Soust-Verdaguer et al., 2023): falls under the competence of BIM technology, as it mainly involves the automatic extraction of information from the Revit model, specifically geometric and material information, and then computes life cycle sustainability assessment indicators. This plugin is not related to organizational policies, nor organizational interventions at the process level. This plugin is a technology service that provides additional information to the BIM model, specifically quantitative information, concerning durability, such as the lifespan of the building, which can be used for making design decisions concerning the durability of the building. Therefore, this contribution of his falls under the technological level of the BIM ecosystem, which is consistent with Succar's definition of the Technology competency set: a set of digital artifacts that enable data-driven analysis in a BIM environment.

Table 4.9: Maturity assessment (BIMMI) for BIM3LCA

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
BIM3 LCA	Visual-programming script / BIM plugin	S2	G3	Technology	Managed	30

The table 4.9 shows that the plug-in works at a level for creating S2 capabilities, as it utilizes object-level data in Revit to compute results for LCSA, which can be easily shared and compared to results obtained by members of the development team. The level of detail for the assessment is G3, as it will generate a structured and reproducible report for LCSA,

following a set of predefined sustainability standards for use in a certification or compliance process. This level of detail is more advanced than G1, where simple detection occurs, or G2, where exploratory evaluation is performed. Therefore, the overall readiness level is manageable, with a score of 30 on a scale from 0 to 50. This is because the workflow is well defined and consistently applied in the example for the modernization of apartment buildings.

One Click LCA (Besana & Tirelli, 2022): supports the adaptive reuse indicators with just a single click through the possibility of obtaining all the material and quantity data from the existing building model in Revit, as well as the possibility of determining the carbon content of all the elements of the building through the LCA A1-A5 modules, and then combining this with the disassembly index, which measures the ease of disassembling and reusing all the elements of the building, in order to obtain the carbon index of the project (PCI), which measures the potential for carbon savings in the adaptive reuse of building elements.

Table 4.10: Maturity assessment (BIMMI) for One Click LCA

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
One Click LCA	Standalone software	S2	G3	Technology	Managed	30

Based on the BIM Maturity Matrix Assessment (BIMMI) shown in Table 4.10, LCA is defined as a one-click technology competency since it is a computational plug-in to extend the BIM model. Based on the extension stages proposed by Succar, LCA is compatible with Stage 2, Model-Based Collaboration, because it can read the model's Revit geometry, perform the LCA computation, and send the results to the entire development team without requiring users to write code or access network resources. The output is an official report for LCA, which is accepted in the sustainable development field and meets the requirements for G3 certification in terms of the level of detail. One Click LCA is defined as managed since its process is reproducible and successful in an adaptive reuse scenario in a real-world context, such as net-zero modernization in Milan. This makes its score 30 out of 50, since it is a mature system and open to potential improvements while ensuring the achievement of a closed-loop economy in terms of data-driven estimates.

Artificial intelligence (AI) algorithms with BIM/GIS model (Cinquepalmi et al., 2023): using artificial intelligence, can determine a complete geometric and material inventory of a school building in Rome by extracting data from an Autodesk Revit model and incorporating spatial and contextual data within the GIS environment. The machine learning technology also allows for the assessment of the condition of each building element, its historical value, and its ability to connect to the infrastructure, thus quantifying its reuse potential, including filtering by building element type such as walls, floors, structural frames, etc. By comparing data, it is possible to quickly determine which building elements of a building can be reused or demolished by using a quick analysis of their accessibility and zoning using the GIS environment, thus quickly determining the data necessary to determine metrics such as reuse potential, material recovery rates, and carbon savings.

Table 4.11: Maturity assessment (BIMMI) for Artificial intelligence (AI) algorithms with BIM/GIS model

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Artificial intelligence (AI) algorithms with BIM/GIS model	Integrated BIM-GIS framework	S3	G2	Technology	Managed	30

Table 4.11, BIMMI proposed by Succar, is in the technological competence part, since it is a computational analysis tool to support the data available in the BIM model. However, to achieve this, a complete Revit model is required, scripts in Dynamo and Python to run the artificial intelligence algorithms, and interaction with the GIS platform, which enables the achievement of Stage 3: Network Integration, in which data is shared between the platforms and the disciplines in the BIM process. The tool also enables the creation of a structured report for possible reuse, which can be part of the process to achieve a sustainability certification, which is at the level of detail of the G2 assessment, since it is detailed and repeatable, although not official. The process is also detailed and repeatable and is at the manageable level of the BIMMI 5 index, a five-tier BIM maturity matrix that provides a 30-point score.

M&C Bank (Jayasinghe & Waldmann, 2020): is a web tool allows for the application of the adaptive reuse indicators through the automatic generation of a comprehensive list of materials and components of existing buildings through the use of the Autodesk Revit model and Dynamo, where the materials are stored in a web database for searching. This allows for the quantification of construction and demolition costs, waste, and materials. This is necessary to assess suitability for recycling or reuse, which are the main indicators of the effectiveness of applying closed-loop funds to reconstruction projects. This is essential since, through this interface, it is not necessary to have knowledge of how to code in order to query the materials and components for reuse, which is used for making decisions for adaptive reuse strategies, such as determining the materials for reuse in the adaptive reuse strategy for an 11-story apartment building. Therefore, the BIM data used with the web tool is used for generating the necessary quantitative data for the application of the adaptive reuse indicators, such as the material recovery rate, carbon dioxide emission reduction, and cycling.

Table 4.12: Maturity assessment (BIMMI) for M&C Bank

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
M&C Bank	Web-based application (PHP/MySQL)	S2	G2	Technology	Managed	30

As shown in Table 4.12, the M&A Bank is part of the technological competencies, where the BIM model is supplemented by a further level of computation, allowing for the analysis of material flows. The process is based on a model already prepared in Revit, referred to as the “object-oriented” database, from which it is possible to send information to a web application through Dynamo scripts, referring to level 2 of the five-level BIMMI, i.e., Model-based collaboration, where it is possible to exchange information obtained from the model with other stakeholders without the need for integration into the entire network. The results are presented as quantities of materials, together with information on their possible reuse, which can be evaluated against the objectives of the work, reaching the level of detail required for the G2 Assessment. As a result, it is reaching a 30-point rating, referring to a maximum of 0 to 50 points.

BIM-DAS (Mohammed et al., 2024): allows the evaluation of the design for disassembly (DfD), by the extraction of the geometric and material properties of the parts made of steel contained in the Autodesk Revit 2020 model and the subsequent transfer of the data to the MATLAB analytics, in order to obtain the results of the calculation of the Disassembly Assessment Score (DAS) and the Recovery Efficiency Score (SP), which quantify the degree to which the element is light and can be dismantled and recycled again. The results obtained by the analytics are a direct confirmation of the indicators of the Circular Economy, related to the design for disassembly, such as the use of materials and the reduction of the waste produced during the construction process. The BIM DAS tool, by the integration of the BIM and the specific computing environment, is able to provide a report related to the project, highlighting the valuable parts, the demolition plan, and the evidence necessary for the evaluation of the possibility of reusing the building, such as the case of the poultry feed production plant in Makka.

Table 4.13: Maturity assessment (BIMMI) for BIM-DAS

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
BIM-DAS	Integrated BIM framework (Revit + MATLAB)	S3	G2	Technology	Managed	30

Based on Table 4.13, the BIM-DAS falls under the category of technological competence, as it incorporates an analytical component that enriches the BIM model with performance data during the deconstruction phase. This is at stage 3 of the BIM-DAS capabilities, which is network integration, i.e., data exchange between the two tools and processing outside their respective BIM environments. The results are presented as DAS and SP ratings for use at the project level, though they are not yet integrated with the official assessment scheme, which brings the tool to the level of detail defined in the G2 Assessment. The methodology is transparent and replicable, having been applied in a real-world industrial company and matching the managed maturity level of the five-level hierarchy proposed by BIMMI and obtaining 30 out of 50 possible points.

Dynamo (Acampa & Parisi, 2022): links the data provided by the Building Condition Assessment (BCA) directly to the Revit Building Information Modeling (BIM) model, allowing users to visualize the degree of degradation, the presence of defects, and recommendations for on-site maintenance. The automation of the process of collecting information on the state of equipment and displaying it on the elements of the building model generates a matrix of maintenance opportunities, highlighting elements at high risk of degradation and including recommendations for optimal inspection or repair intervals. This quantitative model supports the “ease of maintenance” indicator in the assessment of closed-loop economies, allowing users to optimize this process in cultural heritage sites and public buildings.

Table 4.14: Maturity assessment (BIMMI) for Dynamo

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Dynamo	Visual programming script	S2	G2	Technology	Managed	30

According to the BIM maturity matrix in Table 4.14 developed by Succar, the scenario falls into the technological competence level, as it involves implementing a feature for data integration. This process is based on the finished Revit model, which refers to object modeling, and the use of Dynamo to process the input data provided by the BCA and recommendations regarding the record of maintenance. This process is associated with the second stage of the capability level, Model-based Collaboration, where the data provided by the BIM is processed and shared among the participants. This leads to the production of a detailed report regarding the possibilities of wear and maintenance. This process is then associated with evaluation, but not with the official certification scheme, reaching the level of detail of the G2 Assessment. This process has been documented in the context of the EU-funded project "THE WARMEST" regarding Brunelleschi's Cloister, reaching the level of managed maturity by reaching 30 points on a scale of 0 to 50.

Navisworks (Reffy Whydyastuti Andriani Sukardiputri & Herdiansah, 2025): integrates the Revit model with Navisworks and Archibus to perform facility management, risk mapping, and predictive maintenance. The plug-in, which obtains asset status, failure

probabilities, and maintenance task schedules from the BIM model, generates a dashboard to highlight areas of the model that require minimal maintenance, providing an "ease of maintenance" indicator to achieve the DPUTR's objective of saving resources. This is a case study from Indonesia. This BIM solution, according to Succar's BIM maturity matrix, falls under technological competence and reaches technological maturity level 3 (network integration), as it synchronizes data across the three programs without requiring any code. The resulting risk assessment map and maintenance priority report are included in the degree of detail of the G2 Assessment. This is a documented, commercial, and validated BIM solution, which meets the manageable maturity level of the five-level BIM maturity index hierarchy and obtains a 30-point BIM score from 0 to 50, results shown in Table 4.15.

Table 4.15: Maturity assessment (BIMMI) for Navisworks

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Navisworks	BIM plugin	S3	G2	Technology	Managed	30

WE-BIM Add-in (Quiñones et al., 2022): being a plugin for Autodesk Revit, provides a full list of materials used in the building through the use of the WE-BIM add-on, allowing for the automatic classification of each element of the building according to the construction waste categories (CW) through a hierarchy of detail levels (LoW) to create a detailed waste sheet according to the types of materials used in the building, such as concrete, masonry, wood, etc., for a case study of a residential complex consisting of 16 houses in Seville, Spain. The plugin compares the quantity of waste produced using BIM technology with the final results obtained through manual calculations in Revit and Excel, ensuring the plugin's correctness with 95% compliance. Since this tool tracks the amount of materials that are converted into waste in the design phase, it creates a transparent material flow data that can be utilized to evaluate the recycling potential, monitor the amount of carbon dioxide emissions, and also monitor cost savings indicators such as "building material flow analysis."

Table 4.16: Maturity assessment (BIMMI) for WE-BIM Add-in

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
WE-BIM Add-in	BIM plugin	S2	G2	Technology	Managed	30

The Table 4.16 shows that WE-BIM Add-on falls under the Managed Maturity Level in the Succar BIM Maturity Matrix, ranking 30 points on a scale of 0 to 50. This plug-in is not just for data extraction or detection, as it can automatically generate detailed data regarding material consumption based on the Revit model, classify each type of material based on various types of construction waste according to a hierarchy of low levels of detail, and generate waste reports quantitatively to be easily uploaded to a database. Material Flow Analysis for a closed economy. The results obtained by this work were compared to results obtained by manual calculation and showed 95% compliance, decreasing processing time by 70%. This indicates that the tool can generate documented results to support decision-making in the early stages of design.

CW-LCA BIM tool (Llatas et al., 2022): module that can retrieve all the material information from the Autodesk Revit model, sort all the materials into construction and demolition waste (CDW) categories automatically, and perform the Lifecycle Assessment (LCA) scenarios for recycling or disposal. The result is the quantitative analysis of the waste in the building in the form of the amount of waste in kilograms of concrete, steel, wood, etc., and the impact in the form of global warming potential, toxic emissions dangerous to humans, energy consumption, etc., which can be directly introduced into the Material Flow Analysis model (MFA). The reporting of the amount of materials that can be recovered and thus reduce the demand for primary resources can be used to calculate the performance of the resources in the form of the percentage of recycled materials used in construction, waste prevention coefficient, etc., which can be used to support the decisions of CDW management in the design phase.

Table 4.17: Maturity assessment (BIMMI) for CW-LCA BIM tool

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
CW-LCA BIM tool	BIM plugin	S2	G2	Technology	Managed	30

The plug-in operates in stage 2, model-based collaboration, by working with BIM geometry to provide data on waste streams, which is then used for decision-making through an LCA mechanism. This is done at an appropriate level of detail for G2 Assessment, in which scenario results are analyzed and visualized to compare recycling and disposal techniques. This is documented and validated through manual calculations, with quantified results appropriate for a manageable level of the BIM maturity index, as proposed by Succar. There is no certification process or feedback mechanism for continuous improvement to achieve an integrated or optimized level, resulting in an appropriate 30/50 score in the BIM maturity index as illustrated in Table 4.17.

Autodesk Navisworks (Widjaja et al., 2025): The workflow based on the Navisworks platform, connects the digital twin with Autodesk's Revit and Dynamo softwares to automatically place special length rebars in the structure. The approach quantifies the materials used in the construction process and minimizes the amount of waste generated during the process. The tool quantifies the exact amount of materials needed for each floor and avoids any over length cuts in the process. This approach helps minimize the waste generated during the construction process by around 15%. The tool also helps avoid any clash in the process and minimizes the materials used in the construction process. Therefore, the tool provides the data required for the construction material usage indicator at the design stage.

Table 4.18: Maturity assessment (BIMMI) for Autodesk Navisworks

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Autodesk Navisworks	Standalone BIM Software	S2	G2	Technology	Managed	30

Based on the results illustrated in Table 4.18, it can be noted that the proposed process is in Phase 2 of model-based collaboration, in which the BIM model is used to generate an optimized rebar layout and is sent to a collision detection engine for schedule-based coordination. In this process, data is generated in an output format after processing, applicable for decision-making at the G2 - Evaluation level of detail. This process is documented, verified in accordance with a generally accepted approach, and has repeatable quantitative results of its usage applicable to the level of controlled maturity. Therefore, it can be said that this process is appropriate for a BIMMI score of 30/50, with 10 points being awarded for the maturity level, manageable – 30.

etoolLCD +Dynamo (Han & Rajabifard, 2024): which is developed via the utilization of Dynamo visual scripting and Autodesk Revit, enables the extraction of all the necessary information with regard to the materials of the building model. Following this, the Life Cycle Sustainability Assessment (LCSA) can be automatically assigned to a specific number of materials. Inputting this information into the Hybrid Multi-criteria Decision-Making Process (MCDA), or AHP-TOPSIS, enables calculation of the percentage of a specific material type that may be extracted, reused, or recycled during the building's dismantling. The cyclical index, or the percentage of the specific type of material that enters the production cycle again, may be compared to the cyclical index of materials (MCI), which is defined in the European Commission's closed loop economics. The entire process may be carried out in the BIM environment without the requirement for any coding. Therefore, the evaluation of the cyclical nature of the specific design may be carried out in the early stages of the design process.

Table 4.19: Maturity assessment (BIMMI) for eToolLCD + Dynamo

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
etoolLCD +Dynamo	Integrated BIM Framework	S2	G2	Technology	Managed	30

Table 4.19 using the BIM maturity matrix suggested by Succar, the etoolLCD + Dynamo system functions at the level of level 2 – model-based collaboration (the BIM model is translated into a list of materials in quantities, which is used in conjunction with the LCSA-MCDA modules), and at the level of detail – G2 – Assessment (the list is processed with an assessment of the completeness of the materials, which makes it possible to inform about the process of decision-making). The workflow has already been documented and tested in the case of a conceptual project of an apartment building with four stories and a reinforced concrete frame. Quantitative indicators of the economy cycle are reproduced, which meet the requirements of the level of maturity – manageable. There is no certification, improvement cycles, and integration into the corporate network; therefore, the score in the BIMMI scale is 30 score.

CPD Toolkit (Shevchenko & Francois Cluzel, 2023): the Circular Product Design (CPD) toolkit can calculate the cycling metrics of a product, such as product cycling profiles and a global product cycling index, by manually inputting the amount of materials, usage period, and expiration of the product. The toolkit can calculate the amount of the product's mass that can be recycled, reused, or recovered, which directly leads to the calculation of the Material Circulation Indicator (MCI), which is the ratio of the product's material that continues to circulate. Although this toolkit has no link to a BIM model, its diagnostic process enables a designer to measure the roundness of a specific material in the early stages of design. Therefore, the BIM level of this toolkit is low, as it is an independent toolkit still in development that uses a manual input system. It belongs to the lowest level of BIM, in which object-based information processing is used.

Table 4.20: Maturity assessment (BIMMI) for CPD Toolkit

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
CPD Toolkit	Standalone tool (under development)	S1	G1	Technology	Initial	10

As illustrated in Table 4.20, the CPD toolkit is placed in the initial stage of the maturity level, which is worth 10 points. The CPD toolkit, in its independent and developing

state as a prototype, does not have any BIM-related workflows, programming needs, or standards. The data is entered manually for diagnosis purposes and is incompatible with BIM models. There are no organizational recommendations, performance requirements, or quality control procedures in place for the CPD toolkit's use. This aligns with the requirements for the entry-level stage in the BIM maturity matrix, such as: "No BIM manuals, documentation protocols," or modeling standards... Exchanges suffer from a serious lack of interoperability"), and the CPD toolkit's own features, such as autonomy, manual data entry, and inaccessibility to the public, are mentioned in the CPD Toolkit section. The instrument receives the lowest score 10 / 50 on the BIMMI scale.

BIM-Navisworks + Dynamo scripts (Sakdirat Kaewunruen et al., 2025)

creates a living digital twin of the building. The entire material list will be generated automatically directly from the Revit model through the Dynamo script. The materials will be classified according to the shelf life of each material, which is categorized as reuse, recycling, and/or disposal. The percentage of materials in the building that will be part of this circular loop will be calculated. This is the exact data that is required for calculating the Material Circulation Indicator (MCI). The waste assessment calculation is done in real time as it is dismantled. This will give the designers an immediate idea of the impact that the changes in the design have on the roundness score.

Based on the BIM Maturity Matrix by Succar shown in Table 4.21, the tool operates in "Capability Stage 2 – Model-based Collaboration", in which the BIM model is converted into quantitative data regarding waste flows and transferred to the MCDA module, and in "Granularity Level G2 – Assessment", in which the output is the processed roundness indicator, which is used to make decisions. These characteristics place the tool in the managed level of the BIM Maturity Index, which awards 30 points, in the range of 0 to 50 points. The tool has not yet been integrated into corporate networks or processes of constant improvement and, therefore, has not reached higher levels of integration/optimization; however, the data extraction process, real-time data analysis, and support of the roundness indicator of the circular economy justify the Managed level and 30/50 points.

Table 4.21: Maturity assessment (BIMMI) for BIM-Navisworks + Dynamo scripts

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
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BIM-Navisworks + Dynamo scripts	Standalone BIM Software	S2	G2	Technology	Managed	30
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Life365 (Chowdhury et al., 2023): is a standalone software program that is also enabled with BIM technology. This program is used to perform a simple life cycle assessment of the concrete mixture and estimate the service life of the mixture. In the program, the deterioration of the two mixtures of interest is simulated. From the simulation, an estimate of the expected service life of each of these mixtures is produced. The expected service life of each mixture is used to estimate the Material Longevity Indicator (MLI), which is an estimate of the percentage of functional embodied concrete in the mixture. This is exactly the information that is needed to evaluate the longevity of materials in the circular economy.

Table 4.22: Maturity assessment (BIMMI) for Life365

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
Life365	Standalone BIM Software	S1	G1	Technology	Initial	10

The Life365 system is rated at the ‘Initial’ level of the BIM Maturity Index, with a score of 10 out of 50. While it can perform simplified LCA and lifetime prediction of the concrete mix, it also operates independently. There are no guidelines or standards for its interaction with other BIM-based applications or existing organizational workflows. As a result, there are no established guidelines or mechanisms for its usage. This characterizes the ‘Initial’ level of BIM Maturity. According to Table 4.22, it is important to highlight that the use of software applications is not controlled and unregulated, in addition, the storage, and exchange of data are not defined. Exchanges are suffering from a serious lack of interoperability. Since the Life365 can generate basic detection-type outputs, it is at the early stage of development. Therefore, the rating remains at 10 points.

POD (Parametric Optimization and Decision Support) (Reisinger et al., 2022): platform offers support in the durability of materials since it offers the calculation of the durability and lifetime of materials. This is possible since the platform offers the calculation of life cycle cost (LCC) and lifecycle assessment (LCA) results in the parametric model, using the Grasshopper tool to build the geometric model of the industrial building in the Rhino3D application. Thus, when the designers make any changes in the building's structure or materials used in the building process, the script offers the calculation of the results obtained in the LCC and LCA. The results obtained in the script are then displayed on the side of the geometric model. Therefore, the platform offers data that is used in the evaluation of the materials' durability. Thus, the process of designing the building is made easier in the assembly process.

Table 4.23: Maturity assessment (BIMMI) for POD (Parametric Optimization and Decision Support)

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
POD (Parametric Optimization and Decision Support)	Visual Programming Script (Grasshopper)	S2	G2	Technology	Managed	30

According to the results indicated in Table 4.23, it is clear that POD (Parametric Optimization and Decision Support) is evaluated at a reasonable level of the BIM maturity index with a mark of 30/50. The platform utilizes the visual programming tools provided in Grasshopper and utilizes the tools in Rhino 3D to develop parametric building models that are automatically linked with life cycle cost analysis (LCCA) and life cycle assessment (LCA), which enables quantitative performance indicators such as recycling potential, embodied CO₂, and costs to be used in decision-making regarding the durability of materials. Given that it enables a closed exchange cycle of data in relation to project model and environmental impact calculations, it utilizes Succar's capabilities in Stage 2, model-based collaboration (where the model is enriched with analysis data and is used in conjunction for joint assessment), and operates at a level of detail defined by G2 - Assessment (where the output is an estimated set of indicators rather than raw detection data). The evaluation is also in line with the tool's enhanced parametric workflow, incorporation of production planning

data for design and assembly, and its ability to retain a degree of material durability with data-driven decision support, yet still failing in terms of integration at an enterprise-wide level, standardized BIM guidelines, and continuous improvement cycles that would allow for the next levels of maturity.

EnviBIM (Nehasilová et al., 2022): is also useful in resource conservation through the relationship between the environmental properties of each building element, which include the amount of carbon emitted and its effect on materials used in extraction, and the cost estimates, which allow the designer to calculate the amount of materials and energy used per unit of functional capacity in various alternatives. As it is directly connected with ArchiCAD and Revit programs, it is possible to extract data in quantitative terms from the BIM model, extract data from the Ecoinvent database, and compare it with the data in the COST database, which is used to determine the configuration with maximum material consumption and productivity in the ratio of 1:2.

As for BIM maturity, as in Table 4.24, EnviBIM is at a manageable level on the BIM maturity index. This is because EnviBIM is capable of model-based collaboration (Capability, level 2), which involves sharing quantitative LCA and cost data with external BIM model databases. However, there is no raw data but rather performance metrics, which is what is needed for the level of detail of the G2-Evaluation. This is also true for the managed layer, where there is a need for systematic data exchange, workflow, and information generation to support decision-making and optimization. Thus, the BIM maturity of EnviBIM is said to be at 30/50 for having a well-defined and reproducible workflow that integrates environmental and cost information into the BIM environment, even if not implemented.

Table 4.24: Maturity assessment (BIMMI) for EnviBIM

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
EnviBIM	BIM plugin	S2	G2	Technology	Managed	30

IBLAT (Li et al., 2023): helps in supporting the resource productivity indicator through BIM-integrated life cycle assessment and cost calculation in the entire design process. This enables you to monitor the resources required in terms of materials, energy, and costs to perform a specific educational function, taking the case of a school building. By linking life cycle assessment and life cycle cost calculation with the Revit model, it enables designers to assess different alternatives for enclosing structures and systems in terms of environmental performance per unit of service (such as per classroom, student, or square meter of room space), and select alternatives that provide greater educational usefulness with less or less efficient use of resources.

Table 4.25: Maturity assessment (BIMMI) for IBLAT

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
IBLAT	BIM plugin	S2	G2	Technology	Managed	30

Based on the BIMMI perspective, as indicated in Table 4.25, it is possible to relate IBLAT with a certain level of maturity, which is relatively low and is expected to be around 30 points. This is used as a Revit-based BIM plugin that is used to ensure data consistency between geometry, quantity calculations, and subsequent LCA/LCC calculations during the entire process. This is in line with Stage 2, which includes model-based collaboration and G2 level of detail assessment. The process is also well-structured and repetitive, which is appropriate for developing integrated indicators through models in support of resource efficient selection, though it is in the realm of design and not yet standardized and automated throughout the entire enterprise; thus, it is not an integrated or optimized BIMMI. oughout the entire enterprise, which makes it not an integrated or optimized BIMMI.

UrbanBIM (Borkowski et al., 2025): helps to increase resource efficiency by calculating the carbon footprint of a building. The tool calculates the energy and emissions of materials and building components of a single-family frame building designed in Autodesk Revit. This tool helps in identifying design options that provide the desired characteristics of the building's enclosing structures, such as structural stability and fencing, while reducing

energy consumption and carbon dioxide emissions. Thus, thereby improving the relationship between the useful functions of the building and the productivity of resources.

Table 4.26: Maturity assessment (BIMMI) for UrbanBIM

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
UrbanBIM	BIM plugin	S2	G2	Technology	Defined	20

Table 4.26 shows that UrbanBIM can best be attributed to a "certain" level of maturity with an estimated score of 20/50. It is used as a BIM plugin tightly integrated with Revit, offering an estimated impact metric rather than raw data, which allows for at least "Capability Level 2" and "G2 Level of Detail". However, due to its relatively recent development and free access, the workflows and data transfer protocols used by UrbanBIM are closer to research prototype or pilot use than to institutional use. This process is documented, reproducible, and applicable at the project level, but there is limited evidence of standardization, structured engagement policies, or performance management at the organizational level, making it difficult for UrbanBIM to move to higher levels of the BIMMI maturity model, such as "Managed" or "Integrated."

WRFSS (Waste Recycling Facility Selection System) (Huang et al., 2022): is a plugin for BIM-WMS helps to use the waste indicator during the construction and dismantling stages, where the amount of resources and location are automatically extracted from the Revit residential brick house model and then transferred to the decision support system, where the most suitable objects for recycling are determined and the most cost-effective waste transportation routes are determined. This plugin, combining a BIM model and a warehouse management system, generates quantitative indicators of the amount of resources, distance and costs, allowing the designer or contractor to compare different layout options for the construction site where the demolition of the building will take place, or for reuse. resources in terms of the efficiency of their extraction. Thus, this process belongs to the resource-saving element of waste management during the construction and dismantling of buildings, where optimization of the waste management plan can be achieved.

Table 4.27: Maturity assessment (BIMMI) for WRFSS

Tool	Tool type	Capability stage (score)	Granularity level	BIM competency	Maturity level	Maturity score (0-50)
WRFSS	BIM plugin	S2	G2	Technology	Managed	30

According to the BIM maturity matrix, WRFSS is at a manageable level, which corresponds to a maturity score of 30 out of 50. The plugin facilitates model-based collaboration (Capability creation stage 2) by connecting the Revit/Dynamo model to external logistics data, which is then used to provide estimated waste logistics results (level of detail G2 - Estimate) instead of raw detection data. The repeatable workflow, decision support logic, and reduction in transport distance and costs all demonstrate a level of systemic integration, which is at the project level, but the absence of enterprise-wide standards, constant improvements, or the use of multiple platforms for automation prevents IT departments from reaching higher levels of optimization shown in Table 4.27.

Among all 27 tools analyzed in the master's thesis, the results show that significant attention is paid to the middle part of the BIM maturity scale. The managed range is by far the largest category, comprising almost two-thirds of all instruments, while the defined range accounts for about 20% and the initial range for about 15%. This means that most tools are able to perform their analysis systematically and consistently, but the more advanced ones have reached the stage where they are able to perform more complex procedures. Thus, according to the thesis, what is important about a good tool is its ability to deliver consistent results within a proper BIM process. In more detail, the managed level rating of the tool reflects its highest maturity and practical suitability due to repetitive procedures, documented data flow, and regulated data exchange. In the BIM maturity matrix, this level implies standardized and controlled workflows, thus representing another level after the initial experimental one. Several instruments from this master's thesis can also be characterized by the described characteristics; They are good candidates for quantitative analysis and decision support, but they do not go beyond and are not yet integrated into the organization. Thus, this

set of tools is the most effective of all those discussed here. However, the thesis also demonstrates that relatively few tools can achieve this level of integration or optimization. Therefore, it can be stated that the current problem is not related to a lack of tools, but rather to their integration and standardization, as discussed above.

The most effective solution is “Artificial Intelligence (AI) Algorithms with a BIM/GIS model”, as they reach “S3 stage”, “G2-level of detail”, and maturity level “Manageable” with “a 30/50 rating”. The managed maturity level means that this workflow is standardized, reproducible, and controlled in the context of the BIM maturity matrix. Therefore, the manageable maturity level of the chosen solution makes it the most mature among all those included in this thesis, since it includes not only data extraction, but also computational processing of the entire BIM model. Therefore, the decision under discussion can be described as the strongest decision-making tool.

These other tools also function efficiently, but they are somewhat inferior in their capabilities to the AI BIM/GIS approach. In particular, the BIM-DAS tool is a very good choice, considering its combination with Revit + MATLAB and achieving a manageable stage with 30/50 points. Another tool is PMOOD, which is quite mature because it is an integrated solution combining Rhino 3D, Grasshopper, and Karamba3D, and is evaluated at a manageable development level. However, it can be seen from the thesis that very few tools actually go beyond the managed stage and become integrated and optimized, which means that most of the technologies available today are technologically sound, but have limitations in their integration into the workflow.

Chapter 5 – Conclusions

The main goal of the study is to identify and assess digital tools (plug-ins, scripts, frameworks, and web applications) that support a closed-loop economy. First, this thesis selected and analyzed the 13 most important CE indicators. Then, with the help of an artificial intelligence research assistant, each indicator was matched to suitable digital tools. However, choosing the most accurate tools for creating digital instruments was a challenge. Subsequently, there were two iterations with Undermind AI and Elicit AI. As a result, the Elicit AI Pro version was chosen because it can analyze up to 1000 papers, whereas Undermind AI can analyze only around 500, which is 2 times fewer. In addition, in Elicit AI, you can set criteria for each stage of filtering, from abstract screening to data extraction with manually edited columns, which gives you more accurate and concise results.

As a result, 27 digital tools have been founded and demonstrate that important circular functions such as material flow analysis, embodied carbon calculation, deconstruct ability scores, and demolition construction waste optimization can be calculated directly from BIM models. At the same time, the Maturity Index of BIM tools and their corresponding maturity levels in the digital environment indicate that the digital environment remains at an early or middle maturity level. Based on the Succar's BIM Maturity Index (BIMMI) which is the part of the 301in BIME self-assessment tool, almost all available tools are included in the range of technological competencies and clusters in Stages 1 and 2 of the BIM Maturity Index, which include "Object-oriented Modeling" and "Model-based Collaboration" with the corresponding maturity levels of 'Initial', 'Defined' and 'Managed, which correspond to 10-30 points out of 50. Very few of these tools approach the level of "Integrated" and "Optimized" in terms of their maturity in areas such as "Network Integration," "Interdisciplinary Process Alignment," and "Continuous Productivity Improvement.' This is based on the assumption that although the available tools are technically capable of calculating CE metrics from BIM data, very few of them extend to the process and policy competencies necessary to achieve cyclical transformations in the construction system itself.

From the methodological standpoint, the research proves the effectiveness of the AI-based literature discovery process as a reliable method for researching the emerging and interdisciplinary field. This study has demonstrated the ability to move beyond the initial literature exploration process and into the more refined evidence synthesis process using Elicit Pro, effectively managing the extensive body of evidence while imposing strict screening and data extraction protocols that would be impossible through the more manual

process. This experience has reaffirmed the understanding that the AI-based process is not intended to replace the need for critical thought but rather a high-efficiency engine designed to provide transparency and the ability to process the vast body of available literature.

Ultimately, the study shows that the problem facing the construction sector is not the availability of digital tools, but rather system integration. The problem with ensuring true universality is not the fragmentation of data and the lack of machine-readable standards. An obstacle to full cycling is data fragmentation and the lack of machine-readable standards. To make the transformation happen, the sector must move from a focus on tools to data standardization, thus standards that were originally developed in such a way that they can easily be considered different programs to facilitate the work of digitalization in a circular economy. Practitioners should focus on tools that can be institutionalized through standard guidelines and training. For a researcher and policy maker, the goal is to bridge the gap between technological capabilities and process implementation.

In summary, although BIM-enabled circularity assessment is technologically feasible, its full potential is currently latent. However, in order to advance this maturity level, it is necessary to synchronously evolve digital technologies with circular procurement strategies and standard-based material data and overall process-based approaches to shift the built environment paradigm from linear to circular.

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Appendices

Appendix A

Design for Adaptability (DfA): Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Adaptability and spatial flexibility within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of spatial reconfiguration potential, plan permeability, or generality by utilizing recognized methodologies such as the SAGA method, Justified Plan Graphs, or Space Syntax. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts, while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment such as Autodesk Revit, ArchiCAD, or Rhino, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

Modular Construction and Prefabrication: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Modular Construction and Prefabrication (MCP) and its associated circularity performance, such as prefabrication potential, assembly/disassembly efficiency, or material flow optimization, within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Modularization Potential," "Design for Manufacture and Assembly (DfMA)" efficiency, or "Prefabrication Ratios" by utilizing recognized methodologies such as the Pre-assembly Index, Modular Coordination rules, or DfMA assessment frameworks. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks, abstract conceptual diagrams, or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation, focusing on tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

Design for Durability: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Durability (DfD) and the extension of material service life within a circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Longevity," "Component Service Life," or

"Maintenance Intensity" by utilizing recognized methodologies such as the Longevity Indicator (LI), Service Life Prediction (SLP) models, or Durability Assessment based on ISO 15686 standards. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability principles—such as choosing high-performance, maintainable materials—to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

Adaptive Reuse of building elements (e.g. rooms): Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Adaptive Reuse of existing structures and building elements (e.g., rooms) within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Repurposing Potential," "Residual Service Life," or "Spatial Compatibility" for new functions by utilizing recognized methodologies such as the Adaptive Reuse Potential (ARP) model, Multi-Criteria Decision Analysis (MCDA), or automated Structural Integrity and Decay assessments. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative heritage preservation and repurposing principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making, emphasizing the retention of embodied energy and resource conservation for data published before December 2025.

Design for Disassembly (DfD): Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Disassembly (DfD) and the potential for non-destructive component recovery within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Disassembly Efficiency," "Recyclability Indices," or "Connection Reversibility" by utilizing recognized methodologies such as the Disassembly Capacity (DC) metric, Potential for Deconstruction scores, or the Circular Building Assessment (CBA) framework. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational

scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative "loose-fit" construction principles to automated, quantitative digital assessments of material recovery value and waste reduction potential for data published before December 2025.

Easy Maintenance (Maintainability): Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Easy Maintenance (Maintainability) and the optimization of technical service life within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Maintenance Intensity," "Component Accessibility," or "Repairability" by utilizing recognized methodologies such as Building Information Modeling for Facility Management (BIM-FM) integration, Reliability-Centered Maintenance (RCM), or automated Accessibility Analysis for replacement. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative upkeep strategies to automated, quantitative digital assessments of lifecycle costs and resource efficiency through simplified maintenance protocols for data published before December 2025.

Construction Materials Flow Analysis: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Materials Flow Analysis (MFA) and the tracking of material inputs, stocks, and outputs within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Inflows and Outflows," "Mass Balances," or "Stock Dynamics" by utilizing recognized methodologies such as the Economy-Wide MFA (EW-MFA), Dynamic MFA, or Level(s) Indicator 2.1 for construction material usage. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital

assessments of material circularity across the entire value chain—from raw material production to waste management—for data published before December 2025.

Construction Material Usage: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Material Usage and the volumetric tracking of resource consumption within the circular economy framework. The research objective is to find established software solutions or plugins that automate the estimation of "Material Mass per Unit Area," "Bill of Materials (BoM)," or "Resource Intensity" by utilizing recognized methodologies such as the EU Level(s) Indicator 2.1, Bill of Quantities (BoQ) extraction, or Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative material selection to automated, quantitative digital assessments of the total weight and fraction of materials required throughout a building's lifecycle for data published before December 2025.

Resource Potential Indicator (RPI): Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of the Resource Potential Indicator (RPI) and the technical feasibility of waste redirection within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Waste Reuse Potential," "Redirection Feasibility," or "Technical Recovery Capacity" by utilizing the resource-based paradigm introduced by Park and Chertow, which treats waste as a potential resource contingent on technological knowledge rather than material composition alone. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste management to automated, quantitative digital assessments of the technical potential for resource recovery and reuse for data published before December 2025.

Material Circularity: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Circularity and the performance of resources within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Recyclability," "Circular Content," or "Reusability Potential" by utilizing recognized

methodologies such as the Material Circularity Indicator (MCI), the Longevity Indicator (LI), or Multi-Criteria Decision Analysis (MCDA) coupling material flow and life cycle data. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative circular design principles to automated, quantitative digital assessments of material recovery and resource efficiency suitable for early-stage architectural decision-making for data published before December 2025.

Material Longevity: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Longevity and the extension of resource lifespans within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Service Life," "Residual Value," or "Resource Endurance" by utilizing recognized methodologies such as the Longevity Indicator (LI)—which factors in use, refurbishment, and recycling—as well as Life Cycle Assessment (LCA) tools coupled with Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability strategies to automated, quantitative digital assessments of how long materials remain at their highest value within the built environment for data published before December 2025.

Resource Productivity: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Resource Productivity and the efficiency of structural element utilization within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Resource Efficiency," "Material Intensity," or "Value Extraction per Resource Unit" by utilizing recognized methodologies such as the Eurostat monitoring framework for Resource Productivity, Multi-Criteria Decision Analysis (MCDA) for resource optimization, or automated Building Circularity Assessment (BCA). You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the tracking of material flows through Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as

packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital assessments of how efficiently structural elements are used to minimize waste and maximize service life for data published before December 2025.

Construction and Demolition Waste (C&DW) Management: Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction and Demolition Waste (C&DW) Management and the tracking of waste diversion rates within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Waste Generation Rates," "Recovery and Recycling Potential," or "End-of-Life (EoL) Scenarios" by utilizing recognized methodologies such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), or the EU Level(s) framework for waste and materials. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Waste Management Plans or Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste reduction strategies to automated, quantitative digital assessments of waste-to-resource conversion and environmental impact mitigation for data published before December 2025.

Appendix B

The Figures B.1-B.5 are the BIMMI framework taken from Succar's (2010) research work.

BIM MATURITY MATRIX

		a	b	c	d	e
BIM Competency Areas at Granularity level 1		INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
BIM COMPETENCY SETS TECHNOLOGY	Software: applications, deliverables and data	Usage of software applications is unmonitored and unregulated. 3D Models are relied on to mainly generate accurate 2D representations/deliverables. Data usage, storage and exchanges are not defined within organisations or project teams. Exchanges suffer from a severe lack of interoperability.	Software usage/introduction is unified within an organisation or project teams (multiple organisations). 3D Models are relied upon to generate 2D as well as 3D deliverables. Data usage, storage and exchange are well defined within organisations and project teams. Interoperable data exchanges are defined and prioritised.	Software selection and usage is controlled and managed according to defined deliverables. Models are the basis for 3D views, 2D representations, quantification, specification and analytical studies. Data usage, storage and exchanges are monitored and controlled. Data flow is documented and well-managed. Interoperable data exchanges are mandated and closely monitored.	Software selection and deployment follows strategic objectives, not just operational requirements. Modelling deliverables are well synchronised across projects and tightly integrated with business processes. Interoperable data usage, storage and exchange are regulated and performed as part of an overall organisational or project-team strategy.	Selection/use of software tools is continuously revisited to enhance productivity and align with strategic objectives. Modelling deliverables are cyclically being revised/ optimised to benefit from new software functionalities and available extensions. All matters related to interoperable data usage storage and exchange are documented, controlled, reflected upon and proactively enhanced.
	Hardware: equipment, deliverables and location/mobility	BIM equipment is inadequate; specifications are too low or inconsistent across the organisation. Equipment replacement or upgrades are treated as cost items and performed only when unavoidable.	Equipment specifications – suitable for the delivery of BIM products and services - are defined, budgeted-for and standardised across the organisation. Hardware replacements and upgrades are well-defined cost items.	A strategy is in place to transparently document, manage and maintain BIM equipment. Investment in hardware is well-targeted to enhance staff mobility (where needed) and extend BIM productivity.	Equipment deployments are treated as BIM enablers. Investment in equipment is tightly integrated with financial plans, business strategies and performance objectives.	Existing equipment and innovative solutions are continuously tested, upgraded and deployed. BIM hardware become part of organisation's or project team's competitive advantage.
	Network: solutions, deliverables and security/ access control	Network solutions are non-existent or ad-hoc. Individuals, organisations (single location/ dispersed) and project teams use whatever tools found to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.	Network solutions for sharing information and controlling access are identified within and between organisations. At project level, stakeholders identify their requirements for sharing data/information. Dispersed organisations and project teams are connected through relatively low-bandwidth connections.	Network solutions for harvesting, storing and sharing knowledge within and between organisations are well managed through common platforms (e.g. intranets or extranets). Content and asset management tools are deployed to regulate structured and unstructured data shared across high-bandwidth connections.	Network solutions enable multiple facets of the BIM process to be integrated through seamless real-time sharing of data, information and knowledge. Solutions include project-specific networks/portals which enable data-intensive interchange (interoperable exchange) between stakeholders.	Network solutions are continuously assessed and replaced by the latest tested innovations. Networks facilitate knowledge acquisition, storing and sharing between all stakeholders. Optimisation of integrated data , process and communication channels is relentless.

Figure B.1 BIM Competency set: Technology (Succar, 2010, p. 31)

		BIM COMPETENCY AREAS AT GRANULARITY LEVEL 1					
		a	b	c	d	e	
		INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED	
BIM COMPETENCY SETS	PROCESS	Infrastructure: physical and knowledge-related	The work environment is either not recognised as a factor in staff satisfaction or may not be conducive to productivity. Knowledge is not recognised as an asset; BIM knowledge is typically shared informally between staff (through tips, techniques and lessons learned).	The work environment and workplace tools are identified as factors affecting motivation and productivity. Similarly, knowledge is recognised as an asset; shared knowledge is harvested, documented and thus transferred from tacit to explicit.	The work environment is controlled, modified and it's criteria managed to enhance staff motivation, satisfaction and productivity. Also, documented knowledge is adequately stored.	Environmental factors are integrated into performance strategies. Knowledge is integrated into organisational systems; stored knowledge is made accessible and easily retrievable [refer to the 4 levels of knowledge retention (Arif et al., 2009)].	Physical workplace factors are reviewed constantly to insure staff satisfaction and an environment conducive to productivity. Similarly, knowledge structures responsible for acquisition, representation and dissemination are systematically reviewed and enhanced.
		Products & Services specification, differentiation, project delivery approach and R&D	3D models deliverables (a BIM product) suffer from too high, too low or inconsistent levels of detail.	A "statement defining the object breakdown of the 3D model" (Bouygues, 2007) is available.	Adoption of product/ service specifications similar to Model Progression Specifications (AIA, 2008), BIPS 'information levels' (BIPS, 2008) or similar.	Products and services are specified and differentiated according to Model Progression Specifications or similar.	BIM products and services are constantly evaluated; feedback loops promote continuous improvement.
		Human Resources: competencies, roles, experience and dynamics	There is an absence of defined processes; roles are ambiguous and team structures/dynamics are inconsistent. Performance is unpredictable and productivity depends on individual heroics. A mentality of 'working 'around the system' flourishes.	BIM roles are informally defined and teams are formed accordingly. Each BIM project is planned independently. BIM competency is identified and targeted; BIM heroism fades as competency increases but productivity is still unpredictable.	Cooperation within organisations increases as tools for cross-project communication are made available. Flow of information steadies; BIM roles are visible and targets are achieved more consistently.	BIM roles and competency targets are imbedded within the organisation. Traditional teams are replaced by BIM-oriented ones as new processes become part of organisation's / project team's culture. Productivity is now consistent and predictable.	BIM competency targets are continuously upgraded to match technological advances and align with organisational objectives. Human resource practices are proactively reviewed to insure intellectual capital matches process needs.
		Leadership: innovation and renewal, strategic, organisational, communicative and managerial attributes	Senior leaders/ managers have varied visions about BIM. BIM implementation (according to BIM Stage requirements) is conducted without a guiding strategy. At this maturity level, BIM is treated as a technology stream; innovation is not recognised as a independent value and business opportunities arising from BIM are not acknowledged.	Senior leaders/managers adopt a common vision about BIM. BIM implementation strategy lacks actionable details. BIM is treated as a process-changing, technology stream. Product and process innovations are recognised; business opportunities arising from BIM are identified but not exploited.	The vision to implement BIM is communicated and understood by most staff. BIM implementation strategy is coupled with detailed action plans and a monitoring regime. BIM is acknowledged as a series of technology, process and policy changes which need to be managed without hampering innovation. Business opportunities arising from BIM are acknowledged and used in marketing efforts.	The vision is shared by staff across the organisation and/or project partners. BIM implementation, its requirements and process/ product innovation are integrated into organisational, strategic, managerial and communicative channels. Business opportunities arising from BIM are part of team, organisation or project-team's competitive advantage and are used to attract and keep clients.	Stakeholders have internalised the BIM vision and are actively achieving it (Nightingale & Mize, 2002). BIM implementation strategy and its effects on organisational models are continuously revisited and realigned with other strategies. If alterations are needed, they are proactively implemented. Innovative product/ process solutions and business opportunities are sought-after and followed through relentlessly.

Figure B.2 BIM Competency set: Process (Succar, 2010, p. 32)

		BIM Competency Areas at Granularity level 1				
		a	b	c	d	e
BIM COMPETENCY SETS	POLICY	INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
	Regulatory: rules/ directives, standards/ classifications, guidelines/ benchmarks and codes/ regulations	There are no BIM guidelines, documentation protocols or modelling standards. There is an absence of documentation and modelling standards. There is informal or no quality control plans; neither for 3D models nor for documentation. There are no performance benchmarks for processes, products or services.	Basic BIM guidelines are available (e.g. training manual and BIM delivery standards). Modelling and documentation standards are well defined according to market-accepted standards. Quality targets and performance benchmarks are set.	Detailed BIM guidelines are available (training, standards, workflow, exceptions...). Modelling, representation, quantification, specifications and analytical properties of 3D models are managed through detailed modelling standards and quality plans. Performance against benchmarks is tightly monitored and controlled.	BIM guidelines are integrated into overall policies and business strategies. BIM standards and performance benchmarks are incorporated into quality management and performance improvement systems.	BIM guidelines are continuously and proactively refined to reflect lessons learned and industry best practices. Quality improvement and adherence to regulations and codes are continuously aligned and refined. Benchmarks are repetitively revisited to insure highest possible quality in processes, products and services
	Contractual: responsibilities, rewards and risks	Dependence on pre-BIM contractual arrangements. BIM risks related to model-based collaboration (differ in each market) are not recognised or are ignored.	BIM requirements are recognised. "Statements defining the responsibility of each stakeholder regarding information management" (Bouygues, 2007) are now available.	There is a mechanism to manage shared BIM intellectual property, confidentiality, liability and a system for BIM conflict resolution.	Organisation are aligned through trust and mutual dependency beyond contractual barriers.	Responsibilities, risks and rewards are continuously revisited and realigned to effort. Contractual model are modified to achieve best practices and highest value for all stakeholders.
	Preparatory: research efforts/ deliverables, educational programmes/ deliverables and training programmes	Very little or no training available to BIM staff. Educational/ training mediums are not suitable to achieve the results sought.	Training requirements are defined and are typically provided only when needed. Training mediums are varied allowing flexibility in content delivery.	Training requirements are managed to adhere to pre-set broad competency and performance objectives. Training mediums are tailored to suit trainees and reach learning objectives in a cost-effective manner.	Training is integrated into organisational strategies and performance targets. Training is typically based on staff roles and respective competency objectives. Training mediums are incorporated into knowledge and communication channels.	Training is continuously evaluated and improved upon. Training availability and delivery methods are tailored to allow multi-modal continuous learning.

Figure B.3 BIM Competency set: Policy (Succar, 2010, p. 33)

		a	b	c	d	e	
		INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED	
BIM CAPABILITY STGAES	STAGE 1	Object-based Modelling: single-disciplinary use within a Project Lifecycle Phase	Implementation of an object-based tool. No process or policy changes identified to accompany this implementation.	Pilot projects are concluded. BIM process and policy requirements are identified. Implementation strategy and detailed plans are prepared.	BIM processes and policies are instigated, standardised and controlled.	BIM technologies, processes and policies are integrated into organisational strategies and aligned with business objectives.	BIM technologies, processes and policies are continuously revisited, to benefit from innovation and achieve higher performance targets.
	STAGE 2	Modelling-based Collaboration: multi-disciplinary, fast-tracked interchange of models	Ad-hoc BIM collaboration; in-house collaboration capabilities incompatible with project partners. Trust and respect between project participants may be lacking.	Single-thread, well-defined yet reactive BIM collaboration. There are identifiable signs of mutual trust and respect among project participants.	Multi-thread proactive collaboration; protocols are well documented and managed. There are mutual trust, respect and sharing of risks and rewards among project participants.	Multi-thread collaboration includes downstream players. This is characterised by the involvement of key participants during projects' early lifecycle phases.	Multi-thread team included all key players in an environment characterised by goodwill, trust and respect.
	STAGE 3	Network-based Integration: concurrent interdisciplinary interchange of nD models across Project Lifecycle Phases	Integrated models are generated by a limited set of project stakeholders - possibly behind corporate firewalls. Integration occurs with little or no pre-defined process guides, standards or interchange protocols. There is no formal resolution of stakeholders' roles and responsibilities.	Integrated models are generated by a large subset of project stakeholders. Integration follows predefined process guides, standards and interchange protocols. Responsibilities are distributed and risks are mitigated through contractual means.	Integrated models (or parts of) are generated and managed by most project stakeholders. Responsibilities are clear within temporary project alliances or longer-term partnerships. Risks and rewards are actively managed and distributed.	Integrated models are generated and managed by all key project stakeholders. Network-based integration is the norm and focus is no longer on <i>how</i> to integrate models/ workflows but on proactively detecting and resolving technology, process and policy misalignments.	Integration of models and workflows are continuously revisited and optimised. New efficiencies, deliverables and alignments are actively pursued by a tightly-knit interdisciplinary project team. Integrated models are contributed to by many stakeholders along the construction supply chain.

Figure B.4 BIM Capability sets (Succar, 2010, p. 34)

1	Discovery	A low detail assessment used for basic and semi-formal discovery of BIM Capability and Maturity. Discovery assessments yield a basic numerical score.
2	Evaluation	A more detailed assessment of BIM Capability and Maturity. Evaluation assessments yield a detailed numerical score.
3	Certification	A highly-detailed appraisal of those Competency Areas applicable across disciplines, markets and sectors. Certification appraisal is used for Structured (Staged) Capability and Maturity and yields a formal, Named Maturity Level.
4	Auditing	The most comprehensive appraisal...In addition to competencies covered under Certification, Auditing appraises detailed Competency Areas including those specific to a market, discipline or a sector. Audits are highly customisable, suitable for Non-structured (Continuous) Capability and Maturity and yield a Named Maturity Level plus a Numerical Maturity Score for each Competency Area audited.

Figure B.5 BIM Granularity levels (Succar, 2010, p. 35)

Appendix C

Table C.1: Design for Adaptability (DfA)

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Revit-based transformability-index tool (Diana et al., 2022)	Integrated BIM Framework	Transformability index for reuse of disused healthcare buildings	Case study: Campania's Public Stock of Disused Buildings, Italy	Autodesk Revit + custom VB.NET plug-in	BIM, GIS	Available on request
2	PMOOD (Parametric Multi-Objective Optimization and Decision Support) (Julia et al., 2022)	Integrated BIM Framework	Multi-objective optimization of industrial building design integrating production layout	Pilot project: a hygiene production facility	Rhino3D + Grasshopper + Karamba3D; no advanced coding required	Grasshopper for Rhino3D, Karamba3D	Available on request
3	Building Automated Characterisation (BAC) (Fernandes et al., 2022)	Integrated BIM Framework	Characterisation of existing buildings for sustainable refurbishment and circularity	Case study: residential building in Lisbon, Portugal	BIM software with Uniclass 2015 classification	BIM, Material Passports	Not documented
4	AdRem (Palma et al., 2020)	Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo	Adaptive remediation and reuse planning for contaminated industrial sites	Case study: industrial area of Nitrastur located in La Felguera, Spain	Rhinoceros + Grasshopper with Python scripting; requires advanced coding skills	3D Modeling (Rhino), Parametric Modeling (Grasshopper), Digital Twin capabilities	Not documented

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Table C.2: Modular Construction and Prefabrication

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	MIVES (Modelo Integrado de Valor para una Evaluación Sostenible) (Tan et al., 2024)	Standalone MCDM framework integrated with BIM	DfMA sustainability assessment for building façade retrofit	Case study: Single façade retrofit project in Wuhan, China, comparing five design alternatives	Revit	BIM	Not documented

Table C.3: Design for Durability

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Revit API plugin (Fernández Mora et al., 2022)	BIM plugin	Structural durability index (carbonation)	Case study: Two structural elements in a residential building	Autodesk Revit; no coding required	Autodesk Revit, BIM	Available on request

2	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer-friendly; no coding required	Revit 2019	Not mentioned
3	GeNIe (via PyS-MILE/Dynamo) (Morgenstern & Raupach, 2023)	Visual programming script / BIM plugin	Bayesian inference for concrete deterioration modeling; Probabilistic durability assessment	Case study: Simulated deterioration scenarios	Autodesk Revit	Autodesk Revit	Not mentioned
4	BIM3LCA (Bernardette Soust-Verdaguer et al., 2023)	BIM plugin	LCSA plugin for building envelope refurbishment	Case study: Multi-family building in Camas, Seville	Autodesk Revit 2022; no coding required	Autodesk Revit 2023	Not mentioned
5	Building Automated Characterisation (BAC) (Fernandes et al., 2022)	Integrated BIM Framework	Characterisation of existing buildings for sustainable refurbishment and circularity	Case study: residential building in Lisbon, Portugal	BIM software with Uniclass 2015 classification	BIM, Material Passports	Not mentioned

Table C.4: Adaptive Reuse of building elements (e.g. rooms)

No	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
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1	Building Automated Characterisation (BAC) (Fernandes et al., 2022)	Integrated BIM Framework	Characterisation of existing buildings for sustainable refurbishment and circularity	Case study: residential building in Lisbon, Portugal	BIM software with Uniclass 2015 classification	BIM, Material Passports	Not documented
2	One Click LCA (Besana & Tirelli, 2022)	Standalone software	Embodied carbon assessment (LCA, modules A1–A5); MCI combined with Disassembly Index to form PCI; BCI at building level; compatible with EU Level(s)	Reuse of abandoned building in Milan for net zero carbon	Autodesk Revit	No coding required	Commercially available
3	Artificial intelligence (AI) algorithms with BIM/GIS model (Cinquemani et al., 2023)	Integrated BIM-GIS framework	Adaptive reuse potential assessment for residential conversion	School building in Rome	Autodesk Revit	Requires Dynamo scripting and Python, Power BI, GIS	Research prototype

TableC.5: Design for Disassembly (DfD)

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
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1	M&C Bank (Jayasinghe & Waldmann, 2020)	Web-based application (PHP/MySQL)	Characterisation of existing buildings for sustainable refurbishment and circularity; C&D waste and recyclable/reusable material volumes	Case study: 11-story residential building	Autodesk Revit + Dynamo	No coding for end users; web interface	Not documented
2	BIM-DAS (Mohammed et al., 2024)	Integrated BIM framework (Revit + MATLAB)	Deconstructability Assessment Score (DAS) and Salvage Performance (SP)	Makka poultry feed plant, Egypt	Revit 2020	Technical expertise needed;	Not documented

Table C.6: Easy Maintenance (Maintainability)

No	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Dynamo (Acampa & Parisi, 2022)	Visual programming script	BCA-BIM integration for degradation assessment and opportunity maintenance	EU-funded project case study (WARMEST); Case study: Cultural heritage (Brunelleschi's Cloister), Florence, Italy	Autodesk Revit	Qualitative case study: P+A3:H6 public building (DPUTR Building), Sukabumi City, Indonesia	Commercially available
2	Navisworks (Reffy Whydyastuti Andriani Sukardiputri & Herdiansah, 2025)	BIM plugin	7D facility management, risk mapping, predictive maintenance	Qualitative case study: Public building (DPUTR Building), Sukabumi City, Indonesia	Autodesk Revit	Navisworks, Archibus (BIM 7D plugins)	Commercially available

Table C.7: Construction Materials Flow Analysis

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	WE-BIM Add-in (Quiñones et al., 2022)	BIM plugin	Construction waste quantification, CW types per LoW	16-dwelling residential building, Seville, Spain; Comparison with manual calculations	Autodesk Revit	Revit, Excel	Not documented
2	CW-LCA-BIM tool (Llatas et al., 2022)	BIM plugin	Environmental impact of CW recycling vs. disposal, GWP, HTP, energy	”La María” multi-family housing, Spain; Scenario simulation before construction	Autodesk Revit	No specific LCA expertise required	Not documented
3	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer-friendly; no coding required	BIM to Eco2soft to Excel	Not mentioned
4	BIM3LCA (Soust-Verdaguer et al., 2023)	BIM plugin	Life Cycle Sustainability Assessment (LCSA)	Case study: La María residential building, Seville; Manual vs. automatic quantity take-off comparison	Autodesk Revit	Revit, Excel	Not mentioned

Table C.8: Construction Material Usage

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	WE-BIM Add-in (Quiñones et al., 2022b)	BIM Plugin	Construction waste quantification per LoW	Residential building, Seville, Spain	Revit 2021	Revit 2022	Not publicly available
2	Autodesk Navisworks (Widjaja et al., 2025)	Standalone BIM Software	Clash detection and schedule integration	High-rise commercial building (22 floors), Korea	Autodesk Revit	Revit + Dynamo + Navisworks	Commercial
3	One Click LCA (Besana & Tirelli, 2022)	Standalone software	Embodied carbon assessment (LCA, modules A1–A5); MCI combined with Disassembly Index to form PCI; BCI at building level; compatible with EU Level(s)	Reuse of abandoned building in Milan for net zero carbon	Autodesk Revit	No coding required	Commercially available

Table C.9: Resource Potential Indicator (RPI)

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Building Automated Character	Integrated BIM Framework	Characterisation of existing buildings for sustainable	Case study: residential building in Lisbon,	BIM software with Uniclass 2015	BIM, Material Passports	Not documented

	isation (BAC) (Fernandes et al., 2022)		refurbishment and circularity	Portugal	classification		
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Table C.10: Material Circularity

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer-friendly; no coding required	Revit 2019	Not mentioned
2	etoolLCD + Dynamo (Han & Rajabifard, 2024)	Integrated BIM Framework	BIM-based LCSA and MCDA for demolition waste management; Recycling rate, sustainability scores via AHP-TOPSIS; Recycling rate	Case study of a conceptual four-storey concrete frame residential apartment created in Autodesk Revit	Autodesk Revit; No coding required; visual programming replaces traditional coding	Integrated BIM Framework (Dynamo visual scripting)	Available upon request
3	CPD Toolkit (Shevchenko & Francois Cluzel, 2023)	Standalone tool (under development)	Circular product design toolkit for product-level circularity metrics; Product circularity profiles,	no	Not applicable	No coding; manual data entry for diagnostics	Not yet publicly available

			global product circularity index				
4	BIM-Navisworks + Dynamo scripts (Sakdirat Kaewunruen et al., 2025)	Standalone BIM Software	BIM-driven Digital Twin for demolition waste management	Case study: the BIM model of the existing house is integrated with the proposed method for estimating waste processes in real-time.	Autodesk Revit, Navisworks	Yes; Dynamo scripting required	Available upon request

Table C.11: Material Longevity

№	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer-friendly; no coding required	Revit 2019	Not mentioned
2	Building Automated Characterisation (BAC) (Fernandes et al., 2022)	Integrated BIM Framework	Characterisation of existing buildings for sustainable refurbishment and circularity	Case study: residential building in Lisbon, Portugal	BIM software with Uniclass 2015 classification	BIM, Material Passports	Not documented

3	Life365 (Chowdhury et al., 2023)	Standalone BIM Software	Simplified LCA, service life prediction	Two concrete mixtures (BCS: 0% SCM; ACS: 34% SCM)	Not specified	Not specified	Available upon request from ACI
4	POD (Parametric Optimization and Decision Support) (Reisinger et al., 2022)	Visual Programmin g Script (Grasshoppe r)	Recycling potential; DfA implied through production planning integration	Food and hygiene productio n facility (industria l)	Rhino3D	Rhino3D	Available upon request

Table C.12: Resource Productivity

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environ ment	Digital Integrat ion	Access / Availab ility
1	WE-BIM Add-in (Quiñones et al., 2022)	BIM Plugin	Construction waste quantification per LoW	Residential building , Seville, Spain	Revit 2021	Revit 2022	Not publicly availabl e
2	BIM3LC A (Soust- Verdaguer et al., 2023)	BIM plugin	Life Cycle Sustainability Assessment (LCSA)	Case study: La María residential building, Seville; Manual vs. automatic quantity take-off comparison	Autodesk Revit	Revit, Excel	Not mentio ned
3	EnviBIM (Nehasilová et al., 2022)	BIM plugin	BIM-integrated LCA of building elements by linking environmental data with cost-estimating databases to compare design variants	Three buildings in ArchiCAD and REVIT	ArchiCA D, REVIT	ArchiCA D, REVIT	Freely accessib le

3	CW-LCA-BIM tool (Llatas et al., 2022)	BIM Plugin	Prevented emissions and energy savings from recycling vs. disposal	Residential (multi-family), Seville, Spain	Autodesk Revit 21.1.1	LOD 300 required	Research prototype; Available upon request
4	IBLAT (Li et al., 2023)	BIM Plugin	BIM-integrated life cycle assessment and life cycle costing to support data-consistent	School building, northern China	Revit 2021	Revit 2022	Not mentioned
5	UrbanBIM (Borkowski et al., 2025)	BIM Plugin	Carbon footprint calculation	Single-family shell building	Autodesk Revit 2024.2	Autodesk Revit 2024.3	Currently free, future commercial
6	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer-friendly; no coding required	Revit 2019	Not mentioned

Table C.13: Construction and Demolition Waste (C&DW) Management

Nº	Tool name	Tool type	Focus area	Practical validation	BIM Software Environment	Digital Integration	Access / Availability
1	WE-BIM Add-in (Quiñones et al., 2022b)	BIM Plugin	Construction waste quantification per LoW	Residential building, Seville, Spain	Revit 2021	Revit 2022	Not publicly available
2	CW-LCA-BIM tool (Llatas et al., 2022)	BIM Plugin	Prevented emissions and energy savings from recycling vs. disposal	Residential (multi-family), Seville, Spain	Autodesk Revit 21.1.1	LOD 300 required	Research prototype; Available upon request

							request
3	WRFSS (Huang et al., 2022)	BIM Plugin	Optimal waste recycling facility selection and transport plan	Residential (brick house), Xian, China	Revit	Dynamo + Revit API	Available upon request
4	Eco2soft (Sun et al., 2022)	Integrated BIM framework	Recycling potential comparison of mass timber vs. concrete; GWP and material cycle assessment	Case study: High-rise passive residential building in Tianjin, China	Revit 2019; Designer- friendly; no coding required	Revit 2019	Not mentioned

Appendix D

Identify and categorize functional BIM digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Adaptability and spatial flexibility within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of spatial reconfiguration potential, plan permeability, or generality by utilizing recognized methodologies such as the SAGA method, Justified Plan Graphs, or Space Syntax. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts, while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment such as Autodesk Revit, ArchiCAD, or Rhino, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

No packaged BIM plugin or established software solution currently exists that automates the quantitative assessment of building Design for Adaptability or spatial flexibility using the SAGA method, Justified Plan Graphs, or Space Syntax; the available BIM-integrated circular economy tools address material reuse, recyclability, and waste management rather than spatial reconfiguration potential or plan permeability.

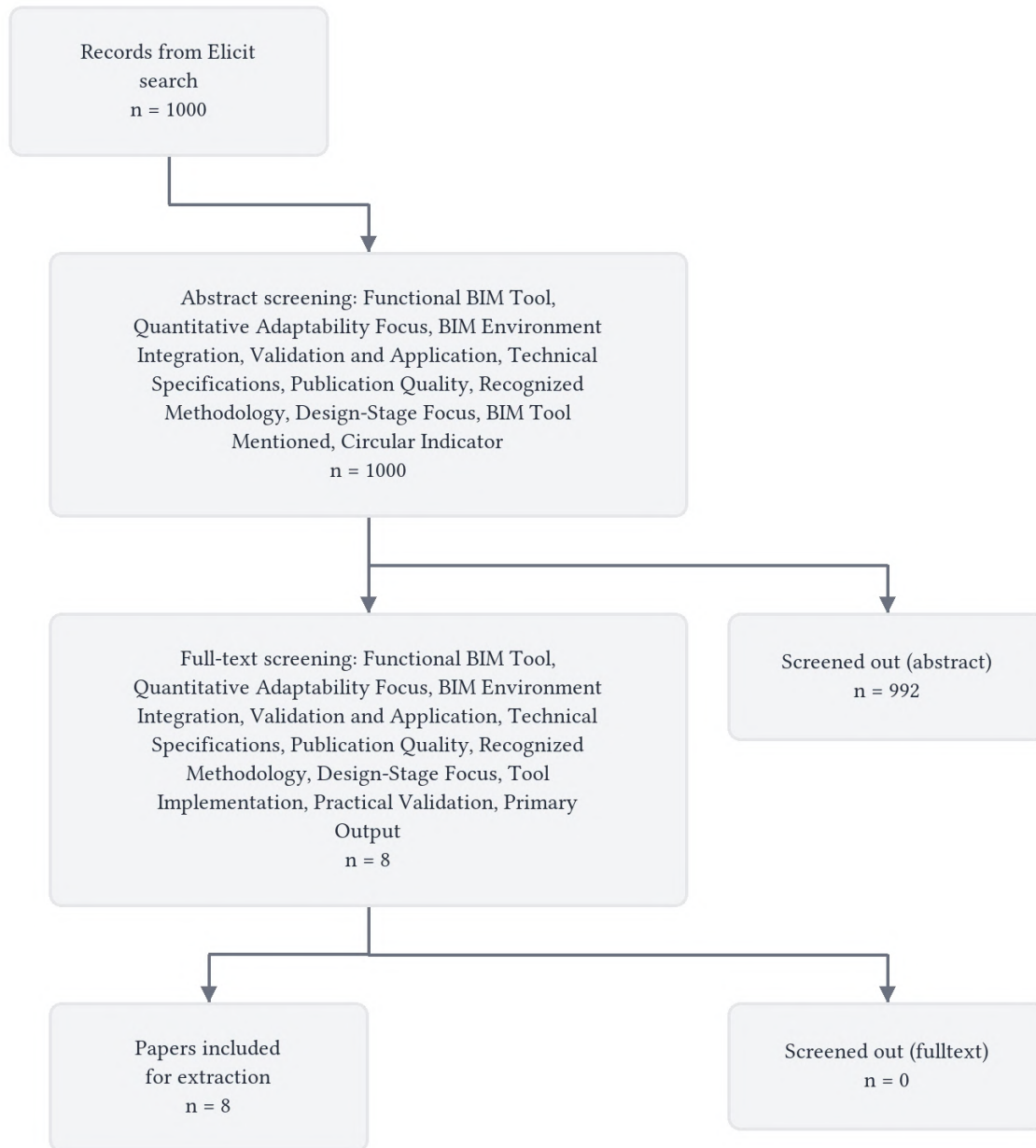
Abstract

No BIM-integrated tool or plugin currently automates the quantitative assessment of building Design for Adaptability or spatial flexibility using recognized spatial analysis methodologies such as the SAGA method, Justified Plan Graphs, or Space Syntax. A review of eight sources identified tools operating within the broader circular economy–BIM intersection, but all address adjacent concerns rather than spatial reconfiguration potential or plan permeability. The closest approximation is the Diana et al. (2022) Revit plug-in, which calculates a “transformability index” using indicators including fragmentation and modifiability for disused healthcare buildings [1], though it does not implement any of the targeted spatial analysis methods and is available only on request [1]. The remaining tools focus on material reuse optimization [2, 3], recyclability assessment [4, 5], life cycle environmental impact [5], or site-scale remediation planning [6]. Only two tools are openly accessible—the Haakonsen et al. (2024) timber-matching script on Zenodo [2] and the Huang et al. (2021) structural reuse script under an MIT license [3] —but both target structural element reuse rather than spatial adaptability.

The identified tools cluster around two BIM ecosystems—Autodesk Revit [1, 5] and Rhinoceros with Grasshopper [2, 3, 6, 7] —and the BIM tool landscape for circular economy is maturing around material circularity and waste

management. However, the specific niche of automated spatial adaptability quantification using graph-based or syntactic methods within a BIM authoring environment remains unoccupied. Established spatial analysis software (e.g., depthmapX for Space Syntax) continues to operate outside BIM workflows, and no packaged plugin bridging these domains was identified among the reviewed sources.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional BIM digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Adaptability and spatial flexibility within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of spatial reconfiguration potential, plan permeability, or generality by utilizing recognized methodologies such as the SAGA method, Justified Plan Graphs, or Space Syntax. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts, while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment such as Autodesk Revit, ArchiCAD, or Rhino, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional BIM Tool:** Does the study describe a functional BIM digital tool or integrated BIM plugin that can be implemented in practice (not just theoretical concepts)?
- **Quantitative Adaptability Focus:** Is the tool specifically designed for quantitative assessment of Design for Adaptability or spatial flexibility as its primary purpose?
- **BIM Environment Integration:** Does the tool operate within established BIM authoring environments such as Autodesk Revit, ArchiCAD, Rhino, or other mainstream BIM software platforms?
- **Validation and Application:** Has the tool been validated through case studies, empirical simulations, or real-world implementation with documented results?
- **Technical Specifications:** Does the study provide specific tool nomenclature and technical details, including the actual name of the tool/plugin and required BIM environment?
- **Publication Quality:** Is this a formal publication with accessible DOI or publication reference (not a conference abstract, editorial, or opinion piece)?
- **Recognized Methodology:** Does the tool utilize recognized quantitative methodologies such as SAGA method, Justified Plan Graphs, Space Syntax, or other validated assessment approaches?
- **Design-Stage Focus:** Is the tool designed to support early-stage design decision-making processes (not solely for post-occupancy evaluation)?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept.
- **Circular Indicator:** Does the paper claim to quantitatively measure Design for Adaptability? Answer 'No' if it is purely qualitative."

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

8 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional BIM Tool:** Does the study describe a functional BIM digital tool or integrated BIM plugin that can be implemented in practice (not just theoretical concepts)?
- **Quantitative Adaptability Focus:** Is the tool specifically designed for quantitative assessment of Design for Adaptability or spatial flexibility as its primary purpose?
- **BIM Environment Integration:** Does the tool operate within established BIM authoring environments such as Autodesk Revit, ArchiCAD, Rhino, or other mainstream BIM software platforms?
- **Validation and Application:** Has the tool been validated through case studies, empirical simulations, or real-world implementation with documented results?
- **Technical Specifications:** Does the study provide specific tool nomenclature and technical details, including the actual name of the tool/plugin and required BIM environment?
- **Publication Quality:** Is this a formal publication with accessible DOI or publication reference (not a conference abstract, editorial, or opinion piece)?
- **Recognized Methodology:** Does the tool utilize recognized quantitative methodologies such as SAGA method, Justified Plan Graphs, Space Syntax, or other validated assessment approaches?
- **Design-Stage Focus:** Is the tool designed to support early-stage design decision-making processes (not solely for post-occupancy evaluation)?
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

8 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Exact Tool Name:**

Extract the proper nomenclature or acronym of the tool. If unnamed, write '[Author] [Year] script'

- **Download Link / Access:**

Find the URL (GitHub, website) or instructions to access the tool. Is it open-source, commercial, or 'Available on request'

- **BIM Requirements:**

List the exact software needed to run this (e.g., Revit 2024 + Dynamo 2.1). Mention if it is easy to install or requires advanced coding.

- **Cost & License:**

Is the tool free, paid, or requires a subscription? Extract any info on licensing.

- **Digital Integration:**

Select technologies this tool works with: Material Passports, AI, IoT, Digital Twin, GIS, Blockchain, VR/AR, 3D Printing.

Results

Characteristics of Included Studies

The review identified eight sources describing BIM-integrated tools or methodologies relevant to circular economy assessment in building design. Notably, none of the identified tools directly implement the specific spatial analysis methodologies named in the research question (SAGA method, Justified Plan Graphs, or Space Syntax). Instead, the tools address adjacent concerns within the circular economy framework, including transformability assessment, material reuse optimization, recyclability evaluation, and life cycle environmental impact quantification. The table below summarizes each tool's key characteristics.

Tool Name	Full Text Retrieved?	BIM Software Environment	Digital Integration	Access / Availability	Cost & License	Focus Area
Diana et al. (2022) script [1]	Yes	Autodesk Revit + custom VB.NET plug-in [1]	BIM, GIS [1]	Available on request [1]	Not mentioned [1]	Transformability index for reuse of disused healthcare buildings
PMOOD (Parametric Multi-Objective Optimization and Decision Support) [7]	Yes	Rhino3D + Grasshopper + Karamba3D; no advanced coding required [7]	Grasshopper for Rhino3D, Karamba3D [7]	Available on request [7]	Not mentioned [7]	Multi-objective optimization of industrial building design integrating production layout
Haakonsen et al. (2024) script [2]	Yes	Rhino + Grasshopper; easy to install, no advanced coding required [2]	Grasshopper, Rhino [2]	Open-source, available at Zenodo [2]	Free and open-source [2]	Matching reclaimed timber elements to design intent

Tool Name	Full Text Retrieved?	BIM Software Environment	Digital Integration	Access / Availability	Cost & License	Focus Area
Huang et al. (2021) script [3]	Yes	Rhino + Grasshopper [3]	Grasshopper (Rhino) [3]	Open-source, MIT license [3]	Free, MIT license [3]	Algorithmic circular design with reused structural elements
Building Automated Characterisation (BAC) [8]	Yes	BIM software with Uniclass 2015 classification; specific platform not explicitly stated [8]	BIM, Material Passports [8]	Not mentioned [8]	Not mentioned [8]	Characterisation of existing buildings for sustainable refurbishment and circularity
AdRem [6]	Yes	Rhinoceros + Grasshopper with Python scripting; requires advanced coding skills [6]	3D Modeling (Rhinoceros), Parametric Modeling (Grasshopper), Digital Twin capabilities [6]	Not mentioned [6]	Not mentioned [6]	Adaptive remediation and reuse planning for contaminated industrial sites
Schwede (2019) script [4]	Yes	Not specified [4]	Computational analysis and database integration (AI implied) [4]	Not mentioned; tool not yet fully developed [4]	Not mentioned [4]	Recyclability assessment using RecyclingGraphs and ConnectionMatrixes
CW-LCA-BIM tool [5]	Yes	Autodesk Revit 21.1.1 + C# with Microsoft Visual Studio 2019 and Revit API [5]	BIM (Autodesk Revit) [5]	Available on request [5]	Not mentioned [5]	LCA-based environmental assessment of construction waste recycling vs. disposal

Full texts were retrieved for all eight sources. The tools span two primary BIM software ecosystems: Autodesk Revit (three tools) [1, 5] and Rhinoceros with Grasshopper (four tools) [2, 3, 6, 7], with one tool (BAC) not explicitly specifying a platform [8]. The Grasshopper-based tools generally require less advanced coding expertise [2, 7], with the exception of AdRem, which requires Python scripting [6]. The Revit-based tools tend to require more advanced development skills, relying on VB.NET [1] or C# programming with the Revit API [5].

Only two tools are confirmed as openly accessible: the Haakonsen et al. (2024) script, hosted on Zenodo [2], and the Huang et al. (2021) script, released under the MIT license [3]. Three tools are described as available on request [1, 5, 7], and three provide no access information at all [4, 6, 8]. The Schwede (2019) approach is explicitly noted as requiring further development before it can function as an applicable design tool [4].

Thematic Analysis

Theme 1: Spatial Transformability and Adaptability Assessment

The research question specifically targets tools that quantify spatial reconfiguration potential, plan permeability, or generality using established spatial analysis methodologies. Among all reviewed tools, the Diana et al. (2022) script comes closest to this objective, as it calculates a "transformability index" based on six indicators: usability, fragmentation, modifiability, roof implementation, external envelope, and window-to-wall ratio [1]. This tool is integrated into Revit as a plug-in that automatically computes the index for each building [1]. However, it does not implement SAGA, Justified Plan Graphs, or Space Syntax; rather, it focuses on the physical and spatial capacity of disused healthcare buildings to accommodate new functions [1].

The PMOOD framework addresses flexibility as one of its optimization objectives for industrial building design, alongside life cycle costs, life cycle assessment, and recycling potential [7]. It integrates production layout planning with building structural design using Karamba3D for structural analysis [7], but its concept of flexibility pertains to production layout adaptability rather than spatial analysis of architectural plan configurations.

No tool in this review implements the SAGA method, Justified Plan Graphs, or Space Syntax within a BIM environment for automated quantitative assessment.

Theme 2: Material Circularity and Reuse Optimization

A substantial cluster of tools focuses on material-level circular economy assessment rather than spatial adaptability. The Haakonsen et al. (2024) script automates the matching of reclaimed building products (specifically timber) to design intent, optimizing for environmental impact including embodied emissions and transportation [2]. Similarly, the Huang et al. (2021) script implements algorithmic formulations for reuse-driven structural design, using the Hungarian Algorithm for optimal matching of available reclaimed elements to design requirements [3]. Both tools are Grasshopper-based and openly available [2, 3].

The Schwede (2019) approach uses RecyclingGraphs and ConnectionMatrixes to assess the decomposability and recyclability of building components [4], while the CW-LCA-BIM tool quantifies environmental impacts of construction waste recycling versus disposal scenarios, finding that recycling prevents 1.4 times the emissions of disposal and saves 85 times the energy consumption for the assessed case [5]. The BAC methodology characterizes existing buildings for refurbishment by assessing disassembly potential and circularity indicators, with integration to material passports [8].

These tools address the broader circular economy framework but operate at the material and component scale rather than the spatial and typological scale implied by the research question.

Theme 3: Site-Scale Remediation and Reuse Planning

The AdRem toolkit operates at an urban/site scale, providing decision support for the adaptive reuse of contaminated industrial sites [6]. It combines remediation technique selection with schematic urban design solutions in a parametric 3D environment [6]. While it addresses adaptive reuse, its focus is on contamination management and site-level

planning rather than building-scale spatial flexibility assessment [6].

Synthesis

The systematic search reveals a fundamental gap: no identified tool directly automates the quantitative assessment of building Design for Adaptability using established spatial analysis methodologies (SAGA, Justified Plan Graphs, or Space Syntax) within a BIM environment. The tools that do exist within the circular economy-BIM intersection address related but distinct concerns, primarily material reuse optimization [2, 3], recyclability assessment [4, 5], and building transformability at a coarser scale [1].

The apparent absence is not simply a search limitation but reflects underlying disciplinary fragmentation. The tools reviewed emerge from two distinct research communities: one focused on structural and material circularity (represented by the Grasshopper-based tools from Haakonsen et al., Huang et al., and the Revit-based CW-LCA-BIM tool), and another focused on building-scale reuse assessment (Diana et al., Fernandes et al., Palma et al.). Spatial analysis methodologies such as Space Syntax and Justified Plan Graphs have their own software ecosystems (e.g., depthmapX, JASS) that remain largely disconnected from BIM authoring environments.

The Diana et al. (2022) transformability index represents the closest approximation, incorporating spatial indicators such as fragmentation and modifiability [1], but it was developed specifically for Italian healthcare building stock and its generalizability to other typologies is uncertain. Moreover, its availability is limited to request-based access [1], and it requires custom VB.NET development within Revit [1], which limits its accessibility as a packaged tool.

Among tools that are both validated through case studies and openly accessible, only the Haakonsen et al. (2024) script [2] and the Huang et al. (2021) script [3] meet this dual criterion, but both focus on structural element reuse rather than spatial adaptability assessment. The remaining tools either lack public access [1, 5–8], remain at a conceptual stage [4], or do not disclose licensing information [1, 4–8].

In summary, the BIM tool landscape for circular economy in construction is maturing around material circularity and waste management, but the specific niche of automated spatial adaptability quantification using recognized graph-based or syntactic methods remains unoccupied. A tool that bridges BIM geometry extraction with Space Syntax or SAGA computations, implemented as a packaged plugin for Revit or Grasshopper with case study validation, would address this gap directly.

References

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Modular Construction and Prefabrication (MCP) and its associated circularity performance, such as prefabrication potential, assembly/disassembly efficiency, or material flow optimization, within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Modularization Potential," "Design for Manufacture and Assembly (DfMA)" efficiency, or "Prefabrication Ratios" by utilizing recognized methodologies such as the Pre-assembly Index, Modular Coordination rules, or DfMA assessment frameworks. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks, abstract conceptual diagrams, or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation, focusing on tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

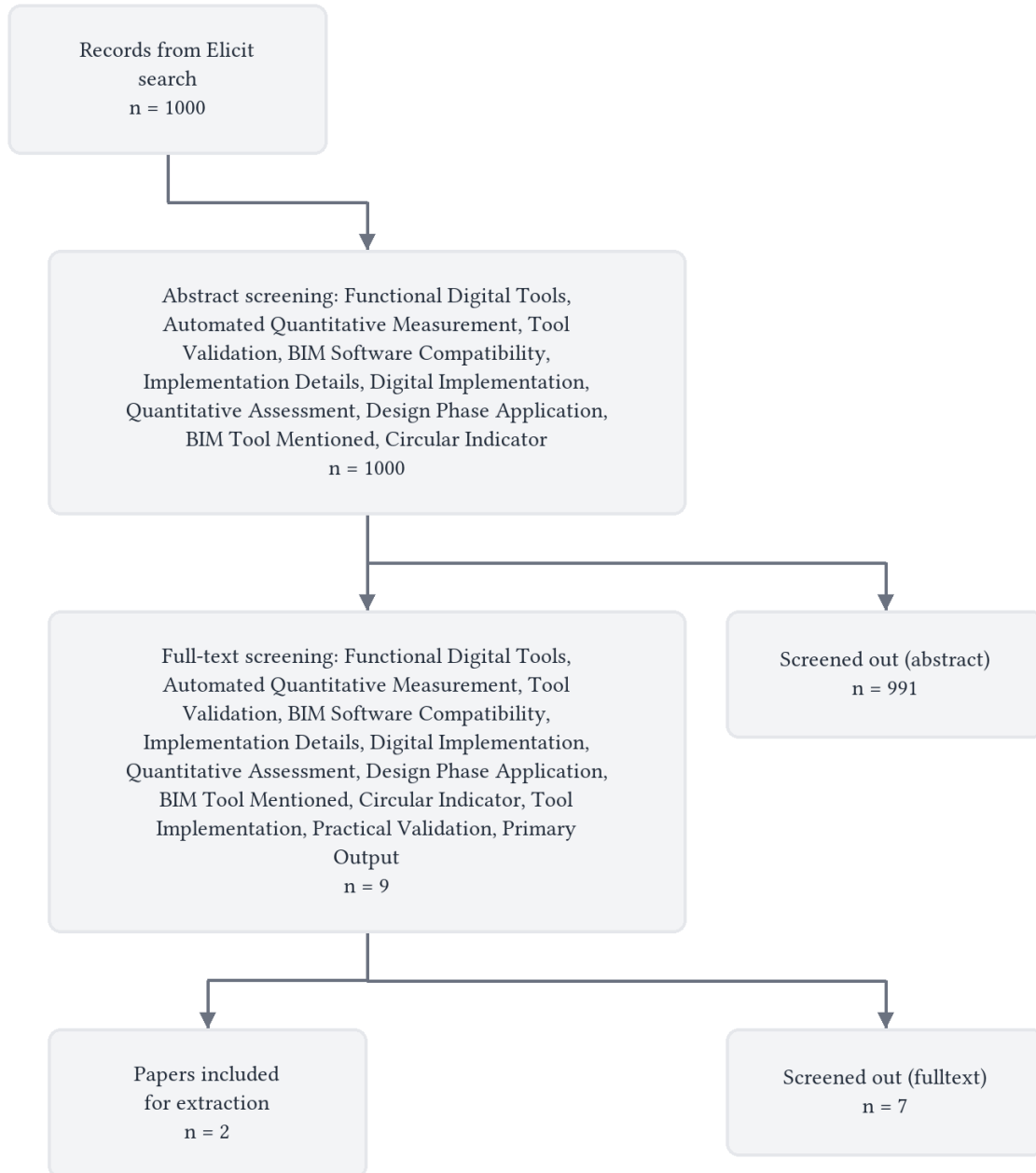
No packaged, publicly accessible digital tools or integrated BIM plugins that automate the quantitative assessment of MCP or circularity performance using recognized methodologies were identified; the two relevant sources describe, respectively, an expert-dependent multi-criteria framework (MIVES) and custom Grasshopper/Python scripts, neither of which constitutes an established, downloadable software solution validated in professional practice.

Abstract

This review of two sources identified no packaged, publicly accessible digital tools or BIM plugins that automate the quantitative assessment of Modular Construction and Prefabrication (MCP) or circularity performance using recognized methodologies such as the Pre-assembly Index or Modular Coordination rules. The MIVES framework, applied within Revit, provides a structured multi-criteria decision-making methodology for evaluating DfMA sustainability across economic, environmental, and social dimensions [1, 1], but it functions as an expert-dependent assessment framework rather than an automated tool, requiring substantial human judgment for parameter weighting and scoring [1], and no download link or access pathway is provided [1]. The Grasshopper/Python scripts developed for

WikiHouse prototype fabrication in Rhino 8 demonstrate significant automation capabilities, reducing CNC preparation times by 94.7% to 99% compared to manual methods [2], but they constitute custom-coded computational scripts validated only in an academic setting [2] and do not implement standardized MCP assessment frameworks or produce circularity indicators such as disassembly indices [2, 2]. Neither source provides a DOI for its primary publication [1, 2], and neither tool has been validated across multiple building types or professional practice contexts [1, 2]. The available evidence does not support the existence of established, packaged software solutions that bridge the gap between qualitative DfMA design principles and automated, quantitative circularity assessments suitable for early-stage architectural decision-making.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Modular Construction and Prefabrication (MCP) and its associated circularity performance, such as prefabrication potential, assembly/disassembly efficiency, or material flow optimization, within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Modularization Potential," "Design for Manufacture and Assembly (DfMA)" efficiency, or "Prefabrication Ratios" by utilizing recognized methodologies such as the Pre-assembly Index, Modular Coordination rules, or DfMA assessment frameworks. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks, abstract conceptual diagrams, or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation, focusing on tools that support the transition from qualitative design principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tools:** Does the study document functional digital tools or BIM plugins specifically designed for quantitative assessment of MCP (Modular Construction Potential) and circularity performance?
- **Automated Quantitative Measurement:** Do the tools automate measurement of at least one of the following: Modularization Potential, Design for Manufacture and Assembly (DfMA) efficiency, or Prefabrication Ratios?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Software Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Tekla, Bentley MicroStation)?
- **Implementation Details:** Does the study provide specific tool nomenclature, required software environment, and implementation details?
- **Digital Implementation:** Does the study go beyond purely theoretical frameworks to include functional digital implementation?
- **Quantitative Assessment:** Do the tools provide quantitative metrics rather than only qualitative assessments?
- **Design Phase Application:** Are the tools applicable for early-stage design decision-making rather than exclusively for post-construction or facility management phases?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept.

- **Circular Indicator:** Does the paper claim to quantitatively measure Modular Construction and Prefabrication? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

9 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional Digital Tools:** Does the study document functional digital tools or BIM plugins specifically designed for quantitative assessment of MCP (Modular Construction Potential) and circularity performance?
- **Automated Quantitative Measurement:** Do the tools automate measurement of at least one of the following: Modularization Potential, Design for Manufacture and Assembly (DfMA) efficiency, or Prefabrication Ratios?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Software Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Tekla, Bentley MicroStation)?
- **Implementation Details:** Does the study provide specific tool nomenclature, required software environment, and implementation details?
- **Digital Implementation:** Does the study go beyond purely theoretical frameworks to include functional digital implementation?
- **Quantitative Assessment:** Do the tools provide quantitative metrics rather than only qualitative assessments?
- **Design Phase Application:** Are the tools applicable for early-stage design decision-making rather than exclusively for post-construction or facility management phases?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept.
- **Circular Indicator:** Does the paper claim to quantitatively measure Modular Construction and Prefabrication? Answer 'No' if it is purely qualitative.
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability')

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

2 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Exact Tool Name:**

Extract the proper nomenclature or acronym of the tool. If unnamed, write '[Author] [Year] script'

- **Download Link / Access:**

Find the URL (GitHub, website) or instructions to access the tool. Is it open-source, commercial, or 'Available on request'

- **Tool Identification:**

Extract the specific nomenclature and technical details of digital tools and BIM plugins designed for MCP assessment, including:

- Exact name/title of the tool or plugin
- Version or iteration if specified
- Developer/company if mentioned
- Required BIM authoring software environment (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation)
- Tool type (standalone software, plugin, add-in, extension, workflow)
- Availability status (commercially available, open-source, prototype, research-only)

- **MCP Assessment Capabilities:**

Extract all quantitative assessment capabilities for Modular Construction and Prefabrication (MCP) and circularity performance, including:

- Prefabrication potential measurement methods
- Assembly/disassembly efficiency metrics
- Material flow optimization capabilities
- Modularization Potential assessment
- Design for Manufacture and Assembly (DfMA) efficiency scoring
- Prefabrication Ratios calculation
- Circularity performance indicators
- Any other MCP-related quantitative metrics the tool measures
- Whether assessment is automated or requires manual input

- **Methodological Framework:**

Extract the specific methodologies and frameworks used by the tool for MCP assessment, including:

- Pre-assembly Index methodology
- Modular Coordination rules implementation
- DfMA assessment frameworks utilized
- MCDM approaches (MIVES, AHP, etc.)
- Industry standards referenced (ISO, ASTM, etc.)
- Calculation algorithms or scoring systems
- Integration with sustainability frameworks
- Any proprietary assessment methods developed

- **Validation Evidence:**

Extract evidence of tool validation and real-world application, including:

- Case studies conducted with the tool

- Empirical simulations in professional contexts
- Building projects where tool was applied
- Industry partnerships or collaborations
- Comparison studies with other tools/methods
- Performance metrics or accuracy validation
- User testing or feedback from practitioners
- Scale and scope of validation (single project vs. multiple projects)

- **Implementation Context:**

Extract details about practical implementation and accessibility, including:

- Professional contexts where tool has been used (design firms, contractors, consultants)
- Project phases supported (conceptual, schematic, design development, construction)
- User skill level requirements
- Training or learning curve mentioned
- Integration with existing BIM workflows
- Data input requirements and sources
- Output formats and visualization capabilities
- Workflow automation level

- **Publication Documentation:**

Extract official publication details documenting the tool's practical implementation, including:

- DOI of the primary publication
- Journal name and publication year
- Authors and institutional affiliations
- Publication type (journal article, conference paper, technical report)
- Any additional supporting publications or technical documentation
- Whether publication includes tool download links or access information

- **Quantitative Results:**

Extract specific quantitative outcomes and performance metrics achieved using the tool, including:

- Measured improvements in prefabrication ratios or modularization scores
- Time savings in design or assessment processes
- Material waste reduction percentages
- Assembly efficiency improvements
- Sustainability index scores or rankings
- Comparative performance against baseline methods
- Error reduction or accuracy improvements
- Cost implications of tool implementation

- **Technical Limitations:**

Extract limitations and constraints of the digital tools for MCP assessment, including:

- Building types or project scales where tool is not suitable
- BIM software version dependencies or compatibility issues
- Data quality or availability requirements

- Computational resource requirements
- Known accuracy limitations or margin of error
- Integration challenges with other software
- User expertise requirements that limit accessibility
- Any theoretical vs. practical implementation gaps noted
- **Tool type:**
Classify the tool into one of these categories:
- **BIM Software:**
State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).
- **Installation Ease:**
Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.
- **Circularity Function:**
Specifically, how does this tool support [Indicator Name]? What is its main automated output (e.g., Disassembly Index)?
- **Collaborations:**
List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing

Results

Characteristics of Included Studies

Characteristic	Tan Tan et al. (2024)	Doris Esenarro Vargas et al. (2025)
Full text retrieved?	Yes	Yes
Tool name	MIVES (Modelo Integrado de Valor para una Evaluación Sostenible) [1]	Unnamed custom scripts in Grasshopper and Python [2]
Tool type	Standalone MCDM framework integrated with BIM [1]	Parametric scripts developed in Grasshopper and Python [2]
Host BIM software	Revit [1]	Rhino 8 [2]
Availability	Not mentioned; no download link or access instructions provided [1]	Available on request; no URL provided [2]
Availability status	Not mentioned [1]	Experimental context; not explicitly stated as commercially available or open-source [2]
MCP focus	DfMA sustainability assessment for building façade retrofit [1]	CNC prefabrication process optimization for WikiHouse prototypes [2]
Validation context	Single façade retrofit project in Wuhan, China, comparing five design alternatives [1]	Controlled experiments with undergraduate students fabricating WikiHouse prototypes [2]

Characteristic	Tan Tan et al. (2024)	Doris Esenarro Vargas et al. (2025)
Publication type	Journal article [1]	Journal article [2]
DOI	Not mentioned [1]	Not mentioned [2]

Both sources address aspects of Design for Manufacture and Assembly (DfMA) within the construction industry, but they differ substantially in scope, methodology, and tool maturity. The MIVES framework operates as a multi-criteria decision-making methodology that relies heavily on expert judgment and BIM data to generate sustainability indices [1], whereas the Grasshopper/Python scripts automate specific fabrication-preparation tasks (file download, data transformation, nesting) within a parametric design environment [2]. Neither source provides a DOI for its primary publication [1, 2], and neither offers a publicly accessible, packaged tool that practitioners can download and deploy independently [1, 2].

Methodological Frameworks

Feature	Tan Tan et al. (2024)	Doris Esenarro Vargas et al. (2025)
Core methodology	MIVES using AHP and value functions within a multi-level requirements tree [1]	Mixed-method experimental design evaluating parametric automation against manual workflows [2]
Assessment approach	Multi-criteria sustainability index across economic, environmental, and social dimensions [1]	Measurement of execution time, precision, margin of error, and material waste [2]
Automation level	Not explicitly mentioned; relies on human intelligence for parameter scoring [1]	High level of automation through parametric scripts [2]
Circularity function	No specific circularity function or disassembly index; sustainability indices may relate to circularity [1]	No specific circularity function mentioned; material waste reduction is the closest proxy [2]
Industry standards referenced	None mentioned [1]	None mentioned [2]
Technology integrations	BIM (Building Information Modelling) [1]	Grasshopper, Python, Rhinoceros, SketchUp, BIM/IFC interoperability [2]

The MIVES framework structures its assessment through a hierarchical requirements tree encompassing requirements, criteria, and indicators, weighted via AHP and evaluated through value functions [1]. This approach is flexible and can be adapted to different project types by adjusting indicators and weightings [1], but it does not automate the measurement of specific MCP metrics such as prefabrication ratios or modularization potential [1]. The Grasshopper/Python scripts, by contrast, directly automate fabrication-preparation workflows and achieve measurable efficiency gains, but they do not implement recognized DfMA assessment frameworks or produce standardized circularity indicators [2, 2].

Quantitative Results

Metric	Tan Tan et al. (2024)	Doris Esenarro Vargas et al. (2025)
Primary output	Sustainability index (SI) scores across five design alternatives; alternative (e) achieved the highest SI [1]	Processing time reductions of 94.7% to 99% compared to manual methods [2]
Material efficiency	Not reported as a standalone metric [1]	2.5 to 4.5 fewer plates used; average waste of 21.06% [2]
Time savings	Not reported [1]	23.85 to 88.85 minutes saved per task; 19 to 90 times faster than manual methods [2]
Comparative performance	Alternative (e) performed best economically and environmentally; alternative (b) excelled socially; alternative (c) achieved balanced performance [1]	Experimental (parametric) group achieved 100% correct transformations versus manual groups [2]
Installation ease	Not mentioned [1]	Requires coding knowledge in Python and Grasshopper; not plug-and-play [2]

The Doris Esenarro Vargas et al. (2025) study provides the more directly quantitative evidence of tool performance, demonstrating that parametric automation reduced CNC preparation times from 63–109 minutes to approximately 0.5–1.3 minutes per task [2]. The MIVES framework, while producing quantitative sustainability indices, functions primarily as a decision-support methodology rather than an automated assessment tool, with outputs dependent on expert-assigned scores [1, 1].

Technical Limitations

Limitation category	Tan Tan et al. (2024)	Doris Esenarro Vargas et al. (2025)
Data quality concerns	High-precision BIM modeling is challenging, leading to variations in data depth [1]	Sensitive to tolerances/kerf, machine condition, and OSB/plywood quality [2]
Subjectivity/accuracy	Reliance on expert judgment introduces subjectivity and potential biases [1]	Limited by small sample size and academic environment [2]
User expertise requirements	Expert input required for scoring, limiting accessibility [1]	Software familiarity with Rhino, Grasshopper, and Python is crucial [2]
Scope limitations	Framework may not cover all sustainability aspects; requires customization [1]	Lacks on-site assembly metrics and seismic resistance testing; validated only for WikiHouse prototypes [2]
Generalizability	Applied to a single façade retrofit project [1]	Conducted in an academic setting without industry partnerships [2]

Both tools face significant generalizability constraints. The MIVES framework was validated through a single pilot

case involving five façade design alternatives for a commercial building in Wuhan [1], while the Grasshopper/Python scripts were tested exclusively with undergraduate students constructing WikiHouse prototypes [2]. Neither tool has been validated across multiple building types, scales, or professional practice contexts.

Synthesis

Against the research question's objective of identifying packaged, accessible digital tools that automate the quantitative assessment of MCP and circularity performance, neither of the two included sources fully satisfies the stated criteria. The MIVES framework provides a structured, multi-criteria methodology for evaluating DfMA sustainability but does not function as an automated digital tool or BIM plugin [1, 1]. It requires substantial expert input for parameter weighting and scoring [1], and no download link or access pathway is provided [1]. The Grasshopper/Python scripts demonstrate clear automation capabilities with dramatic efficiency gains in CNC fabrication preparation [2], but they constitute custom-coded computational scripts rather than a packaged tool [2], and they do not implement recognized MCP assessment methodologies such as the Pre-assembly Index or Modular Coordination rules [2].

The divergence between these two sources reflects two distinct approaches to digital support for DfMA: decision-support frameworks that structure evaluation but depend on human judgment (MIVES), and process-automation scripts that accelerate specific fabrication tasks but lack broader assessment capabilities. Neither approach produces automated outputs aligned with established circularity indicators such as disassembly indices or material passport data [1, 2]. The MIVES framework integrates only with BIM at a general level [1], while the Grasshopper/Python scripts integrate with Rhino and SketchUp but do not connect to material passport systems, digital twins, or other circular economy infrastructure [2].

In terms of readiness for early-stage architectural decision-making, the MIVES framework is conceptually closer to this goal, as it supports comparison across design alternatives during the design development phase [1]. However, its dependence on expert scoring and lack of automation limit its scalability. The Grasshopper/Python scripts operate at a later stage of the workflow (fabrication preparation) and are constrained to the WikiHouse system [2], limiting their applicability to broader architectural practice. Both tools remain at a prototype or research-only stage of development, with validation limited to single-project or academic contexts [1, 2].

References

1. Tan Tan, Lang Zheng, Fan Xue, et al (2024) MIVES MULTI-CRITERIA FRAMEWORK TO SUSTAINABILITY INDEX OF DESIGN FOR MANUFACTURE AND ASSEMBLY. *Journal of Civil Engineering and Management*. <https://doi.org/10.3846/jcem.2024.20953>
2. Doris Esenarro Vargas, Emerson Porras, Jesica Vilchez Cairo, et al (2025) Use of Parametric Digital Tools in Grasshopper and Python for Optimization of CNC Prefabrication Process in WikiHouse Prototype Construction. *Buildings*. <https://doi.org/10.3390/buildings15213895>

Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Durability (DfD) and the extension of material service life within a circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Longevity," "Component Service Life," or "Maintenance Intensity" by utilizing recognized methodologies such as the Longevity Indicator (LI), Service Life Prediction (SLP) models, or Durability Assessment based on ISO 15686 standards. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability principles—such as choosing high-performance, maintainable materials—to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025.

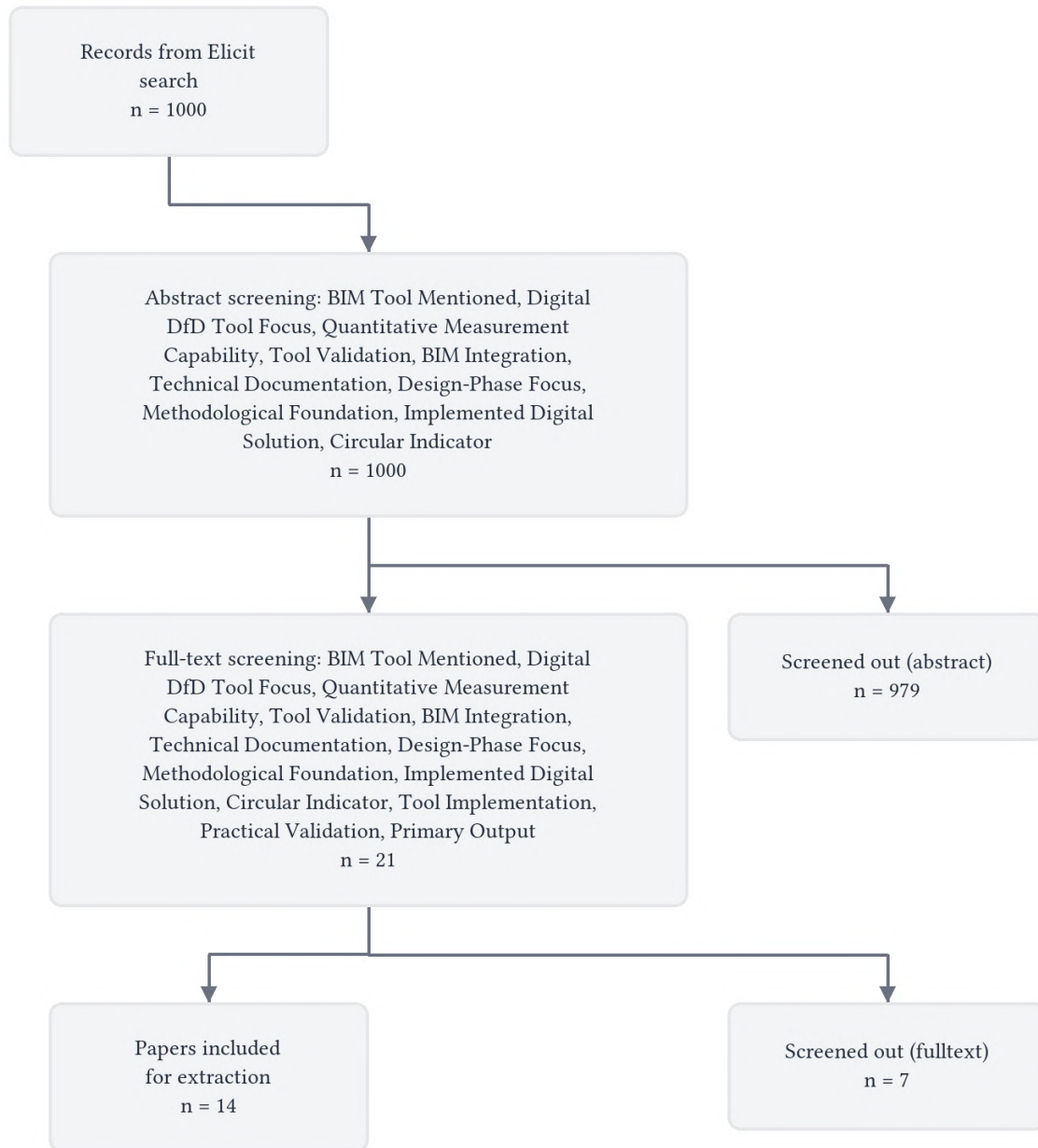
No packaged, commercially available BIM plugin currently exists that automates the quantitative assessment of Design for Durability using recognized methodologies such as ISO 15686, the Longevity Indicator, or Service Life Prediction models; the closest tools are research prototypes for concrete carbonation and chloride ingress prediction in Autodesk Revit, while the only accessible commercial tools (Tally, Eco2soft, FirstRate5) address life cycle environmental assessment rather than service life prediction.

Abstract

No commercially available, packaged BIM plugin currently automates the full spectrum of Design for Durability (DfD) metrics—Material Longevity, Component Service Life, or Maintenance Intensity—using recognized methodologies such as the Longevity Indicator, Service Life Prediction models, or ISO 15686 standards. A systematic examination of 14 primary studies published between 2019 and 2025 reveals that the closest approximations are two research prototypes targeting concrete deterioration: a Revit API plugin that calculates time until carbonation and carbonation depth using the Spanish Structural Code [1], and a Dynamo/GeNIe workflow that applies Bayesian inference to predict carbonation and chloride ingress probabilities in reinforced concrete [2]. Neither implements ISO 15686 explicitly, and both are available only upon request from their developers [1, 2]. The only packaged commercial

tools identified—Tally [3], Eco2soft [4], and FirstRate5 [3] —serve life cycle assessment and energy rating functions rather than durability prediction. The remaining tools address adjacent domains including building recyclability rates [5], circularity indicators such as the Building Circularity Indicator and Disassembly Index [6], recycling potential of structural systems [4], and infrastructure pavement maintenance optimization [7, 8]. Autodesk Revit is the dominant platform across 11 of 14 studies [1–3, 5, 9–11], and most tools support early-stage design integration [1, 6, 7, 9], yet 11 of 14 remain research prototypes without standardized installers or public repositories. The field has prioritized environmental impact quantification and circularity scoring over service life prediction, leaving a significant gap between the qualitative durability principles embedded in current design practice and the automated, quantitative DfD assessments that architects require for early-stage decision-making.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Durability (DfD) and the extension of material service life within a circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Longevity," "Component Service Life," or "Maintenance Intensity" by utilizing recognized methodologies such as the Longevity Indicator (LI), Service Life Prediction (SLP) models, or Durability Assessment based on ISO 15686 standards. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability principles—such as choosing high-performance, maintainable materials—to automated, quantitative digital assessments suitable for early-stage architectural decision-making for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Digital DfD Tool Focus:** Does this study describe digital tools or BIM plugins specifically designed for quantitative assessment of building Design for Durability (DfD)?
- **Quantitative Measurement Capability:** Do the tools described automate measurement of at least one of the following: Material Longevity, Component Service Life, or Maintenance Intensity?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Integration:** Do the tools integrate with or support BIM workflows and established BIM authoring software?
- **Technical Documentation:** Does the study provide sufficient technical details including tool names, software requirements, and implementation methods?
- **Design-Phase Focus:** Are the tools designed for early-stage design decision-making (rather than exclusively for post-construction monitoring)?
- **Methodological Foundation:** Do the tools utilize recognized methodologies or standards for durability assessment?
- **Implemented Digital Solution:** Does the study describe implemented digital tools (rather than purely theoretical frameworks without digital implementation)?

- **Circular Indicator:** Does the paper claim to quantitatively measure Design for durability? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

21 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Digital DfD Tool Focus:** Does this study describe digital tools or BIM plugins specifically designed for quantitative assessment of building Design for Durability (DfD)?
- **Quantitative Measurement Capability:** Do the tools described automate measurement of at least one of the following: Material Longevity, Component Service Life, or Maintenance Intensity?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Integration:** Do the tools integrate with or support BIM workflows and established BIM authoring software?
- **Technical Documentation:** Does the study provide sufficient technical details including tool names, software requirements, and implementation methods?
- **Design-Phase Focus:** Are the tools designed for early-stage design decision-making (rather than exclusively for post-construction monitoring)?
- **Methodological Foundation:** Do the tools utilize recognized methodologies or standards for durability assessment?
- **Implemented Digital Solution:** Does the study describe implemented digital tools (rather than purely theoretical frameworks without digital implementation)?
- **Circular Indicator:** Does the paper claim to quantitatively measure Design for durability? Answer 'No' if it is purely qualitative.
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

14 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identity:**

Extract the specific nomenclature and technical specifications of digital tools or BIM plugins designed for quantitative Design for Durability (DfD) assessment, including:

- Official tool/plugin name or commercial designation
- Version number if specified
- Developer/company name
- Required BIM authoring software environment (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)
- Tool accessibility status (packaged commercial tool, open-source plugin, proprietary solution)
- Exclude purely theoretical frameworks or custom-coded scripts not available as packaged tools

- **DfD Assessment Capabilities:**

Extract quantitative assessment capabilities specifically for building Design for Durability and material service life extension within circular economy frameworks, including:

- Specific durability metrics automated (Material Longevity, Component Service Life, Maintenance Intensity, etc.)
- Recognized methodologies implemented (Longevity Indicator (LI), Service Life Prediction (SLP) models, ISO 15686 Durability Assessment standards)
- Types of building materials or components assessed
- Calculation algorithms or assessment models used
- Integration with circular economy principles (reduce, reuse, recycle approaches)

- **Validation Evidence:**

Extract evidence of practical validation and professional implementation for DfD assessment tools, including:

- Case studies demonstrating tool application in real building projects
- Empirical simulations or testing results
- Professional contexts where tool has been used (architectural firms, engineering consultancies, research institutions)
- Performance validation data comparing tool outputs to actual building performance
- Peer review or industry certification status
- Limitations or constraints identified during practical application

- **Automation Features:**

Extract details about the tool's automation capabilities for transitioning from qualitative durability principles to quantitative digital assessments, including:

- Level of automation provided (fully automated calculations, semi-automated with user input, manual data entry required)
- Integration with early-stage architectural decision-making workflows
- Data input requirements and sources
- Output formats and visualization capabilities
- Real-time assessment capabilities during design iteration
- Compatibility with existing BIM workflows and data standards

- **Publication Documentation:**

Extract official publication details documenting the tool's practical implementation and validation for DfD assessment, including:

- Primary publication DOI documenting tool implementation
- Publication title and authors
- Journal or conference where published
- Publication year (must be before December 2025)
- Additional supporting publications or technical documentation
- Availability of tool documentation or user manuals

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

choose one option from specifies possible answer below

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Circularity Function:**

Specifically, how does this tool support design for durability? What is its main automated output (e.g., Disassembly Index)? what is the focus area?

Results

Characteristics of Included Studies

The 14 sources reviewed span from 2019 to 2025 and cover a range of BIM-integrated tools and frameworks targeting durability, sustainability, and circularity assessment in the built environment. Notably, while the research question specifically targets tools for quantitative Design for Durability (DfD) assessment using recognized methodologies such as the Longevity Indicator (LI), Service Life Prediction (SLP) models, or ISO 15686 standards, none of the identified sources describe a packaged, commercially available tool that directly automates these specific metrics. Instead, the landscape is populated by research prototypes, custom scripts, and integrated BIM frameworks that address adjacent concerns—life cycle assessment (LCA), recyclability, circularity indicators, deterioration modeling, and fatigue assessment—which collectively inform durability-related decision-making.

Study	Full Text Retrieved?	Study Type	Primary Focus	BIM Platform	Tool Name / Designation	Tool Type
C. Oreto et al., 2023	Yes	Primary study	Road pavement LCA/LCCA and maintenance planning [7]	Autodesk Civil 3D [7]	Oreto et al. 2023 Script (Dynamo-based IBIM plugin) [7]	Visual programming script [7]
Víctor Fernández Mora et al., 2022	Yes	Primary study	Structural durability index (carbonation) [1]	Autodesk Revit [1]	Fernández Mora et al. 2022 Script (Revit API plugin) [1]	BIM plugin [1]
Qiming Sun et al., 2022	Yes	Primary study	Recycling potential comparison of mass timber vs. concrete [4]	Revit 2019 [4]	Eco2soft [4]	Integrated BIM framework [4]
Hendrik Morgenstern et al., 2023	Yes	Primary study	Bayesian inference for concrete deterioration modeling [2]	Autodesk Revit [2]	GeNIe (via PyS-MILE/Dynamo) [2]	Visual programming script / BIM plugin [2]
K. Xing et al., 2020	Yes	Primary study	Cloud-BIM platform for building component reuse [12]	Autodesk Revit, Graphisoft ArchiCAD [12]	Xing et al. 2020 Script (Cloud-BIM platform) [12]	Cloud-based platform [12]
Alireza Fereydooni Eftekhari et al., 2024	Yes	Primary study	Automated building recyclability rate (BRR) calculation [5]	Revit 2021 [5]	Eftekhari et al. 2024 Script (Python/IFC) [5]	Integrated BIM framework [5]
I. A. Nhamage et al., 2023	Yes	Primary study	Fatigue assessment in metallic railway bridges [13]	Autodesk Revit [13]	ANSYS, MATLAB, DYNAMO API [13]	Integrated BIM framework [13]
B. Soust-Verdaguer et al., 2023	Yes	Primary study	LCSA plug-in for building envelope refurbishment [9]	Autodesk Revit 2022 [9]	BIM3LCA_structBIM [9]	BIM plugin [9]

Study	Full Text Retrieved?	Study Type	Primary Focus	BIM Platform	Tool Name / Designation	Tool Type
Aorigele Orgil Borjigin et al., 2022	Yes	Primary study	Digital twin sustainability assessment for light rail [10]	Revit 2021 [10]	Autodesk Revit 2021 [10]	Integrated BIM framework [10]
Quddus Tushar et al., 2022	Yes	Primary study	BIM-based LCA of precast sandwich panels [3]	Autodesk Revit with Tally plugin [3]	FirstRate5, Tally [3]	BIM plugin [3]
C. Oreto et al., 2021	Yes	Primary study	BIM-LCA integration for road pavement maintenance [8]	Autodesk Civil 3D [8]	Oreto et al. 2021 Script (Dynamo-based) [8]	Visual programming script [8]
J. Fernandes et al., 2022	Yes	Primary study	Circularity methodology for building refurbishment [6]	Not specified [6]	Fernandes et al. 2022 Script (BAC methodology) [6]	BIM plugin [6]
M. Morandotti et al., 2019	Yes	Primary study	Resilience assessment for adaptive reuse of heritage [14]	Not specified [14]	Morandotti et al. 2019 Script (VPL-based) [14]	Visual programming script [14]
Vitaliy Bassist et al., 2025	Yes	Primary study	BIM-based technical inspection and physical wear monitoring [11]	Autodesk Revit [11]	Autodesk Revit (with cloud environment) [11]	Integrated BIM framework [11]

All 14 sources are primary studies reporting tool development or application; no systematic reviews or meta-analyses were included. The dominant BIM platform is Autodesk Revit (used in 11 of 14 studies), with two studies employing Autodesk Civil 3D for infrastructure applications [7, 8] and one referencing Graphisoft ArchiCAD alongside Revit [12]. Two studies did not specify their BIM host software [6, 14]. The majority of tools are research prototypes—custom Dynamo scripts, Python workflows, or API-based plugins—rather than commercially packaged, installable software. Only Eco2soft [4], Tally [3], and FirstRate5 [3] are identified as packaged commercial tools, though none of these directly automate DfD metrics such as Material Longevity or Service Life Prediction per ISO 15686.

Tool Capabilities and DfD Assessment Coverage

A critical finding of this review is that no identified tool directly implements recognized DfD methodologies such as the Longevity Indicator (LI), Service Life Prediction (SLP) models, or ISO 15686-based durability assessment as packaged, accessible software. The tools instead address related but distinct domains. The table below maps each tool's assessment capabilities against the DfD criteria specified in the research question.

Study	Durability Metrics Automated	Recognized DfD Methodology (LI/SLP/ISO 15686)		Circular Economy Integration	Main Automated Output
			Materials/Components Assessed		
C. Oreto et al., 2023	Pavement performance decay, maintenance scheduling [7]	Not mentioned [7]	Road asphalt pavement layers [7]	LCA/LCCA for circular economy-oriented maintenance [7]	Life cycle indicators for pavement solutions [7]
Fernández Mora et al., 2022	Time until carbonation, carbonation depth [1]	Spanish Structural Code (related but not ISO 15686) [1]	Concrete structural elements [1]	Not explicitly mentioned [1]	Carbonation timeline and durability index [1]
Qiming Sun et al., 2022	Recycling potential (RP) at material, component, building levels [4]	Not mentioned [4]	Mass timber and concrete [4]	GWP and material cycle assessment [4]	Recycling potential score and GWP [4]
Morgenstern et al., 2023	Carbonation depth, chloride ingress, probability of failure [2]	Bayesian inference for deterioration models [2]	Concrete structures [2]	Efficient planning of repair measures [2]	Probabilistic durability assessment [2]
K. Xing et al., 2020	Component physical condition tracking [12]	Not mentioned [12]	Internal framed glazed systems [12]	Reuse-oriented product-service system [12]	Component reusability assessment and eco-efficiency [12]
Eftekhari et al., 2024	Recyclability rates, hazardous material presence [5]	European codes, Italian regulations [5]	Various building materials [5]	Building Recyclability Rate (BRR) [5]	BRR score [5]
Nhamage et al., 2023	Fatigue damage estimation [13]	Not mentioned [13]	Metallic railway bridge components [13]	Not mentioned [13]	Fatigue damage visualization [13]

Study	Durability Metrics Automated	Recognized DfD Methodology (LI/SLP/ISO 15686)	Materials/Components Assessed	Circular Economy Integration	Main Automated Output
Soust-Verdaguer et al., 2023	Environmental, economic, social LCSA indicators [9]	Not mentioned [9]	Building envelope materials (EPS, mineral wool) [9]	Not explicitly mentioned [9]	Triple-bottom-line LCSA scores [9]
Borjigin et al., 2022	Energy consumption, CO2 emissions, life cycle costs [10]	Not mentioned [10]	PCAT light rail system components [10]	Not explicitly mentioned [10]	LCA/LCC quantitative outputs [10]
Tushar et al., 2022	Embodied and operational energy, CO2 emissions [3]	ISO 14040-14044 (LCA, not durability) [3]	Precast concrete sandwich panels [3]	Fly ash integration for reduced impacts [3]	LCA environmental impact scores [3]
C. Oreto et al., 2021	Environmental impact category indicators [8]	Not mentioned [8]	Road asphalt pavement [8]	Sustainable pavement recycling practices [8]	Environmental impact report [8]
Fernandes et al., 2022	Material Circularity Indicator, Disassembly Index, BCI [6]	Not mentioned [6]	Existing building stock materials [6]	Building Circularity Indicator (BCI) [6]	BCI score [6]
Morandotti et al., 2019	PAV (Performance Adequacy and Vulnerability), RTE [14]	Not mentioned [14]	Heritage building structural elements [14]	Not mentioned [14]	PAV and RTE indices [14]
Bassist et al., 2025	Physical wear indicator [11]	Integration with structural calculation software (LIRA-SAPR) [11]	Building structural elements [11]	Cloud-based BIM for condition monitoring [11]	Physical wear specification [11]

Only two tools—the Fernández Mora et al. (2022) Revit plugin and the Morgenstern et al. (2023) Dynamo/GeNIe workflow—directly automate durability-specific metrics for building structural elements. The Fernández Mora tool calculates time until carbonation and carbonation depth in concrete elements using the Spanish Structural Code [1], while the Morgenstern workflow uses Bayesian inference to predict carbonation and chloride ingress probabilities in reinforced concrete [2]. Both address concrete deterioration mechanisms that are central to service life prediction, yet neither explicitly implements ISO 15686 or the Longevity Indicator methodology. The physical wear indicator

tracked by Bassist et al. (2025) represents a simpler quantitative measure of degradation over time [11], but lacks the probabilistic sophistication of the other two approaches.

The remaining tools focus predominantly on environmental sustainability (LCA/LCCA) or circularity metrics rather than durability per se. Fernandes et al. (2022) is the only study that computes a Disassembly Index alongside a Building Circularity Indicator [6], which is the closest approximation to a DfD-specific output among the circularity-oriented tools. Eftekhari et al. (2024) automates the Building Recyclability Rate using European Waste Catalogue classifications [5], while Sun et al. (2022) calculates recycling potential using a BIM-Eco2soft-Excel workflow [4].

Automation and Workflow Integration

Study	Automation Level	Early-Stage Design Integration	Real-Time Assessment	Data Input Requirements	Ease of Use for Architects
C. Oreto et al., 2023	Fully automated with some user input for templates [7]	Yes [7]	Yes, via Dynamo [7]	Excel spreadsheets for data templates [7]	User-friendly via visual scripting [7]
Fernández Mora et al., 2022	Semi-automated with user input for inspection data [1]	Yes [1]	Results stored in BIM model [1]	Cover, tensile strength, occluded air [1]	Plug-and-play within Revit; no coding required [1]
Qiming Sun et al., 2022	Semi-automated [4]	Yes, early design optimization [4]	Not explicitly mentioned [4]	Material composition and life cycle parameters [4]	Designer-friendly; no coding required [4]
Morgenstern et al., 2023	Fully automated Bayesian inference [2]	Yes [2]	Yes, 4D durability assessment [2]	Machine-readable diagnosis data [2]	Requires Python expertise [2]
K. Xing et al., 2020	Fully automated data exchange [12]	Yes [12]	Yes, real-time tracking [12]	IFC data attributes, RFID tags [12]	User-friendly web interface [12]
Eftekhari et al., 2024	Fully automated [5]	Yes [5]	Not mentioned [5]	BIM models and EWC [5]	Requires Python coding [5]
Nhamage et al., 2023	Semi-automated [13]	Limited [13]	Partial, via Input Module [13]	BrIM models, traffic data [13]	Requires ANSYS/MATLAB expertise [13]
Soust-Verdaguer et al., 2023	Semi-automated with manual element selection [9]	Yes, real-time [9]	Yes [9]	Predefined solution library [9]	Plug-and-play; no coding required [9]
Borjigin et al., 2022	Semi-automated [10]	Yes [10]	Yes [10]	Revit models and bill of quantities [10]	User-friendly; no coding required [10]

Study	Automation Level	Early-Stage Design Integration	Real-Time Assessment	Data Input Requirements	Ease of Use for Architects
Tushar et al., 2022	Semi-automated [3]	Yes, through BIM [3]	Potential [3]	Customized LCA database [3]	User-friendly; no coding required [3]
C. Oreto et al., 2021	Fully automated with user customization [8]	Yes, dynamic updating [8]	Yes [8]	BIM model and external databases [8]	Visual scripting; some scripting knowledge may help [8]
Fernandes et al., 2022	Semi-automated [6]	Yes [6]	Yes [6]	External databases (Uniclass 2015) [6]	Plug-and-play with GUI [6]
Morandotti et al., 2019	Semi-automated [14]	Yes [14]	Not explicitly mentioned [14]	Informative model parameters [14]	Future plans for user-friendly product [14]
Bassist et al., 2025	Semi-automated [11]	Compatible with BIM workflows [11]	Not explicitly mentioned [11]	Technical inspection data [11]	User-friendly within Revit [11]

A clear divide exists between tools accessible to architects without programming skills and those requiring Python, C#, or specialist software expertise. The BIM3LCA_structure plugin [9], the Fernández Mora et al. durability plugin [1], the Fernandes et al. BAC plugin [6], and the commercial tools Tally and FirstRate5 [3] are described as plug-and-play solutions that integrate into standard Revit workflows. In contrast, the Morgenstern et al. workflow requires a 762-node Dynamo script with embedded Python [2], and the Eftekhari et al. approach demands bespoke Python programming [5]. The Nhamage et al. framework relies on ANSYS and MATLAB, limiting its accessibility to engineers with finite element analysis expertise [13].

Most tools claim integration with early-stage design workflows, with eight of 14 explicitly supporting real-time or dynamic assessment during design iteration [1, 2, 6–10, 12]. IFC compatibility is noted in several studies, including Morgenstern et al. (2023), which exports results in IFC-compatible files [2], and Xing et al. (2020), which uses IFC for cross-platform interoperability [12].

Validation Evidence

Study	Case Study	Validation Type	Limitations Identified
C. Oreto et al., 2023	Rural road in Italy [7]	LCA/LCCA comparison of maintenance scenarios [7]	Need for uncertainty analysis and social LCA [7]
Fernández Mora et al., 2022	Two structural elements in a residential building [1]	Carbonation analysis in real building elements [1]	Not explicitly mentioned [1]

Study	Case Study	Validation Type	Limitations Identified
Qiming Sun et al., 2022	High-rise passive residential building in Tianjin, China [4]	Material consumption, waste, and GWP comparison [4]	Not mentioned [4]
Morgenstern et al., 2023	Simulated deterioration scenarios [2]	50,000 Bayesian simulations; reproducibility testing [2]	No real-world building case study mentioned [2]
K. Xing et al., 2020	Major new hospital (glazed systems) [12]	Economic and carbon intensity comparison [12]	Limited by low-cost equipment and mock-up platform [12]
Eftekhari et al., 2024	Residential building [5]	BRR sensitivity to hazardous materials (20% presence reduces BRR by ~10%) [5]	Difficulty retrieving Italian recyclability data [5]
Nhamage et al., 2023	Five-span metallic railway bridge in Portugal [13]	Two fatigue scenarios over 100-year period [13]	Need for real traffic data [13]
Soust-Verdaguer et al., 2023	Multi-family building in Camas, Seville [9]	Comparison of EPS vs. mineral wool solutions [9]	Focus limited to new materials [9]
Borjigin et al., 2022	PCAT light rail system [10]	LCA/LCC of concrete slabs and rail components [10]	Not mentioned [10]
Tushar et al., 2022	Precast sandwich panel analysis [3]	Monte Carlo simulation and regression models [3]	Not explicitly discussed [3]
C. Oreto et al., 2021	Not mentioned [8]	Not mentioned [8]	Not mentioned [8]
Fernandes et al., 2022	Building in Lisbon (1919–1945 archetype) [6]	BAC methodology tested on BIM model [6]	Does not replace on-site inspections [6]
Morandotti et al., 2019	Heritage buildings at University of Pavia [14]	Semi-automated parameter retrieval via VPL scripts [14]	Not mentioned [14]
Bassist et al., 2025	Main educational building, Vinnytsia National Technical University (2004 and 2024 reports) [11]	Correlation between service life end and performance loss [11]	Not explicitly mentioned [11]

Thirteen of 14 studies report some form of case study or empirical simulation, though the depth and rigor of validation varies considerably. Only Morgenstern et al. (2023) provides extensive computational validation with 50,000 Bayesian simulations examining sample size influence and reproducibility [2], while most others rely on single case study demonstrations. The Oreto et al. (2021) framework notably lacks any reported case study application [8]. No study reports independent third-party validation, industry certification, or formal comparison of tool outputs against measured in-situ building performance data.

Technology Integration and Accessibility

The tools exhibit varying degrees of integration with emerging digital technologies. Xing et al. (2020) presents the most technologically diverse integration, combining IoT (RFID tags), cloud computing, GIS (Google Maps), and

potential blockchain integration within a single platform [12]. Morgenstern et al. (2023) integrates Bayesian network software (GeNIe/BayesFusion) with Revit through PySMILE and Dynamo [2]. Borjigin et al. (2022) and Nhamage et al. (2023) both leverage digital twin concepts [10, 13]. Material Passports are referenced by Eftekhari et al. (2024) [5] and implicitly by Sun et al. (2022) through their Material Cycle Database [4]. Fernandes et al. (2022) explicitly targets building passport creation for circularity [6].

Regarding accessibility, the majority of tools are available only upon request from the authors [1–3, 5, 6, 8, 9, 13, 14]. Oreto et al. (2023) provides supplementary materials via an MDPI repository [7], and Sun et al. (2022) similarly offers open data [4]. No study provides a GitHub repository or downloadable installer for the tools developed. The commercial tools Eco2soft [4], Tally [3], and FirstRate5 [3] are the only packaged products available through standard commercial channels, but they serve LCA and energy rating functions rather than DfD-specific assessment.

Synthesis

The fundamental tension revealed by this review is between the research question's demand for packaged DfD tools implementing ISO 15686, LI, or SLP methodologies and the actual state of the field, where such tools do not exist as accessible, commercially available software. This gap is not simply a matter of insufficient research but reflects structural characteristics of the domain.

The two tools that most closely approximate DfD functionality—the Fernández Mora et al. (2022) carbonation assessment plugin [1] and the Morgenstern et al. (2023) Bayesian deterioration modeling workflow [2]—both focus narrowly on concrete deterioration mechanisms (carbonation and chloride ingress). These are critical service life parameters for reinforced concrete, but they cover only a subset of the durability concerns relevant to whole-building DfD assessment. The Fernández Mora tool is more accessible, operating as a plug-and-play Revit plugin that does not require coding [1], whereas the Morgenstern workflow demands Python scripting expertise and a complex 762-node Dynamo script [2], limiting its practical adoption by architects despite its greater analytical sophistication.

The dominance of LCA-focused tools (8 of 14 studies) over durability-specific tools suggests that the BIM tool development community has prioritized environmental impact quantification—driven by regulatory pressure and green building certification schemes—over service life prediction. Tools like Tally [3], Eco2soft [4], and the various Dynamo-based LCA scripts [7, 8] provide robust environmental assessment but do not answer the fundamental DfD question of how long a material or component will perform adequately in service. The circularity-oriented tools (Fernandes et al., 2022; Eftekhari et al., 2024; Sun et al., 2022) address material end-of-life pathways and recyclability [4–6] but similarly do not predict service life duration.

The infrastructure-focused tools (C. Oreto et al., 2021 and 2023; Borjigin et al., 2022; Nhamage et al., 2023) represent a parallel development trajectory where pavement performance modeling [7, 8] and fatigue assessment [13] are more established, likely because infrastructure assets have longer regulatory traditions of performance-based maintenance planning. The transferability of these approaches to building-scale DfD assessment remains undemonstrated.

A key accessibility barrier is that 11 of 14 tools are research prototypes available only upon request or not at all, with no standardized installation procedures [1–3, 5, 6, 8, 9, 11–14]. For architects seeking ready-to-use DfD tools for early-stage design, the practical options reduce to: (1) the Fernández Mora et al. Revit plugin for concrete carbonation assessment, which requires contacting the authors [1]; (2) Tally for embodied impact assessment as a proxy for material selection [3]; and (3) the BIM3LCA_structure plugin for LCSA-based material comparison during refurbishment [9]. None of these fully satisfies the research question's requirement for ISO 15686-compliant, automated DfD quantification. The Bassist et al. (2025) approach of tracking physical wear indicators within Revit's cloud environment [11] offers the simplest operational pathway for durability monitoring but lacks predictive modeling capabilities.

In summary, the field currently offers a constellation of tools that collectively address fragments of the DfD assessment challenge—concrete deterioration prediction, environmental impact quantification, circularity scoring, and component condition tracking—but no single integrated solution automates the full spectrum of Material Longevity, Component Service Life, and Maintenance Intensity metrics using recognized durability standards within a commercially accessible BIM plugin.

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Adaptive Reuse of existing structures and building elements (e.g., rooms) within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Repurposing Potential," "Residual Service Life," or "Spatial Compatibility" for new functions by utilizing recognized methodologies such as the Adaptive Reuse Potential (ARP) model, Multi-Criteria Decision Analysis (MCDA), or automated Structural Integrity and Decay assessments. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative heritage preservation and repurposing principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making, emphasizing the retention of embodied energy and resource conservation for data published before December 2025.

No established, packaged digital tool or BIM plugin currently exists that provides an integrated, automated quantitative assessment of Repurposing Potential, Residual Service Life, and Spatial Compatibility for building adaptive reuse using recognized methodologies such as ARP or MCDA; instead, the available landscape consists of specialized, partially overlapping solutions—including element-matching scripts for Grasshopper, a BIM-based circularity indicator plugin, a multi-criteria BIM-GIS screening framework, and the commercially available One Click LCA for embodied carbon—each addressing only a subset of the adaptive reuse evaluation pipeline and requiring combination across multiple software environments to approximate comprehensive early-stage assessment.

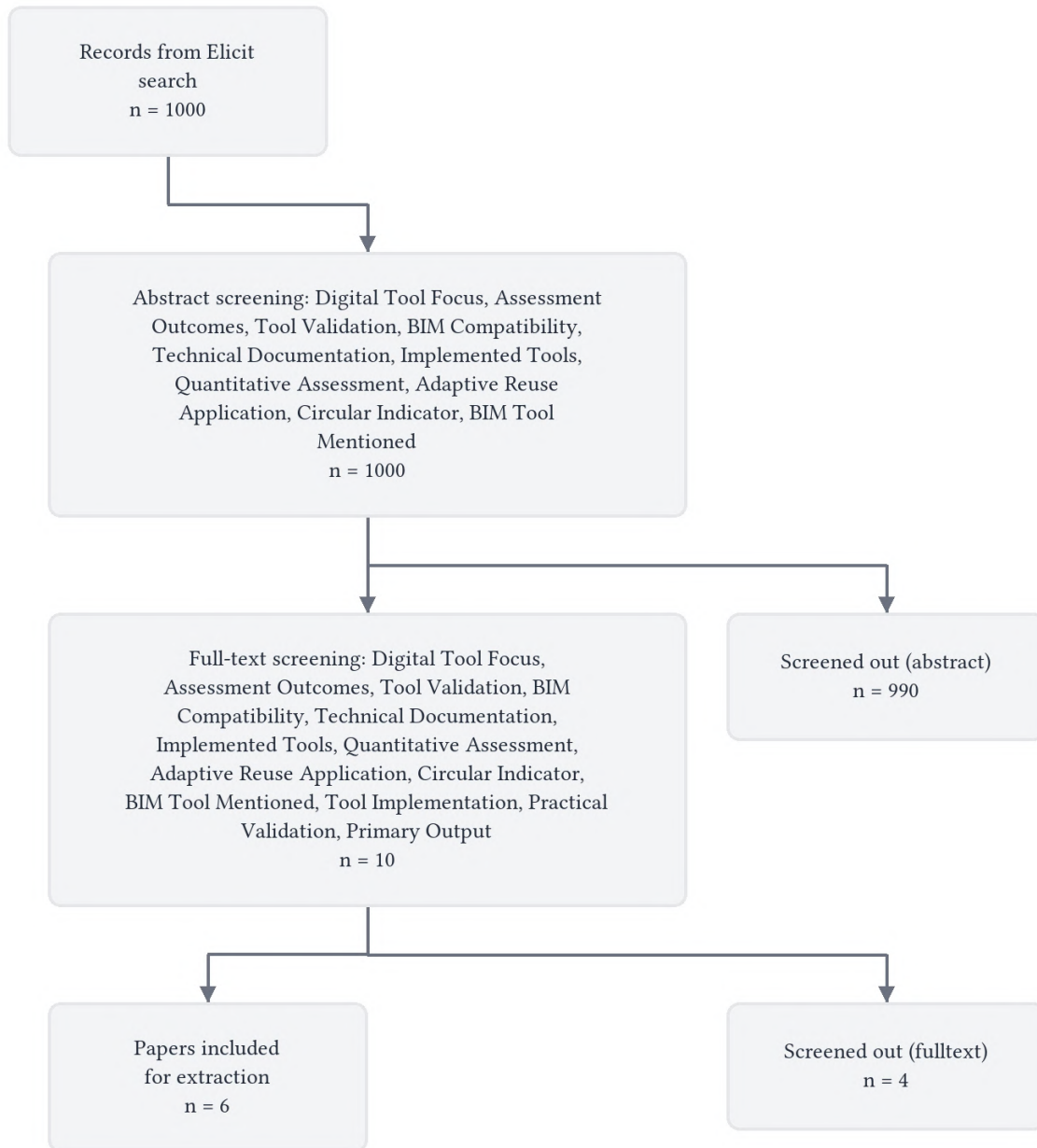
Abstract

Six digital tools operating within BIM environments were identified as relevant to the quantitative assessment of building adaptive reuse within the circular economy framework, yet none provides an integrated, automated evaluation of Repurposing Potential, Residual Service Life, and Spatial Compatibility as a unified assessment. The tools span two primary platforms: Rhino/Grasshopper (the Huang et al. 2021 Hungarian Algorithm script [1], the Haakon-

sen et al. 2024 reclaimed element matching tool [2], and the WASP plugin [3]) and Autodesk Revit (the Cinquepalmi et al. 2023 BIM-GIS framework [4] and One Click LCA [5]), plus one unspecified BIM platform (the Fernandes et al. 2022 Plugin for Circularity [6]). Each tool addresses a distinct sub-problem—structural element matching [1, 2], building-level circularity indicators [6], multi-criteria conversion screening [4], embodied carbon quantification [5], or disassembly sequence planning [3]—rather than the full adaptive reuse decision pipeline. No tool explicitly implements the Adaptive Reuse Potential (ARP) model, and only the Haakonsen et al. (2024) weighted incidence matrix approximates MCDA [2]. None performs automated structural integrity and decay assessment.

Of the six tools, only One Click LCA is commercially available as a packaged product [5]; two are open-source Grasshopper components available for free download [1, 2], while the remaining three are research prototypes without confirmed public distribution [3, 4, 6]. Professional-context validation is limited: the Haakonsen et al. (2024) tool achieved a 40% GWP reduction in an actual public building project in Oslo [2], and One Click LCA demonstrated an 82–91% embodied carbon reduction relative to new construction benchmarks in a Milan reuse project [5], but both address only partial aspects of adaptive reuse. The current tooling landscape thus consists of specialized, partially overlapping solutions that would need to be combined across multiple software environments to approximate a comprehensive early-stage adaptive reuse assessment, highlighting a significant gap between the aspirations of automated quantitative evaluation and the capabilities of available digital tools.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Adaptive Reuse of existing structures and building elements (e.g., rooms) within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Repurposing Potential," "Residual Service Life," or "Spatial Compatibility" for new functions by utilizing recognized methodologies such as the Adaptive Reuse Potential (ARP) model, Multi-Criteria Decision Analysis (MCDA), or automated Structural Integrity and Decay assessments. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative heritage preservation and repurposing principles to automated, quantitative digital assessments suitable for early-stage architectural decision-making, emphasizing the retention of embodied energy and resource conservation for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Digital Tool Focus:** Does this study describe digital tools or BIM plugins specifically designed for quantitative assessment of building adaptive reuse?
- **Assessment Outcomes:** Do the tools automate evaluation of at least one of the following: "Repurposing Potential," "Residual Service Life," or "Spatial Compatibility"?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation (not purely theoretical)?
- **BIM Compatibility:** Are the tools designed for or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)?
- **Technical Documentation:** Does the study provide sufficient technical detail to extract tool nomenclature, BIM environment, and implementation documentation?
- **Implemented Tools:** Does the study focus on implemented digital tools rather than purely theoretical frameworks without digital implementation?
- **Quantitative Assessment:** Do the tools include quantitative assessment capabilities rather than focusing solely on qualitative heritage preservation?
- **Adaptive Reuse Application:** Are the tools designed for adaptive reuse of existing structures rather than exclusively for new construction?
- **Circular Indicator:** Does the paper claim to quantitatively measure Adaptive Reuse of building elements (e.g. rooms)? Answer 'No' if it is purely qualitative.

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

10 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Digital Tool Focus:** Does this study describe digital tools or BIM plugins specifically designed for quantitative assessment of building adaptive reuse?
- **Assessment Outcomes:** Do the tools automate evaluation of at least one of the following: "Repurposing Potential," "Residual Service Life," or "Spatial Compatibility"?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation (not purely theoretical)?
- **BIM Compatibility:** Are the tools designed for or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)?
- **Technical Documentation:** Does the study provide sufficient technical detail to extract tool nomenclature, BIM environment, and implementation documentation?
- **Implemented Tools:** Does the study focus on implemented digital tools rather than purely theoretical frameworks without digital implementation?
- **Quantitative Assessment:** Do the tools include quantitative assessment capabilities rather than focusing solely on qualitative heritage preservation?
- **Adaptive Reuse Application:** Are the tools designed for adaptive reuse of existing structures rather than exclusively for new construction?
- **Circular Indicator:** Does the paper claim to quantitatively measure Adaptive Reuse of building elements (e.g. rooms)? Answer 'No' if it is purely qualitative.
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

6 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific nomenclature and name of any digital tool, plugin, or software solution designed for quantitative assessment of building adaptive reuse within the circular economy framework. Include:

- Official tool/plugin name
- Version number if provided
- Developer/organization
- Whether it's a standalone tool, plugin, or integrated feature
- Any alternative names or abbreviations used in the study

• **BIM Compatibility:**

Extract the required BIM authoring software environment(s) that the tool operates within, specifically focusing on professional platforms mentioned in the research question. Include:

- Primary BIM software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)
- Required software versions or compatibility requirements
- Any additional software dependencies
- Integration method (native plugin, add-on, external tool with data exchange)

• **Assessment Capabilities:**

Extract the specific quantitative assessment functionalities for adaptive reuse evaluation, focusing on the three key areas mentioned in the research question. Include:

- Repurposing Potential assessment capabilities
- Residual Service Life evaluation features
- Spatial Compatibility analysis functions
- Any other adaptive reuse assessment metrics
- Automated vs. semi-automated vs. manual assessment processes
- Types of building elements assessed (structural, spatial, mechanical, etc.)

• **Methodological Framework:**

Extract the underlying methodologies or analytical frameworks implemented by the tool for quantitative adaptive reuse assessment. Include:

- Use of Adaptive Reuse Potential (ARP) model
- Multi-Criteria Decision Analysis (MCDA) implementation
- Structural Integrity and Decay assessment methods
- Embodied energy calculation approaches
- Life Cycle Assessment (LCA) integration
- Circular economy metrics or indicators
- Any proprietary or hybrid methodological approaches

• **Validation Evidence:**

Extract evidence of tool validation through practical implementation in professional contexts. Include:

- Case studies where the tool was applied
- Empirical simulations or testing described
- Professional project implementations
- Comparison with manual assessment methods
- Accuracy or reliability metrics reported

- User validation feedback
- Scale and complexity of validation projects (building types, sizes, contexts)

- **Tool Accessibility:**

Extract information about the availability and accessibility of the tool as a packaged solution (excluding custom scripts or theoretical frameworks). Include:

- Commercial availability status
- Cost or pricing model (free, subscription, one-time purchase)
- Distribution method (official marketplace, direct download, proprietary)
- Technical requirements for implementation
- User training or expertise requirements
- Whether it's research prototype vs. commercially available product

- **Primary Publication:**

Extract the official DOI and complete bibliographic details of the primary publication documenting the tool's practical implementation (not just theoretical description). Include:

- Full DOI of primary publication
- Publication title, authors, journal, and year
- Whether this is the original tool development paper or a practical implementation study
- Any secondary publications providing additional implementation details
- Conference vs. journal publication status

- **Quantitative Outputs:**

Extract the specific quantitative metrics, scores, or assessments that the tool generates for adaptive reuse decision-making. Include:

- Types of numerical outputs (scores, percentages, indices, ratios)
- Scales or ranges used for assessments
- Units of measurement for different assessment criteria
- How results are visualized or presented to users
- Integration with early-stage architectural decision-making processes
- Comparison capabilities between different reuse scenarios

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

choose one option or add if you answer if the option is incorrect

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support [Indicator Name]? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The review encompasses six sources published between 2021 and 2024, each presenting a distinct digital tool or methodological framework relevant to the quantitative assessment of building adaptive reuse within the circular economy. The tools span two primary BIM environments—Rhino/Grasshopper and Autodesk Revit—and range from open-source research prototypes to commercially available software. Notably, none of the identified tools explicitly implement the Adaptive Reuse Potential (ARP) model as defined in the research question, and only one source references a weighted incidence matrix approach analogous to Multi-Criteria Decision Analysis (MCDA).

Study	Full Text Retrieved?	Tool Name	Tool Type	BIM Environment	Primary Focus	Case Study Context
Yijiang Huang et al., 2021	Yes	Huang et al. (2021) Script [1]	Visual programming script (Grasshopper) [1]	Rhino/Grasshopper [1]	Structural element reuse matching via Hungarian Algorithm [1]	Reuse of 2,371 timber elements from a conventional house into geodesic domes [1]
J. Fernandes et al., 2022	Yes	Plugin for Circularity (BAC methodology) [6]	BIM plugin [6]	BIM software (not specified) [6]	Circularity indicators for refurbishment (MCI, PCI, BCI) [6]	Residential building in Lisbon, 1919–1945 archetype [6]
F. Cinquepalmi et al., 2023	Yes	Cinquepalmi et al. (2023) Script [4]	Integrated BIM-GIS framework [4]	Autodesk Revit (with Dynamo, Power BI) [4]	Adaptive reuse potential assessment for residential conversion [4]	School building in Rome [4]

Study	Full Text Retrieved?	Tool Name	Tool Type	BIM Environment	Primary Focus	Case Study Context
S. M. Haakonsen et al., 2024	Yes	Haakonsen et al. (2024) Script [2]	Visual programming script (Grasshopper) [2]	Rhino with Grasshopper [2]	Matching reclaimed timber with design intent, minimizing GWP [2]	Two-storey public building in Oslo using reclaimed barn timber [2]
D. Besana et al., 2022	Yes	One Click LCA [5]	Standalone software [5]	Autodesk Revit [5]	Embodied carbon assessment (LCA, modules A1–A5) [5]	Reuse of abandoned building in Milan for net zero carbon [5]
Farkhondeh Vahdati et al., 2024	Yes	WASP plugin for Grasshopper [3]	BIM plugin (Grasshopper) [3]	Rhinoceros (Rhino) [3]	Design for Disassembly simulation and aggregation [3]	3x3 m Iranian timber pavilion-inspired roof structure [3]

Full texts were retrieved for all six sources. The studies divide evenly between the Rhino/Grasshopper ecosystem (three tools) and the Autodesk Revit ecosystem (two tools, plus one unspecified BIM platform). The tools address different facets of the circular economy rather than providing a unified adaptive reuse assessment: two focus on matching reclaimed structural elements to new designs [1, 2], one on circularity indicators at the building level [6], one on multi-criteria pre-evaluation for building conversion [4], one on embodied carbon quantification [5], and one on disassembly sequence planning [3]. No tool was identified that simultaneously evaluates Repurposing Potential, Residual Service Life, and Spatial Compatibility as an integrated automated assessment.

Assessment Capabilities and Methodological Frameworks

Tool	Repurposing Potential	Residual Service Life	Spatial Compatibility	Methodological Basis	Automation Level
Huang et al. (2021) Script	Evaluates capacity of new designs to reuse stock materials [1]	Not explicitly assessed; structural mechanics considered during matching [1]	Cost matrix and Hungarian Algorithm match inventory elements to target geometry [1]	Hungarian Algorithm for combinatorial optimization; circular economy metrics (matching cost, inventory utilization, floor area) [1]	Automated [1]
Plugin for Circularity (BAC)	Analyzes existing architecture and construction systems for refurbishment [6]	Embodied Energy and Life Cycle GWP calculated per EN 15978:2011 [6]	Characterizes building systems for compatibility with refurbishment strategies [6]	MCI combined with Disassembly Index to form PCI; BCI at building level; compatible with EU Level(s) Framework [6]	Automated via BIM plugin [6]
Cinquepalmi et al. (2023) Script	Evaluates conversion potential across five performance areas [4]	Assesses building condition via safety and energy efficiency indicators [4]	Evaluates usability, adequacy, and site quality using GIS [4]	Multi-criteria evaluation with five performance areas (Safety, Well-being, Usability, Energy efficiency, Site quality); BIM-GIS integration [4]	Automated using BIM-GIS and Dynamo [4]
Haakonsen et al. (2024) Script	Matches demand elements with supply based on cross-section, material, and length [2]	Indirectly considered through quality and condition of reclaimed elements [2]	Geometry and dimensional matching of elements [2]	Weighted incidence matrix (MCDA-like); greedy algorithm; embodied emissions and transportation impact (partial LCA) [2]	Automated [2]

Tool	Repurposing Potential	Residual Service Life	Spatial Compatibility	Methodological Basis	Automation Level
One Click LCA	Evaluates embodied carbon associated with material production, transport, and construction [5]	Assesses emissions from construction materials and systems [5]	Focus on reusing existing structures and minimizing new materials [5]	LCA per EN 15978:2011; EPD-based embodied carbon calculations [5]	Semi-automated (BIM data export to standalone software) [5]
WASP	Not explicitly assessed [3]	Not explicitly assessed [3]	Not explicitly assessed [3]	DfD principles; discrete computational design for aggregation and assembly simulation [3]	Not applicable to adaptive reuse metrics [3]

The methodological landscape is fragmented. Only the Fernandes et al. (2022) Plugin for Circularity implements established circular economy indicators (MCI, PCI, BCI) combined with LCA metrics in a structured framework compatible with European standards [6]. The Cinquepalmi et al. (2023) framework comes closest to a holistic adaptive reuse assessment by spanning five performance domains—including safety, well-being, usability, energy efficiency, and site quality—and automating verification through Dynamo scripts [4]. However, it remains a research prototype without a packaged distribution [4]. The Haakonsen et al. (2024) tool is the only one employing a weighted incidence matrix approach that approximates MCDA, incorporating both embodied emissions and transportation costs into its scoring function [2]. None of the tools implement an explicit ARP model or automated structural integrity and decay assessment as specified in the research question.

Quantitative Outputs

Tool	Primary Output Metrics	Units	Visualization	Scenario Comparison
Huang et al. (2021) Script	Total matching cost, inventory utilization, total floor area [1]	Square meters (floor area) [1]	Bi-objective plots via MOO tool from DSE [1]	Implicit through multi-objective optimization [1]
Plugin for Circularity (BAC)	MCI (0–1 scale), PCI, SCI, BCI; Embodied Energy; Life Cycle GWP [6]	Circularity indicators per square meter; EE and GWP per EN 15978:2011 [6]	Immediate circularity indicators per m ² as reference values [6]	Simulation of new refurbishment options with comparative circularity assessments [6]

Tool	Primary Output Metrics	Units	Visualization	Scenario Comparison
Cinquepalmi et al. (2023) Script	Scores, percentages, indices across five performance areas with threshold values [4]	Meters, percentages, various units per indicator [4]	Dashboard format using Power BI [4]	Comparison between different buildings [4]
Haakonsen et al. (2024) Script	Total score in kg CO ₂ equivalents; GWP reduction percentage [2]	kg CO ₂ equivalents [2]	Graphical representation integrated in architectural model [2]	Scores calculated for different reuse scenarios [2]
One Click LCA	Embodied carbon emissions (kg CO ₂ e/m ²); performance classification [5]	kg CO ₂ e/m ² [5]	Reports with graphs [5]	Benchmarking against new construction and retrofit averages [5]
WASP	No quantitative adaptive reuse metrics reported [3]	Not applicable [3]	Not applicable [3]	Not applicable [3]

The quantitative outputs vary substantially in scope and granularity. The Haakonsen et al. (2024) tool demonstrated a 40% reduction in greenhouse gas potential when substituting 140 demand elements with 82 reclaimed timber elements, yielding a total score of 133.5 kg CO₂ equivalents [2]. The Besana et al. (2022) case study achieved an 82% to 91% reduction in embodied carbon compared to standard new construction using One Click LCA, reaching 89 kg CO₂e/m² [5, 5]. The Fernandes et al. (2022) framework provides the most granular circularity assessment, generating MCI scores on a 0-to-1 scale at the product level, which aggregate through PCI and SCI to a building-level BCI [6]. The Cinquepalmi et al. (2023) framework is unique in providing a multi-domain dashboard across five performance areas with defined threshold values, enabling rapid screening of buildings for conversion suitability [4].

Validation Evidence

Tool	Case Study Scale	Key Quantitative Result	Comparison to Baseline	Professional Context
Huang et al. (2021) Script	2,371 timber elements [1]	Demonstrated optimization across matching cost vs. inventory utilization trade-off [1]	Not reported [1]	Research demonstration; tool freely available online [1]
Plugin for Circularity (BAC)	Single residential building archetype in Lisbon [6]	Circularity indicators generated for 1919–1945 archetype [6]	Not reported [6]	Described as useful for architects and engineers [6]

Tool	Case Study Scale	Key Quantitative Result	Comparison to Baseline	Professional Context
Cinquepalmi et al. (2023) Script	Single school building in Rome [4]	Automated verification via Dynamo and Power BI completed [4]	Not reported [4]	Research demonstration only [4]
Haakonsen et al. (2024) Script	182 demand elements, two-storey public building in Oslo [2]	40% reduction in GWP; 82 reclaimed elements substituted for 140 demand elements [2]	Compared to using all-new materials [2]	Actual design project (Sletteløkka community house) [2]
One Click LCA	Abandoned building reuse project in Milan [5]	82–91% reduction in embodied carbon vs. new construction averages [5]	Benchmarked against standard new construction and retrofit values [5]	Professional design project with certified performance reports [5]
WASP	3x3 m roof structure [3]	No quantitative adaptive reuse metrics; aggregation simulation only [3]	Not reported [3]	Research simulation [3]

Only two tools were validated through actual professional design projects: the Haakonsen et al. (2024) script, applied to the Sletteløkka community house extension in Oslo [2], and One Click LCA, used in a building reuse project in Milan with comparison against industry benchmarks [5]. The remaining four tools were validated through research-level case studies or simulations of limited scale. The WASP plugin validation was confined to a 3x3 m roof structure, which limits generalizability to larger building-scale applications [3].

Tool Accessibility and Practical Availability

Tool	Availability	Cost	Distribution	Coding Required?	Architect-Friendly?
Huang et al. (2021) Script	Open-source, MIT license [1]	Free [1]	Direct download [1]	Some coding for customization (C#/Julia backends); Grasshopper visual interface [1]	Moderate; requires Grasshopper familiarity [1]
Plugin for Circularity (BAC)	Not mentioned; likely research prototype [6]	Not mentioned [6]	Not mentioned [6]	No coding required; plug-and-play BIM plugin [6]	Yes; designed for architects and engineers [6]

Tool	Availability	Cost	Distribution	Coding Required?	Architect-Friendly?
Cinquepalmi et al. (2023) Script	Research prototype [4]	Not mentioned [4]	Not mentioned [4]	Requires Dynamo scripting and Python [4]	Limited; requires technical expertise [4]
Haakonsen et al. (2024) Script	Open-source [2]	Free [2]	Zenodo repository [2]	No coding required; plug-and-play in Grasshopper [2]	Yes; designed for non-coding users [2]
One Click LCA	Commercially available [5]	Not specified (commercial) [5]	Direct access [5]	No coding required [5]	Yes; described as simple yet complete [5]
WASP	Not explicitly stated [3]	Not mentioned [3]	Not mentioned [3]	Plugin for Grasshopper; developed in Python; unclear if user coding needed [3]	Generally user-friendly for practitioners [3]

One Click LCA is the only commercially available, packaged product among the six tools [5]. Two tools—the Huang et al. (2021) script and the Haakonsen et al. (2024) script—are freely available as open-source Grasshopper components [1, 2]. The Plugin for Circularity (BAC) and the Cinquepalmi et al. (2023) framework remain research prototypes without confirmed public distribution channels [4, 6]. From a usability standpoint, the Haakonsen et al. (2024) tool and One Click LCA are the most accessible, explicitly designed for users without programming expertise [2, 5], whereas the Cinquepalmi et al. (2023) framework requires familiarity with Dynamo scripting and Python [4].

Technology Integrations

Several tools extend beyond their core BIM environments through integrations with complementary technologies. The Cinquepalmi et al. (2023) framework integrates GIS for spatial analysis, Power BI for dashboard visualization, and the authors note potential future integration with AI algorithms and IoT sensors for real-time data collection [4]. The Fernandes et al. (2022) Plugin for Circularity connects to three external databases—a Classification System Database (Uniclass 2015), a Building Characterisation Database, and a Circularity Database—and supports the creation of building circularity passports [6]. The Besana et al. (2022) study references digital twin technology for maintenance-phase analysis alongside One Click LCA and Revit integration [5]. The WASP plugin offers compatibility with Fologram for VR/AR streaming to devices such as HoloLens 2 [3]. The two element-matching tools (Huang et al. 2021 and Haakonsen et al. 2024) operate primarily within the Rhino/Grasshopper ecosystem without significant external technology integrations [1, 2].

Synthesis

The central finding of this review is that no single tool currently provides an integrated, automated quantitative assessment of Repurposing Potential, Residual Service Life, and Spatial Compatibility as envisioned in the research

question. The apparent gap can be explained by the fact that each tool was developed to address a specific sub-problem within the circular economy rather than the full adaptive reuse decision pipeline.

The divergence in tool capabilities maps onto distinct stages of the adaptive reuse workflow. The two element-matching tools (Huang et al. 2021 and Haakonsen et al. 2024) operate at the component level, optimizing the assignment of reclaimed structural members to new design geometries [1, 2]. These are most relevant when a stock of salvaged elements exists and the design task is to determine feasible configurations. By contrast, the Cinquepalmi et al. (2023) framework operates at the building level, screening entire structures for conversion suitability across multiple performance domains before detailed design begins [4]. The Fernandes et al. (2022) Plugin for Circularity bridges these scales by computing circularity indicators from product to building level, but focuses on refurbishment rather than functional repurposing [6]. One Click LCA provides a narrow but well-validated carbon accounting function that is complementary to, rather than substitutive of, adaptive reuse assessment [5]. WASP addresses downstream disassembly planning rather than upstream reuse evaluation [3].

The methodological heterogeneity further explains the absence of a unified tool. The Cinquepalmi et al. (2023) multi-criteria approach with threshold-based indicators across five domains [4] is conceptually closest to the ARP model and MCDA frameworks specified in the research question, yet it was developed for a specific use case (non-residential to residential conversion) and remains a research prototype requiring Dynamo scripting expertise [4, 4]. The Haakonsen et al. (2024) weighted incidence matrix [2] offers the most MCDA-like functionality among the tools but is limited to structural element matching and does not assess broader spatial or functional compatibility. The Fernandes et al. (2022) framework applies established Ellen MacArthur Foundation indicators (MCI) combined with a Disassembly Index [6], providing methodological rigor but without explicit ARP or structural decay assessment capabilities.

From a practical accessibility standpoint, the tools that are most readily deployable—One Click LCA (commercial, plug-and-play) [5, 5] and the Haakonsen et al. (2024) script (open-source, Zenodo, no coding) [2, 2]—address only partial aspects of adaptive reuse assessment. The most comprehensive frameworks (Cinquepalmi et al. 2023 and Fernandes et al. 2022) remain research prototypes with uncertain availability [4, 6]. This creates a practical tension: architects seeking to perform early-stage adaptive reuse assessments would need to combine multiple tools across different software environments—for example, using the Haakonsen et al. (2024) script in Grasshopper for element matching alongside One Click LCA via Revit for carbon benchmarking, supplemented by manual application of the Cinquepalmi et al. (2023) performance criteria.

The validation evidence further differentiates tool maturity. Only the Haakonsen et al. (2024) script and One Click LCA have been applied in actual professional design projects with quantified outcomes (40% GWP reduction and 82–91% embodied carbon reduction, respectively) [2, 5]. These results, while encouraging, derive from specific building types (timber public building and abandoned urban structure, respectively) and cannot be directly generalized across building typologies or material systems. The remaining tools have been validated only through single research-level case studies of limited scale [1, 3, 4, 6].

In summary, the current tooling landscape for quantitative adaptive reuse assessment within BIM environments consists of specialized, partially overlapping solutions rather than integrated platforms. A designer seeking to automate the full adaptive reuse evaluation pipeline—from building-level screening through element-level matching to circularity and carbon quantification—would need to assemble a workflow spanning multiple tools, BIM platforms, and data exchange formats. The most promising path toward an integrated solution would combine the multi-criteria building-level screening of the Cinquepalmi et al. (2023) approach [4], the circularity indicator framework of Fernandes et al. (2022) [6], and the element-level matching algorithms of Huang et al. (2021) or Haakonsen et al. (2024) [1, 2], packaged within a single BIM environment with standardized data schemas.

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Disassembly (DfD) and the potential for non-destructive component recovery within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Disassembly Efficiency," "Recyclability Indices," or "Connection Reversibility" by utilizing recognized methodologies such as the Disassembly Capacity (DC) metric, Potential for Deconstruction scores, or the Circular Building Assessment (CBA) framework. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative "loose-fit" construction principles to automated, quantitative digital assessments of material recovery value and waste reduction potential for data published before December 2025.

No established, commercially available BIM plugin or packaged software solution currently exists for automated quantitative DfD assessment using recognized frameworks such as Disassembly Capacity, Circular Building Assessment, or Disassembly Network Analysis; the five identified tools — M&C Bank, Octopus solver (Grasshopper/Rhino), Longo Plugin (Revit), BIM-DAS (Revit), and RecyclingGraphs — all remain inaccessible research prototypes validated only through single case studies, leaving the field without a professional-grade, downloadable tool for holistic disassembly and material recovery quantification.

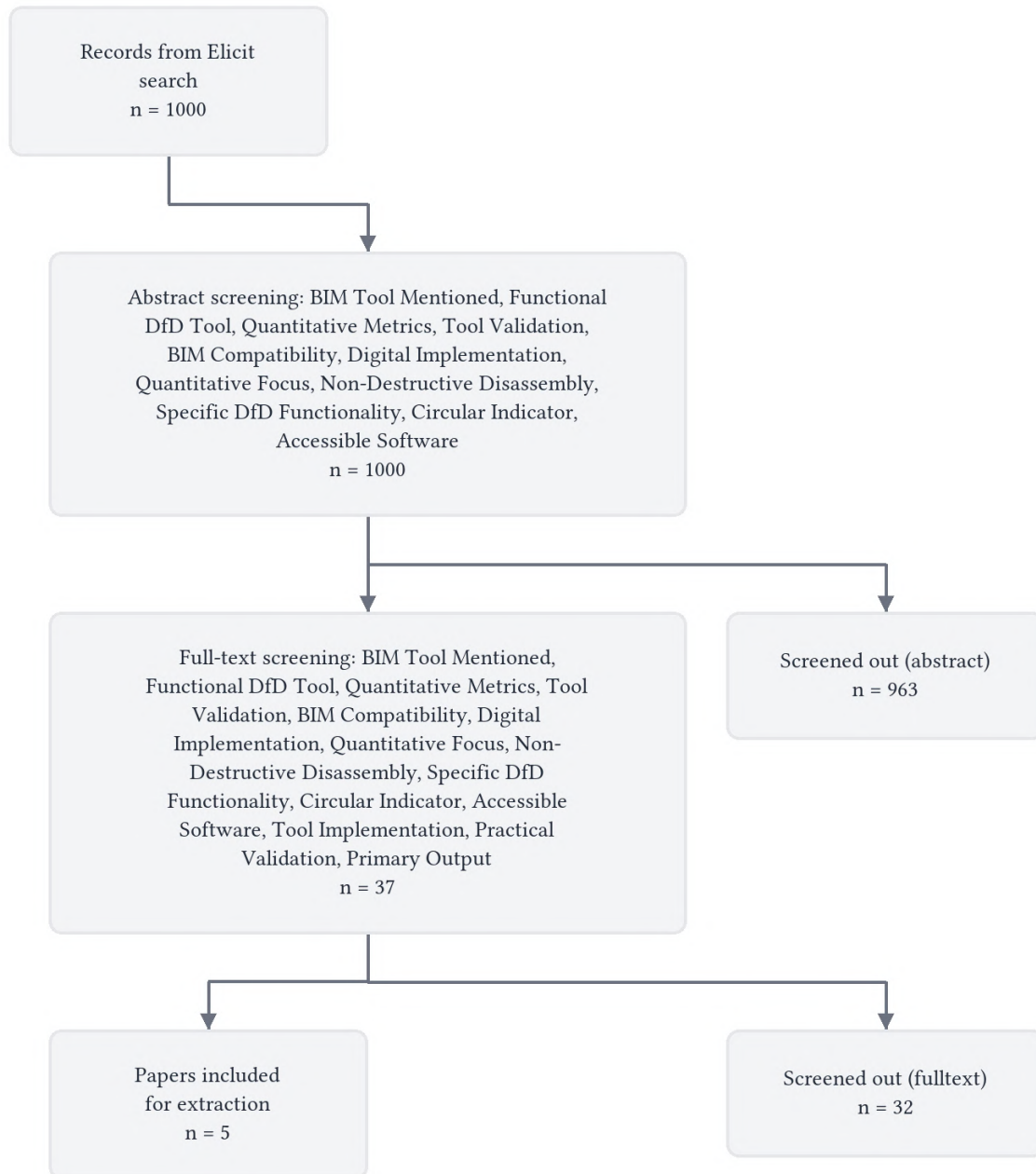
Abstract

No commercially available, packaged BIM plugin or software solution currently exists for the automated quantitative assessment of building Design for Disassembly (DfD) using recognized methodologies such as the Disassembly Capacity (DC) metric, Circular Building Assessment (CBA) framework, or Disassembly Network Analysis (DNA). Five BIM-integrated tools were identified — M&C Bank [1], the Octopus solver in Grasshopper for Rhino [2], the Longo (2020) Plugin [3], BIM-DAS [4], and RecyclingGraphs/ConnectionMatrixes [5] — but all remain research prototypes with limited accessibility [1–5], and none implement the standardized DfD assessment frameworks specified in the research objective [1–5]. Three tools operate within Autodesk Revit [1, 3, 4] and one within Rhino/Grasshopper [2],

but none are downloadable or commercially distributed [1–5].

Among the identified prototypes, BIM-DAS offers the most comprehensive DfD scoring system, producing both a Deconstructability Assessment Score and a Salvage Performance metric validated on a real-world factory deconstruction in Egypt [4], while the Octopus-based workflow demonstrated a 72.7% reduction in mechanical carbon emissions through multi-objective optimization of steel structure deconstruction [2]. The Longo Plugin provides the most architect-friendly interface as a plug-and-play Revit checklist producing a normalized 0–1 Disassembly Classification Index [3, 3]. However, all tools are validated on single case studies or conceptual models [1–5], most are restricted to steel structures [2, 4], and several require specialized programming or simulation expertise beyond typical architectural practice [2, 4]. The field remains at a pre-commercial stage, with no tool yet achieving the transition from research prototype to accessible, professional-grade software for holistic DfD quantification.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Design for Disassembly (DfD) and the potential for non-destructive component recovery within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Disassembly Efficiency," "Recyclability Indices," or "Connection Reversibility" by utilizing recognized methodologies such as the Disassembly Capacity (DC) metric, Potential for Deconstruction scores, or the Circular Building Assessment (CBA) framework. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative "loose-fit" construction principles to automated, quantitative digital assessments of material recovery value and waste reduction potential for data published before December 2025."

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Functional DfD Tool:** Does the study describe functional digital tools or BIM plugins specifically designed for quantitative assessment of Design for Disassembly (DfD)?
- **Quantitative Metrics:** Do the tools measure specific quantitative metrics such as "Disassembly Efficiency," "Recyclability Indices," "Connection Reversibility," or utilize established methodologies (DC metric, Potential for Deconstruction scores, CBA framework)?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, SketchUp)?
- **Digital Implementation:** Does the study go beyond purely theoretical frameworks to include functional digital implementation?
- **Quantitative Focus:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative assessment or "loose-fit" construction principles?
- **Non-Destructive Disassembly:** Are the tools designed for non-destructive disassembly rather than demolition?
- **Specific DfD Functionality:** Do the tools provide specific DfD functionality rather than describing only general BIM capabilities?

- **Circular Indicator:** Does the paper claim to quantitatively measure Design for Disassembly? Answer 'No' if it is purely qualitative.
- **Accessible Software:** Are the tools available as packaged software solutions, commercial plugins, or widely accessible add-ons?

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

37 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Functional DfD Tool:** Does the study describe functional digital tools or BIM plugins specifically designed for quantitative assessment of Design for Disassembly (DfD)?
- **Quantitative Metrics:** Do the tools measure specific quantitative metrics such as "Disassembly Efficiency," "Recyclability Indices," "Connection Reversibility," or utilize established methodologies (DC metric, Potential for Deconstruction scores, CBA framework)?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, SketchUp)?
- **Digital Implementation:** Does the study go beyond purely theoretical frameworks to include functional digital implementation?
- **Quantitative Focus:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative assessment or "loose-fit" construction principles?
- **Non-Destructive Disassembly:** Are the tools designed for non-destructive disassembly rather than demolition?
- **Specific DfD Functionality:** Do the tools provide specific DfD functionality rather than describing only general BIM capabilities?
- **Circular Indicator:** Does the paper claim to quantitatively measure Design for Disassembly? Answer 'No' if it is purely qualitative.
- **Accessible Software:** Are the tools available as packaged software solutions, commercial plugins, or widely accessible add-ons?
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

5 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific nomenclature and classification of digital tools or BIM plugins designed for quantitative DfD assessment, including:

- Exact name/title of the tool or plugin
- Whether it's a packaged software solution, plugin, or add-in (vs. theoretical framework)
- Current accessibility status (commercially available, open-source, research prototype, or inaccessible custom code)
- Version information if provided
- Developer/organization responsible for the tool

- **BIM Platform Requirements:**

Extract the required BIM authoring software environment and technical specifications for DfD tools, including:

- Primary BIM software platform (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)
- Additional required software or environments (e.g., Dynamo, Python scripting)
- Version compatibility requirements
- Operating system requirements if specified
- Any required file formats (IFC, proprietary formats)

- **Quantitative Assessment Capabilities:**

Extract specific quantitative metrics and assessment capabilities for measuring DfD and component recovery potential, including:

- Automated measurement of "Disassembly Efficiency," "Recyclability Indices," or "Connection Reversibility"
- Material recovery value calculations
- Waste reduction potential quantification
- Time-based disassembly assessments
- Economic valuation of recovered components
- Any scoring systems or numerical outputs provided

- **Methodological Framework:**

Extract the recognized methodologies and assessment frameworks integrated into the digital tools, including:

- Use of Disassembly Capacity (DC) metric
- Implementation of Potential for Deconstruction scores
- Integration of Circular Building Assessment (CBA) framework
- Network analysis methods (e.g., DNA - Disassembly Network Analysis)
- Other established DfD assessment methodologies
- Integration with circular economy principles or frameworks

- **Validation Evidence:**

Extract evidence of practical validation and professional implementation for DfD tools, including:

- Case studies conducted with the tool
- Empirical simulations or testing results
- Professional context applications (architectural firms, construction companies)
- Building types or scales tested (residential, commercial, infrastructure)
- Quantitative validation results or performance metrics
- Comparison with manual assessment methods

- **Publication Documentation:**

Extract official publication details documenting the tool's practical implementation, including:

- Official DOI of the primary publication
- Publication date (must be before December 2025)
- Journal or conference name
- Author information
- Additional supporting publications or technical documentation
- Peer-review status of the publication

- **DfD Application Scope:**

Extract the specific scope and applications of the tool within DfD and circular economy contexts, including:

- Building components or systems addressed (connections, facades, structural elements)
- Construction materials covered (steel, concrete, timber, composite)
- Lifecycle stages supported (design, construction, end-of-life)
- Integration with broader circular economy workflows
- Transition from qualitative to quantitative assessment capabilities

- **Technical Functionality:**

Extract detailed technical functionality and automation capabilities for DfD assessment tools, including:

- Level of automation (fully automated, semi-automated, manual input required)
- Data input requirements and sources
- Output formats and reporting capabilities
- Integration with material databases or libraries
- Real-time assessment capabilities during design process
- Workflow integration with existing BIM processes

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type**

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support [Design for Disassembly? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The five included sources span from 2019 to 2024 and represent a range of BIM-integrated approaches to Design for Disassembly (DfD) assessment. None of the identified tools constitute fully packaged, commercially available software products; all remain at the research prototype or conceptual stage. The table below summarizes the key characteristics of each source.

Study	Full Text Retrieved?	Tool Name	Tool Type	BIM Platform	Validation Context	Primary DfD Output
L. B. Jayasinghe et al., 2020	Yes	M&C Bank [1]	Web-based application (PHP/MySQL) [1]	Autodesk Revit + Dynamo [1]	11-story residential building [1]	C&D waste and recyclable/reusable material volumes [1]
Baolin Huang et al., 2024	Yes	Octopus solver in Grasshopper for Rhino [2]	Visual programming script (Grasshopper) [2]	Rhino/Grasshopper + Visual Studio, Elefront plugin [2]	Lightweight steel roof truss on university campus [2]	Minimum mechanical carbon emissions (MCE), deconstruction period (DP), working efficiency (WE) [2]
Letícia França Mattaraia Longo et al., 2020	Yes	Longo (2020) Plugin [3]	BIM plugin (Revit) [3]	Autodesk Revit [3]	Three conceptual warehouse models (concrete, steel, timber) [3]	Disassembly Classification Index (0–1 scale) [3]

Study	Full Text Retrieved?	Tool Name	Tool Type	BIM Platform	Validation Context	Primary DfD Output
Alaa Mohammed et al., 2024	Yes	BIM-DAS [4]	Integrated BIM framework (Revit + MATLAB) [4]	Revit 2020 [4]	Makka poultry feed plant, Egypt [4]	Deconstructability Assessment Score (DAS) and Salvage Performance (SP) [4]
D. Schwede et al., 2019	Yes	RecyclingGraphs / Connection-Matrixes [5]	Theoretical methodology with BIM translation [5]	Not specified [5]	Four wall structures [5]	Recyclability and processing compatibility ratings (A, B, C categories) [5]

All five sources were available as full texts. Three tools operate within Autodesk Revit [1, 3, 4], one uses Rhino/Grasshopper [2], and one does not specify a host platform [5]. Only one source (Baolin Huang et al., 2024) provides an official DOI [2]; the remaining four do not report DOIs or formal journal publication details in the extracted text [1, 3–5]. Critically, none of the tools are currently available as packaged, downloadable software: three are described as available upon request [2–4], and two provide no access information at all [1, 5].

Effects: Quantitative Assessment Capabilities

The tools vary substantially in the DfD metrics they automate, the granularity of their outputs, and the degree to which they align with recognized assessment frameworks such as Disassembly Capacity (DC) or Circular Building Assessment (CBA). The table below details the quantitative assessment features of each tool.

Tool	Automated DfD Metric	Scoring System	Material Recovery Calculation	Time-Based Assessment	Economic Valuation	Carbon/Environmental Metric
M&C Bank [1]	No explicit disassembly efficiency metric [1]	Recyclable and reusable volumes calculated from predefined data libraries [1]	Yes — subtracts reusable and recyclable volumes from total volume [1]	Not mentioned [1]	Not mentioned [1]	Not mentioned [1]

Tool	Automated DfD Metric	Scoring System	Material Recovery Calculation	Time-Based Assessment	Economic Valuation	Carbon/Environmental Metric
Octopus solver (Grasshopper) [2]	Machinery working efficiency (WE) [2]	MCE (min), DP (min), WE (max) as Pareto-optimal outputs [2]	Not explicitly mentioned [2]	Yes — deconstruction period (DP) calculated [2]	Not mentioned [2]	Yes — mechanical carbon emissions reduced by 72.7% (from 9.614 to 2.613 kgCO ₂ /kg) [2]
Longo (2020) Plugin [3]	Disassembly Classification Index (0–1 scale) [3]	Formula: C.D. of each element × Weighted Average / number of elements (or m ²) [3]	Implied through classification system linking to reuse potential [3]	Not mentioned [3]	Not mentioned [3]	Not mentioned [3]
BIM-DAS [4]	Deconstructability Assessment Score (DAS) = weighted sum of Dscore and Rscore [4]	SP = SP _{ru} + SP _{rc} – γ (landfill adjustment) [4]	Yes — salvage performance quantifies reusability (SP _{ru}) and recyclability (SP _{rc}) [4]	Not explicitly mentioned [4]	Yes — cost savings of 173,070 EGP reported in case study [4]	Not mentioned [4]
RecyclingGraphs [5]	Number of connections (#) and average ratings in categories A, B, C [5]	Rating scales for disassembly and processing compatibility [5]	Not mentioned [5]	Not mentioned [5]	Not mentioned [5]	Not mentioned [5]

BIM-DAS offers the most comprehensive scoring framework, combining deconstructability and recovery into a single weighted metric (DAS) alongside a separate salvage performance indicator (SP) that distinguishes reusability from recyclability and accounts for landfill losses [4]. It is also the only tool that reports economic valuation data from its case study [4]. The Longo (2020) Plugin provides a normalized 0–1 disassembly classification that is conceptually closest to a Disassembly Capacity metric, though it does not reference DC, CBA, or DNA frameworks explicitly [3]. The Octopus-based workflow is the only approach to incorporate environmental performance (carbon emissions) into a multi-objective optimization framework for deconstruction [2], achieving a reported 72.7% reduction in mechanical carbon emissions when comparing optimized DfD schemes to real-world deconstruction [2]. The M&C Bank focuses on material flow quantification rather than disassembly scoring per se [1], while RecyclingGraphs provides a connection-level assessment of material compatibility and separability without aggregating results into a

single index [5].

None of the five tools explicitly implement the Disassembly Capacity (DC) metric, Circular Building Assessment (CBA) framework, or Disassembly Network Analysis (DNA) methodology [1–5]. The methodological foundations are instead bespoke: BIM-DAS uses Analytical Hierarchy Process (AHP) for factor weighting [4]; the Octopus workflow applies SPEA-2 evolutionary optimization [2]; RecyclingGraphs employs graph-theoretic decomposition of material–connection relationships [5]; and the Longo plugin uses a weighted-average classification formula [3]. Integration with circular economy principles is most explicit in the M&C Bank, which serves as a centralized database for material reuse and recycling information [1], and in BIM-DAS, which targets waste reduction and resource optimization [4].

Technical Functionality and Accessibility

Tool	Automation Level	Coding Required?	Real-Time Design Feedback	Material Database Integration	Key Limitations
M&C Bank [1]	Semi-automated; manual adjustments for reusable volumes [1]	No coding for end users; web interface [1]	Not mentioned [1]	Yes — predefined data libraries for recycling/reuse potentials [1]	Limited to structural elements only [1]
Octopus (Grasshopper) [2]	Semi-automated; manual parameter setup required [2]	Yes — Grasshopper visual programming and Visual Studio [2]	Implied through parametric modeling [2]	Not mentioned [2]	Restricted to steel structures and end-of-life stage [2]; outputs exported to Excel [2]
Longo (2020) Plugin [3]	Semi-automated; structured data input on material characteristics [3]	No — plug-and-play within Revit [3]	Not explicitly mentioned [3]	Implied through Revit classification system [3]	Conceptual models only; no real-world building validation [3]
BIM-DAS [4]	Semi-automated; custom parameters require manual entry [4]	Technical expertise needed; not plug-and-play [4]	Yes — estimates salvageable materials at any lifecycle point [4]	Integrated with Revit material parameters [4]	Single case study in Egypt; MATLAB simulation required alongside Revit [4, 4]
RecyclingGraphs [5]	Semi-automated; automatic geometric analysis with manual setup [5]	Not specified; further development needed [5]	Future potential only [5]	Implied for material properties [5]	Applied only to wall structures; no packaged tool exists [5, 5]

All five tools are semi-automated, requiring varying degrees of manual input [1–5]. The Longo Plugin is the most architect-friendly, described as a plug-and-play Revit plugin with a checklist interface that does not require coding [3]. The M&C Bank is similarly accessible via a web browser without coding [1]. In contrast, the Octopus-based workflow demands proficiency in Grasshopper visual programming and is not suitable for architects without technical expertise [2]. BIM-DAS requires mathematical modeling knowledge and supplementary MATLAB simulation [4, 4], while RecyclingGraphs remains a conceptual methodology awaiting implementation as a usable design tool [5].

Regarding broader technology integrations, the tools show limited connectivity beyond their immediate BIM environments. The M&C Bank integrates with MySQL databases and Dynamo scripting [1]. The Octopus workflow connects to Grasshopper, Elefront, and Excel [2]. BIM-DAS extends to MATLAB for simulation [4]. None of the tools integrate with Material Passports, Digital Twins, AI, IoT, GIS, blockchain, or VR/AR technologies [5].

Application Scope

Tool	Materials Covered	Building Components	Lifecycle Stages	Geographic/Structural Context
M&C Bank [1]	Concrete, metal, masonry, wood [1]	Columns, beams, floors, walls, foundations [1]	Design, construction, end-of-life [1]	11-story residential building [1]
Octopus (Grasshopper) [2]	Steel [2]	Roof purlins, trusses, central supports, cables [2]	End-of-life only [2]	University campus, China [2]
Longo (2020) Plugin [3]	Steel, concrete, timber [3]	Connections, facades, structural elements [3]	Design, construction, end-of-life [3]	Conceptual warehouse models, Brazil [3]
BIM-DAS [4]	Steel [4]	Demountable connections, reusable components [4]	Design, construction, end-of-life [4]	Factory building, Egypt [4]
RecyclingGraphs [5]	Implied (wall materials) [5]	Wall structures, connections [5]	Design, construction, end-of-life [5]	Four wall assemblies (no geographic context) [5]

The M&C Bank and Longo Plugin cover the broadest range of construction materials [1, 3], while BIM-DAS and the Octopus workflow are narrowly scoped to steel structures [2, 4]. Only the Octopus approach is restricted to the end-of-life stage exclusively [2]; the remaining tools support multiple lifecycle stages including early design [1, 3–5]. BIM-DAS is the only tool validated on a real-world deconstruction project with reported economic outcomes [4], while the Octopus workflow provides the only empirical comparison between actual and optimized deconstruction operations [2].

Synthesis

The central finding of this review is that no established, commercially available BIM plugin or packaged software solution currently exists for the automated quantitative assessment of DfD within recognized frameworks such as DC,

CBA, or DNA. All five identified tools are research prototypes with limited accessibility [1–5], and none implement the specific standardized methodologies named in the research question [1–5].

The apparent heterogeneity in tool outputs — ranging from material volumes to carbon emissions to composite deconstructability scores — reflects fundamentally different conceptualizations of what “DfD assessment” means. The M&C Bank treats DfD as a material flow management problem [1], quantifying recoverable mass without scoring ease of disassembly. The Octopus workflow frames DfD as a machinery optimization problem, targeting carbon emissions and schedule efficiency during the physical deconstruction process [2]. BIM-DAS and the Longo Plugin are the only tools that directly produce a composite deconstructability score [3, 4], with BIM-DAS additionally capturing salvage performance as a separate indicator [4]. RecyclingGraphs addresses the problem at the material-connection interface, assessing separability and compatibility rather than producing a building-level index [5].

The variation in BIM platform choices introduces practical fragmentation. Three tools require Revit [1, 3, 4] and one requires Rhino [2], meaning no single BIM environment supports more than three of these prototypes. The tools also differ in their demands on users: the Longo Plugin and M&C Bank are accessible to architects without programming skills [1, 3], while the Octopus workflow and BIM-DAS require specialized technical competencies in visual programming or mathematical modeling [2, 4].

The validation evidence across studies is uniformly thin. Each tool has been tested on a single case study or a small set of conceptual models [1–5], with no cross-validation, no comparison between tools, and no benchmarking against manual assessment methods. BIM-DAS provides the strongest empirical grounding through a real-world factory deconstruction with cost savings data [4], while the Octopus workflow offers the most rigorous quantitative comparison between actual and optimized deconstruction scenarios, demonstrating a 72.7% reduction in carbon emissions [2]. The Longo Plugin and RecyclingGraphs remain validated only through conceptual or simplified structural models [3, 5].

For practitioners seeking an immediately usable tool, BIM-DAS within Revit 2020 represents the closest approximation to a functional DfD assessment system, as it produces both a deconstructability score and a salvage performance metric within the BIM authoring environment [4], and it has been validated on a real deconstruction project [4]. However, it requires MATLAB for simulation [4], is scoped only to steel structures [4], and is not available as a downloadable plugin [4]. For carbon-focused deconstruction planning of steel structures, the Octopus-based Grasshopper workflow offers a validated multi-objective optimization approach [2], but it demands visual programming expertise and is similarly restricted in material scope [2, 2]. The field remains at a pre-commercial stage, with no tool yet bridging the gap between research prototype and professional-grade, accessible software for holistic DfD quantification.

References

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3. Letícia França Mattaraia Longo (2020) Projeto para desmontagem e BIM: ferramentas projetuais para aperfeiçoar a reutilização de materiais. <https://doi.org/10.11606/t.102.2020.tde-23112020-223721>

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5. D. Schwede (2019) Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling. IOP Conference Series: Earth and Environment. <https://doi.org/10.1088/1755-1315/323/1/012044>

Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Easy Maintenance (Maintainability) and the optimization of technical service life within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Maintenance Intensity," "Component Accessibility," or "Repairability" by utilizing recognized methodologies such as Building Information Modeling for Facility Management (BIM-FM) integration, Reliability-Centered Maintenance (RCM), or automated Accessibility Analysis for replacement. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative upkeep strategies to automated, quantitative digital assessments of lifecycle costs and resource efficiency through simplified maintenance protocols for data published before December 2025.

No commercially available BIM plugin or packaged digital tool currently automates the quantitative assessment of "Maintenance Intensity," "Component Accessibility," or "Repairability" as standardized outputs; the closest functional solutions—Dynamo scripts in Revit for degradation indexing, Navisworks/Archibus for BIM 7D risk mapping, Power BI dashboards via VCAD for lifecycle data visualization, and Dalux FM for maintenance order management—each support elements of BIM-FM integration for maintainability but require substantial manual configuration, lack RCM implementation, and do not produce circular economy-aligned maintainability indices.

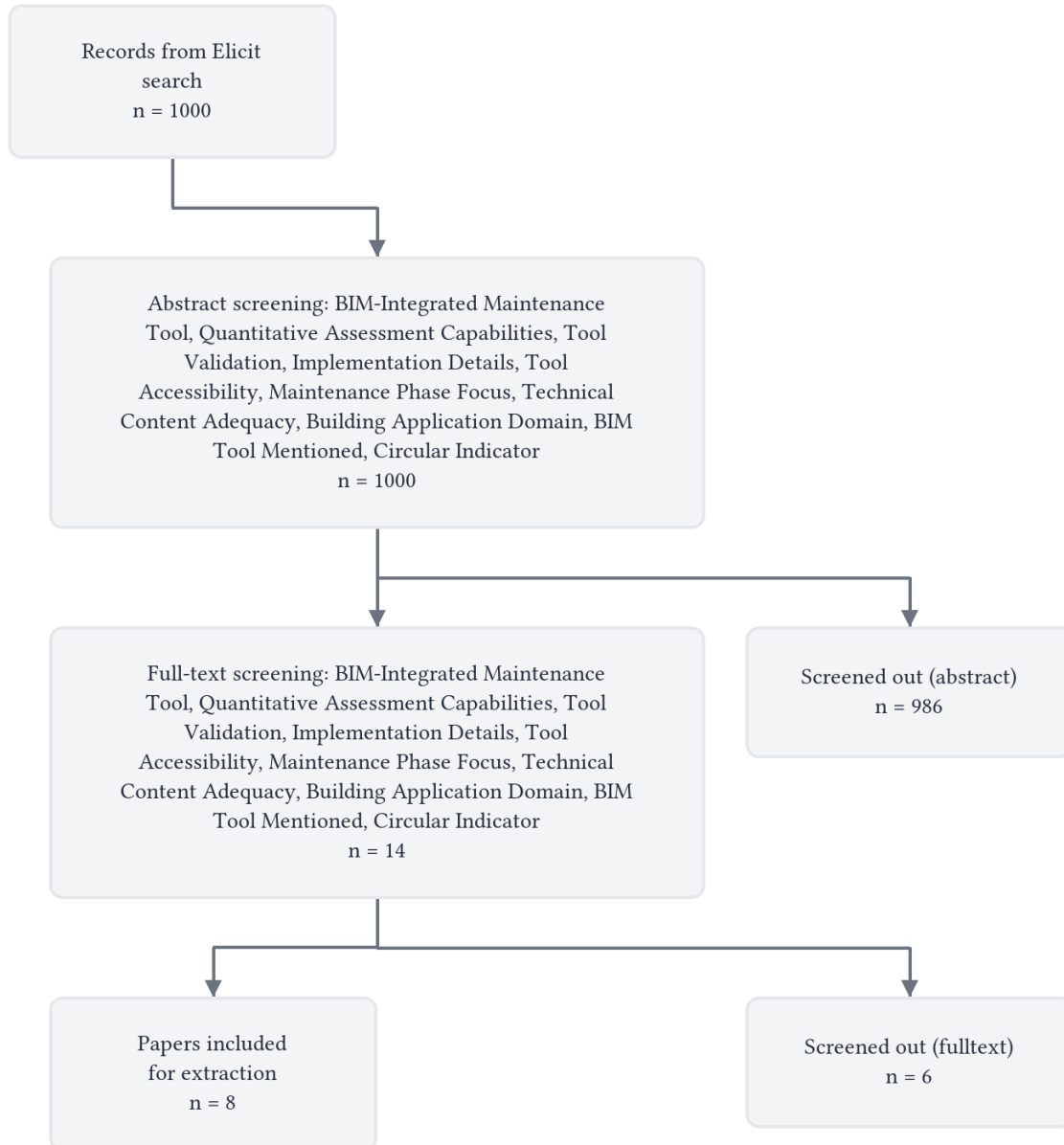
Abstract

Eight case studies published between 2020 and 2025 were examined to identify packaged digital tools within BIM environments that automate the quantitative assessment of building maintainability—specifically "Maintenance Intensity," "Component Accessibility," and "Repairability"—in support of technical service life optimization. Ten distinct tools were cataloged, nine of which are commercially available [1–5], operating predominantly within Autodesk Revit. The most functionally relevant solutions include Dynamo scripts for linking degradation databases to BIM models with chromatic and numerical condition outputs [1], Navisworks and Archibus as BIM 7D plugins for risk mapping and predictive maintenance scheduling [2], Microsoft Power BI dashboards (via VCAD) for lifecycle data

visualization [3], DB Link for SFM-BIM data transfer [4], and Dalux FM for structured maintenance order management [5]. However, no commercially available tool directly automates the computation of maintainability indices as standardized quantitative outputs; each requires substantial configuration and manual input to approximate such assessments [1, 4, 6].

No study implements Reliability-Centered Maintenance (RCM) as a recognized framework [1–8], and none reports circular economy indicators as measured outputs [1, 2, 5]. The strongest quantitative evidence comes from a BIM 7D simulation reporting 45.83% downtime reduction and 19.2% cost savings over ten years compared with traditional maintenance [2], though these derive from simulation rather than longitudinal empirical measurement. Only one study integrates IoT sensors for automated data collection [8], and only one research prototype incorporates fault tree analysis for reliability-based reasoning [8, 8]. Recurring practical barriers include data loss during IFC interoperability exchanges [5], data compatibility challenges between BIM and external databases [4], and high software costs [1]. The current tool landscape thus supports condition documentation and maintenance workflow management within BIM-FM integration but falls short of providing turnkey, automated quantitative maintainability assessment aligned with circular economy principles.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of building Easy Maintenance (Maintainability) and the optimization of technical service life within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Maintenance Intensity," "Component Accessibility," or "Repairability" by utilizing recognized methodologies such as Building Information Modeling for Facility Management (BIM-FM) integration, Reliability-Centered Maintenance (RCM), or automated Accessibility Analysis for replacement. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative upkeep strategies to automated, quantitative digital assessments of lifecycle costs and resource efficiency through simplified maintenance protocols for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **BIM-Integrated Maintenance Tool:** Does the study describe a functional digital tool or BIM plugin specifically designed for building maintenance assessment that is integrated with or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation)?
- **Quantitative Assessment Capabilities:** Does the tool provide quantitative assessment capabilities for at least one of the following: Maintenance Intensity, Component Accessibility, or Repairability?
- **Tool Validation:** Is the tool validated through case studies, empirical simulations, or professional implementation?
- **Implementation Details:** Does the study provide specific tool nomenclature, required software environment, and implementation details?
- **Tool Accessibility:** Is the tool available as a packaged software solution or commercially/publicly available plugin (rather than custom-coded scripts or bespoke solutions not available as packaged tools)?
- **Maintenance Phase Focus:** Does the study focus on maintenance/operational phase activities (rather than exclusively on construction phase activities)?
- **Technical Content Adequacy:** Does the study contain substantial technical content (i.e., is it not merely a conference abstract, editorial, or opinion piece without technical detail)?
- **Building Application Domain:** Is the tool designed for building applications (rather than exclusively for non-building applications such as industrial machinery or vehicles)?

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Easy Maintenance (Maintainability)? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

14 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **BIM-Integrated Maintenance Tool:** Does the study describe a functional digital tool or BIM plugin specifically designed for building maintenance assessment that is integrated with or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation)?
- **Quantitative Assessment Capabilities:** Does the tool provide quantitative assessment capabilities for at least one of the following: Maintenance Intensity, Component Accessibility, or Repairability?
- **Tool Validation:** Is the tool validated through case studies, empirical simulations, or professional implementation?
- **Implementation Details:** Does the study provide specific tool nomenclature, required software environment, and implementation details?
- **Tool Accessibility:** Is the tool available as a packaged software solution or commercially/publicly available plugin (rather than custom-coded scripts or bespoke solutions not available as packaged tools)?
- **Maintenance Phase Focus:** Does the study focus on maintenance/operational phase activities (rather than exclusively on construction phase activities)?
- **Technical Content Adequacy:** Does the study contain substantial technical content (i.e., is it not merely a conference abstract, editorial, or opinion piece without technical detail)?
- **Building Application Domain:** Is the tool designed for building applications (rather than exclusively for non-building applications such as industrial machinery or vehicles)?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Easy Maintenance (Maintainability)? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

8 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identity:**

Extract the specific nomenclature and technical details of digital tools or BIM plugins designed for quantitative maintenance assessment, including:

- Exact name of the tool/plugin/software
- Tool type: BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."
- Version number if specified
- Developer/company
- Required BIM authoring software environment (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD)
- Tool category (standalone software, BIM plugin, integrated module, cloud-based platform)
- Availability status (commercially available, open-source, research prototype)

- **Maintenance Assessment Capabilities:**

Extract quantitative maintenance assessment capabilities specifically for building Easy Maintenance and technical service life optimization, including:

- Maintenance Intensity evaluation features
- Component Accessibility analysis capabilities
- Repairability assessment functions
- Lifecycle cost calculation features
- Resource efficiency metrics
- Circular economy indicators measured
- Specific building elements or systems assessed (structural, MEP, envelope, etc.)
- Output formats (reports, visualizations, dashboards, alerts)

- **Methodology Integration:**

Extract recognized methodologies and frameworks integrated into the tool for maintenance assessment, including:

- Building Information Modeling for Facility Management (BIM-FM) integration
- Reliability-Centered Maintenance (RCM) implementation
- Automated Accessibility Analysis methods
- Building Condition Assessment (BCA) processes
- Quantitative degradation assessment methods (e.g., GDE/UnB)
- Industry standards compliance (ISO, ASTM, local codes)
- Data sources utilized (sensors, inspections, historical data)
- Algorithmic approaches for automation

- **Validation Evidence:**

Extract evidence of practical validation and professional implementation, including:

- Case study details (building type, location, duration)
- Empirical simulation results with quantitative outcomes
- Professional context applications (architecture firms, facility management companies, government agencies)
- Performance metrics achieved (cost savings, time reduction, accuracy improvements)
- User validation methods (focus groups, questionnaires, expert interviews)

- Comparison with traditional/manual methods
- Limitations or challenges identified in practical use

- **Automation Level:**

Extract details about the degree of automation in quantitative maintenance assessment, including:

- Manual input requirements vs automated data collection
- Real-time monitoring capabilities
- Automated alert/notification systems
- Integration with IoT sensors or external databases
- Visual programming language (VPL) usage (e.g., Dynamo, Grasshopper)
- Batch processing capabilities
- User interface complexity and learning curve
- Decision support automation features

- **Publication Details:**

Extract official publication information documenting the tool's practical implementation, including:

- Official DOI of primary publication
- Publication title and journal/conference name
- Publication year (must be before December 2025)
- Authors and institutional affiliations
- Study type (case study, experimental validation, comparative analysis)
- Peer review status
- Additional supporting publications or technical documentation

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support [Indicator Name]? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The eight included sources span publication years from 2020 to 2025 and encompass a range of building types, geographic contexts, and BIM-based approaches to maintenance assessment. All studies employ case study methodologies, though they differ substantially in the specific digital tools evaluated, the building typologies addressed, and the depth of quantitative validation reported.

Study	Full Text Retrieved?	Study Type	Building Type / Context	Geographic Location	Primary BIM Software	Key Digital Tool(s) Evaluated
G. Acampa et al., 2022	Yes	Case study [1]	Cultural heritage (Brunelleschi's Cloister) [1]	Florence, Italy [1]	Autodesk Revit [1]	Dynamo visual programming scripts [1]
Reffy Whydyastuti et al., 2025	Yes	Qualitative case study [2]	Public building (DPUTR Building) [2]	Sukabumi City, Indonesia [2]	Autodesk Revit 2023 [2]	Navisworks, Archibus (BIM 7D plugins) [2]
A. Harode et al., 2022	Yes	Case study with focus group validation [3]	Healthcare and academic facilities [3]	Not specified [3]	Navisworks [3]	Microsoft Power BI, VCAD, HoloLens 2 [3]
Ryan Loeh et al., 2021	Yes	Case study [4]	Military facility (Building A, 1980s construction) [4]	New Jersey, USA [4]	Autodesk Revit [4]	DB Link, BUILDER SMS, Microsoft Access [4]
Vitaliy Bassist et al., 2025	Yes	Case study [7]	Educational building (university main building) [7]	Vinnitsia, Ukraine [7]	Autodesk Revit [7]	Revit cloud environment, LIRA-SAPR [7]
Murilo Rocha Moura et al., 2024	Yes	Case study [6]	Unfinished public building (federal higher education annex) [6]	Brazil [6]	Autodesk Revit [6]	GDE/UnB methodology integrated into Revit [6]
Xiang Xie et al., 2020	Yes	Case study [8]	Academic/research building (IfM, University of Cambridge) [8]	Cambridge, UK [8]	Not specified [8]	AR-enhanced inspection system with digital twin platform [8]
Pablo Barreto et al., 2024	Yes	Case study and experimental validation [5]	Historic building (Escola de Belas Artes, UFBA) [5]	Salvador, Brazil [5]	Autodesk Revit [5]	Dalux FM [5]

All eight studies are case-study-based investigations; none employ randomized controlled designs or large-sample comparative analyses. Seven of the eight studies use Autodesk Revit as the primary BIM authoring environment [1, 2, 4–7], with one study centering on Navisworks [3] and one not specifying a BIM authoring platform [8]. Three studies focus specifically on heritage or historic buildings [1, 5, 7], three address public or institutional buildings [2, 4, 6], and two involve academic or research facilities [3, 8]. Geographic coverage spans Europe, Southeast Asia, South America, and North America.

Digital Tools Identified

The following table catalogs the specific digital tools and their technical characteristics as reported across the included studies.

Tool Name	Tool Type	Developer	BIM Environment	Availability	Focus Area
Dynamo [1]	Visual programming script [1]	Autodesk [1]	Autodesk Revit [1]	Commercially available [1]	BCA-BIM integration for degradation assessment and opportunity maintenance [1]
Navisworks [2]	BIM plugin [2]	Not specified in study [2]	Autodesk Revit [2]	Commercially available [2]	7D facility management, risk mapping, predictive maintenance [2]
Archibus [2]	BIM plugin [2]	Not specified in study [2]	Autodesk Revit [2]	Commercially available [2]	7D facility management, cost estimation [2]
Microsoft Power BI [3]	Cloud-based platform [3]	Microsoft [3]	Navisworks [3]	Commercially available [3]	Lifecycle data dashboards for FM [3]
VCAD [3]	Standalone BIM software [3]	BLogic [3]	Navisworks [3]	Commercially available [3]	BIM-to-Power BI data conversion [3]
iConstruct [3]	BIM plugin [3]	iConstruct [3]	Revit [3]	Commercially available [3]	BIM-to-Power BI template generation [3]
Pro-Revit Tools [3]	BIM plugin [3]	Not specified [3]	Revit [3]	Commercially available [3]	BIM-to-Power BI template generation [3]
DB Link [4]	BIM plugin [4]	Autodesk [4]	Autodesk Revit [4]	Commercially available [4]	SFM-BIM data transfer [4]

Tool Name	Tool Type	Developer	BIM Environment	Availability	Focus Area
Dalux FM [5]	Standalone BIM software [5]	Not specified [5]	Autodesk Revit [5]	Commercially available [5]	BIM-FM integration for maintenance scheduling and service order management [5]
AR-enhanced inspection system [8]	Integrated BIM framework [8]	Not specified [8]	Not specified [8]	Research prototype [8]	Environmental anomaly detection and fault isolation for O&M [8]

Of the ten distinct tools identified, nine are commercially available [1–5] and one is a research prototype [8]. Notably, no study identified a packaged, standalone tool that directly automates the calculation of “Maintenance Intensity,” “Component Accessibility,” or “Repairability” as discrete quantitative indices. Instead, the tools serve as enabling platforms—for data visualization, condition assessment integration, or lifecycle data management—that facilitate but do not fully automate these specific assessments. Two studies do not identify any specific plugin or tool beyond the general use of Autodesk Revit itself [6, 7], instead relying on manual or semi-manual integration of assessment data into the BIM environment.

Maintenance Assessment Capabilities

Capability	G. Acampa et al., 2022	Reffy Whydyas-tuti et al., 2025	A. Harode et al., 2022	Ryan Loeh et al., 2021	Vitaliy Bassist et al., 2025	Murilo Rocha Moura et al., 2024	Xiang Xie et al., 2020	Pablo Barreto et al., 2024
Maintenance intensity evaluation	Degradation level index [1]	Real-time tracking, condition-based planning [2]	Not explicitly addressed [3]	Visual filters for condition assessments [4]	Physical wear indicators [7]	GDE/UnB deterioration grading [6]	AR platform with asset databases [8]	Service order management, cost control [5]
Component accessibility analysis	BIM and Dynamo scripts [1]	Color-coded risk mapping [2]	Real-time data via HoloLens 2 [3]	Mobile/tablet BIM viewing [4]	Structured specification for monitoring [7]	Not mentioned [6]	AR visualization of hidden assets [8]	Omniclass classification [5]

Capability	G. Acampa et al., 2022	Reffy Whydyastuti et al., 2025	A. Harode et al., 2022	Ryan Loeh et al., 2021	Vitaliy Bassist et al., 2025	Murilo Rocha Moura et al., 2024	Xiang Xie et al., 2020	Pablo Barreto et al., 2024
Repairability assessment	Technological and operational connection matrix [1]	Preventive schedule development [2]	Not explicitly addressed [3]	Maintainability checking [4]	Defect elimination methods [7]	Not mentioned [6]	FTA-based decision tree [8]	Not explicitly addressed [5]
Lifecycle cost calculation	Revit-based economic analysis [1]	Traditional vs. BIM 7D cost comparison [2]	Dashboard-supported cost analysis [3]	Not explicitly addressed [4]	Estimated building life from wear data [7]	Not mentioned [6]	Not explicitly addressed [8]	Not explicitly addressed [5]
Output formats	Color-scale degradation maps, numerical degradation index [1]	Color-coded risk maps, cost/downtime reports [2]	Dashboards, visualizations [3]	Visualization, mobile views [4]	Not specified [7]	3D views classified by deterioration level [6]	AR platform overlays [8]	Not specified beyond software functions [5]

The most comprehensive quantitative assessment capabilities were reported by Acampa et al. (2022), whose Dynamo-based workflow provides both chromatic degradation scales and numerical degradation indices linked to economic gain analysis [1], and by Whydyastuti et al. (2025), whose BIM 7D approach produces color-coded risk maps with cost-benefit comparisons [2]. Several studies address component accessibility through augmented or mixed reality overlays that reveal hidden building elements to maintenance personnel [3, 8], while only Acampa et al. (2022) explicitly formalize repairability through a technological and operational connection matrix for opportunity maintenance [1]. No study reported circular economy indicators as measured outputs [1–8].

Methodology Integration

Methodology	Studies Integrating It
BIM-FM integration	All eight studies [1–8]
Building Condition Assessment (BCA)	G. Acampa et al., 2022 [1]; Reffy Whydyastuti et al., 2025 [2]; Vitaliy Bassist et al., 2025 [7]
Quantitative degradation assessment (GDE/UnB, physical wear)	Vitaliy Bassist et al., 2025 [7]; Murilo Rocha Moura et al., 2024 [6]
Fault Tree Analysis (FTA) / decision trees	Xiang Xie et al., 2020 [8]
Automated accessibility analysis (AR-based)	Xiang Xie et al., 2020 [8]
Reliability-Centered Maintenance (RCM)	None [1–8]
Industry standards compliance (UNI 8290)	G. Acampa et al., 2022 [1]

Methodology	Studies Integrating It
Interoperability standards (IFC, COBie)	Pablo Barreto et al., 2024 [5]

BIM-FM integration is the universal methodological thread across all studies, though the depth of integration varies considerably. No study implements Reliability-Centered Maintenance (RCM) as a recognized framework [1–8], which is a notable gap given the research question's emphasis on this methodology. Only one study (Acampa et al., 2022) references compliance with a formal building classification standard (UNI 8290) [1], and only one (Barreto et al., 2024) explicitly addresses interoperability through IFC and COBie formats [5]. Algorithmic automation for maintenance assessment is limited: Dynamo scripts for database-BIM linkage [1], BIM parameter filtering [6], and binary segmentation-based anomaly detection [8] represent the only documented computational approaches.

Automation Level

Automation Dimension	High Automation	Partial Automation	Predominantly Manual
Data collection	IoT sensor integration (Xie et al., 2020) [8]	Dynamo-scripted database linking (Acampa et al., 2022) [1]; VCAD automated data transformation (Harode et al., 2022) [3]; IFC/COBie exchange (Barreto et al., 2024) [5]	Manual inspection input (Loeh et al., 2021; Moura et al., 2024; Bassist et al., 2025) [4, 6, 7]
Real-time monitoring	Digital twin platform (Xie et al., 2020) [8]; HoloLens 2 data delivery (Harode et al., 2022) [3]	Cloud-based BIM updates (Bassist et al., 2025) [7]; Dalux FM alerts (Barreto et al., 2024) [5]	No real-time capability (Loeh et al., 2021; Moura et al., 2024) [4, 6]
Decision support	FTA decision tree (Xie et al., 2020) [8]; Color-coded risk mapping (Whydyastuti et al., 2025) [2]	Economic gain analysis (Acampa et al., 2022) [1]; Dashboard analytics (Harode et al., 2022) [3]	Visual filters only (Loeh et al., 2021) [4]; Manual interpretation (Moura et al., 2024) [6]

Only one study integrates IoT sensors for automated data collection [8], while most rely on manual field inspections as the primary data source [4, 6, 7]. The BIM 7D approach described by Whydyastuti et al. (2025) lacks IoT sensor integration, which the authors themselves identify as a limitation requiring future research [2]. Visual programming through Dynamo is employed in only one study [1], and no study reports the use of Grasshopper or other parametric scripting environments. The learning curve and user interface complexity are largely unreported, with only Harode et al. (2022) explicitly addressing usability through a focus group evaluation [3] and Barreto et al. (2024) noting a relatively user-friendly mobile interface with QR code functionality [5].

Validation Evidence and Performance Metrics

Study	Validation Method	Quantitative Performance Outcomes	Comparison with Traditional Methods	Key Limitations
G. Acampa et al., 2022	EU-funded project case study (WARMEST) [1]	Economic gain from opportunity maintenance quantified (specific values not reported) [1]	Not explicitly compared [1]	High software costs [1]
Reffy Whydyastuti et al., 2025	In-depth interviews with facility managers and technical staff [2]	45.83% downtime reduction; 19.2% cost savings over 10 years [2]	BIM 7D vs. traditional maintenance approaches [2]	Reliance on initial digital documentation; no IoT sensor integration [2]
A. Harode et al., 2022	Focus group of 6 industry experts; PSSUQ questionnaire [3]	Average PSSUQ scores of 4–5 out of scale [3]	Real-time data access vs. traditional methods [3]	Power BI–HoloLens 2 integration still in infancy [3]
Ryan Loeh et al., 2021	Focus group of NJDMAVA FM staff [4]	Method 2 initial completion time: 161 minutes [4]	Automated hybrid method faster than fully manual method [4]	Data compatibility issues; intermediate database setup effort [4]
Vitaliy Bassist et al., 2025	Analysis of inspection reports from 2004 and 2024 [7]	Relationship established between service life end and performance loss [7]	BIM advantages over traditional documentation noted [7]	BIM models not yet fully integrated into traditional workflows [7]
Murilo Rocha Moura et al., 2024	Single-building case study [6]	Visual and quantitative data generated for decision-making [6]	Not explicitly compared [6]	Difficulty using BIM for all data processing [6]
Xiang Xie et al., 2020	Deployment at IfM building, University of Cambridge [8]	Binary segmentation effective for temperature anomaly detection [8]	Not explicitly compared [8]	System requires further development [8]
Pablo Barreto et al., 2024	Experimental validation with Dalux FM [5]	Functional validation of BIM-FM workflow (no cost/time metrics reported) [5]	Not explicitly compared [5]	Data loss during IFC format exchange; software limitations [5]

The strongest quantitative validation comes from Whydyastuti et al. (2025), who report a 45.83% reduction in downtime and 19.2% cost savings over a ten-year period when comparing BIM 7D with traditional maintenance approaches [2]. However, these figures derive from simulation rather than empirical longitudinal measurement. Harode et al.

(2022) provide the most rigorous usability validation through a structured PSSUQ questionnaire administered to six industry experts [3]. Most studies report functional demonstrations rather than controlled performance comparisons, and none employ pre-post experimental designs or matched-facility comparisons. Interoperability challenges—particularly data loss during IFC export [5] and data compatibility issues between BIM and external databases [4]—emerge as recurring practical barriers.

Technology Integrations

Integration Technology	Studies Reporting Integration
Cloud platforms	A. Harode et al., 2022 (Azure SQL, Neo4j) [3]; Vitaliy Bassist et al., 2025 (Revit cloud) [7]
Augmented/Mixed Reality	A. Harode et al., 2022 (HoloLens 2) [3]; Xiang Xie et al., 2020 (custom AR system) [8]
Digital Twins	Xiang Xie et al., 2020 [8]
IoT sensors	A. Harode et al., 2022 (edge devices) [3]; Xiang Xie et al., 2020 (Monnit wireless sensors) [8]
GIS	Ryan Loeh et al., 2021 [4]
Interoperability standards (IFC, COBie)	Pablo Barreto et al., 2024 [5]

Digital twin and IoT integration remain limited to two studies [3, 8], and no study reports integration with material passports, blockchain, or 3D printing technologies. The absence of material passport integration is particularly relevant given the research question's emphasis on circular economy frameworks.

Synthesis

The central finding across these eight studies is that no commercially available, packaged digital tool currently automates the quantitative assessment of "Maintenance Intensity," "Component Accessibility," or "Repairability" as discrete, standardized outputs within a BIM environment. Instead, the field relies on integrated BIM frameworks—combinations of BIM authoring software, visual programming scripts, external databases, and FM platforms—that require substantial configuration and manual input to approximate such assessments.

The apparent heterogeneity in reported capabilities and outcomes can be explained by three factors. First, the studies target fundamentally different building typologies: heritage buildings with irreplaceable components and idiosyncratic geometries [1, 5] demand qualitatively different maintenance logic than standardized public buildings with replaceable modular systems [2, 4]. The Dynamo-based degradation indexing approach of Acampa et al. (2022), for instance, was specifically tailored to the UNI 8290 classification adapted for historic structures [1], limiting its direct transferability to non-heritage contexts. Conversely, the BIM 7D simulation by Whydyastuti et al. (2025) addresses a contemporary public building where component standardization enables more straightforward predictive scheduling [2].

Second, the level of automation correlates strongly with the extent of external technology integration. The two studies demonstrating the highest automation—Xie et al. (2020) with IoT-enabled digital twins [8] and Harode et al. (2022) with Power BI dashboards linked to mixed reality headsets [3]—incorporate sensor networks and cloud analytics that extend beyond the BIM authoring environment itself. Studies confined to Revit-internal workflows without IoT or cloud integration consistently report greater manual input requirements [4, 6]. This suggests that

achieving automated quantitative maintenance assessment requires a systems-integration approach rather than a single-tool solution.

Third, the absence of RCM implementation across all studies [1–8] indicates a disconnect between established maintenance engineering methodologies and current BIM-FM tool development. The tools identified operate primarily at the level of condition documentation and visualization rather than at the level of reliability analysis and failure-mode-driven maintenance optimization. The closest approximation to reliability-based reasoning is the fault tree analysis employed by Xie et al. (2020) for linking environmental symptoms to failed assets [8], but this remains a research prototype rather than a deployable tool [8].

The most actionable commercially available solutions for practitioners seeking to move toward quantitative maintenance assessment within BIM are Dalux FM for structured maintenance order management and scheduling [5], Dynamo scripts within Revit for linking degradation databases to BIM models with automated parameter updates [1], and Power BI dashboards via VCAD for lifecycle data visualization and analysis [3]. Each requires significant initial configuration effort—Loeh et al. (2021) document 161 minutes for initial data transfer setup even with semi-automated methods [4]—and none provides a turnkey solution for the specific maintainability indices sought by the research question.

References

1. G. Acampa, C. Parisi (2022) Cultural heritage management: optimising procedures and maintenance costs. *Valori e Valutazioni*. <https://doi.org/10.48264/vvsiev-20212907>
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3. A. Harode, M. Ensafi, W. Thabet (2022) Linking BIM to Power BI and HoloLens 2 to Support Facility Management: A Case Study Approach. *Buildings*. <https://doi.org/10.3390/buildings12060852>
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6. Murilo Rocha Moura, Lorrana da Silva Nunes, Anthony Alves Lima, et al (2024) Gestão da manutenção de edifício público inacabado apoiado por BIM. *ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO*. <https://doi.org/10.46421/entac.v20i1.6319>
7. Vitaliy Bassist (2025) TRADITIONAL PRINCIPLES OF INSPECTION AND FORMATION OF TECHNICAL DOCUMENTATION, USE OF BIM TECHNOLOGIES, POSSIBILITY OF SOLVING PROBLEMS. *Modern technology, materials and design in construction*. <https://doi.org/10.31649/2311-1429-2025-1-80-86>

8. Xiang Xie, Q. Lu, David Rodenas-Herráiz, et al (2020) Visualised inspection system for monitoring environmental anomalies during daily operation and maintenance. <https://doi.org/10.1108/ecam-11-2019-0640>

Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Materials Flow Analysis (MFA) and the tracking of material inputs, stocks, and outputs within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Inflows and Outflows," "Mass Balances," or "Stock Dynamics" by utilizing recognized methodologies such as the Economy-Wide MFA (EW-MFA), Dynamic MFA, or Level(s) Indicator 2.1 for construction material usage. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital assessments of material circularity across the entire value chain—from raw material production to waste management—for data published before December 2025.

No commercially available, packaged BIM plugin or software tool currently automates standardized MFA methodologies (EW-MFA, Dynamic MFA, or Level(s) Indicator 2.1) for construction materials; the closest functional alternatives are Revit-based plugins such as WE-BIM Add-in, CW-LCA-BIM, and BIM3LCA that automate construction waste quantification and LCA-based environmental assessment with real-time BoM extraction, but these address only proxy indicators of material circularity rather than formal material flow accounting across the full value chain.

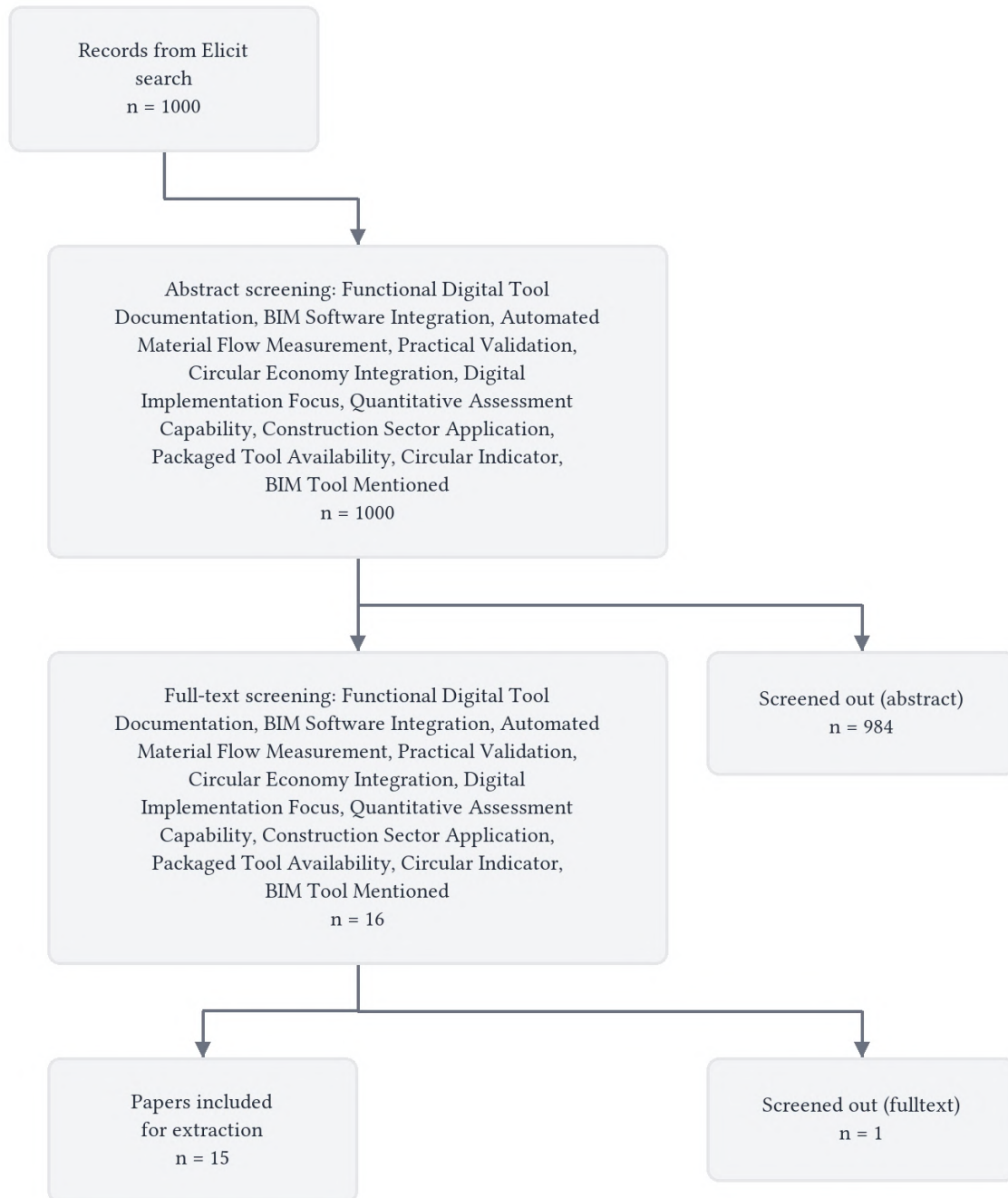
Abstract

Fifteen digital tools and BIM-integrated solutions for construction materials flow analysis were identified and categorized across publications from 2020–2024. The most functional packaged tools operate within Autodesk Revit, including WE-BIM Add-in for construction waste quantification [1], CW-LCA-BIM for environmental impact assessment of recycling versus disposal scenarios [2], BIM3LCA for life cycle sustainability assessment [3], and WasteBIM for automated solid waste reporting [4]. Additional validated solutions include Eco2soft as a standalone LCA tool for recycling potential calculation [5], ScanR for pre-demolition material cataloging via LiDAR and survey methods

[6], a Grasshopper-based matching algorithm for reclaimed timber reuse achieving 40% GWP reduction [7], and Regenerate as a freely available web-based circular economy engagement tool with over 520 downloads [8]. However, none of these tools explicitly implements the standardized MFA methodologies specified in the research question — Economy-Wide MFA, Dynamic MFA, or Level(s) Indicator 2.1 — as automated, packaged features. Only one study applies Dynamic MFA through the Open Dynamic Material System Model (ODYM) within a digital twin framework [9], and only one methodology is designed for compatibility with the EU Level(s) Framework using formal circularity indicators (MCI, BCI) [10]; both remain research prototypes rather than deployable tools.

The current tool landscape predominantly addresses construction-phase waste quantification and LCA-based environmental assessment rather than comprehensive material flow tracking from extraction through end-of-life [1, 2, 4]. Tools that achieve full life-cycle scope do so through LCA databases rather than MFA-specific frameworks [3, 5]. Automated BoM extraction from BIM models with real-time design synchronization is confirmed for several Revit plugins [1–3], but tool accessibility remains a significant gap: most Revit-based plugins lack confirmed commercial availability or distribution channels [1–3], while WasteBIM is limited to Revit version 2019 [4]. The field is characterized by a maturity tradeoff in which the most methodologically rigorous MFA implementations are custom-coded research prototypes [9, 11], whereas the most accessible tools provide proxy indicators of circularity rather than standardized MFA metrics. No fully integrated, commercially available solution currently automates recognized MFA methodologies within a professional BIM environment.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Materials Flow Analysis (MFA) and the tracking of material inputs, stocks, and outputs within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Inflows and Outflows," "Mass Balances," or "Stock Dynamics" by utilizing recognized methodologies such as the Economy-Wide MFA (EW-MFA), Dynamic MFA, or Level(s) Indicator 2.1 for construction material usage. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital assessments of material circularity across the entire value chain—from raw material production to waste management—for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tool Documentation:** Does the study document functional digital tools or BIM plugins specifically designed for Construction Materials Flow Analysis with quantitative assessment capabilities?
- **BIM Software Integration:** Are the tools compatible with established BIM authoring software platforms (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation)?
- **Automated Material Flow Measurement:** Do the tools demonstrate capability to automatically measure material flows such as "Material Inflows and Outflows," "Mass Balances," or "Stock Dynamics"?
- **Practical Validation:** Are the tools demonstrated through case studies, empirical simulations, or real-world professional contexts to show practical workability and reliability?
- **Circular Economy Integration:** Do the tools explicitly support material circularity assessment across the value chain from raw material production to waste management?
- **Digital Implementation Focus:** Does the study focus on practical digital solutions rather than purely theoretical frameworks or conceptual models without functional software tools?
- **Quantitative Assessment Capability:** Do the tools provide quantitative measurement capabilities rather than only qualitative material management assessment?
- **Construction Sector Application:** Are the MFA tools specifically designed for or adapted to construction materials and processes rather than other industries (manufacturing, agriculture, etc.)?
- **Packaged Tool Availability:** Are the tools available as ready-to-use software or plugins rather than requiring custom coding or bespoke programming solutions?

- **Circular Indicator:** Does the paper claim to quantitatively measure Construction Materials Flow Analysis? Answer 'No' if it is purely qualitative.
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

16 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional Digital Tool Documentation:** Does the study document functional digital tools or BIM plugins specifically designed for Construction Materials Flow Analysis with quantitative assessment capabilities?
- **BIM Software Integration:** Are the tools compatible with established BIM authoring software platforms (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation)?
- **Automated Material Flow Measurement:** Do the tools demonstrate capability to automatically measure material flows such as "Material Inflows and Outflows," "Mass Balances," or "Stock Dynamics"?
- **Practical Validation:** Are the tools demonstrated through case studies, empirical simulations, or real-world professional contexts to show practical workability and reliability?
- **Circular Economy Integration:** Do the tools explicitly support material circularity assessment across the value chain from raw material production to waste management?
- **Digital Implementation Focus:** Does the study focus on practical digital solutions rather than purely theoretical frameworks or conceptual models without functional software tools?
- **Quantitative Assessment Capability:** Do the tools provide quantitative measurement capabilities rather than only qualitative material management assessment?
- **Construction Sector Application:** Are the MFA tools specifically designed for or adapted to construction materials and processes rather than other industries (manufacturing, agriculture, etc.)?
- **Packaged Tool Availability:** Are the tools available as ready-to-use software or plugins rather than requiring custom coding or bespoke programming solutions?
- **Circular Indicator:** Does the paper claim to quantitatively measure Construction Materials Flow Analysis? Answer 'No' if it is purely qualitative.
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

15 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific nomenclature and classification of digital tools or BIM plugins designed for Construction Materials Flow Analysis, including:

- Exact name/title of the tool or plugin
- Type of solution (standalone software, BIM plugin, integrated module, etc.)
- Required BIM authoring software environment (Autodesk Revit, Rhino/Grasshopper, ArchiCAD, etc.)
- Version information if available
- Developer/organization responsible for the tool

- **MFA Methodology:**

Extract the specific Material Flow Analysis methodologies and frameworks implemented by the tool for quantitative assessment in circular economy contexts, including:

- Economy-Wide MFA (EW-MFA) implementation
- Dynamic MFA capabilities
- Level(s) Indicator 2.1 for construction material usage
- Other recognized MFA methodologies utilized
- Specific quantitative metrics measured (material inflows, outflows, mass balances, stock dynamics)
- Calculation methods and algorithms employed

- **Material Tracking Features:**

Extract detailed capabilities for tracking material inputs, stocks, and outputs within the circular economy framework, including:

- Types of construction materials tracked (concrete, steel, timber, plastics, etc.)
- Tracking scope (raw material production, construction phase, use phase, end-of-life, waste management)
- Data inputs required (material quantities, specifications, sources, destinations)
- Real-time vs. static tracking capabilities
- Integration with supply chain data
- Waste stream monitoring and classification

- **Automated BoM Generation:**

Extract specific capabilities for automated Bills of Materials (BoM) generation and material quantification, including:

- Automatic extraction of material quantities from BIM models
- BoM formatting and export options
- Integration with material databases
- Cost estimation capabilities
- Environmental impact calculations linked to BoM
- Customization options for different project types
- Updates and synchronization with design changes

- **Validation Context:**

Extract evidence of practical implementation and validation through case studies or empirical simulations in professional contexts, including:

- Specific case studies or pilot projects described
- Professional contexts where tool was applied (building types, project scales, geographic locations)

- Validation methods employed (accuracy testing, comparison with manual calculations, field verification)
- Performance metrics and results achieved
- User feedback or adoption rates
- Limitations or challenges identified during implementation

- **Circular Economy Functionality:**

Extract specific features supporting the transition from qualitative to quantitative digital assessments of material circularity, including:

- Circularity indicators calculated or tracked
- Support for reuse, recycling, and recovery strategies
- Material passport or digital twin capabilities
- Life cycle assessment integration
- End-of-life scenario modeling
- Circular design optimization features
- Connection to circular economy databases or standards

- **Tool Accessibility:**

Extract information about the accessibility and availability of the digital tool as a packaged solution, including:

- Commercial availability (free, paid, subscription-based)
- Installation requirements and system compatibility
- User interface and ease of use
- Training or expertise required
- Technical support and documentation provided
- Distribution channels (official websites, app stores, vendor networks)
- Distinction from custom-coded computational scripts or theoretical frameworks

- **Publication Details:**

Extract bibliographic information for the primary publication documenting the tool's practical implementation, including:

- Official DOI of the primary publication
- Publication date (must be before December 2025)
- Journal or conference name
- Authors and institutional affiliations
- Publication type (journal article, conference paper, technical report)
- Peer review status
- Citation metrics if available

- **Tool Type**

- **Focus area:**

Specifically, how does this tool support [Indicator Name]? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The review identified 15 sources documenting digital tools or methodologies for quantitative assessment of construction materials flow analysis within the circular economy framework. The studies span from 2020 to 2024 and cover a range of tool types, BIM environments, and geographic contexts.

Study	Full text retrieved?	Tool Name	Tool Type	BIM Environment	Case Study Location	Focus Area
R. Quiñones et al., 2022	Yes	WE-BIM Add-in [1]	BIM plugin [1]	Autodesk Revit [1]	Seville, Spain [1]	Construction waste quantification [1]
C. Llatas et al., 2022	Yes	CW-LCA-BIM tool [2]	BIM plugin [2]	Autodesk Revit [2]	Spain [2]	Environmental impact of CW recycling vs. disposal [2]
J. Fernandes et al., 2022	Yes	Plugin for Circularity (unnamed) [10]	BIM plugin [10]	Not specified [10]	Lisbon, Portugal [10]	Building Circularity Indicator (BCI) [10]
Qiming Sun et al., 2022	Yes	Eco2soft [5]	Standalone software [5]	Autodesk Revit 2019 [5]	Tianjin, China [5]	Recycling Potential (RP) calculation [5]
F. Heisel et al., 2022	Yes	ScanR [6]	Composite method (LiDAR + survey) [6]	Rhinoceros3D/Grasshopper [6]	Massachusetts, USA [6]	Material intensity and embodied carbon [6]
B. Soust-Verdaguer et al., 2023	Yes	BIM3LCA [3]	BIM plugin [3]	Autodesk Revit [3]	Seville, Spain [3]	Life Cycle Sustainability Assessment (LCSA) [3]
C. Gillott et al., 2023	Yes	Regenerate [8]	Web-based application [8]	Not specified [8]	UK (new-build project) [8]	CE design workflow and BoM collection [8]
S. M. Haakonsen et al., 2024	Yes	Matching Algorithm (unnamed) [7]	Visual programming script [7]	Rhino/Grasshopper [7]	Oslo, Norway [7]	Reclaimed material matching and GWP reduction [7]

Study	Full text retrieved?	Tool Name	Tool Type	BIM Environment	Case Study Location	Focus Area
F. Geremicca et al., 2024	Yes	Custom DT integration [9]	Integrated module [9]	Autodesk Revit + Unreal Engine [9]	Pittsburgh, PA, USA [9]	Urban metabolism MFA via digital twin [9]
Soroosh Ataee et al., 2022	Yes	Unnamed (future Grasshopper plugin) [11]	Python-based plugin (planned) [11]	Rhinoceros Grasshopper [11]	Brussels, Belgium [11]	Infrastructure material stock and GHG emissions [11]
Fernanda Carrion Da Luz et al., 2024	Yes	Unnamed (Revit + Dynamo + Python) [12]	Visual programming script [12]	Autodesk Revit [12]	Not specified [12]	Construction and demolition waste quantification [12]
Giovanna Ferreira Alves et al., 2024	Yes	Passaporte de Materiais (PM) [13]	Integrated module within Revit [13]	Autodesk Revit with Dynamo [13]	Paraná, Brazil [13]	Material passport for wood frame panels [13]
Pio Lorenzo Cocco et al., 2023	Yes	Digital Material Bank (DMB) [14]	Cloud-based database [14]	Not specified [14]	Marche region, Italy [14]	Post-earthquake CDW reuse [14]
F. Donati et al., 2020	Yes	RaMa-Scene [15]	Standalone web-based application [15]	None required [15]	Not building-specific [15]	Macro-level CE scenario modeling [15]
Marielle Martins Santos et al., 2022	Yes	WasteBIM [4]	BIM plugin (API) [4]	Autodesk Revit (limited to version 2019) [4]	Brazil [4]	Solid waste quantification from buildings [4]

Full texts were retrieved for all 15 studies. The majority of tools operate within the Autodesk Revit environment (9 of 15), with three tools developed for or planned for Rhino/Grasshopper [6, 7, 11], and two operating as platform-independent web applications [8, 15]. Case studies span Europe (Spain, Portugal, Norway, Belgium, Italy, UK), the Americas (USA, Brazil), and Asia (China), reflecting broad geographic coverage.

Tool Classification and Maturity

The 15 identified solutions can be organized into distinct categories based on their tool type, accessibility, and maturity level.

Tool	Commercial Availability	Open-Source?	Packaged Solution?	Key Limitation
WE-BIM Add-in [1]	Not mentioned [1]	Not mentioned	Yes (Revit plugin) [1]	Most time-consuming step is element modeling [1]
CW-LCA-BIM tool [2]	Not mentioned [2]	Not mentioned	Yes (Revit plugin) [2]	No specific LCA expertise required [2]
Circularity Plugin [10]	Not mentioned [10]	Not mentioned	Under development [10]	Does not replace on-site inspection [10]
Eco2soft [5]	Paid (online access) [5]	No	Yes (standalone) [5]	Default parameters more suitable for European buildings [5]
ScanR [6]	Commercial hardware (iPad Pro) [6]	Not mentioned	Composite method [6]	Current mobile scanning limitations [6]
BIM3LCA [3]	Not mentioned [3]	Not mentioned	Yes (Revit plugin) [3]	Not mentioned [3]
Regenerate [8]	Free [8]	Not mentioned	Yes (web app) [8]	Over 520 downloads reported [8]
Matching Algorithm [7]	Free (open-source) [7]	Yes (Zenodo) [7]	Yes (Grasshopper component) [7]	Accurate documentation of supply elements [7]
DT-MFA Integration [9]	Not mentioned [9]	Not mentioned	No (custom framework) [9]	Limited to single building case study [9]
Ataee et al. model [11]	Not mentioned [11]	Not mentioned	No (planned plugin) [11]	Limited to single case study [11]
Dynamo-Python workflow [12]	Not mentioned [12]	Not mentioned	No (custom script) [12]	Requires BIM and programming expertise [12]
Passaporte de Materiais [13]	Not mentioned [13]	Not mentioned	No (manual data entry required) [13]	Lack of synchronization between Revit and Dynamo [13]
Digital Material Bank [14]	Not mentioned [14]	Not mentioned	Under development [14]	Regulatory integration difficulties [14]
RaMa-Scene [15]	Free and open-source [15]	Yes (Zenodo) [15]	Yes (web platform) [15]	Room for improvement per user feedback [15]

Tool	Commercial Availability	Open-Source?	Packaged Solution?	Key Limitation
WasteBIM [4]	Not mentioned [4]	Not mentioned	Yes (API for Revit) [4]	Incompatible with Revit versions after 2019 [4]

Only three tools are confirmed as freely and openly available: Regenerate as a web-based application with over 520 downloads [8], RaMa-Scene as a free open-source web platform distributed via Zenodo [15], and the reclaimed-material matching algorithm for Grasshopper also available on Zenodo [7]. Eco2soft is a commercially available paid tool accessible via an official website [5]. Several solutions remain custom-coded or under development, including the Dynamo-Python workflow [12], the Passaporte de Materiais requiring manual data entry [13], and the parametric infrastructure model planned as a future Grasshopper plugin [11].

MFA Methodology and Quantitative Capabilities

A critical assessment dimension concerns whether and how each tool implements recognized MFA methodologies. The research question specifically targets Economy-Wide MFA (EW-MFA), Dynamic MFA, and Level(s) Indicator 2.1.

Tool	EW-MFA	Dynamic MFA	Level(s) 2.1	LCA Integration	Circularity Indicators
WE-BIM Add-in	Not mentioned [1]	Not mentioned [1]	Not mentioned [1]	Not mentioned [1]	CW types per LoW [1]
CW-LCA-BIM	Not mentioned [2]	Not mentioned [2]	Not mentioned [2]	Yes (LCA impact factors) [2]	GWP, HTP, energy [2]
Circularity Plugin	Not mentioned [10]	Not mentioned [10]	Compatible with EU Level(s) [10]	Yes (EE, GWP per EN 15978) [10]	MCI, PCI, SCI, BCI [10]
Eco2soft	Not mentioned [5]	Not mentioned [5]	Not mentioned [5]	Yes (Eco2soft LCA) [5]	Recycling Potential (RP) [5]
ScanR	Not mentioned [6]	Not mentioned [6]	Not mentioned [6]	Embodied carbon [6]	Material intensity (kg/m ²) [6]
BIM3LCA	Not mentioned [3]	Not mentioned [3]	Not mentioned [3]	Yes (ISO 21931-1 LCSA) [3]	Environmental, economic, social impacts [3]
Regenerate	Not mentioned [8]	Not mentioned [8]	Not mentioned [8]	Embodied carbon [8]	Material quantities, recycling metrics [8]
Matching Algorithm	Not mentioned [7]	Not mentioned [7]	Not mentioned [7]	GWP of reclaimed elements [7]	Emissions reduction via reuse [7]

Tool	EW-MFA	Dynamic MFA	Level(s) 2.1	LCA Integration	Circularity Indicators
DT-MFA Integration	Not mentioned [9]	Yes (ODYM) [9]	Not mentioned [9]	Dynamic MFA via Eurostat [9]	Material inflows and outflows [9]
Ataee et al. model	Implied [11]	Implied (hybrid exchange data) [11]	Not mentioned [11]	Yes (hybrid LCA-MFA) [11]	Material stock, LCEGHG [11]
Dynamo-Python workflow	Not mentioned [12]	Not mentioned [12]	Not mentioned [12]	Not mentioned [12]	Waste quantities [12]
Passaporte de Materiais	Not mentioned [13]	Not mentioned [13]	Not mentioned [13]	Yes (LCA data incorporated) [13]	Material recovery potential [13]
Digital Material Bank	Not mentioned [14]	Not mentioned [14]	Not mentioned [14]	Yes (LCA for environmental footprint) [14]	Reuse potential [14]
RaMa-Scene	Not mentioned [15]	Not mentioned [15]	Not mentioned [15]	Not explicitly [15]	CE scenario impacts via EXIOBASE [15]
WasteBIM	Not mentioned [4]	Not mentioned [4]	Not mentioned [4]	Not mentioned [4]	Waste by class and material type [4]

None of the 15 tools explicitly implements Economy-Wide MFA (EW-MFA) or Level(s) Indicator 2.1 as a named, automated methodology. Only one tool — the Digital Twin MFA Integration by Geremicca et al. — employs Dynamic MFA through the Open Dynamic Material System Model (ODYM) using the Eurostat methodology [9]. The parametric infrastructure model by Ataee et al. implies dynamic MFA capabilities through hybrid exchange data and integration of LCA with MFA across spatial scales [11], but this tool remains at a conceptual stage without packaging as a deployable plugin. The circularity plugin described by Fernandes et al. is the only tool explicitly designed to be compatible with the EU Level(s) Framework [10], employing the Material Circularity Indicator (MCI), Product Circularity Indicator (PCI), System Circularity Indicator (SCI), and Building Circularity Indicator (BCI) [10].

Most tools instead focus on proxy indicators of material circularity: waste quantification per the European List of Waste [1, 2], recycling potential at material and component levels [5], embodied carbon [6, 8], or life cycle sustainability indicators [3]. LCA integration is present in at least nine tools, typically serving as the primary mechanism for environmental impact quantification rather than as a formal MFA framework.

Material Tracking and Automated BoM Generation

Tool	Materials Tracked	Tracking Scope	Automated BoM Extraction	Real-Time Updates	Export Options
WE-BIM Add-in	CW per building element [1]	Construction phase [1]	Yes (waste quantification factors) [1]	Yes [1]	Excel [1]

Tool	Materials Tracked	Tracking Scope	Automated BoM Extraction	Real-Time Updates	Export Options
CW-LCA-BIM	Concrete, steel, plastics [2]	Construction phase [2]	Yes (volume and mass by element) [2]	Yes [2]	LoW classification [2]
Circularity Plugin	Various construction materials [10]	Existing building stock, refurbishment [10]	Implied [10]	Not mentioned [10]	Not mentioned [10]
Eco2soft	CLT, concrete, steel, biomass [5]	Material to building level, full life cycle [5]	Yes (from Revit) [5]	Not mentioned [5]	BIM to Eco2soft to Excel [5]
ScanR	Timber, plaster, insulation [6]	Construction phase, end-of-life [6]	No (survey-based) [6]	No (static) [6]	Excel spreadsheet [6]
BIM3LCA	Steel, concrete, wood [3]	Full life cycle [3]	Yes (BoM x impact factors) [3]	Yes [3]	Excel [3]
Regenerate	Not specified [8]	Construction phase, end-of-life [8]	No (manual BoM input) [8]	Not mentioned [8]	Web-based reporting [8]
Matching Algorithm	Timber (reclaimed) [7]	Construction phase [7]	Not mentioned [7]	Not mentioned [7]	Grasshopper visualization [7]
DT-MFA Integration	Concrete, steel, drywall, glass [9]	Construction phase [9]	Yes (from Revit) [9]	Currently static, future real-time planned [9]	Not mentioned [9]
Ataee et al. model	Asphalt, concrete, steel, gravel, etc. [11]	Initial and recurrent embodied flows [11]	Implied [11]	Planned for future [11]	Not mentioned [11]
Dynamo-Python	Concrete, steel, timber, others [12]	Construction and demolition [12]	Yes (Revit + Dynamo) [12]	Implied by automation [12]	Spreadsheet [12]
Passaporte de Materiais	Wood frame panel [13]	Material characteristics for recovery [13]	No (manual entry) [13]	No (static) [13]	Not mentioned [13]
Digital Material Bank	Post-earthquake building elements [14]	End-of-life, waste management [14]	Yes (BIM + 3D scan conversion) [14]	Yes (cloud publication) [14]	Interactive reports/dashboards [14]
RaMa-Scene	Secondary raw materials (macro-level) [15]	Economy-wide (not building-specific) [15]	No [15]	Not mentioned [15]	Web-based visualization [15]

Tool	Materials Tracked	Tracking Scope	Automated BoM Extraction	Real-Time Updates	Export Options
WasteBIM	Construction waste by material type [4]	Construction phase [4]	Yes (from Revit) [4]	Implied for waste generation [4]	Reports (General, PGRCC, Real vs. Planned) [4]

Automated BoM extraction from BIM models is a capability present in approximately nine tools, with the strongest implementations found in tools directly integrated with Autodesk Revit. The WE-BIM Add-in [1], CW-LCA-BIM [2], BIM3LCA [3], and WasteBIM [4] all extract material quantities directly from the Revit model and apply waste quantification factors or impact factors automatically. Real-time synchronization with design changes is confirmed for WE-BIM Add-in [1], CW-LCA-BIM [2], and BIM3LCA [3], allowing designers to observe the effects of alternative design decisions immediately.

The tracking scope remains heavily concentrated on the construction phase. Only Eco2soft [5] and BIM3LCA [3] explicitly cover the full building life cycle from raw material production through end-of-life. Most waste-focused tools (WE-BIM Add-in, CW-LCA-BIM, WasteBIM, Dynamo-Python workflow) are limited to construction-phase waste quantification [1, 2, 4, 12]. End-of-life considerations are addressed by tools focused on deconstruction and reuse — ScanR for pre-demolition material cataloging [6], the Digital Material Bank for post-earthquake material recovery [14], and the matching algorithm for reclaimed timber reuse [7].

Validation and Case Study Evidence

Tool	Case Study	Building Type / Scale	Validation Method	Key Quantitative Result
WE-BIM Add-in [1]	16-dwelling residential building, Seville [1]	Residential [1]	Comparison with manual calculations [1]	Steel structure reduced waste by 56% vs. reinforced concrete [1]
CW-LCA-BIM [2]	"La María" multi-family housing, Spain [2]	Residential [2]	Scenario simulation before construction [2]	Recycling prevented 14.6 t emissions, saved 148.5 GJ energy [2]
Circularity Plugin [10]	1919–1945 archetype building, Lisbon [10]	Residential (refurbishment) [10]	Compatibility with EU Level(s) Framework [10]	Not mentioned [10]
Eco2soft [5]	8-floor passive residential building, Tianjin [5]	Residential, 3000 m ² [5]	Sensitivity analysis [5]	Mass timber RP 73% vs. RC 34%; CLT GWP −174.0 kgCO ₂ /m ² [5]
ScanR [6]	Building in Ithaca, NY [6]	Building slated for deconstruction [6]	Rapid implementation with minimal training [6]	Results documented in Table 2 [6]

Tool	Case Study	Building Type / Scale	Validation Method	Key Quantitative Result
BIM3LCA [3]	La María residential building, Seville [3]	Public housing, multi-family [3]	Manual vs. automatic quantity take-off comparison [3]	Real-time LCSA calculations consistent with manual take-offs [3]
Regenerate [8]	Live new-build project (concept stage) [8]	New construction [8]	Stakeholder feedback and industry workshops [8]	Over 520 downloads [8]
Matching Algorithm [7]	Sletteløkka community house, Oslo [7]	Public building (two-storey timber) [7]	GWP comparison with/without reclaimed materials [7]	82 reclaimed elements substituted for 140 demand elements; 40% GWP reduction [7]
DT-MFA Integration [9]	MCSI building, University of Pittsburgh [9]	University building [9]	Eurostat MFA methodology, ODYM [9]	Not mentioned [9]
Ataee et al. model [11]	Boulevard du Souverain, Brussels [11]	Road + light railway infrastructure [11]	Based on construction details and fieldwork [11]	REGHG represents ~30% of LCEGHG over 60 years [11]
Dynamo-Python [12]	Not specified [12]	Not specified [12]	Not mentioned [12]	Not mentioned [12]
Passaporte de Materiais [13]	Wood frame panel, Tecverde, Paraná [13]	Single-family homes (wood frame) [13]	Not mentioned [13]	49 parameters across 9 categories populated [13]
Digital Material Bank [14]	Post-earthquake Marche region, Italy [14]	Post-disaster CDW [14]	Baseline trial [14]	Not mentioned [14]
RaMa-Scene [15]	Use cases (not building-specific) [15]	Economy-wide scenarios [15]	Live tests with practitioners, scientists, students [15]	Not mentioned [15]
WasteBIM [4]	Single-family residence (PCML system) [4]	Residential [4]	Comparative analysis across construction systems [4]	Less efficient in PCML; corrections needed for accuracy [4]

Thirteen of the 15 studies report at least one case study or pilot application. The strongest validation evidence comes from tools that compare automated outputs against manual calculations: BIM3LCA demonstrated consistency between manual and automatic material quantity take-offs [3], and WE-BIM Add-in validated its results through comparison with manual calculations [1]. The matching algorithm achieved a measurable 40% reduction in GWP when substituting reclaimed timber elements [7]. Eco2soft produced substantial comparative results, showing mass timber buildings achieving 73% recycling potential versus 34% for reinforced concrete, with CLT variants achieving negative carbon emissions at $-174.0 \text{ kgCO}_2/\text{m}^2$ [5].

Two studies lack any case study validation: the Dynamo-Python workflow by Carrion Da Luz et al. does not report a specific applied case [12], and the Passaporte de Materiais study does not describe formal validation methods beyond populating parameters from company databases [13]. WasteBIM notably revealed performance issues, showing lower efficiency when applied to the cast-in-place concrete wall (PCML) construction system and requiring corrections for accurate results [4], compounded by incompatibility with Revit versions after 2019 [4].

Circular Economy Functionality

The tools vary considerably in the depth and breadth of their circular economy support. The most comprehensive circularity assessment is offered by the Fernandes et al. methodology, which calculates Material Circularity Indicator (MCI), Product Circularity Indicator (PCI), System Circularity Indicator (SCI), and Building Circularity Indicator (BCI), incorporating a Disassembly Index for end-of-life assessment [10]. Regenerate provides a structured CE design workflow organized around four overarching principles — Design for Adaptability, Design for Deconstructability, Circular Material Selection, and Resource Efficiency [8] — and collects recycling and waste metrics for benchmarking [8].

Tools supporting material reuse strategies include ScanR, which generates material databases to link local supply with demand for deconstruction contexts [6]; the matching algorithm, which optimizes reclaimed material assignment to minimize environmental impact [7]; and the Digital Material Bank, which creates a cloud-accessible database of reusable building elements from post-earthquake demolition [14]. The Passaporte de Materiais supports end-of-life scenario considerations by documenting material characteristics for recovery and reuse across 49 parameters [13].

End-of-life scenario modeling is explicitly supported by the CW-LCA-BIM tool, which simulates recycling versus disposal scenarios and quantifies avoided emissions and energy savings [2], and by the DT-MFA integration using Dynamic MFA through ODYM [9]. RaMa-Scene operates at a fundamentally different scale, supporting macro-economic CE scenario modeling using the EXIOBASE input-output database rather than building-level analysis [15].

Synthesis

The apparent contradiction across these 15 studies is that while a substantial and growing number of digital tools claim to support circular economy assessment in construction, none fully implements the standardized MFA methodologies (EW-MFA, Dynamic MFA, Level(s) Indicator 2.1) that the research question prioritizes. This disconnect can be explained through several mechanisms.

Scale mismatch between MFA methodologies and tool design. EW-MFA and Dynamic MFA are macroeconomic or stock-level methodologies designed for national or regional material accounting. The 13 building-scale tools reviewed operate at the project or element level, where waste quantification factors [1], LCA impact factors [2], and recycling potential calculations [5] serve as practical proxies. Only the DT-MFA integration by Geremicca et al. bridges this gap by applying the Eurostat MFA methodology and ODYM at the building level [9], and the parametric model by Ataee et al. integrates hybrid MFA with LCA for infrastructure assets [11]. Both, however, remain custom frameworks rather than packaged tools. RaMa-Scene operates at the appropriate macroeconomic scale for EW-MFA-type analysis but uses input-output monetary data rather than physical material flows, and is not connected to BIM environments [15].

Dominance of waste quantification over comprehensive material flow tracking. Six tools (WE-BIM Add-in, CW-LCA-BIM, WasteBIM, Dynamo-Python workflow, Regenerate waste metrics, and the Digital Material Bank) focus primarily on construction waste outputs rather than tracking complete material flows from extraction through end-

of-life [1, 2, 4, 8, 12, 14]. This concentration reflects the regulatory pressure from the EU Waste Framework Directive's 70% recovery target for non-hazardous construction waste [2] and the practical availability of waste generation data, which is more readily quantifiable than full life-cycle material stocks. The tools that do address full life-cycle tracking — Eco2soft [5] and BIM3LCA [3] — achieve this through LCA databases rather than MFA-specific frameworks.

Maturity and accessibility tradeoffs. The most methodologically rigorous approaches (Dynamic MFA via ODYM [9], hybrid LCA-MFA for infrastructure [11]) are custom-coded integrations that do not meet the accessibility criterion of packaged, deployable tools. Conversely, the most accessible tools — Regenerate with 520+ downloads [8] and RaMa-Scene as a free web platform [15] — offer the least specificity for building-level MFA. The Revit-based plugins (WE-BIM Add-in, CW-LCA-BIM, BIM3LCA, WasteBIM) occupy a middle ground: they are functional within professional BIM environments and provide real-time automated outputs [1–3], but their commercial availability and distribution remain largely unspecified [1–3]. WasteBIM's restriction to Revit 2019 [4] illustrates a common sustainability challenge for academic tool development.

Geographic and regulatory context dependence. Tool calibration is often region-specific: WE-BIM Add-in uses waste quantification factors validated from residential buildings in Andalusia, Spain [1]; Eco2soft's default parameters are more suitable for European buildings, limiting applicability in China without local database adaptation [5]; and the Digital Material Bank is designed specifically for Italian post-earthquake regulatory contexts [14]. Tools that aim for broader applicability, such as Regenerate [8] and BIM3LCA [3], achieve this through more generic circularity principles or standardized frameworks (ISO 21931-1 [3]) but may sacrifice the precision of locally calibrated waste indices.

In summary, the current landscape reveals a field in transition. At the building scale, the most functional tools for practitioners are Revit-based plugins that automate construction waste quantification and LCA-based environmental assessment (WE-BIM Add-in [1], CW-LCA-BIM [2], BIM3LCA [3]), supplemented by the Eco2soft standalone tool for recycling potential analysis [5] and Regenerate for CE engagement and benchmarking [8]. For material reuse and end-of-life applications, ScanR [6] and the Grasshopper-based matching algorithm [7] offer practical pre-demolition and design-for-reuse capabilities. Formal MFA methodologies remain confined to research prototypes, with the Geremicca et al. DT-MFA integration [9] representing the closest approximation to Dynamic MFA in a digital twin context. No tool currently provides a fully integrated, packaged solution that automates standardized MFA indicators (EW-MFA, Dynamic MFA, or Level(s) 2.1) within a commercially available BIM environment.

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Material Usage and the volumetric tracking of resource consumption within the circular economy framework. The research objective is to find established software solutions or plugins that automate the estimation of "Material Mass per Unit Area," "Bill of Materials (BoM)," or "Resource Intensity" by utilizing recognized methodologies such as the EU Level(s) Indicator 2.1, Bill of Quantities (BoQ) extraction, or Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative material selection to automated, quantitative digital assessments of the total weight and fraction of materials required throughout a building's lifecycle for data published before December 2025.

Validated BIM-based tools for automated quantitative material assessment include Autodesk Revit's native Quantity Take-Off (the most widely adopted), the WE-BIM Add-in for waste classification, One-Click LCA and Tally for life cycle environmental impact, Naviate Rebar Extension for rebar detailing, Diroots for schedule extraction, and Dynamo for generative design optimization—all operating within Revit (or ArchiCAD for general QTO)—but none currently integrates EU Level(s) Indicator 2.1 or Material Passport methodologies, leaving a significant gap between available tool capabilities and the full lifecycle material tracking demanded by circular economy frameworks.

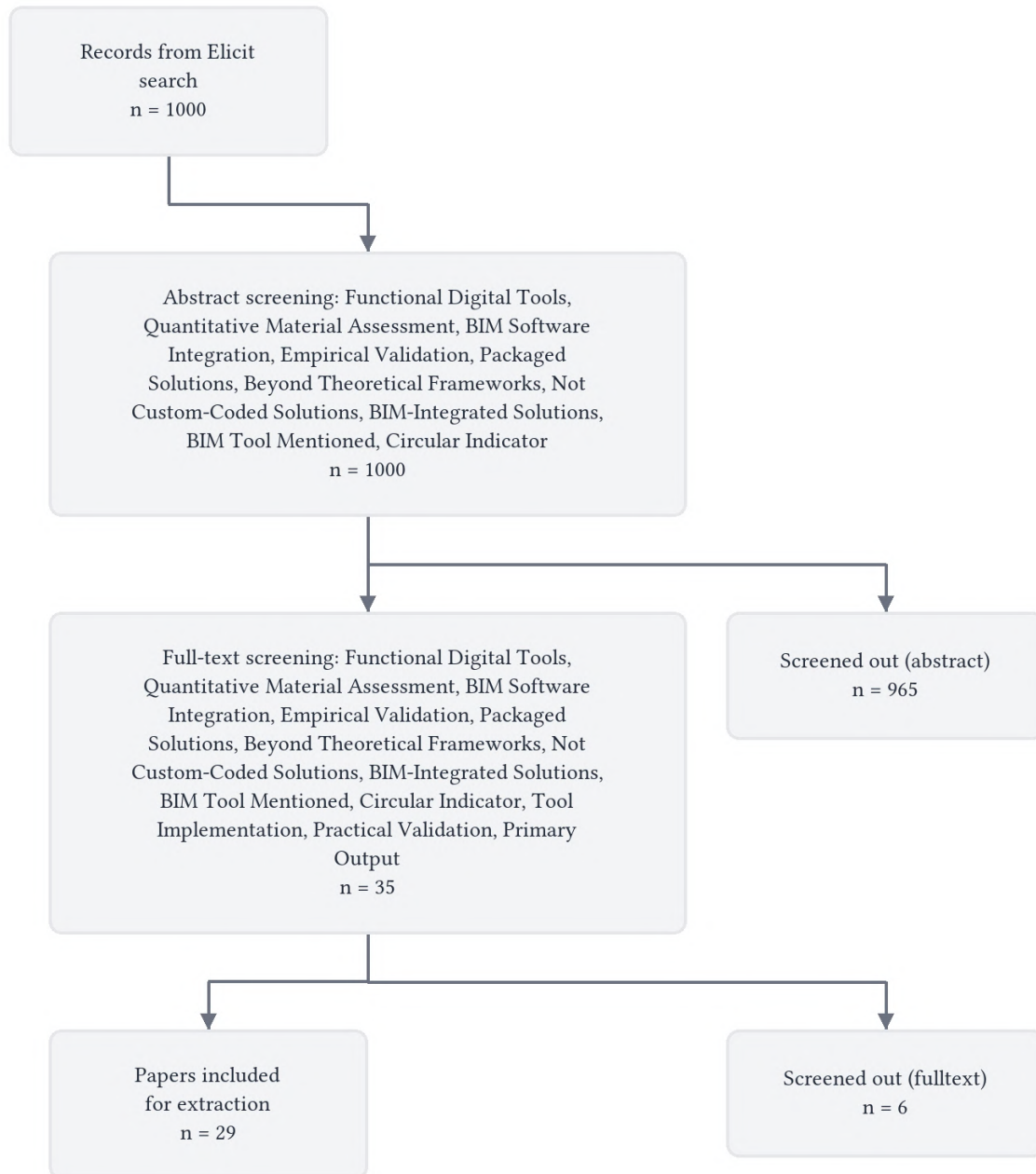
Abstract

Twenty-nine case studies published before December 2025 identify a landscape of BIM-based tools for quantitative material assessment that is dominated by Autodesk Revit's native Quantity Take-Off functionality, used in 28 of 29 sources [1–3], with ArchiCAD 23 representing the sole alternative BIM authoring platform [4]. Five purpose-built plugins extend native capabilities into more specialized domains: the WE-BIM Add-in automates construction waste classification per European List of Waste codes [5], One-Click LCA [6] and Tally [7] provide integrated life cycle environmental impact assessment, Naviate Rebar Extension supports detailed rebar BoM extraction [8], and Diroots enhances schedule extraction [9]. Dynamo visual programming scripts enable generative design optimization, yielding material savings of up to 13.38% in concrete and 20.87% in reinforcement [10], while a BIM–Digital Twin

framework reduced rebar cutting waste by 93.58% [11]. For straightforward volumetric QTO, reported deviations between BIM and manual methods range from near-zero (0.0007%–0.03% for simple geometries [2, 12]) to over 35% for complex buildings where manual methods are error-prone [13], with time savings of 20–90% depending on task complexity [3, 12].

Despite this breadth of validated tools, no identified solution currently implements the EU Level(s) Indicator 2.1 framework or Material Passport standards for full lifecycle material tracking [5, 12, 14]. Advanced technology integrations—such as Digital Twins [11, 15]—remain isolated to individual studies, and no tool combines waste quantification, environmental impact assessment, and material passport functionality in a single workflow. The evidence confirms that accessible, packaged BIM tools can reliably automate BoQ extraction and volumetric material tracking, but a significant gap persists between current tool capabilities and the comprehensive, lifecycle-oriented quantitative material assessment envisioned by circular economy policy frameworks.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction Material Usage and the volumetric tracking of resource consumption within the circular economy framework. The research objective is to find established software solutions or plugins that automate the estimation of "Material Mass per Unit Area," "Bill of Materials (BoM)," or "Resource Intensity" by utilizing recognized methodologies such as the EU Level(s) Indicator 2.1, Bill of Quantities (BoQ) extraction, or Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative material selection to automated, quantitative digital assessments of the total weight and fraction of materials required throughout a building's lifecycle for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tools:** Does the study describe actual functional software solutions, plugins, or integrated tools that are operational and accessible to practitioners (rather than purely theoretical concepts)?
- **Quantitative Material Assessment:** Do the tools specifically address automated calculation of material quantities, masses, volumes, or resource consumption metrics?
- **BIM Software Integration:** Do the tools operate within or integrate with recognized BIM platforms (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, Tekla Structures)?
- **Empirical Validation:** Does the study demonstrate practical implementation through real-world case studies, pilot projects, or empirical simulations in professional contexts?
- **Packaged Solutions:** Are the tools described as software packages, plugins, or add-ins that can be obtained and implemented by practitioners without requiring custom programming?
- **Beyond Theoretical Frameworks:** Does the study go beyond presenting only conceptual models, theoretical approaches, or methodological discussions to include actual software tools?
- **Not Custom-Coded Solutions:** Are the tools described as something other than one-off programming solutions, custom scripts, or proprietary code that isn't available as packaged tools for broader professional use?
- **BIM-Integrated Solutions:** Do the solutions integrate with BIM workflows rather than operating as standalone databases without integration capabilities with 3D modeling environments?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

- **Circular Indicator:** Does the paper claim to quantitatively measure Construction Material Usage? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

35 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional Digital Tools:** Does the study describe actual functional software solutions, plugins, or integrated tools that are operational and accessible to practitioners (rather than purely theoretical concepts)?
- **Quantitative Material Assessment:** Do the tools specifically address automated calculation of material quantities, masses, volumes, or resource consumption metrics?
- **BIM Software Integration:** Do the tools operate within or integrate with recognized BIM platforms (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, Tekla Structures)?
- **Empirical Validation:** Does the study demonstrate practical implementation through real-world case studies, pilot projects, or empirical simulations in professional contexts?
- **Packaged Solutions:** Are the tools described as software packages, plugins, or add-ins that can be obtained and implemented by practitioners without requiring custom programming?
- **Beyond Theoretical Frameworks:** Does the study go beyond presenting only conceptual models, theoretical approaches, or methodological discussions to include actual software tools?
- **Not Custom-Coded Solutions:** Are the tools described as something other than one-off programming solutions, custom scripts, or proprietary code that isn't available as packaged tools for broader professional use?
- **BIM-Integrated Solutions:** Do the solutions integrate with BIM workflows rather than operating as standalone databases without integration capabilities with 3D modeling environments?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Construction Material Usage? Answer 'No' if it is purely qualitative.
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

29 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific nomenclature and categorization of each digital tool or BIM plugin designed for quantitative construction material assessment, including:

- Exact tool/plugin name as referenced in the study
- Tool type (integrated BIM plugin, standalone software, web-based platform, etc.)
- Required BIM authoring software environment (e.g., Autodesk Revit, ArchiCAD, Rhino/Grasshopper, SketchUp, etc.)
- Version information if specified
- Developer/organization responsible for the tool
- **Quantitative Assessment Capabilities:**

Extract all quantitative material assessment functionalities and automated calculations the tool performs, specifically focusing on:

- Material Mass per Unit Area calculations
- Bill of Materials (BoM) generation and extraction
- Resource Intensity measurements
- Volumetric tracking of material consumption
- Construction waste quantification
- Material flow analysis capabilities
- Any other automated quantitative material metrics the tool calculates
- Level of automation (fully automated, semi-automated, manual input required)

- **Validation Evidence:**

Extract detailed information about practical validation and professional implementation of the tool, including:

- Case study details (building types, locations, scale)
- Empirical simulation results and accuracy metrics
- Professional contexts where tested (architectural firms, construction companies, research institutions)
- Validation methodology used
- Comparison with manual calculations or other tools
- Accuracy percentages or error margins reported
- Real-world application examples
- User acceptance or adoption evidence

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

Choose one of them: BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support Construction Material Usage? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The 29 included sources encompass a range of study types, geographic contexts, building typologies, and digital tools applied to quantitative material assessment within BIM environments. The majority employ Autodesk Revit as the primary BIM authoring platform, with a smaller number utilizing specialized plugins or alternative software. Most studies adopt a comparative case study design, benchmarking BIM-derived quantities against conventional manual calculations.

Study	Full Text Retrieved?	Primary Tool(s)	Tool Type	Host BIM Software	Building/Infrastructure Type	Geographic Context
R. Quiñones et al., 2022	Yes	WE-BIM Add-in [5]	BIM Plugin [5]	Revit 2021 [5]	Residential building [5]	Seville, Spain [5]
D. Widjaja et al., 2025	Yes	Revit + Dynamo + Navisworks [11]	Integrated BIM Framework [11]	Autodesk Revit [11]	High-rise commercial building (22 floors) [11]	Korea [11]
N'tani Chingaipe et al., 2023	Yes	One-Click LCA plugin [6]	BIM Plugin [6]	Autodesk Revit [6]	Public buildings (steel and concrete frames) [6]	Zhejiang, China [6]
Syach Reza Fachlevi et al., 2023	Yes	Autodesk Revit 2022 [16]	Standalone BIM Software [16]	Autodesk Revit 2022 [16]	Multipurpose building [16]	Indonesia [16]

Study	Full Text Retrieved?	Primary Tool(s)	Tool Type	Host BIM Software	Building/Infrastructure Type	Geographic Context
Aorigele Orgil Borjigin et al., 2022	Yes	Autodesk Revit 2021 [15]	Integrated BIM Framework [15]	Revit 2021 [15]	Light rail infrastructure (PCAT slabs) [15]	Europe (H2020 project) [15]
Amannda Cândido de Senna et al., 2019	Yes	Autodesk Revit [17]	Standalone BIM Software [17]	Autodesk Revit [17]	Residential building (PMCMV program) [17]	Brazil [17]
Marina Montemuro Varela et al., 2020	Yes	ArchiCAD 23 [4]	Standalone BIM Software [4]	ArchiCAD 23 [4]	Residential building (PMCMV program) [4]	Brazil [4]
Rizki Adithya Wibowo et al., 2025	Yes	Autodesk Revit 2025 [1]	Standalone BIM Software [1]	Autodesk Revit 2025 [1]	Multi-story building (XYZ Project) [1]	Indonesia [1]
Taufik Rendra et al., 2025	Yes	Autodesk Revit [18]	Standalone BIM Software [18]	Autodesk Revit [18]	Irrigation infrastructure (North Building) [18]	Indonesia [18]
Hossam Wefki et al., 2025	Yes	Dynamo 2.18.1 in Revit 2024 [10]	Visual Programming Script [10]	Autodesk Revit 2024 [10]	Chalet and multi-story building [10]	Not specified [10]
Muhamad Yusuf Mahendra et al., 2023	Yes	Autodesk Revit [19]	Standalone BIM Software [19]	Autodesk Revit [19]	Steel structure (industrial building) [19]	Cikarang, Indonesia [19]
Prajakta Jangam et al., 2023	Yes	Revit + Autodesk Insight [20]	Integrated BIM Framework [20]	Autodesk Revit [20]	Slum rehabilitation residential (G+2) [20]	Pune, India [20]
Dila Rivana et al., 2024	Yes	Revit [21]	Standalone BIM Software [21]	Autodesk Revit [21]	Mid-rise commercial building [21]	Indonesia [21]
Gerardo Sistos-Sescosse et al., 2025	Yes	Tally [7]	BIM Plugin [7]	Autodesk Revit [7]	Office building (flooring systems) [7]	Sydney, Australia [7]
Quini Athaya Putri et al., 2024	Yes	Autodesk Revit [22]	Standalone BIM Software [22]	Autodesk Revit [22]	Government building (Satpol PP) [22]	Bantul, Indonesia [22]

Study	Full Text Retrieved?	Primary Tool(s)	Tool Type	Host BIM Software	Building/Infrastructure Type	Geographic Context
Fransisca Michille Tigauw et al., 2023	Yes	Autodesk Revit [23]	Standalone BIM Software [23]	Autodesk Revit [23]	Skewed bridge substructure [23]	Indonesia [23]
Filza Wiranti et al., 2022	Yes	Autodesk Revit [2]	Standalone BIM Software [2]	Autodesk Revit [2]	Box culvert (toll road) [2]	Indonesia [2]
Tika Tresnandhini Kusuman-ingroem et al., 2023	Yes	Revit [12]	Standalone BIM Software [12]	Autodesk Revit [12]	Elevated toll road (JORR) [12]	Indonesia [12]
I Putu Leo Pramana et al., 2024	Yes	Autodesk Revit 2024 [24]	Standalone BIM Software [24]	Autodesk Revit 2024 [24]	Lecture hall (two-story, ~1,032 m ²) [24]	Indonesia [24]
P. Agus et al., 2025	Yes	Autodesk Revit [3]	Standalone BIM Software [3]	Autodesk Revit [3]	Traditional village office building [3]	Bali, Indonesia [3]
Vanessa Lima Carneiro et al., 2023	Yes	Revit + Naviate Rebar Extension [8]	BIM Plugin [8]	Revit 2022 [8]	Educational module (government) [8]	Brazil [8]
Andi Rizky Vanath et al., 2023	Yes	Autodesk Revit 2021 (Student Version) [25]	Standalone BIM Software [25]	Autodesk Revit 2021 [25]	Educational building (Poltekkes) [25]	Maluku, Indonesia [25]
Gigih Prasetya et al., 2024	Yes	Revit + Navisworks [13]	Standalone BIM Software + Plugin [13]	Autodesk Revit [13]	Lecture hall building [13]	Indonesia [13]
Elvis Alejandro Carrizales Lujan et al., 2023	Yes	Autodesk Revit [26]	Integrated BIM Framework [26]	Autodesk Revit 2021 [26]	Three educational institutions [26]	Peru [26]
Ariany Frederika et al., 2024	Yes	Revit + Navisworks [27]	Standalone BIM Software [27]	Autodesk Revit [27]	Hospital building [27]	Denpasar, Indonesia [27]
Prof. Ravi G. Maske et al., 2023	Yes	Revit + Diroots + Dynamo [9]	BIM Plugin [9]	Autodesk Revit [9]	G+14 residential building; LIC Ludhiana project [9]	India [9]

Study	Full Text Retrieved?	Primary Tool(s)	Tool Type	Host BIM Software	Building/Infrastructure Type	Geographic Context
Bianca de Cássia Agrela Gabalde et al., 2025	Yes	Revit [14]	Standalone BIM Software [14]	Autodesk Revit [14]	Residential towers (160 units) [14]	São Paulo, Brazil [14]
Leticia Moreira Alves et al., 2025	Yes	Autodesk Revit [28]	Not specified [28]	Autodesk Revit [28]	Industrial electrical panels [28]	Maceió, Brazil [28]
Osvaldo Sélos Rodrigues et al., 2020	Yes	Revit + Dynamo [29]	Integrated BIM Framework [29]	Autodesk Revit [29]	Retrofit project (campus building) [29]	Limeira, Brazil [29]

Full texts were retrieved for all 29 sources. The geographic distribution is heavily weighted toward Indonesia (13 studies), followed by Brazil (6 studies), with the remainder spread across Spain, Korea, China, Europe, India, Australia, and Peru. Building types span residential, commercial, institutional, and infrastructure projects. Autodesk Revit is the dominant BIM platform, used in 28 of 29 studies, with only one study employing ArchiCAD 23 [4]. The tool types range from native Revit QTO functionality (the majority) to dedicated BIM plugins (WE-BIM Add-in, One-Click LCA, Tally, Naviate Rebar Extension, Diroots), visual programming scripts (Dynamo), and integrated multi-software frameworks.

Tool Identification and Categorization

The identified tools can be grouped into distinct categories based on their primary function and relationship to the BIM authoring environment.

Tool Name	Category	Primary Function	Host Software	Automation Level	Accessibility
WE-BIM Add-in [5]	BIM Plugin [5]	Construction waste quantification per LoW [5]	Revit 2021 [5]	Fully automated [5]	Not publicly available [5]
One-Click LCA [6]	BIM Plugin [6]	LCA with embodied carbon and material mass [6]	Autodesk Revit [6]	Fully automated [6]	Commercial [6]
Tally [7]	BIM Plugin [7]	TRACI LCA impact indicators [7]	Autodesk Revit [7]	Fully automated [7]	Commercial [7]

Tool Name	Category	Primary Function	Host Software	Automation Level	Accessibility
Naviate Rebar Extension [8]	BIM Plugin [8]	Rebar BoM and quantitative extraction [8]	Revit 2022 [8]	Semi-automated [8]	Commercial (Symetri) [8]
Dirroots [9]	BIM Plugin [9]	Schedule extraction and element identification [9]	Autodesk Revit [9]	Semi-automated [9]	Not specified [9]
Dynamo (Revit) [10]	Visual Programming Script [10]	Generative design optimization for material savings [10]	Revit 2024 [10]	High with manual parameter input [10]	Open-source (bundled with Revit) [10]
Dynamo (general use) [29]	Visual Programming Script [29]	Budget automation and data export [29]	Autodesk Revit [29]	Semi-automated [29]	Open-source [29]
Autodesk Revit (native QTO) [1]	Standalone BIM Software [1]	Volumetric QTO for concrete and rebar [1]	Self-contained [1]	Fully automated [1]	Commercial [2]
ArchiCAD 23 [4]	Standalone BIM Software [4]	Material mass, BoM, and volumetric tracking [4]	Self-contained [4]	Semi-automated [4]	Commercial [4]
Autodesk Navisworks [11]	Standalone BIM Software [11]	Clash detection and schedule integration [13]	Standalone [13]	High [13]	Commercial [13]
Autodesk Insight [20]	Integrated BIM Framework [20]	Energy consumption and CO2 analysis [20]	Autodesk Revit [20]	Semi-automated [20]	Commercial [20]

The overwhelming dominance of Autodesk Revit's native QTO functionality is notable: 20 of the 29 studies rely primarily on Revit's built-in schedule and material extraction capabilities without additional plugins [1–3, 12, 14, 16–19, 21–28]. Only five studies employ purpose-built plugins for material assessment (WE-BIM Add-in [5], One-Click LCA [6], Tally [7], Naviate Rebar Extension [8], and Dirroots [9]), and these tend to address more specialized assessment needs such as waste classification, life cycle impacts, or rebar detailing. ArchiCAD represents the sole non-Autodesk BIM authoring environment in the review [4].

Quantitative Assessment Capabilities

The core quantitative capabilities reported across studies vary considerably in scope and sophistication. The table below summarizes the primary automated outputs and assessment functionalities documented in each source.

Study	Volumetric QTO	BoM/BoQ Extraction	Waste Quantification	LCA/Carbon Assessment	Cost Estimation	Automation Level
R. Quiñones et al., 2022	Yes (m ³ per element) [5]	No [5]	Yes (per LoW codes) [5]	No [5]	No [5]	Fully automated [5]
D. Widjaja et al., 2025	Yes [11]	Yes [11]	Yes (rebar cutting waste) [11]	No [11]	Yes (17.75% savings) [11]	Fully automated [11]
N'tani Chingaipe et al., 2023	Yes [6]	Yes [6]	No [6]	Yes (embodied carbon) [6]	No [6]	Fully automated [6]
Syach Reza Fachlevi et al., 2023	Yes [16]	Yes [16]	No [16]	No [16]	No [16]	Semi-automated [16]
Aorigele Orgil Borjigin et al., 2022	Yes [15]	Yes (BoQ) [15]	No [15]	Yes (LCA: energy, CO2) [15]	Yes (LCC) [15]	Fully automated [15]
Amannda Cândido de Senna et al., 2019	No [17]	No [17]	No [17]	No [17]	No [17]	Semi-automated [17]
Marina Montemuro Varela et al., 2020	Yes [4]	Yes [4]	No [4]	No [4]	No [4]	Semi-automated [4]
Rizki Adithya Wibowo et al., 2025	Yes [1]	Yes [1]	Implied [1]	No [1]	Yes [1]	Fully automated [1]
Taufik Rendra et al., 2025	Yes [18]	Yes [18]	No [18]	No [18]	No [18]	Fully automated [18]
Hossam Wefki et al., 2025	Yes [10]	Yes [10]	No [10]	No [10]	Yes [10]	High with manual input [10]
Muhamad Yusuf Mahendra et al., 2023	Yes [19]	Yes [19]	Implied [19]	No [19]	Yes (5D) [19]	Fully automated [19]
Prajakta Jangam et al., 2023	No [20]	No [20]	No [20]	Yes (energy, CO2) [20]	Yes [20]	Semi-automated [20]
Dila Rivana et al., 2024	Yes [21]	Yes (BoQ) [21]	No [21]	No [21]	No [21]	Fully automated [21]

Study	Volumetric QTO	BoM/BoQ Extraction	Waste Quantification	LCA/Carbon Assessment	Cost Estimation	Automation Level
Gerardo Sistos-Sescosse et al., 2025	No [7]	No [7]	No [7]	Yes (TRACI LCA) [7]	No [7]	Fully automated [7]
Quini Athaya Putri et al., 2024	Yes [22]	Yes [22]	Yes (0.97% waste level) [22]	No [22]	No [22]	Fully automated [22]
Fransisca Michille Tigauw et al., 2023	Yes [23]	No [23]	No [23]	No [23]	Yes [23]	Semi-automated [23]
Filza Wiranti et al., 2022	Yes [2]	No [2]	No [2]	No [2]	No [2]	Fully automated [2]
Tika Tresnandhini Kusumaningroem et al., 2023	Implied [12]	No [12]	No [12]	No [12]	No [12]	Semi-automated [12]
I Putu Leo Pramana et al., 2024	Yes [24]	Yes [24]	Implied [24]	No [24]	Yes [24]	Fully automated [24]
P. Agus et al., 2025	Yes [3]	Yes [3]	No [3]	No [3]	Yes [3]	Fully automated [3]
Vanessa Lima Carneiro et al., 2023	Yes [8]	Yes [8]	No [8]	No [8]	No [8]	Semi-automated [8]
Andi Rizky Vanath et al., 2023	Yes [25]	Yes [25]	No [25]	No [25]	Yes [25]	Fully automated [25]
Gigih Prasetia et al., 2024	Yes [13]	No [13]	No [13]	No [13]	No [13]	High [13]
Elvis Alejandro Carrizales Lujan et al., 2023	No [26]	No [26]	No [26]	No [26]	Yes [26]	Semi-automated [26]
Ariany Frederika et al., 2024	Yes [27]	Yes [27]	No [27]	No [27]	Yes [27]	Fully automated [27]

Study	Volumetric QTO	BoM/BoQ Extraction	Waste Quantification	LCA/Carbon Assessment	Cost Estimation	Automation Level
Prof. Ravi G. Maske et al., 2023	Implied [9]	Implied [9]	No [9]	No [9]	No [9]	Semi-automated [9]
Bianca de Cássia Agrela Gabalde et al., 2025	Yes [14]	Yes [14]	No [14]	No [14]	Yes [14]	Fully automated [14]
Leticia Moreira Alves et al., 2025	No [28]	Yes [28]	No [28]	No [28]	Yes [28]	Automated [28]
Osvaldo Sélos Rodrigues et al., 2020	No [29]	Yes [29]	No [29]	No [29]	Yes [29]	Semi-automated [29]

Volumetric QTO is the most prevalent capability, reported in approximately 22 of 29 studies. BoM/BoQ extraction is the second most common function (approximately 19 studies). Only three studies address construction waste quantification directly: the WE-BIM Add-in classifies waste by European List of Waste codes [5], the Widjaja et al. framework reduces rebar cutting waste from 12.93% to 0.83% [11], and Putri et al. report an average waste level of 0.97% using BIM-optimized cutting patterns [22]. LCA or embodied carbon assessment is addressed by only four studies, using One-Click LCA [6], Tally [7], Autodesk Insight [20], or a Revit-to-Excel LCA workflow [15]. No study explicitly references the EU Level(s) Indicator 2.1 or Material Passport frameworks.

Effects: Accuracy and Efficiency of BIM-Based Quantification

The central quantitative finding across the majority of studies is the deviation between BIM-derived and manually calculated quantities for concrete, reinforcement, and other structural materials. The table below consolidates reported accuracy metrics.

Study	Material Element	BIM vs. Manual Deviation	Direction of BIM Estimate	Time Savings	Cost Impact
Syach Reza Fachlevi et al., 2023	Footplate, foundation, column, beam	0.11–2.72 m ³ (absolute) [16]	Mixed [16]	Not reported [16]	Not reported [16]
Rizki Adithya Wibowo et al., 2025	Columns	0% (identical: 891.6 m ³) [1]	Equal [1]	Not reported [1]	Not reported [1]
Rizki Adithya Wibowo et al., 2025	Beams	11.12% (122.88 m ³ less) [1]	BIM lower [1]	Not reported [1]	IDR 294.8M savings [1]
Taufik Rendra et al., 2025	Structural elements	±2% [18]	Mixed [18]	Faster than manual [18]	Not reported [18]

Study	Material Element	BIM vs. Manual Deviation	Direction of BIM Estimate	Time Savings	Cost Impact
Hossam Wefki et al., 2025	Concrete	Up to 13.38% savings [10]	BIM lower (optimized) [10]	120–930 s computation [10]	2.7%–17% cost reduction [10]
Hossam Wefki et al., 2025	Reinforcement	Up to 20.87% savings [10]	BIM lower (optimized) [10]	120–930 s computation [10]	Included in above [10]
Muhamad Yusuf Mahendra et al., 2023	Steel structure	3.45% lower [19]	BIM lower [19]	Not reported [19]	3.45% savings [19]
Dila Rivana et al., 2024	Profile steel	+47.78% [21]	BIM higher [21]	Faster for design changes [21]	Not reported [21]
Dila Rivana et al., 2024	Concrete	+21.83% [21]	BIM higher [21]	Faster for design changes [21]	Not reported [21]
Dila Rivana et al., 2024	Reinforcement	+2.00% [21]	BIM higher [21]	Faster for design changes [21]	Not reported [21]
Quini Athaya Putri et al., 2024	Reinforcing steel (columns/beams)	11% overall [22]	BIM lower [22]	Not reported [22]	0.97% waste level [22]
Fransisca Michille Tigauw et al., 2023	Concrete (bridge)	10.66% [23]	Not specified [23]	Not reported [23]	IDR 1.05B difference [23]
Fransisca Michille Tigauw et al., 2023	Reinforcement (bridge)	5.13% [23]	Not specified [23]	Not reported [23]	IDR 207M difference [23]
Filza Wiranti et al., 2022	All elements (box culvert)	0.03% overall [2]	BIM slightly higher [2]	Not reported [2]	Not reported [2]
Tika Tresnandhini Kusuman-ingroem et al., 2023	Concrete	0.0007% [12]	Negligible [12]	49% faster (initial); 90% faster (redesign) [12]	Not reported [12]
Tika Tresnandhini Kusuman-ingroem et al., 2023	Rebar	0.6742% [12]	Negligible [12]	20% faster (initial); 67% faster (redesign) [12]	Not reported [12]
I Putu Leo Pramana et al., 2024	Concrete (columns/beams)	26.92% optimization [24]	BIM lower (optimized) [24]	Not reported [24]	Significant savings [24]
I Putu Leo Pramana et al., 2024	Reinforcement	13.55% optimization [24]	BIM lower (optimized) [24]	Not reported [24]	Significant savings [24]
P. Agus et al., 2025	Concrete	11.63% [3]	Not specified [3]	37.72% faster overall [3]	24.02% lower cost [3]

Study	Material Element	BIM vs. Manual Deviation	Direction of BIM Estimate	Time Savings	Cost Impact
P. Agus et al., 2025	Formwork	-5.99% [3]	BIM lower [3]	Included above [3]	Included above [3]
P. Agus et al., 2025	Reinforcement	36.26% [3]	Not specified [3]	Included above [3]	Included above [3]
Vanessa Lima Carneiro et al., 2023	56 budget items	Average 1.19% difference [8]	Mixed [8]	Not reported [8]	0.83% cost decrease [8]
Andi Rizky Vanath et al., 2023	Structural work	10.4% [25]	Not specified [25]	Not reported [25]	Not reported [25]
Andi Rizky Vanath et al., 2023	Architectural work	5.4% [25]	Not specified [25]	Not reported [25]	Not reported [25]
Gigih Prasetya et al., 2024	Structural (manual vs. Revit)	35.76% [13]	Not specified [13]	Not reported [13]	Not reported [13]
Gigih Prasetya et al., 2024	Architectural (manual vs. Revit)	43.14% [13]	Not specified [13]	Not reported [13]	Not reported [13]
Gigih Prasetya et al., 2024	Structural (Revit vs. Clash Detection)	1.51% [13]	Near-identical [13]	Not reported [13]	Not reported [13]
Elvis Alejandro Carrizales Lujan et al., 2023	Architecture (3 projects)	5.35%–27.0% [26]	BIM higher [26]	Not reported [26]	+7.46%, +9.34%, -1.56% [26]
Elvis Alejandro Carrizales Lujan et al., 2023	Structures (3 projects)	-4.4%–30.6% [26]	Mixed [26]	Not reported [26]	Included above [26]
Ariany Frederika et al., 2024	Concrete	-5.73% (ratio 1:0.946) [27]	BIM lower [27]	Not reported [27]	-2.95% cost [27]
Ariany Frederika et al., 2024	Reinforcement	-2.42% (ratio 1:0.976) [27]	BIM lower [27]	Not reported [27]	IDR 552.5M savings [27]

The reported deviations between BIM and manual methods span an extraordinarily wide range, from near-zero (0.0007% for concrete [12]; 0.03% overall [2]) to over 40% (43.14% for architectural elements [13]; 47.78% for profile steel [21]). Time savings, where reported, are substantial: up to 49% for initial concrete QTO and 90% when accommodating design changes [12], and a 37.72% reduction in overall project preparation time [3].

For waste quantification specifically, the WE-BIM Add-in demonstrated that switching from a reinforced concrete structure to a steel structure reduced waste by 56% and increased the recycling rate by 49% [5]. The Widjaja et al. framework achieved a 93.58% reduction in rebar cutting waste through heuristic optimization algorithms integrated

into the BIM-Digital Twin workflow [11]. Putri et al. reported an average waste level of only 0.97% when using BIM-optimized bar bending schedules [22].

For generative design optimization, the Dynamo-based model by Wefki et al. achieved material savings of up to 13.38% in concrete and 20.87% in reinforcement across three case studies, with cost reductions between 2.7% and 17% [10].

Synthesis

The wide variance in reported BIM-versus-manual deviations across studies warrants careful examination rather than a simple conclusion that "BIM is more accurate." Several factors systematically explain the heterogeneity.

Modeling fidelity and level of development. Studies reporting near-zero deviations (0.0007%–0.67% [12]; 0.03% [2]; $\pm 2\%$ [18]) involved relatively simple, well-defined structural geometries: a box culvert [2], an elevated toll road segment [12], and an irrigation building [18]. In these cases, both BIM and manual methods model essentially the same geometry with equivalent assumptions. In contrast, studies reporting large deviations (35–47% [3, 13, 21]) involved complex buildings with design changes during construction [21], or cases where the manual method was documented as highly error-prone [13]. The Gigih Prasetya et al. finding that Revit and Clash Detection differed by only 1.51% for structural elements while manual methods deviated by 35.76% [13] strongly suggests that in complex projects, the manual method—not BIM—is the primary source of discrepancy.

Direction of deviation and its implications for material use. When BIM produces lower estimates (as in several Indonesian and Brazilian studies [1, 19, 22, 27]), this typically indicates that BIM captures geometric intersections and joint details that manual methods over-count, resulting in material savings. Conversely, when BIM produces higher estimates (as in Dila Rivana et al. [21] and Carrizales Lujan et al. [26]), this may reflect BIM's capacity to capture details that manual methods omit. These opposing directions are not contradictory; they reflect different baseline assumptions in the conventional methods used across countries and project types.

Distinction between QTO accuracy and design optimization. Most studies (approximately 20 of 29) evaluate BIM as a measurement tool—comparing its volumetric output against a conventional calculation of the same design. A smaller subset uses BIM as an optimization tool to actively reduce material quantities through generative design [10] or rebar layout optimization [11]. The latter category reports larger "savings" (13–21% for materials [10]; 93.58% waste reduction [11]) because the comparison is between an optimized and a non-optimized design, not merely between two measurement methods applied to the same design. The Pramana et al. study reporting 26.92% concrete optimization [24] falls in this optimization category rather than a pure measurement comparison.

Plugin-augmented versus native Revit workflows. The specialized plugins (WE-BIM Add-in, One-Click LCA, Tally) provide capabilities that native Revit does not: waste classification by European codes [5], full life cycle environmental impact assessment [6, 7], and material-level environmental indicators [7]. These tools address the circular economy dimension of the research question more directly than native QTO workflows. However, their validation evidence is limited to single case studies each, and none has been benchmarked against the EU Level(s) framework or Material Passport standards. The WE-BIM Add-in is the only tool that directly automates waste type classification [5], making it the most aligned with circular economy material tracking among the identified solutions.

Geographic and regulatory context. The concentration of studies in Indonesia (13 of 29) reflects the recent regulatory mandate for BIM adoption by the Indonesian Ministry of Public Works [3, 27]. These studies share a common validation approach (BIM vs. manual per national standards such as SNI 2847 [16]) but vary widely in reported deviations, from 0.03% [2] to 36.26% [3]. This variation is better explained by project complexity and modeler expertise than by geographic factors per se. The Brazilian studies similarly adopt a comparison-with-traditional-methods

approach but benefit from the government's PMCMV program providing standardized designs for benchmarking [4, 17].

Ease of use and adoption barriers. All tools were described as user-friendly and not requiring coding for basic operations [1, 2, 5–7]. However, several studies note that achieving accurate results requires careful model setup, appropriate family selection, and sufficient level of detail [8, 14, 17]. The Dynamo-based tools, while technically accessible through visual programming, require familiarity with parametric logic [10, 11, 29]. The Osvaldo Sélos Rodrigues et al. study explicitly noted that interoperability between Revit, Dynamo, and Excel remains a challenge [29].

Technology integrations. Advanced integrations remain rare. Only Widjaja et al. incorporated Digital Twin technology with real-time scheduling synchronization [11], and Borjigin et al. used a digital twin environment for lifecycle assessment [15]. No study reported integrations with Material Passports, blockchain, IoT, GIS, or 3D printing for material tracking purposes [3, 5, 12, 14]. The LCA-focused studies used plugin-based integrations (One-Click LCA with Revit [6]; Tally with Revit [7]; OpenLCA with ArchiCAD via Ecoinvent [4]) but these remain siloed from construction waste management and material passport workflows.

In summary, for straightforward volumetric QTO of concrete and reinforcement in well-defined structural geometries, Autodesk Revit's native functionality provides accuracy within 0–5% of manual methods and substantial time savings (20–90% depending on the task). For waste quantification aligned with circular economy goals, the WE-BIM Add-in is the only purpose-built tool identified, though it lacks broad availability. For environmental impact assessment, One-Click LCA and Tally provide automated LCA integration within Revit, though their decision outputs can be inconclusive when multiple impact indicators conflict [7]. For material optimization beyond measurement, Dynamo-based generative design scripts offer the most significant material reduction potential (up to 20.87% reinforcement savings [10]), but these require parametric setup expertise. None of the identified tools currently integrates the full material lifecycle tracking envisioned by the EU Level(s) Indicator 2.1 or Material Passport frameworks.

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of the Resource Potential Indicator (RPI) and the technical feasibility of waste redirection within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Waste Reuse Potential," "Redirection Feasibility," or "Technical Recovery Capacity" by utilizing the resource-based paradigm introduced by Park and Chertow, which treats waste as a potential resource contingent on technological knowledge rather than material composition alone. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste management to automated, quantitative digital assessments of the technical potential for resource recovery and reuse for data published before December 2025.

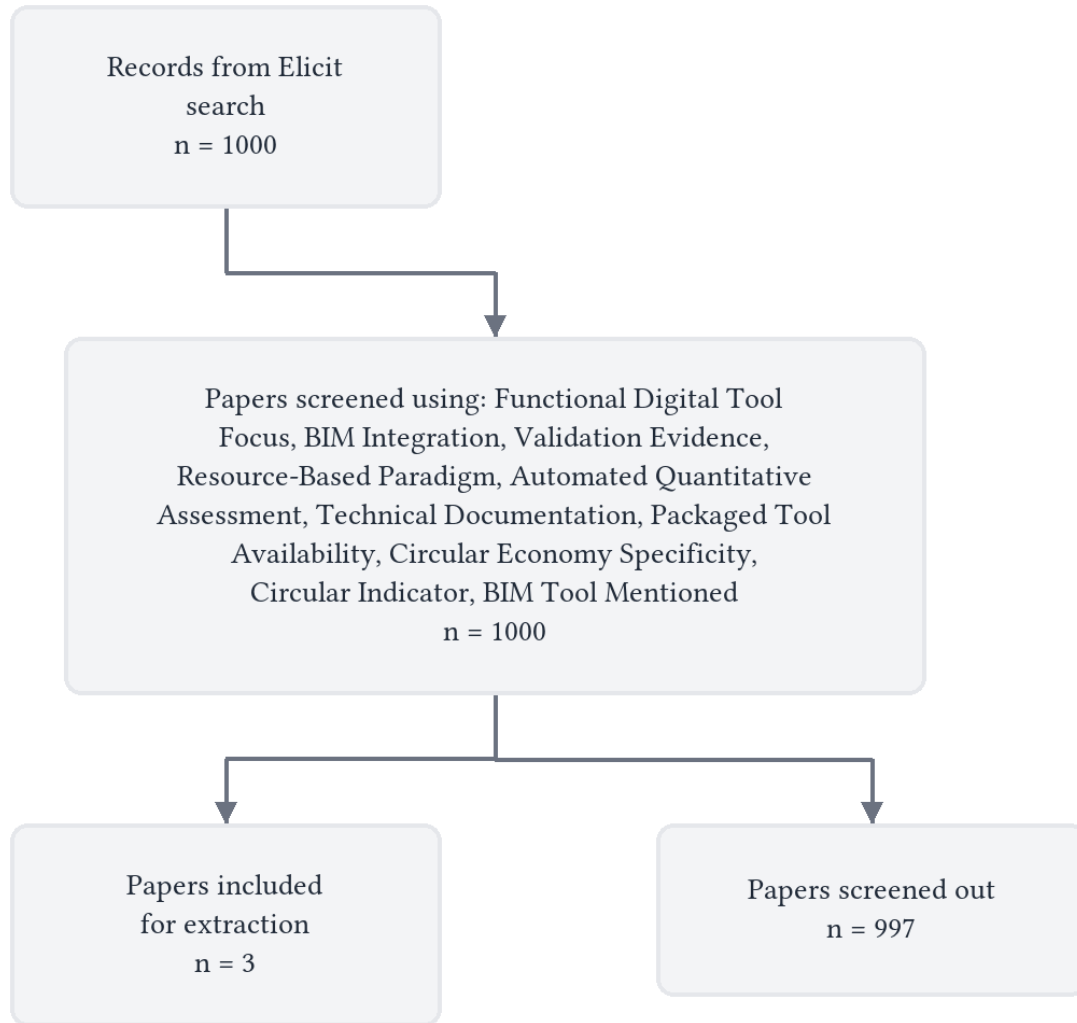
No established, packaged BIM plugin or digital tool currently exists that automates the quantitative assessment of the Resource Potential Indicator (RPI) or applies Park and Chertow's resource-based paradigm to waste redirection feasibility; the closest identified approaches — WasteBIM (a Revit API for waste volume quantification), a Plugin for Circularity (computing multi-level circularity indicators including disassembly potential), and a RecyclingGraph framework (assessing material recyclability through connection matrices) — each address adjacent aspects of circular economy assessment but none is commercially available, none evaluates resource recovery potential as a function of technological knowledge, and all remain at research-prototype or conceptual stages.

Abstract

No established, packaged digital tool or BIM plugin currently automates the quantitative assessment of the Resource Potential Indicator (RPI) as defined by Park and Chertow's resource-based paradigm. Three BIM-linked approaches were identified — WasteBIM, a Plugin for Circularity, and a RecyclingGraph/ConnectionMatrix framework — but none explicitly treats waste value as contingent on technological knowledge rather than material composition alone [1–3]. WasteBIM is a functional Autodesk Revit API (limited to versions up to 2019) that automates construction waste volume quantification using fixed loss indices but does not evaluate resource recovery potential [1, 1]. The

Plugin for Circularity, developed as part of the Circular EcoBIM project, computes multi-level circularity indicators (MCI, PCI, SCI, BCI), Embodied Energy, and Life Cycle GWP through a GUI-based BIM plugin connected to external databases [2, 2], and evaluates disassembly potential and end-of-life material strategies [2], making it the closest existing approach to automated technical recovery assessment. The RecyclingGraph approach provides a structured method for evaluating material recyclability and connection disassembly feasibility [3] but remains a conceptual framework without software implementation [3]. None of the three tools is commercially distributed or openly downloadable [1–3], and none incorporates context-dependent technological feasibility assessment — a core requirement of the resource-based paradigm. The transition from qualitative waste management to automated, quantitative digital assessment of resource recovery potential within BIM environments remains incomplete in the current tool landscape.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed

for the quantitative assessment of the Resource Potential Indicator (RPI) and the technical feasibility of waste redirection within the circular economy framework. The research objective is to find established software solutions or plugins that automate the evaluation of "Waste Reuse Potential," "Redirection Feasibility," or "Technical Recovery Capacity" by utilizing the resource-based paradigm introduced by Park and Chertow, which treats waste as a potential resource contingent on technological knowledge rather than material composition alone. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste management to automated, quantitative digital assessments of the technical potential for resource recovery and reuse for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tool Focus:** Does the study describe functional digital tools or BIM plugins specifically designed for quantitative assessment of Resource Potential Indicator (RPI), waste reuse potential, redirection feasibility, or technical recovery capacity within circular economy frameworks?
- **BIM Integration:** Are the tools integrated with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, Tekla Structures) rather than being standalone or proprietary systems?
- **Validation Evidence:** Does the study provide validation through case studies, empirical simulations, or professional implementation contexts demonstrating real-world functionality?
- **Resource-Based Paradigm:** Do the tools utilize the resource-based paradigm treating waste as potential resources based on technological recovery potential rather than material composition alone?
- **Automated Quantitative Assessment:** Does the study focus on automated, quantitative digital assessments rather than manual, qualitative, or purely theoretical approaches?
- **Technical Documentation:** Does the study provide sufficient technical documentation including tool nomenclature, BIM platform requirements, and verifiable implementation details?
- **Packaged Tool Availability:** Are the tools available as packaged tools or plugins accessible to practitioners (not custom-coded scripts or algorithms)?
- **Circular Economy Specificity:** Does the study specifically emphasize waste resource potential or circular economy applications rather than general sustainability assessment?
- **Circular Indicator:** Does the paper claim to quantitatively measure Resource Potential Indicator (RPI)? Answer 'No' if it is purely qualitative.
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract complete identification details for digital tools or BIM plugins designed for circular economy waste assessment, including:

- Specific tool/plugin name (exact nomenclature as stated in publication)
- Tool type (standalone software, BIM plugin, API, extension, etc.)
- Required BIM authoring software environment (Autodesk Revit, Rhino/Grasshopper, ArchiCAD, etc.)
- Integration method (native plugin, external API, workflow integration)
- Version or release information if available

- **Circular Economy Functions:**

Extract all circular economy and waste management functions performed by the tool, specifically focusing on:

- Resource Potential Indicator (RPI) assessment capabilities
- Waste Reuse Potential evaluation features
- Redirection Feasibility analysis functions
- Technical Recovery Capacity assessment tools
- Material recyclability analysis
- Component disassembly evaluation
- Resource recovery optimization
- Any other circular economy metrics or assessments supported

- **Quantitative Assessment Methods:**

Extract how the tool automates quantitative assessment and moves beyond qualitative approaches, including:

- Specific quantitative metrics calculated (numerical indicators, percentages, scores)
- Automated calculation methods and algorithms used
- Data inputs required for quantitative analysis
- Output formats and visualization of quantitative results
- Integration with databases or material libraries for automated assessment
- Workflow automation features for batch processing or iterative analysis

- **Resource-Based Paradigm Application:**

Extract evidence of how the tool applies the resource-based paradigm (Park and Chertow approach) that treats waste as potential resource based on technological knowledge rather than material composition alone, including:

- How the tool considers technological knowledge in waste assessment
- Methods for evaluating resource potential beyond material properties
- Integration of technical feasibility factors in resource evaluation
- Consideration of available technologies for waste redirection
- Assessment of context-dependent resource recovery possibilities

- **Validation Evidence:**

Extract all evidence of practical validation through case studies, empirical simulations, or professional implementations, including:

- Specific case study descriptions and contexts
- Types of buildings or projects where tool was tested
- Professional environments where tool was implemented
- Empirical simulation details and scenarios tested
- Results or outcomes from validation studies
- Performance metrics or effectiveness measures reported
- Comparison with alternative methods or manual processes

- **Tool Accessibility:**

Extract information about the practical accessibility and availability of the tool as a packaged solution, including:

- Current availability status (commercially available, open source, research prototype)
- Distribution method (software marketplace, direct download, licensing)
- Installation requirements and technical specifications
- User interface description and ease of use factors
- Training or expertise requirements for implementation
- Clear distinction from purely theoretical frameworks or custom-coded scripts
- Evidence that tool is available as packaged solution rather than custom development

- **Primary Documentation:**

Extract complete bibliographic details for the primary publication documenting the tool's practical implementation, including:

- Official DOI of the primary publication
- Full citation details (authors, title, journal/conference, year, volume, pages)
- Publication type (journal article, conference paper, technical report)
- Additional supporting publications or technical documentation
- Any supplementary materials or datasets mentioned
- Publication date to confirm it meets the pre-December 2025 requirement

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

Choose one of them: BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support Resource Potential Indicator (RPI)? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

Study	Full Text Retrieved?	Tool Name	Tool Type	BIM Software	Validation Context	Availability Status
Marielle Martins Santos et al., 2022	Yes	WasteBIM [1]	BIM Plugin / API [1]	Autodesk Revit (up to version 2019) [1]	Single-family residence using in-situ cast concrete wall system (PCML) [1]	Research prototype [1]
J. Fernandes et al., 2022	Yes	Plugin for Circularity (Building Automated Characterisation methodology) [2]	BIM Plugin [2]	Not explicitly stated [2]	Historical building in Lisbon (1919–1945 archetype) [2]	Under development; not yet packaged [2]
D. Schwede et al., 2019	Yes	RecyclingGraph / Connection-Matrix approach (no formal tool name) [3]	Not specified; conceptual framework requiring further implementation [3]	Not specified [3]	Four wall structure typologies modeled in BIM [3]	Conceptual; not available as packaged solution [3]

All three sources were retrieved in full text. None of the identified approaches constitutes a commercially available, packaged tool explicitly designed for calculating a Resource Potential Indicator (RPI) as formulated by Park and

Chertow. Rather, each addresses adjacent aspects of circular economy assessment within BIM environments at varying levels of maturity: WasteBIM is a functional research prototype limited to waste quantification [1], the Plugin for Circularity is an in-development BIM add-on for circularity indicator computation [2], and the RecyclingGraph approach remains a theoretical framework awaiting software implementation [3].

Circular Economy Functions and Quantitative Assessment Capabilities

Feature Domain	WasteBIM (Santos et al., 2022)	Plugin for Circularity (Fernandes et al., 2022)	RecyclingGraph Approach (Schwede et al., 2019)
RPI Assessment	Not mentioned [1]	Not explicitly mentioned [2]	Not explicitly mentioned [3]
Waste Reuse Potential	Not addressed; focuses on waste volume quantification [1]	Evaluates end-of-life strategies including reuse, refurbishment, remanufacture, and recycling [2]	Assesses recyclability and incineration ability of materials [3]
Disassembly Evaluation	Not addressed [1]	Disassembly Index quantifying connections between construction elements [2]	Connections evaluated for disassembly potential and material compatibility [3]
Circularity Indicators	Not addressed [1]	MCI, PCI, SCI, BCI, Embodied Energy, Life Cycle GWP [2]	Integrated recyclability assessment ($C = \text{SQRT}(A \times B)$) [3]
Resource Recovery Optimization	Not addressed [1]	Tailored refurbishment strategies for increased material recovery [2]	Prediction of demolition material flows and necessary processing technologies [3]
Automated Quantitative Output	General Report, PGRCC, Real vs. Planned Report (waste volumes, dumpster counts) [1]	Circularity indicator scores per square meter [2]	Numeric values and color-coded matrices; future automation envisioned [3]
Database Integration	Revit material library [1]	Classification System Database (Uniclass 2015), Building Characterisation Database, Circularity Database [2]	Implied for future development [3]

None of the three tools directly implements an RPI assessment or explicitly applies the Park and Chertow resource-based paradigm [1–3]. WasteBIM is narrowly scoped to construction waste quantification using loss indices applied to BIM-extracted material quantities, generating reports on waste volumes per phase and required dumpsters [1]. It does not evaluate resource recovery potential or consider technological knowledge as a determinant of waste value [1]. The Plugin for Circularity comes closest to a resource-based assessment by computing multi-level circularity indicators (MCI at material level through BCI at building level) and integrating Embodied Energy and Life Cycle GWP metrics [2], while also evaluating disassembly potential and end-of-life material strategies [2]. The RecyclingGraph approach provides a structured method for evaluating material recyclability and connection disassembly through

matrix representations [3], and its assessment of material compatibility and processing technology requirements aligns conceptually with evaluating technical recovery capacity [3], though it lacks software implementation.

Validation Evidence

Validation Aspect	WasteBIM (Santos et al., 2022)	Plugin for Circularity (Fernandes et al., 2022)	RecyclingGraph Approach (Schwede et al., 2019)
Case Study Type	Single-family residence, PCML system [1]	Historical residential building, Lisbon (1919–1945 archetype) [2]	Four wall structure typologies [3]
Validation Method	Six-step methodology including BIM modeling and comparative analysis of waste quantities [1]	BIM modeling with circularity indicator computation [2]	Translation of BIM models into RecyclingGraphs and ConnectionMatrixes [3]
Key Outcomes	API less efficient for PCML system than previously validated systems; corrections required for accurate results [1]	Qualitative results on materials and composition; circularity indicators per m ² reported [2]	Prediction of demolition material flows and identification of processing technologies [3]
Comparison with Alternatives	Compared with prior validated systems [1]	Not mentioned [2]	Not mentioned [3]
Professional Implementation	Autodesk Revit environment [1]	BIM software environment [2]	Not mentioned [3]

All three approaches were validated at a case-study level rather than through large-scale professional deployment. WasteBIM was the only tool tested in a working Autodesk Revit environment, though its performance was found to be limited for the specific construction system evaluated, requiring manual corrections to loss indices [1]. The Plugin for Circularity was tested on a single historical building archetype, providing circularity indicator outputs per square meter and demonstrating a "reliable basis for data collection and standardization" [2]. The RecyclingGraph approach was validated purely through the structural analysis of four wall typologies without implementation in a professional software environment [3].

Tool Accessibility and Usability

Accessibility Dimension	WasteBIM (Santos et al., 2022)	Plugin for Circularity (Fernandes et al., 2022)	RecyclingGraph Approach (Schwede et al., 2019)
Availability	Research prototype; available upon request [1]	Under development; available upon request [2]	Not available as software [3]
Coding Required	No coding required; some manual data entry needed [1]	No coding; GUI-based plug-and-play design intended [2]	Further development needed; coding status unclear [3]

Accessibility Dimension	WasteBIM (Santos et al., 2022)	Plugin for Circularity (Fernandes et al., 2022)	RecyclingGraph Approach (Schwede et al., 2019)
User Friendliness	Simple interactivity but could benefit from further automation [1]	Designed with GUI for architect accessibility [2]	Not yet implemented as user-facing tool [3]
Version/Platform Constraints	Limited to Revit versions up to 2019 [1]	BIM software not specified [2]	BIM software not specified [3]
Open Source / Commercial	Not specified [1]	Not specified [2]	Not specified [3]
Technology Integrations	Autodesk Revit, Dynamo routines [1]	Uniclass 2015 database, Building Characterisation Database, Circularity Database, EU Level(s) Framework compatibility [2]	Implied future database integration [3]

No tool identified in this review is commercially distributed or openly downloadable. WasteBIM, while functional, is constrained to Autodesk Revit versions no newer than 2019 [1] and is described as needing updates to loss indices and expanded construction system coverage [1]. The Plugin for Circularity features a graphical user interface for archetype identification and is designed to be accessible to architects without coding expertise [2], but remains under active development as part of the Circular EcoBIM project [2]. The RecyclingGraph approach explicitly requires further development before it can be considered an applicable design tool [3].

Synthesis

The central finding of this review is that no established, packaged digital tool or BIM plugin currently automates the quantitative assessment of the Resource Potential Indicator (RPI) as defined by Park and Chertow's resource-based paradigm. None of the three identified approaches explicitly treats waste value as contingent on technological knowledge rather than material composition alone [1–3].

The apparent gap can be explained by examining what each tool actually measures. WasteBIM operates at the most basic level of waste management digitization — converting BIM geometry into material mass and waste volume estimates using fixed loss indices [1]. It does not assess whether generated waste has recovery potential; it simply quantifies how much waste will be produced. The Plugin for Circularity advances considerably further by computing multi-level circularity indicators (MCI through BCI) and integrating life-cycle environmental metrics [2], and by evaluating disassembly connections and end-of-life strategies for materials [2]. This positions it as the closest existing approach to automated technical recovery assessment, though it frames its outputs in terms of circularity scores rather than resource potential per se. The RecyclingGraph approach provides a rigorous structural representation of material-connection relationships that could theoretically underpin an RPI calculation — particularly through its assessment of disassembly feasibility and material compatibility [3] — but it remains a representational framework without software implementation [3].

The maturity gap across these tools is also relevant. WasteBIM, despite being the most implementation-ready as a functional Revit plugin, is the least aligned with resource-based assessment because it does not evaluate recovery potential [1]. Conversely, the RecyclingGraph approach, which is most conceptually aligned with evaluating technical recovery capacity through its material-connection analysis [3], is the furthest from practical software availability

[3]. The Plugin for Circularity occupies a middle position on both dimensions: it incorporates substantive circularity metrics and disassembly evaluation [2] while being actively developed as an installable BIM plugin with a graphical interface [2].

A key limitation shared across all three tools is the absence of context-dependent technological feasibility assessment. While the Plugin for Circularity evaluates end-of-life strategies and the RecyclingGraph approach considers processing technologies [3], neither dynamically incorporates regionally available recycling infrastructure or evolving technological capabilities — a core requirement of the Park and Chertow paradigm. The transition from qualitative waste management to automated, quantitative digital assessment of resource recovery potential remains incomplete across the current tool landscape. The most actionable path forward appears to involve extending circularity-indicator-based BIM plugins (such as the Plugin for Circularity) with technology-dependent resource potential modules that incorporate regional processing capability data and dynamic feasibility scoring.

References

1. Marielle Martins Santos, Reymard Sávio Sampaio de Melo, Renata Degraf Miara, Elaine Pinto Varela Alberte (2022) Avaliação de facilidade de uso e eficiência de API para quantificação de resíduos a partir de modelo BIM. XIX ENCONTRO NACIONAL DE TECNOLOGIA DO AMBIENTE CONSTRUÍDO. <https://doi.org/10.46421/entac.v19i1.1978>
2. J. Fernandes, P. Ferrão, J. Silvestre, et al (2022) Advancing Circular Economy in the existing building stock: A methodology to support building characterisation for sustainable refurbishment design. Acta Polytechnica CTU Proceedings. <https://doi.org/10.14311/app.2022.38.0599>
3. D. Schwede (2019) Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling. IOP Conference Series: Earth and Environment. <https://doi.org/10.1088/1755-1315/323/1/012044>

Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Circularity and the performance of resources within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Recyclability," "Circular Content," or "Reusability Potential" by utilizing recognized methodologies such as the Material Circularity Indicator (MCI), the Longevity Indicator (LI), or Multi-Criteria Decision Analysis (MCDA) coupling material flow and life cycle data. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative circular design principles to automated, quantitative digital assessments of material recovery and resource efficiency suitable for early-stage architectural decision-making for data published before December 2025.

Of the ten tools identified across the literature, only two—One Click LCA (a Revit plugin) and Eco2soft (an LCA platform with Revit connectivity)—are commercially available, case-study-validated solutions for quantitative circularity-related assessment in BIM environments, though neither directly automates Material Circularity Indicator (MCI) computation, revealing that no packaged BIM plugin currently exists that implements recognized circularity-specific methodologies such as MCI or the Longevity Indicator in an accessible, plug-and-play format for early-stage architectural decision-making.

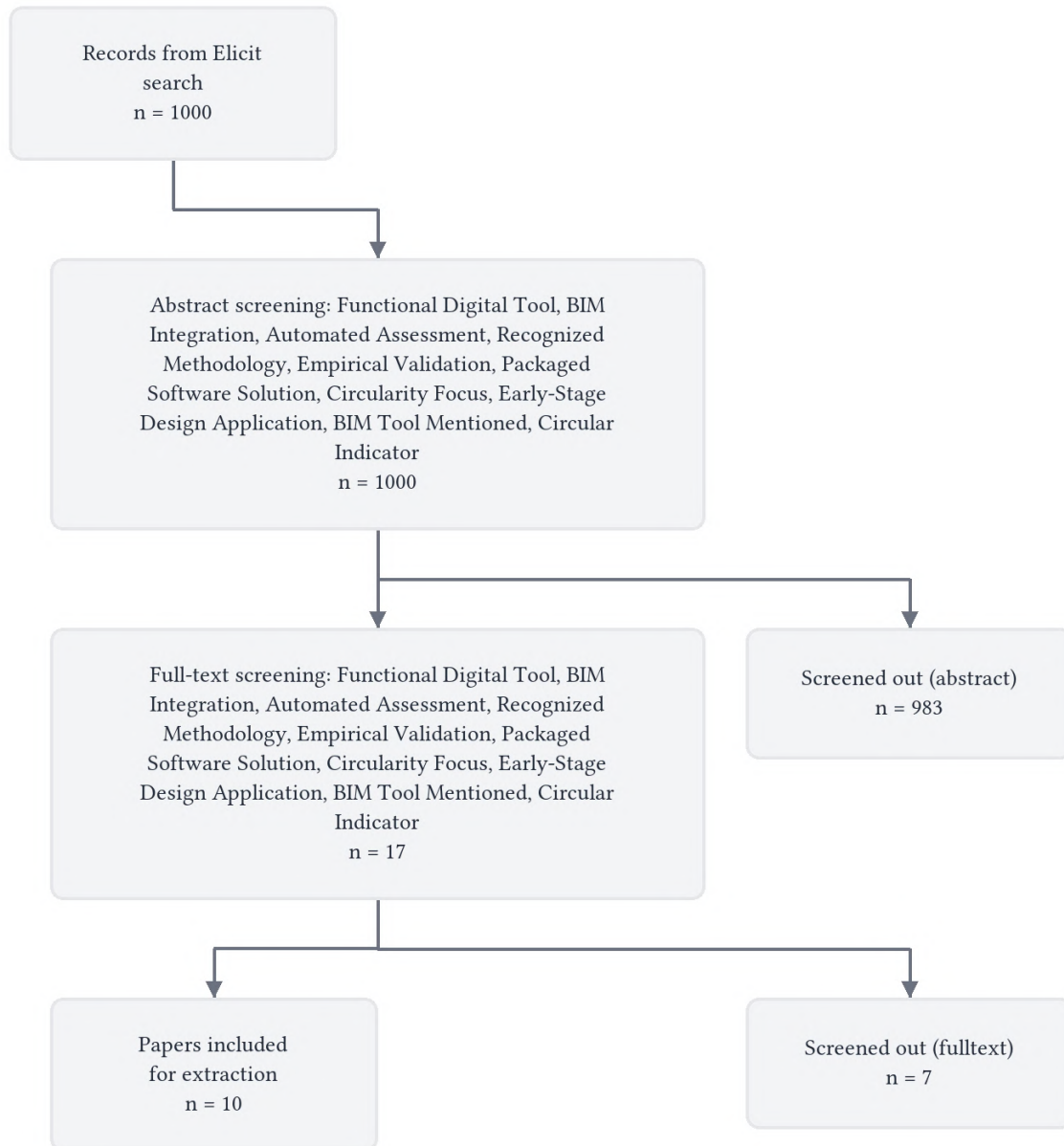
Abstract

Ten sources published between 2019 and 2025 were examined to identify functional, BIM-integrated digital tools for quantitative circular economy assessment in building design. Of the ten tools identified, only two represent commercially available, packaged solutions validated through case studies: **Eco2soft**, a designer-friendly LCA platform integrated with Autodesk Revit 2019 via an Excel-based workflow that computes Recycling Potential using the Material Cycle Status methodology [1, 1, 1], and **One Click LCA**, a Revit plugin that evaluates reuse content indicators (ranging from 39% to 73% across construction systems) alongside parametric life cycle assessment [2, 2, 2]. Neither tool, however, directly implements the Material Circularity Indicator (MCI) methodology. The only tool explic-

itly computing MCI and its hierarchical extensions (Product, System, and Building Circularity Indicators) remains an unnamed research prototype without a specified BIM platform or public access pathway [3, 3, 3]. A Dynamo-based framework within Revit employs hybrid MCDA (AHP-TOPSIS) for ranking demolition waste management scenarios by sustainability score [4, 4], offering the closest alignment with the MCDA criterion but requiring visual programming expertise rather than functioning as a plug-and-play tool [5]. The remaining tools—including the BIM-based Material Passport with BuildingOne [6], the PixelFrame structural reuse system in Rhino/Karamba3D [7], the CELAVI Python framework [8], and the CPD Toolkit [9] —are either research prototypes available upon request, require coding, or remain under development.

The current landscape thus reveals a significant gap between recognized circularity methodologies and their implementation in accessible BIM tools: commercially mature platforms provide environmental metrics with circularity as a supplementary output, while dedicated circularity assessment tools have not yet transitioned from research prototypes to packaged software. Autodesk Revit is the dominant host platform, appearing in five of seven BIM-connected tools [1, 2, 4, 5], with no solutions identified for ArchiCAD. For practitioners requiring immediate BIM-integrated circularity assessment, One Click LCA and Eco2soft are the most viable options, though automated MCI computation within a packaged BIM plugin does not yet exist in commercially available form.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Circularity and the performance of resources within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Recyclability," "Circular Content," or "Reusability Potential" by utilizing recognized methodologies such as the Material Circularity Indicator (MCI), the Longevity Indicator (LI), or Multi-Criteria Decision Analysis (MCDA) coupling material flow and life cycle data. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative circular design principles to automated, quantitative digital assessments of material recovery and resource efficiency suitable for early-stage architectural decision-making for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tool:** Does the study describe a functional digital tool or BIM plugin specifically designed for quantitative material circularity assessment (rather than purely theoretical discussions)?
- **BIM Integration:** Is the tool integrated with or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, Tekla)?
- **Automated Assessment:** Does the tool provide automated quantitative measurement of at least one key circularity metric (recyclability, circular content, or reusability potential)?
- **Recognized Methodology:** Does the tool implement recognized circularity assessment methodologies such as Material Circularity Indicator (MCI), Longevity Indicator (LI), Multi-Criteria Decision Analysis (MCDA), or other validated circular economy frameworks?
- **Empirical Validation:** Does the study include empirical validation through case studies, simulations, or practical implementations in professional contexts?
- **Packaged Software Solution:** Is the tool available as a packaged software solution (installable plugin, extension, or standalone software) rather than requiring custom coding or extensive programming knowledge?
- **Circularity Focus:** Does the tool specifically focus on material circularity metrics rather than being limited to general environmental impact assessment without circularity quantification?
- **Early-Stage Design Application:** Is the tool applicable to early-stage architectural decision-making during design development phases (rather than being exclusively for post-construction or demolition-only applications)?

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Material Circularity? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

17 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional Digital Tool:** Does the study describe a functional digital tool or BIM plugin specifically designed for quantitative material circularity assessment (rather than purely theoretical discussions)?
- **BIM Integration:** Is the tool integrated with or compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, Bentley MicroStation, Tekla)?
- **Automated Assessment:** Does the tool provide automated quantitative measurement of at least one key circularity metric (recyclability, circular content, or reusability potential)?
- **Recognized Methodology:** Does the tool implement recognized circularity assessment methodologies such as Material Circularity Indicator (MCI), Longevity Indicator (LI), Multi-Criteria Decision Analysis (MCDA), or other validated circular economy frameworks?
- **Empirical Validation:** Does the study include empirical validation through case studies, simulations, or practical implementations in professional contexts?
- **Packaged Software Solution:** Is the tool available as a packaged software solution (installable plugin, extension, or standalone software) rather than requiring custom coding or extensive programming knowledge?
- **Circularity Focus:** Does the tool specifically focus on material circularity metrics rather than being limited to general environmental impact assessment without circularity quantification?
- **Early-Stage Design Application:** Is the tool applicable to early-stage architectural decision-making during design development phases (rather than being exclusively for post-construction or demolition-only applications)?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Material Circularity? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

10 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific nomenclature and technical details of any digital tools or BIM plugins designed for quantitative circular economy assessment, including:

- Exact name/brand of the tool or plugin
- Version number (if specified)
- Required BIM authoring software environment (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, etc.)
- Type of integration (native plugin, external software with BIM connectivity, standalone tool with BIM import/export)
- Developer/company name

- **Circularity Assessment Capabilities:**

Extract all quantitative circular economy metrics and assessment capabilities specifically related to material circularity, including:

- Specific metrics measured (Recyclability, Circular Content, Reusability Potential, Material Recovery Rates, etc.)
- Recognized methodological frameworks used (Material Circularity Indicator (MCI), Longevity Indicator (LI), Multi-Criteria Decision Analysis (MCDA), material flow analysis, life cycle data integration)
- Types of data inputs required (material properties, quantities, life cycle data, etc.)
- Output formats and metrics provided

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

Choose from one of them: BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

Results

Characteristics of Included Studies

The review encompasses ten sources published between 2019 and 2025, spanning BIM-integrated plugins, standalone frameworks, and integrated workflows for quantitative circular economy assessment in the built environment and product design domains. The studies vary considerably in scope: some focus on building-level circularity assessment during design or end-of-life phases, while others address product-level recycling metrics or supply-chain-scale circularity modeling. Table 1 summarizes the key characteristics.

Study	Full Text Retrieved?	Research Focus	Tool Type	Tool Name	Host BIM Software	Circularity Metrics
J. Fernandes et al., 2022	Yes	Building re-furbishment circularity assessment using MCI-based indicators [3]	BIM Plugin [3]	Unnamed BIM plugin (referred to as "Fernandes et al. (2022) Script") [3]	Not specified [3]	MCI, PCI, SCI, BCI, EE, GWP [3]
Qiming Sun et al., 2022	Yes	Comparing recycling potential of mass timber vs. concrete buildings [1]	Integrated BIM Framework [1]	Eco2soft [1]	Autodesk Revit 2019 [1]	Recycling Potential (RP), GWP, AP, PEI [1]
M. Honic et al., 2019	Yes	BIM-based Material Passport for recycling potential and environmental impact [6]	Integrated BIM Framework [6]	BIM-based Material Passport (with BuildingOne) [6]	Not specified [6]	Recycling grade (1–5), GWP, AP, PEI [6]
Dongchen Han et al., 2024	Yes	BIM-based LCSA and MCDA for demolition waste management [4]	Integrated BIM Framework [4]	eToolLCD + Dynamo [4]	Autodesk Revit [4]	Recycling rate, sustainability scores via AHP-TOPSIS [4]
M. Al-Obaidy et al., 2022	Yes	Parametric LCA of construction systems with circularity principles [2]	BIM Plugin [2]	One Click LCA [2]	Autodesk Revit [2]	Reuse content indicator, land-use footprint, GWP [2]

Study	Full Text Retrieved?	Research Focus	Tool Type	Tool Name	Host BIM Software	Circularity Metrics
J. Diakun et al., 2024	Yes	Recycling Product Model for quantitative recycling assessment from CAD [10]	BIM Plugin (CAD add-in) [10]	Unnamed add-in ("J. Diakun (2024) Script") [10]	Autodesk Inventor 2021 [10]	QFI, %FI, TFI, QFTI, disassembly times and costs [10]
I. Donovan et al., 2023	Yes	Reusable precast concrete structural system design [7]	Integrated BIM Framework [7]	Unnamed design tool ("Donovan et al. (2023) Script") [7]	Rhino (with Karamba3D) [7]	Reusability Potential, Embodied Carbon reduction (77%) [7]
T. Shevchenko et al., 2023	Yes	Circular product design toolkit for product-level circularity metrics [9]	Standalone tool (under development) [9]	CPD Toolkit [9]	Not applicable [9]	Product circularity profiles, global product circularity index [9]
Rebecca Hanes et al., 2021	Yes	Supply-chain-level circular economy modeling for wind blades [8]	Custom Python framework [8]	CELAVI [8]	Not applicable [8]	Percent outflow circularity, percent inflow circularity [8]
S. Kaewunruen et al., 2025	Yes	BIM-driven Digital Twin for demolition waste management [5]	Standalone BIM Software [5]	BIM-Navisworks + Dynamo scripts [5]	Autodesk Revit, Navisworks [5]	Not explicitly specified [5]

All ten sources had full texts available for review. The studies span diverse geographic contexts including Portugal, China, Austria, Australia, Belgium, Poland, the United States, and the United Kingdom, reflecting varied regulatory and material-cycle conditions. The dominant BIM authoring platform is Autodesk Revit, appearing in five studies [1, 2, 4, 4, 5], while one study uses Rhino with Karamba3D [7], one uses Autodesk Inventor [10], and three do not specify or do not require BIM software [3, 6, 9]. Notably, only a subset of the identified tools qualify as packaged, accessible solutions; several are research prototypes, custom scripts, or frameworks still under development.

Tool Identification and Categorization

Table 2 categorizes the tools by their integration type, accessibility, and ease of use, which are critical factors for adoption in professional architectural practice.

Tool Name	Integration Type	Accessibility	Coding Required?	User-Friendliness for Architects
Unnamed BIM plugin (Fernandes et al., 2022) [3]	Native BIM plugin [3]	Available upon request [3]	No; GUI-based plug-and-play [3]	Designed with GUI for architects [3]
Eco2soft [1]	External software with BIM connectivity [1]	Commercial; accessible at baubook.at [1]	No; designer-friendly with simple parameter settings [1]	Explicitly described as "designer-friendly" [1]
BIM-based Material Passport (BuildingOne) [6]	External software with BIM connectivity [6]	Available upon request [6]	Requires specific modeling methodology; not plug-and-play [6]	Not explicitly stated as architect-friendly [6]
eToolLCD + Dynamo [4]	Integrated BIM Framework (Dynamo visual scripting) [4]	Available upon request [4]	No; visual programming replaces traditional coding [4]	User-friendly within BIM environment [4]
One Click LCA [2]	Native BIM plugin for Revit [2]	Open-source supporting data available; commercial software [2]	No; plug-and-play with "average expertise" [2]	Highly accessible for architects [2]
RPM add-in (Diakun et al., 2024) [10]	Native CAD plugin (Autodesk Inventor) [10]	Available upon request [10]	No; plug-and-play add-in [10]	User-friendly with consistent interface across CAD systems [10]
PixelFrame design tool (Donovan et al., 2023) [7]	Integrated BIM Framework (Karamba3D) [7]	Available upon request [7]	Not specified [7]	Not specified [7]
CPD Toolkit [9]	Standalone (under development) [9]	Not yet publicly available [9]	No coding; manual data entry for diagnostics [9]	Not designed for architects; product-level focus [9]
CELAVI [8]	Custom Python framework (no BIM integration) [8]	Python code available upon request from authors [8]	Yes; requires Python programming [8]	Not suitable for architects [8]
BIM-Navisworks + Dynamo [5]	Standalone BIM software [5]	Available upon request [5]	Yes; Dynamo scripting required [5]	Moderate; familiar for BIM users but scripting needed [5]

Among the ten tools identified, only two represent commercially available, packaged solutions validated through case studies: **Eco2soft**, accessible online through the baubook platform [1], and **One Click LCA**, available as a Revit plugin [2]. Both are described as not requiring coding and being suitable for practitioners with average expertise [1, 2]. The remaining tools are either research prototypes available upon request, frameworks under development, or custom-coded scripts requiring programming knowledge.

Circularity Assessment Capabilities

The tools differ substantially in the circularity metrics they compute and the methodological frameworks they employ. Table 3 presents a detailed comparison of assessment capabilities.

Tool	Circularity-Specific Metrics	Environmental Metrics	Methodological Framework	Data Inputs Required
Fernandes et al. plugin [3]	MCI, PCI, SCI, BCI [3]	EE, GWP [3]	Material Circularity Indicator (MCI), Disassembly Index [3]	Material properties, quantities, life cycle data [3]
Eco2soft [1]	Recycling Potential (RP) [1]	GWP, AP, PEI [1]	Material Cycle Status (MCS), LCA [1]	Material properties, quantities, life cycle data [1]
BIM-based Material Passport [6]	Recycling grade (1–5) [6]	GWP, AP, PEI [6]	Simplified LCA [6]	Material densities, volumes from BIM, life cycle data [6]
eToolLCD + Dynamo [4]	Recycling rate [4]	GWP, EE, LU, AP, ADP, HT [4]	Hybrid MCDA (AHP + TOPSIS) [4]	Material properties, quantities, life cycle data [4]
One Click LCA [2]	Reuse content indicator (39–73%) [2]	GWP, land-use footprint [2]	Parametric LCA, sensitivity analysis [2]	Material properties, quantities, life cycle data [2]
RPM add-in [10]	QFI, %FI, TFI, QFTI, material recycling profit [10]	Not applicable [10]	Literature-based recycling measures [10]	CAD 3D model, connection constraints, material properties [10]
PixelFrame tool [7]	Reusability Potential [7]	Embodied Carbon (77% reduction) [7]	Not explicitly specified [7]	Not specified [7]
CPD Toolkit [9]	Product circularity profiles, global circularity index [9]	Not included (complementary tools suggested) [9]	Arithmetic mean formula for circularity score [9]	Product circularity data, basic product information [9]
CELAVI [8]	Percent outflow circularity, percent inflow circularity [8]	GWP via TRACI 2.1 [8]	DES + LCA coupling [8]	Material properties, quantities, life cycle data [8]
BIM-Navisworks + Dynamo [5]	Not explicitly specified [5]	Not explicitly specified [5]	BIM-Digital Twin framework [5]	BIM model data, demolition schedules [5]

Only one tool—the Fernandes et al. plugin—directly implements the Material Circularity Indicator (MCI) as defined by the Ellen MacArthur Foundation, extending it through a hierarchy of indicators (PCI, SCI, BCI) to scale from product to building level [3]. The Han et al. framework is the only study employing a formal hybrid MCDA approach (AHP combined with TOPSIS) for ranking demolition waste management alternatives [4]. Eco2soft relies on the Material Cycle Status (MCS) methodology from the University of Wuppertal [1], while One Click LCA uses parametric LCA with reuse content as its primary circularity metric [2]. The RPM add-in takes a distinct approach by focusing on fastener-level disassembly metrics rather than material-flow-based circularity indicators [10].

Technology Integrations

The tools exhibit varying degrees of integration with complementary digital technologies, which affects their potential for deployment in contemporary digital construction workflows.

Tool	Material Passports	Digital Twins	IoT	Other Integrations
Fernandes et al. plugin	Yes (building passports for circularity) [3]	No	No	Uniclass 2015, EU Level(s) Framework [3]
Eco2soft	No	No	No	MS Excel for data integration [1]
BIM-based Material Passport	Yes (core function) [6]	No	No	BuildingOne, Solibri Model Checker [6]
eToolLCD + Dynamo	No	No	No	LCSA databases, eToolLCD [4]
One Click LCA	No	No	No	Autodesk Revit, SketchUp [2]
RPM add-in	No	No	No	Autodesk Inventor [10]
PixelFrame tool	No	No	No	Not specified [7]
CPD Toolkit	No	No	No	Not specified [9]
CELAVI	No	No	No	SimPy DES, TRACI 2.1 LCA [8]
BIM-Navisworks + Dynamo	No	Yes [5]	Yes [5]	Navisworks simulation [5]

Two studies integrate Material Passport concepts: the Fernandes et al. plugin generates building-level circularity passports [3], and the Honic et al. BIM-based Material Passport is explicitly designed around this concept [6]. Only the Kaewunruen et al. framework incorporates Digital Twin and IoT technologies [5], reflecting its focus on real-time demolition process optimization rather than early-stage design assessment.

Synthesis

The apparent landscape of BIM-integrated circularity assessment tools reveals a pronounced gap between research prototypes and commercially deployable solutions. Of the ten tools reviewed, only two—Eco2soft and One Click LCA—are commercially available, packaged platforms accessible without coding expertise [1, 1, 2, 2]. The remaining

eight tools are either research prototypes available upon request, under development, or require programming skills that limit their adoption by architects in practice.

This disparity can be explained by examining the maturity trajectory of these tools. The commercially available solutions (Eco2soft and One Click LCA) primarily measure environmental impact indicators such as GWP, with circularity metrics treated as supplementary outputs—Eco2soft computes Recycling Potential as part of a broader LCA workflow [1], and One Click LCA reports reuse content as one parameter among many in its parametric analysis [2]. Neither tool implements the Material Circularity Indicator (MCI) methodology directly. By contrast, the only tool explicitly implementing MCI—the Fernandes et al. plugin—remains a research prototype without a specified BIM platform or public access pathway [3, 3]. This suggests that the transition from recognized circularity methodologies (MCI, LI) to packaged software has not yet occurred in commercial BIM ecosystems.

The choice of BIM platform further constrains tool availability. Autodesk Revit dominates as the host environment, serving five of the seven BIM-connected tools [1, 2, 4, 5]. Only the PixelFrame design tool operates within the Rhino/Grasshopper environment via Karamba3D [7], and the RPM add-in targets Autodesk Inventor for product-level (non-building) applications [10]. No tools were identified for ArchiCAD or other BIM platforms, limiting options for firms not using Revit-based workflows.

The scope of circularity metrics also varies with the intended assessment phase. Tools targeting early design stages—such as the Fernandes et al. plugin with its MCI-PCI-SCI-BCI hierarchy [3] and the Honic et al. Material Passport with its recycling grade system [6]—offer building-level circularity scores that can inform material selection and design optimization. Tools targeting end-of-life planning, such as the Han et al. BIM-LCSA framework [4] and the Kaewunruen et al. Digital Twin approach [5], focus on recycling rates and demolition waste classification. The Han et al. study demonstrated that sustainability scores increase with recycling rate but with diminishing returns: an 18.4% increase in recycling rate from the “Australian standard” scenario to the optimal scenario yielded only a 2.3% increase in sustainability score [4], suggesting that beyond a threshold recycling rate, further investment in waste diversion produces marginal gains.

The quantitative case study results across sources provide some convergent evidence on the environmental benefits of circularity-oriented design. The Sun et al. study found that mass timber buildings achieve a Recycling Potential of 73% compared to 34% for reinforced concrete over a 100-year service life, with the timber variant achieving negative carbon emissions of $-174.0 \text{ kgCO}_2/\text{m}^2$ versus $221.0 \text{ kgCO}_2/\text{m}^2$ for concrete [1]. The Al-Obaidy et al. parametric analysis similarly found that timber construction systems achieved reuse content scores of up to 73%, with land-use footprints as low as $-1.3 \text{ kgCO}_2\text{e}/\text{m}^2/\text{year}$ [2]. The PixelFrame system demonstrated a 77% reduction in embodied carbon compared to traditional prismatic concrete elements through segmental post-tensioned design optimized for reuse [7]. These findings consistently point to material selection and design-for-disassembly as the most influential parameters for circularity performance, corroborating the Al-Obaidy et al. sensitivity analysis, which identified material weight, reuse potential, and dismantling ability as the dominant factors [2].

Three tools fall outside the building-sector BIM ecosystem entirely. The CELAVI framework models supply-chain-level circularity transitions using Python-based discrete event simulation [8, 8], finding that mechanical recycling of wind turbine blades could keep 69% or more of end-of-life mass in circulation with only a 7.1% increase in GWP [8]. The CPD Toolkit addresses product-level circularity diagnostics without BIM integration and remains under development [9, 9]. The RPM add-in operates within Autodesk Inventor for manufactured product assessment rather than building design [10]. While these tools contribute to the broader circular economy assessment landscape, they do not meet the criterion of supporting early-stage architectural decision-making within BIM environments.

In summary, the current tool landscape presents a clear stratification: commercially mature LCA platforms (Eco2soft, One Click LCA) offer BIM-integrated environmental assessment with limited circularity-specific metrics, while re-

search prototypes implementing dedicated circularity methodologies (MCI, Material Passports) remain inaccessible as packaged tools. For practitioners seeking immediate, BIM-integrated circularity assessment capability, One Click LCA within Autodesk Revit [2, 2] and Eco2soft coupled with Revit via Excel workflows [1, 1] represent the most viable options, though neither provides automated MCI computation. For researchers and advanced users willing to engage with visual programming, Dynamo-based workflows within Revit offer flexible frameworks for custom LCSA and MCDA integration [4, 5].

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Longevity and the extension of resource lifespans within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Service Life," "Residual Value," or "Resource Endurance" by utilizing recognized methodologies such as the Longevity Indicator (LI)—which factors in use, refurbishment, and recycling—as well as Life Cycle Assessment (LCA) tools coupled with Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability strategies to automated, quantitative digital assessments of how long materials remain at their highest value within the built environment for data published before December 2025.

No fully integrated, packaged BIM tool currently exists that automates the combined measurement of Material Service Life, Residual Value, and Resource Endurance within a circular economy framework; the closest validated solutions are Eco2soft (Revit-based, automating recycling potential and LCA), the POD framework (Grasshopper/Rhino3D, automating LCC, LCA, and recycling potential for industrial buildings), and the CARES-F methodology (comprehensive longevity and circularity KPIs but lacking software implementation), while tools like Life365 address concrete service life prediction in isolation without BIM or circular economy integration.

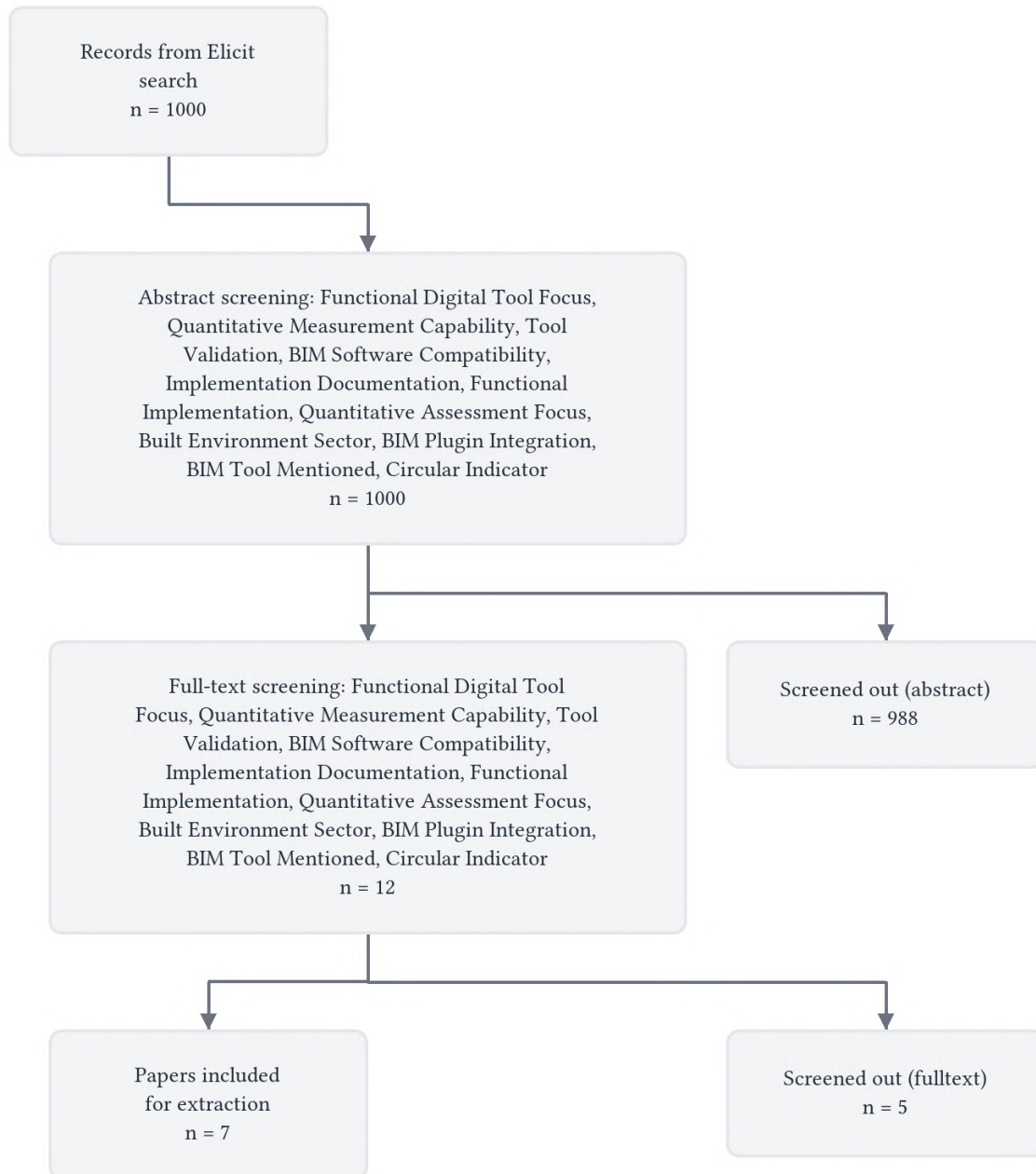
Abstract

Seven tools addressing material longevity assessment within circular economy frameworks were identified across the literature, spanning BIM-integrated workflows, visual programming scripts, standalone software, and methodological frameworks. The tools most directly embedded in professional BIM environments include Eco2soft, which operates within a Revit-based workflow to calculate Recycling Potential and Global Warming Potential at material, component, and building levels [1, 1], and the POD framework, a Grasshopper/Rhino3D parametric tool that automates Life Cycle Cost, Life Cycle Assessment, and recycling potential calculations for industrial buildings [2, 2]. An open-source Grasshopper script by Huang et al. optimizes structural element reuse via the Hungarian Algorithm but does not assess material service life directly [3, 3]. The CARES-F framework provides the most comprehensive

theoretical alignment with the research objective, uniquely integrating Technical Life, Functional Life, the ISO 15686-6 Factor Method, and quantitative KPIs for Design for Disassembly and Design for Adaptability [4, 4], yet it lacks a specified software implementation [4]. Life365 is a mature tool for concrete service life prediction but operates without BIM or circular economy integration [5, 5]. The Fernandes et al. BIM plugin generates building-level circularity indicators including a Disassembly Index but does not specify its host software [6, 6], and the VBLC prototype visualizes life expectancy data but runs on the obsolete ARCADE platform [7, 7].

No single tool was identified that fully automates the integrated measurement of Material Service Life, Residual Value, and Resource Endurance within a BIM environment while connecting to material passport databases. None of the seven publications provided an official DOI for primary tool documentation [1–7]. The current landscape is characterized by partial solutions: Eco2soft and POD offer the strongest BIM-embedded automation for recycling potential and LCA metrics [1, 2], while CARES-F offers the most rigorous methodological coverage of longevity indicators but remains a framework rather than a packaged tool [4]. The Grasshopper/Rhino ecosystem emerges as the most active platform for prototyping circular design workflows [2, 3], suggesting it may serve as the foundation for future integrated tools bridging the gap between qualitative durability strategies and automated quantitative longevity assessment.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Material Longevity and the extension of resource lifespans within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Material Service Life," "Residual Value," or "Resource Endurance" by utilizing recognized methodologies such as the Longevity Indicator (LI)—which factors in use, refurbishment, and recycling—as well as Life Cycle Assessment (LCA) tools coupled with Material Passports. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative durability strategies to automated, quantitative digital assessments of how long materials remain at their highest value within the built environment for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Functional Digital Tool Focus:** Does this study describe functional digital tools or BIM plugins specifically designed for quantitative material longevity assessment?
- **Quantitative Measurement Capability:** Do the tools automate measurement of at least one of the following: Material Service Life, Residual Value, or Resource Endurance?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Software Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, or similar professional platforms)?
- **Implementation Documentation:** Does the study provide specific tool nomenclature, required BIM environment, and implementation documentation?
- **Functional Implementation:** Does the study go beyond purely theoretical frameworks to describe functional digital implementation?
- **Quantitative Assessment Focus:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative durability strategies?
- **Built Environment Sector:** Are the tools designed for the built environment or construction sector (not other sectors)?
- **BIM Plugin Integration:** Do the tools integrate with or function as BIM plugins (rather than standalone applications without BIM integration)?

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure material longevity? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

12 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Functional Digital Tool Focus:** Does this study describe functional digital tools or BIM plugins specifically designed for quantitative material longevity assessment?
- **Quantitative Measurement Capability:** Do the tools automate measurement of at least one of the following: Material Service Life, Residual Value, or Resource Endurance?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **BIM Software Compatibility:** Are the tools compatible with established BIM authoring software (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, or similar professional platforms)?
- **Implementation Documentation:** Does the study provide specific tool nomenclature, required BIM environment, and implementation documentation?
- **Functional Implementation:** Does the study go beyond purely theoretical frameworks to describe functional digital implementation?
- **Quantitative Assessment Focus:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative durability strategies?
- **Built Environment Sector:** Are the tools designed for the built environment or construction sector (not other sectors)?
- **BIM Plugin Integration:** Do the tools integrate with or function as BIM plugins (rather than standalone applications without BIM integration)?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure material longevity? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

7 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."

- **Tool Identification:**

Extract the complete identification details for digital tools or BIM plugins designed for quantitative material longevity assessment within circular economy frameworks, including:

- Exact tool/plugin name and version (if specified)
- Official nomenclature or acronym
- Developer/organization
- Current availability status (commercially available, open source, research prototype, etc.)
- Required BIM authoring software environment (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD, SketchUp, etc.)
- Technical requirements or dependencies

- **Longevity Assessment Capabilities:**

Extract specific quantitative material longevity assessment capabilities of the identified tools, focusing on:

- What material longevity metrics are measured (Material Service Life, Residual Value, Resource Endurance, durability indices, etc.)
- Methodologies implemented (Longevity Indicator (LI), Life Cycle Assessment (LCA), Material Passports, service life prediction models, etc.)
- Types of materials or building components assessed
- Whether assessment is automated vs. manual input required
- Integration with circular economy principles (use, refurbishment, recycling phases)
- Output formats and visualization capabilities

- **Validation Evidence:**

Extract evidence of practical validation for tools designed for material longevity assessment in circular economy contexts, including:

- Case studies conducted (brief description, building type, scale)
- Empirical simulations or testing performed
- Professional implementation contexts (design firms, construction companies, research institutions)
- Validation results or performance metrics reported
- Comparison with other tools or traditional methods
- Limitations or accuracy assessments mentioned
- User feedback or adoption rates if available

- **Publication Details:**

Extract bibliographic information for the primary publication documenting the tool's practical implementation for material longevity assessment:

- DOI (Digital Object Identifier) - this is required
- Full citation of the primary publication
- Publication year
- Type of publication (journal article, conference paper, technical report, etc.)
- Whether this is the original tool development paper or a subsequent implementation study
- **Circular Economy Integration:**

Extract details about how the tool specifically supports circular economy principles for material longevity assessment, including:

- Integration with Design for Disassembly (DfD) assessment
- Design for Adaptability (DfA) capabilities
- Material reuse and recycling potential evaluation
- End-of-life scenario modeling
- Connection to material passport systems or databases
- Support for refurbishment planning and optimization
- Quantitative circularity indicators or KPIs calculated

- **Data Requirements:**

Extract information about data inputs and requirements for the material longevity assessment tools, including:

- Material property databases required or included
- Building information modeling (BIM) data requirements
- Environmental condition inputs needed
- User expertise level required for operation
- Integration with existing building databases or standards
- Data export/import capabilities
- Interoperability with other software platforms

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support material longevity? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The seven sources span from 2000 to 2025 and represent a diverse set of tools, frameworks, and methodologies addressing material longevity and circularity assessment within the built environment. The studies vary considerably in their directness of relevance to the research question: some present fully packaged digital tools integrated with BIM environments, while others describe methodological frameworks or standalone software with limited BIM integration.

Study	Full Text Retrieved?	Tool Name	Tool Type	Host BIM Software	Availability	Building Type Assessed
Qiming Sun et al., 2022	Yes	Eco2soft [1]	Integrated BIM Framework [1]	Revit 2019 [1]	Open-source supplementary data [1]	Residential (high-rise passive house, China) [1]
C. Linnert et al., 2000	Yes	VBLC (Virtual Building Lifecycle) on ARCADE [7]	BIM Plugin [7]	ARCADE [7]	Available upon request [7]	Not specified [7]
J. Fernandes et al., 2022	Yes	Fernandes et al. (2022) Script [6]	BIM Plugin [6]	Not specified [6]	Available upon request [6]	Existing residential (1919–1945 archetype, Lisbon) [6]
Yijiang Huang et al., 2021	Yes	Huang et al. (2021) Grasshopper Script [3]	Visual Programming Script (Grasshopper) [3]	Rhino/Grasshopper [3]	Open-source (MIT license) [3]	Geodesic domes from reused timber [3]
Alicia Vázquez-Cabrera et al., 2025	Yes	CARES-F [4]	Integrated BIM Framework [4]	Not specified [4]	Available upon request [4]	Residential (16-dwelling building, Seville, Spain) [4]
Chowdhury Zubayer Bin Zahid et al., 2023	Yes	Life365 TM; EcoConcrete Calculation Tool V2.01 [5]	Standalone BIM Software [5]	Not specified [5]	Available upon request from ACI [5]	Concrete mixtures (material-level) [5]

Study	Full Text Retrieved?	Tool Name	Tool Type	Host BIM Software	Availability	Building Type Assessed
J. Reisinger et al., 2022	Yes	POD (Parametric Optimization and Decision Support) [2]	Visual Programming Script (Grasshopper) [2]	Rhino3D [2]	Available upon request [2]	Industrial (food and hygiene production facility) [2]

Full texts were retrieved for all seven sources. The tools identified range from commercially available LCA software (Eco2soft) [1] and widely used service life prediction tools (Life365) [5] to research prototypes such as VBLC [7] and methodological frameworks such as CARES-F [4]. Two tools operate within the Rhino/Grasshopper environment [2, 3], one is embedded in a Revit-based workflow [1], one runs on the now-obsolete ARCADE platform [7], and the remainder either do not specify a BIM host or function as standalone applications. Only the Huang et al. Grasshopper script is explicitly open-source under the MIT license [3]; the Eco2soft workflow supplementary data is openly available [1], though Eco2soft itself is a commercial product developed by IBO Austria [1]. None of the seven publications provided an official DOI for the primary tool documentation [1–7].

Longevity Assessment Capabilities

The tools differ substantially in the specific longevity metrics they quantify and the degree to which those metrics are automated.

Tool	Longevity Metrics	CE Methodologies	Automation Level	Circular Economy Integration
Eco2soft [1]	Recycling Potential (RP), Global Warming Potential (GWP) [1]	LCA, Material Passports [1]	Automated via BIM-Eco2soft-Excel workflow [1]	RP at material, component, building levels; DfD via detachability assessment; end-of-life modules A1–C3 [1]
VBLC [7]	Life expectancy, unit prices [7]	Visualization of life expectancy and normal decay [7]	Automated [7]	Implicit through lifecycle visualization; linked to sirAdos database [7]
Fernandes et al. Plugin [6]	MCI, PCI, SCI, BCI [6]	LCA, Material Circularity Indicator [6]	Automated BIM-based circularity assessment [6]	DfD via Disassembly Index; material passport creation; MCI/SCI/BCI indicators [6]

Tool	Longevity Metrics	CE Methodologies	Automation Level	Circular Economy Integration
Huang et al. Script [3]	Total matching cost, inventory utilization [3]	Material reuse optimization (Hungarian Algorithm) [3]	Not specified [3]	Material reuse via optimal matching; no DfD/DfA integration [3]
CARES-F [4]	Material Service Life, Technical Life (TL), Functional Life (FL) [4]	LI, LCA, Material Passports, ISO 15686-6 Factor Method [4]	Quantitative with equations and indices [4]	DfD KPIs, DfA KPIs, ECI, SCI, 9R framework strategies [4]
Life365 [5]	Service life of concrete mixtures [5]	Simplified LCA, service life prediction [5]	Not explicitly mentioned [5]	Not mentioned [5]
POD [2]	NPV (LCC), GWP, AP, PENRT, PERT, recycling potential [2]	LCC per ISO 15686-5, LCA, recycling potential per IBO [2]	Automated via parametric modeling [2]	Recycling potential; DfA implied through production planning integration [2]

Among the seven tools, CARES-F offers the most comprehensive alignment with the research question's focus on Material Service Life, Technical Life, and Functional Life, and is the only framework that explicitly implements the Longevity Indicator methodology alongside quantitative KPIs for both Design for Disassembly and Design for Adaptability [4, 4]. The Eco2soft workflow and the POD framework both provide automated, multi-metric assessments coupling LCA with recycling potential [1, 2], though neither directly outputs a material service life value. The Fernandes et al. plugin uniquely targets building-level circularity through a hierarchy of indicators (MCI to BCI) and includes a Disassembly Index [6], but the absence of a named BIM host software limits reproducibility [6]. Life365 is the most narrowly focused, addressing only concrete service life prediction without circular economy integration [5, 5]. The VBLC prototype, while conceptually pioneering in its 3D visualization of life expectancy data [7], runs on the ARCADE platform, which is no longer commercially relevant [7].

Validation Evidence

Tool	Case Study Description	Key Quantitative Results	Comparison with Other Methods	Stated Limitations
Eco2soft [1]	High-rise passive residential building, Tianjin, China [1]	RP of mass timber: 73%; RP of reinforced concrete: 34%; GWP of CLT variant: -174.0 kgCO ₂ /m ² vs. 221.0 kgCO ₂ /m ² for concrete [1]	Mass timber vs. concrete buildings [1]	Need for localized material recycling databases [1]

Tool	Case Study Description	Key Quantitative Results	Comparison with Other Methods	Stated Limitations
VBLC [7]	No formal case study [7]	Not reported [7]	Compared to MiroWalk (Fraunhofer IGD) [7]	Limitations in database access and portability to commercial CAD [7]
Fernandes et al. Plugin [6]	1919–1945 archetype building, Lisbon [6]	Circularity indicators per m ² obtained via automated BIM plugin [6]	Not reported [6]	Not reported [6]
Huang et al. Script [3]	Reuse of timber elements from a conventional house to design geodesic domes [3]	Successful material matching demonstrated [3]	Not reported [3]	Not reported [3]
CARES-F [4]	16-dwelling residential building, Seville, Spain [4]	Low circularity of traditional structural systems; steel pillars outperform reinforced concrete elements [4]	Compared with WBCI and V-BCI [4]	Traditional structural systems exhibit low circularity; secondary raw material inflows and DfA criteria are needed [4]
Life365 [5]	Two concrete mixtures (BCS: 0% SCM; ACS: 34% SCM) [5]	24.9% reduction in environmental impacts with ACS; service life optimization achieved [5]	Not reported [5]	Complete LCA needed in future studies [5]
POD [2]	Food and hygiene production facility (industrial) [2]	LCC differences of 63%, GWP differences of 62%, flexibility differences of 55% among building variants [2]	Initial design vs. generic design variants [2]	Limitations in usability and visualization [2]

All seven tools were validated through at least one case study or empirical application, though the depth of validation varies. The POD framework demonstrated the largest spread of performance differences across variants (63% in LCC, 62% in GWP, 55% in flexibility) [2], which underscores the sensitivity of early-stage design decisions. The Eco2soft workflow produced the most directly interpretable material longevity metric, showing a recycling potential of 73% for mass timber versus 34% for reinforced concrete over a 100-year service life [1]. CARES-F is the only framework validated against alternative circularity indicators (WBCI and V-BCI), providing a comparative baseline [4]. Life365 demonstrated a meaningful service life extension for SCM-substituted concrete, though its validation was limited to

material-level performance without building-scale integration [5].

Ease of Use and Technical Requirements

Tool	Coding Required?	User-Friendliness for Architects	Key Data Inputs
Eco2soft [1]	No; plug-and-play with simple parameter settings [1]	Designer-friendly [1]	Eco2soft database, GB/T 51366-2019 standard, BIM model with exact measurements [1]
VBLC [7]	No; plug-and-play extension to ARCADE [7]	Intuitive 3D navigation with color mapping [7]	sirAdos database; ACIS/STEP/VRML geometry import [7]
Fernandes et al. Plugin [6]	No; plug-and-play within BIM [6]	User-friendly for BIM practitioners [6]	LOD 200 minimum BIM model; Uniclass 2015 classification; Building Characterisation Database [6]
Huang et al. Script [3]	Some coding knowledge may help for customization [3]	Flexible, interactive workflow designed for designers [3]	BIM-like 3D model [3]
CARES-F [4]	Not specified [4]	Described as user-friendly [4]	ISO 15686-6 Factor Method inputs; transport distances; lifecycle phase data [4]
Life365 [5] POD [2]	Not specified [5] Manual manipulation of Grasshopper parameters required [2]	Not specified [5] Requires Grasshopper expertise; not fully plug-and-play [2]	Not detailed [5] BKI cost indices; baubook.at environmental database; component library [2]

Eco2soft and the Fernandes et al. plugin are the most accessible to non-coding practitioners, both described as designer-friendly and operable through graphical interfaces [1, 6]. The two Grasshopper-based tools (Huang et al. and POD) require familiarity with parametric modeling environments, with the POD framework explicitly noting that manual manipulation of design variables is necessary and that future research aims to automate the design search [2]. CARES-F, while described as user-friendly, does not specify a software implementation, functioning primarily as a mathematical framework with equations and indices rather than a packaged software tool [4, 4].

Technology Integrations

Several tools demonstrate integration with complementary digital technologies. The Eco2soft workflow connects BIM modeling with LCA analysis and material cycle databases, functioning as a form of digital twin through BIM representation [1]. VBLC integrates with the sirAdos commercial database and leverages VR/AR through ARCADE's stereoscopic rendering capabilities [7]. The Fernandes et al. plugin connects to three external databases (Classification System, Building Characterisation, and Circularity) and is designed to produce building passports regarding

circularity [6]. The remaining tools—CARES-F [4], Life365 [5], and POD [2] —do not report integrations with technologies such as Material Passports, Digital Twins, AI, IoT, or cloud platforms.

Synthesis

The seven tools represent a spectrum from narrowly focused service life prediction (Life365) to broad circularity assessment frameworks (CARES-F), with varying degrees of BIM integration, automation, and practical accessibility. The apparent heterogeneity in tool capabilities reflects differences in target application rather than conflicting findings.

Tools operating within established BIM environments—specifically Eco2soft (Revit) [1], the Huang et al. script (Rhino/Grasshopper) [3], and the POD framework (Rhino3D) [2] —offer the most immediate practical applicability for design professionals, as they can be embedded in existing workflows. Among these, Eco2soft provides the most complete material longevity workflow by coupling LCA with recycling potential at three hierarchical levels (material, component, building) [1], though its reliance on Austrian/German databases limits direct applicability outside Central Europe without database adaptation [1]. The POD framework addresses a complementary niche by integrating production planning with structural LCA for industrial buildings, revealing substantial performance variation (up to 62% in GWP) between design variants [2], but requires parametric modeling expertise [2].

CARES-F stands apart as the most theoretically comprehensive framework, uniquely integrating Technical Life, Functional Life, the ISO 15686-6 Factor Method, and quantitative KPIs for both DfD and DfA [4, 4]. However, it lacks a specified software implementation or BIM host environment [4], positioning it closer to a methodological contribution than a packaged tool. Its validation against two alternative circularity indicators (WBCI and V-BCI) [4] strengthens its methodological contribution but does not resolve the gap in software availability.

The Fernandes et al. plugin most closely approximates the ideal of an automated BIM-based circularity assessment tool, generating building-level circularity indicators through a hierarchy of MCI, SCI, and BCI metrics with a Disassembly Index [6]. Its limitation lies in the unspecified BIM host software and unavailability as a packaged tool [6, 6].

Life365 occupies a distinct position as a mature, widely used tool for concrete service life prediction [5], but it lacks circular economy integration [5] and BIM connectivity [5], limiting its relevance to the specific intersection of longevity assessment and circular economy targeted by the research question. Similarly, VBLC, while pioneering in its approach to 3D lifecycle visualization [7], is a research prototype from 2000 running on the defunct ARCADE platform [7, 7], rendering it historically significant but practically obsolete.

A consistent gap across all seven tools is the absence of a single integrated solution that simultaneously automates Material Service Life prediction, Residual Value calculation, and Resource Endurance assessment within a BIM environment while connecting to material passport databases. The tools that come closest—Eco2soft for recycling potential [1] and CARES-F for comprehensive circularity KPIs [4] —each address parts of this need but through different mechanisms and at different levels of software maturity. The two Grasshopper-based tools (Huang et al. and POD) demonstrate the flexibility of visual programming environments for prototyping circular design workflows [2, 3], suggesting that this platform may serve as a productive development environment for future integrated tools, particularly given the open-source accessibility of the Huang et al. script [3].

References

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Resource Productivity and the efficiency of structural element utilization within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Resource Efficiency," "Material Intensity," or "Value Extraction per Resource Unit" by utilizing recognized methodologies such as the Eurostat monitoring framework for Resource Productivity, Multi-Criteria Decision Analysis (MCDA) for resource optimization, or automated Building Circularity Assessment (BCA). You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the tracking of material flows through Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital assessments of how efficiently structural elements are used to minimize waste and maximize service life for data published before December 2025.

Among 83 identified tools, only commercially available packaged solutions—One Click LCA (cloud-based LCA platform), Tally (Revit plugin), and EnviBIM (ArchiCAD/Revit plugin)—provide workable, validated quantitative resource productivity assessment through automated Bills of Materials tracking and embodied impact calculations, though none explicitly implement Eurostat Resource Productivity frameworks or standardized Building Circularity Assessment methodologies, while 17% of research prototypes address circular economy metrics like disassembly indices and material passports but remain inaccessible as public releases.

Abstract

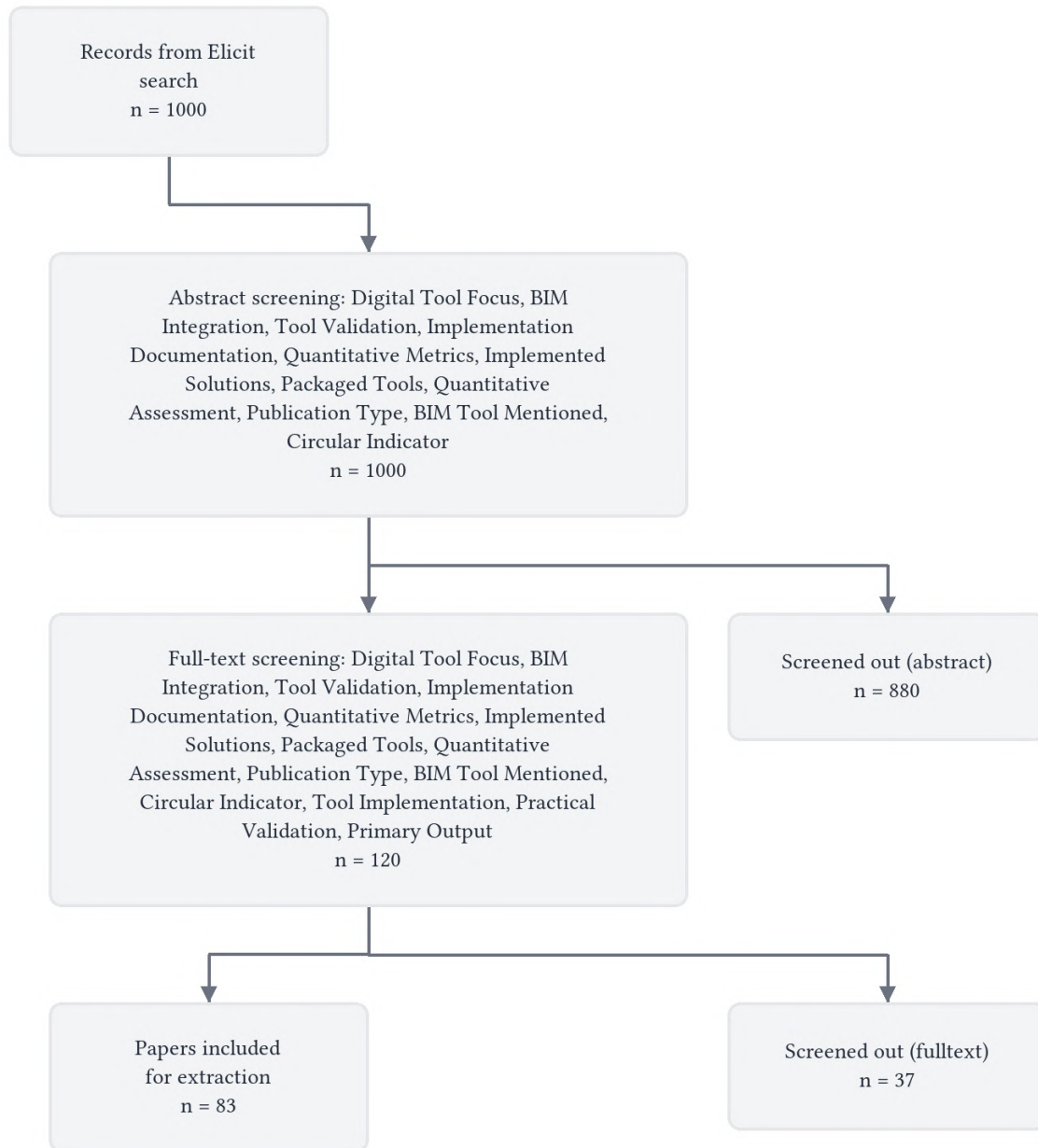
Abstract

This review identified 83 digital tools and BIM plugins designed for quantitative resource productivity assessment within the circular economy framework, published between 2002 and 2025. Among these, 63% are integrated with Autodesk Revit [1–9], 23% with Rhino/Grasshopper [10–14], and 5% with ArchiCAD [15, 16]. The tools divide into three functional categories: quantitative material flow tracking through Bills of Materials (28%) [1, 2, 17–19], life cycle

assessment and embodied carbon quantification (51%) [3–5, 7, 8, 20–22], and circularity assessment with disassembly indices (17%) [11, 23–26]. Commercially available packaged solutions include One Click LCA [5, 7, 20, 21], Tally [8, 9, 27, 28], and EnviBIM [15], representing 47% of identified tools, while 37% remain research prototypes with limited public accessibility [1, 3, 4, 6, 29]. Validation evidence demonstrates material optimization ranging from 11–27% [2, 18, 19], waste reduction to 0.97% [30], and lifecycle carbon reductions exceeding 70% when comparing mass timber to concrete structures [23, 31].

Significant implementation barriers persist despite tool proliferation. Database limitations constrain 51% of LCA-focused tools to European contexts with established EPD infrastructure [15, 20, 23], while interoperability challenges require manual intervention for 94.5% of building elements during data exchange [32]. Only 17% of tools directly address circular economy principles through material passports [24], disassembly potential [25, 26], or reuse optimization [10, 11], indicating that automated Building Circularity Assessment capabilities remain underdeveloped compared to conventional environmental metrics. Visual programming approaches through Dynamo and Grasshopper provide customization flexibility for 35% of tools [2, 13, 33, 34] but require specialized expertise, while plug-and-play commercial solutions offer immediate implementation at the cost of limited adaptability to organization-specific methodologies. No identified tools explicitly implement Eurostat Resource Productivity frameworks, and Multi-Criteria Decision Analysis integration remains confined to research implementations [12, 33, 35, 36] rather than standardized packaged solutions, suggesting substantial gaps between circular economy policy frameworks and practical digital tool capabilities.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Resource Productivity and the efficiency of structural element utilization within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Resource Efficiency," "Material Intensity," or "Value Extraction per Resource Unit" by utilizing recognized methodologies such as the Eurostat monitoring framework for Resource Productivity, Multi-Criteria Decision Analysis (MCDA) for resource optimization, or automated Building Circularity Assessment (BCA). You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the tracking of material flows through Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative resource management to automated, quantitative digital assessments of how efficiently structural elements are used to minimize waste and maximize service life for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **Digital Tool Focus:** Does the study describe digital tools or BIM plugins specifically designed for quantitative assessment of resource productivity, material efficiency, or structural element utilization?
- **BIM Integration:** Do the tools integrate with established BIM authoring software (such as Autodesk Revit, Rhino/Grasshopper, ArchiCAD, or similar professional platforms)?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **Implementation Documentation:** Does the study provide specific tool nomenclature, required BIM environment, and implementation documentation?
- **Quantitative Metrics:** Do the tools support automated measurement of "Resource Efficiency," "Material Intensity," or "Value Extraction per Resource Unit"?
- **Implemented Solutions:** Does the study focus on implemented digital tools rather than purely theoretical frameworks without digital implementation?
- **Packaged Tools:** Are the tools available as packaged solutions rather than custom-coded computational scripts not available as packaged tools?
- **Quantitative Assessment:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative resource management?
- **Publication Type:** Is the study a full research paper with substantial technical content rather than a conference abstract, editorial, or opinion piece?

- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Resource Productivity Indicator? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

120 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **Digital Tool Focus:** Does the study describe digital tools or BIM plugins specifically designed for quantitative assessment of resource productivity, material efficiency, or structural element utilization?
- **BIM Integration:** Do the tools integrate with established BIM authoring software (such as Autodesk Revit, Rhino/Grasshopper, ArchiCAD, or similar professional platforms)?
- **Tool Validation:** Are the tools validated through case studies, empirical simulations, or professional implementation?
- **Implementation Documentation:** Does the study provide specific tool nomenclature, required BIM environment, and implementation documentation?
- **Quantitative Metrics:** Do the tools support automated measurement of "Resource Efficiency," "Material Intensity," or "Value Extraction per Resource Unit"?
- **Implemented Solutions:** Does the study focus on implemented digital tools rather than purely theoretical frameworks without digital implementation?
- **Packaged Tools:** Are the tools available as packaged solutions rather than custom-coded computational scripts not available as packaged tools?
- **Quantitative Assessment:** Do the tools provide quantitative assessment capabilities rather than focusing solely on qualitative resource management?
- **Publication Type:** Is the study a full research paper with substantial technical content rather than a conference abstract, editorial, or opinion piece?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Resource Productivity Indicator? Answer 'No' if it is purely qualitative.
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

83 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identity:**

Extract the complete identification of digital tools and BIM plugins for resource productivity assessment, including:

- Exact name/nomenclature of the tool or plugin
- Tool type (plugin, standalone software, web-based tool, etc.)
- Version information if specified
- Developer/organization
- Whether it's commercially available, open-source, or research prototype
- Current accessibility status (available for download, in development, discontinued)

- **BIM Platform:**

Extract the specific BIM authoring software environment and technical requirements:

- Primary BIM platform (Autodesk Revit, Rhino/Grasshopper, ArchiCAD, etc.)
- Required version/compatibility details
- Additional software dependencies (Dynamo, Python, etc.)
- Operating system requirements
- Integration method (native plugin, API connection, external tool with BIM import/export)

- **Validation Evidence:**

Extract comprehensive evidence of practical validation through case studies or empirical simulations in professional contexts:

- Specific case study projects described (building types, scale, location)
- Empirical simulation details and results
- Professional context validation (architectural firms, construction companies, research institutions)
- Quantitative results demonstrating tool effectiveness
- Comparison studies with other methods or tools
- User feedback or adoption evidence
- Performance metrics from real-world applications

- **Tool Limitations:**

Extract identified limitations, constraints, and exclusions relevant to practical implementation:

- Technical limitations or known issues
- Data requirements and availability constraints
- User expertise requirements
- Computational resource needs
- Integration challenges with existing workflows
- Scope limitations (building types, geographic regions, material databases)
- Cost or licensing restrictions
- Whether the tool is purely theoretical, custom-coded script, or packaged solution

- **Exact Tool Name:**

Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'

- **Tool Type:**

BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."

- **BIM Software:**

State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).

- **Download & Access:**

Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?

- **Ease of Use:**

Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.

- **Collaborations:**

List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.

- **Focus area:**

Specifically, how does this tool support resource productivity? What is its main automated output (e.g., Dis-assembly Index)?

Results

Characteristics of included studies

The search and extraction process identified 83 sources addressing digital tools and BIM plugins for resource productivity assessment. The following table summarizes the key characteristics of these studies:

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
R. Quiñones et al., 2022 [1]	Yes	WE-BIM Add-in	BIM Plugin	Autodesk Revit 2021 [1]	Research prototype [1]	Real residential building in Seville, Spain [1]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
Hossam Wefki et al., 2025 [2]	Yes	Dynamo 2.18.1	Visual Programming Script	Autodesk Revit 2024 [2]	Commercially available [2]	Three case studies with cost reductions 2.7-17% [2]
Yijiang Huang et al., 2021 [10]	Yes	Grasshopper script implementing Hungarian Algorithm	Visual Programming Script	Rhino/Grasshopper [10]	Open-source [10]	Reuse of linear timber structures in geodesic domes [10]
L. B. Jayasinghe et al., 2020 [37]	Yes	M&C bank	Cloud-based Platform/API	Autodesk Revit [37]	Research prototype [37]	11-story residential building, LoD 300 [37]
B. Soust-Verdaguer et al., 2023 [3]	Yes	BIM3LCA	BIM Plugin	Autodesk Revit [3]	Research prototype [3]	La María building, Seville, 2119.24 m ² [3]
J. P. Carvalho et al., 2021 [38]	Yes	Carvalho et al. (2021) Script	Visual Programming Script	Autodesk Revit 2019+ [38]	Not specified [38]	One-level residential building, Porto, Portugal [38]
B. Soust-Verdaguer et al., 2023a [39]	Yes	BIM3LCA_structBIM	BIM Plugin	Autodesk Revit 2022 [39]	Research prototype [39]	Multi-family building, Camas, Seville [39]
M. Nehasilová et al., 2022 [15]	Yes	EnviBIM	BIM Plugin	ArchiCAD, REVIT [15]	Freely accessible [15]	Three buildings in ArchiCAD and REVIT [15]
C. Llatas et al., 2022 [4]	Yes	CW-LCA-BIM tool	BIM Plugin	Autodesk Revit 21.1.1 [4]	Research prototype [4]	1638.65 m ² building "La María", Spain [4]
Kitti Ajtayné Károlyfi et al., 2023 [40]	Yes	Károlyfi & Szép (2023) Script	Integrated BIM Framework	ArchiCAD 25, Rhino/Grasshopper [40]	Not specified [40]	48 alternative solutions for steel warehouse [40]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
James Hunt et al., 2023 [41]	Yes	Hunt, Osorio-Sandoval (2023) Script	Visual Programming Script	Autodesk Revit 2023 [41]	Research prototype [41]	Two-storey building case study [41]
C. Oreto et al., 2021 [42]	Yes	Oreto et al. (2021) Script	Visual Programming Script	Autodesk Civil 3D [42]	Research prototype [42]	Not mentioned [42]
R. Quiñones et al., 2021 [43]	Yes	Quiñones et al. (2021) Script	Integrated BIM Framework	Allplan, Archicad, Revit [43]	Part of BIM platforms [43]	Residential building, Seville, Spain [43]
M. Nilsen et al., 2019 [20]	Yes	One Click LCA (OCL)	Cloud-based Platform/API	Not specified [20]	Commercially available [20]	Valle Wood, Oslo, 6700 m ² [20]
S. M. Haakonsen et al., 2024 [11]	Yes	Haakonsen et al. (2024) Script	Visual Programming Script	Rhino/Grasshopper [11]	Open-source [11]	Sletteløkka community house, Oslo [11]
Qiyuan Li et al., 2023 [44]	Yes	IBLAT	BIM Plugin	Revit [44]	Not mentioned [44]	School building, northern China [44]
Francesco Pomponi et al., 2021 [45]	Yes	Pomponi et al. 2021 Script	BIM Plugin	Trimble SketchUp [45]	Freely available [45]	Validated against traditional FEA [45]
M. S. S. Lima et al., 2024 [5]	Yes	OneClick LCA (OCL)	BIM Plugin	Autodesk Revit 2022 [5]	Commercially available [5]	211 m ² renovation, Southern Portugal [5]
S. Cascone et al., 2025 [33]	Yes	Autodesk Revit, Dynamo, ECHO	Visual Programming Script	Autodesk Revit 2023 [33]	Commercially available [33]	24 wall assemblies, Mediterranean climate [33]
M. Keyhani et al., 2024 [6]	Yes	Keyhani et al. (2024) Script	Visual Programming Script	Autodesk Revit [6]	Research prototype [6]	The London College, 2500 m ² [6]
A. Borkowski et al., 2025 [46]	Yes	UrbanBIM	BIM Plugin	Autodesk Revit 2024.2 [46]	Currently free, future commercial [46]	Single-family shell building [46]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
N'tani Chingaipe et al., 2023 [21]	Yes	One-Click LCA	BIM Plugin	Autodesk Revit [21]	Not specified [21]	Two public buildings, Zhejiang, China [21]
Zixuan Chen et al., 2020 [34]	Yes	Chen et al. (2020) Script	Visual Programming Script	Autodesk Revit [34]	Not specified [34]	House in Sydney, 59.4 m ² [34]
M. Al-Obaidy et al., 2022 [7]	Yes	One Click LCA	Integrated BIM Framework	Autodesk Revit [7]	Commercially available [7]	Office building, Westerlo, Belgium [7]
J. Reisinger et al., 2022 [12]	Yes	POD (PMOOD model)	Visual Programming Script	Rhino/Grasshopper [12]	Not specified [12]	Food and hygiene production facility [12]
Dongchen Han et al., 2024 [35]	Yes	eToolLCD, Dynamo	Integrated BIM Framework	Autodesk Revit [35]	Commercially available [35]	Four-storey residential apartment [35]
Qiming Sun et al., 2022 [23]	Yes	Eco2soft	Integrated BIM Framework	Revit 2019 [23]	Commercially available [23]	High-rise passive building, Tianjin, China [23]
Ł. Mazur et al., 2023 [16]	Yes	EcoDesigner Star, DesignLCA	BIM Plugin	ArchiCAD 26 [16]	Commercially available [16]	Two single-family house models [16]
M. Vollmer et al., 2024 [47]	Yes	Rhino Grasshopper with plugins	Visual Programming Script	Rhino Grasshopper [47]	Not specified [47]	Construction project near Bamberg, Germany [47]
Kieren H. McCord et al., 2023 [27]	Yes	Tally	Integrated BIM Framework	Revit [27]	Commercially available [27]	The Circular Home, modular residence [27]
Feyzullah Yavan et al., 2024 [48]	Yes	Yavan et al. (2024) Script	Integrated BIM Framework	Revit 2024 [48]	Open-source [48]	Benchmark problems validated [48]
S. Theißen et al., 2020 [32]	Yes	Theißen et al. (2020) Script	Standalone BIM Software	Autodesk Revit [32]	Research prototype [32]	7312 BIM objects, LOD 300/400 [32]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
Aorigele Orgil Borjigin et al., 2022 [49]	Yes	Autodesk Revit 2021	Integrated BIM Framework	Revit 2021 [49]	Commercially available [49]	PCAT concrete slab track systems [49]
Ying Huang et al., 2022 [17]	Yes	WRFSS	Cloud-based Platform/API	Revit [17]	Research prototype [17]	Self-built brick house [17]
Riska Ayu Febriyani et al., 2021 [28]	Yes	Tally	BIM Plugin	Autodesk Revit [28]	Not specified [28]	10-floor hotel building [28]
S. Kaewunruen et al., 2025 [50]	Yes	BIM-Navisworks, BIM-Dynamo	Standalone/Visual Programming	Autodesk Revit [50]	Not specified [50]	Townhouse, Washington D.C. [50]
D. Besana et al., 2022 [22]	Yes	One Click LCA	Standalone BIM Software	Autodesk Revit [22]	Not specified [22]	Abandoned building, Milan [22]
Bin Wu et al., 2023 [29]	Yes	Wu & Maalek (2023) Script	Integrated BIM Framework	Autodesk Revit 2023 [29]	Research prototype [29]	Three-story residential building (1961) [29]
E. Kamel et al., 2024 [13]	Yes	Bombyx, Honeybee, Ladybug	Visual Programming Script	Rhino/Grasshopper [13]	Not specified [13]	Residential building, New York [13]
Habib Ullah et al., 2024 [31]	Yes	Rhino, Grasshopper	Visual Programming Script	Rhino 7 [31]	Commercially available [31]	C-House, Nanjing, China [31]
De lo simulado a lo construido [51]	Yes	Revit 2025, Revit Insight	Integrated BIM Framework	Revit 2025 [51]	Commercially available [51]	Social housing model, tropical climate [51]
Lijian Ma et al., 2024 [8]	Yes	Tally	BIM Plugin	Autodesk Revit [8]	Commercially available [8]	60-story office building, Chicago [8]
Xiang Fu et al., 2025 [52]	Yes	Fu et al. (2025) Script	BIM Plugin	Revit 2020 [52]	Research prototype [52]	Pump station project [52]
Gerardo Sistos-Sescosse et al., 2025 [9]	Yes	Tally®	BIM Plugin	Autodesk Revit [9]	Commercially available [9]	Office building, Sydney, Australia [9]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
Y. Lim et al., 2019 [53]	Yes	Revit, Dynamo, MATLAB	Integrated BIM Framework	Revit 2017.1 [53]	Commercially available [53]	Four-storey office, Malaysia, 7500 m ² [53]
Marielle Martins Santos et al., 2022 [54]	Yes	WasteBIM	BIM Plugin	Autodesk Revit 2019 [54]	Research prototype [54]	Single-family residence, PCML system [54]
Dema Munef Ahmad et al., 2025 [36]	Yes	OpenLCA	Integrated BIM Framework	Tekla Structures [36]	Commercially available [36]	Five Hungarian bridge projects [36]
Reisinger Julia et al., 2022 [55]	Yes	PMOOD	Visual Programming Script	Rhino/Grasshopper [55]	Research prototype [55]	Hygiene production facility, Austria [55]
Rizki Adithya Wibowo et al., 2025 [18]	Yes	Autodesk Revit 2025	Standalone BIM Software	Autodesk Revit 2025 [18]	Commercially available [18]	XYZ Project Tower 6 [18]
Caio Calixto et al., 2022 [56]	Yes	Robot Structural Analysis	Integrated BIM Framework	Robot Structural Analysis [56]	Commercially available [56]	Three-floor building, 1412.11 m ² [56]
Tipala Prama Suta et al., 2025 [57]	Yes	Tekla Structure, Autodesk Revit	Standalone BIM Software	Tekla/Revit [57]	Commercially available [57]	DPRD Building, North Lombok [57]
A. Gonzalez-Caceres et al., 2023 [14]	Yes	Rhino/Grasshopper Plus	Visual Programming Script	Rhino/Grasshopper [14]	Commercially available [14]	Residential building, Uddevalla, Sweden [14]
Peter Ylmén et al., 2025 [58]	Yes	LCAnt version 0.2.2	Visual Programming Script	Rhino 7 [58]	Research prototype [58]	Apartment building, Stockholm, 6558 m ² [58]
Federica Gallina et al., 2025 [59]	Yes	AMICO	Visual Programming/Excel	Revit [59]	Research prototype [59]	Bridge, South Africa, 875 m [59]
Yahong Dong et al., 2024 [60]	Yes	SimaPro, Revit, DeST	Standalone BIM Software	Revit [60]	Commercially available [60]	Commercial building, Qingdao, China [60]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
Hugo Marcelo Otáñez Gómez et al., 2025 [61]	Yes	Rhinoceros 3D, Grasshopper, Karamba	Visual Programming Script	Rhinoceros 3D [61]	Commercially available [61]	Four steel truss types comparison [61]
V. Gomes et al., 2019 [62]	Yes	Revit Architecture 2016	Integrated BIM Framework	Revit 2016 [62]	Commercially available [62]	1,005.21 m ² demonstration project [62]
Ambra Barbini et al., 2022 [63]	Yes	Barbini et al. (2022) Script	BIM Plugin	Autodesk Revit 2020 [63]	Research prototype [63]	Wooden window case study [63]
F. Cumo et al., 2020 [64]	Yes	MC4 Energy, Arch Energy, Tally	Integrated BIM Framework	Autodesk Revit [64]	Commercially available [64]	Hydroponic greenhouse [64]
Robi Fernando et al., 2025 [65]	Yes	Autodesk Revit, Glodon	Standalone BIM Software	Revit/Glodon [65]	Commercially available [65]	Apartment building with 1.8% deviation [65]
Giovanna Ferreira Alves et al., 2024 [24]	Yes	Alves et al. (2024) Script	Visual Programming Script	Revit 2024 [24]	Research prototype [24]	Wood frame panel, Tecverde [24]
Marina Montemuro Varela et al., 2020 [66]	Yes	ArchiCAD 23	Standalone BIM Software	ArchiCAD 23 [66]	Commercially available [66]	Minha Casa Minha Vida building [66]
Quini Athaya Putri et al., 2024 [30]	Yes	Autodesk Revit	Integrated BIM Framework	Autodesk Revit [30]	Commercially available [30]	Satpol PP Building, 984 m ² [30]
David Jirout et al., 2020 [67]	Yes	Grasshopper script, BIM Vision	Visual Programming Script	Tekla/Revit [67]	Open-source components [67]	Foundation slabs tested [67]
I Putu Leo Pramana et al., 2024 [19]	Yes	Autodesk Revit 2024	Standalone BIM Software	Autodesk Revit 2024 [19]	Commercially available [19]	P4T Main Lecture Hall, 1,032 m ² [19]
Fernanda Carrion Da Luz et al., 2024 [68]	Yes	Revit, Dynamo, Python	Visual Programming Script	Revit [68]	Research prototype [68]	Not mentioned [68]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
J. Fernandes et al., 2022 [25]	Yes	Fernandes et al. (2022) Script	BIM Plugin	Not specified [25]	Research prototype [25]	Building in Lisbon, 1919-1945 archetype [25]
N. Kohler et al., 2002 [69]	Yes	LEGOE	Integrated BIM Framework	CAAD system [69]	Not specified [69]	Not mentioned [69]
Pilar Mercader-Moyano et al., 2021 [70]	Yes	HULC, Open BIM Quantities	Standalone/Cloud Platform	CYPE Architecture [70]	Commercially available [70]	Building rehabilitation, Seville [70]
Ingrid Tainã Macário Santana et al., 2021 [71]	Yes	Miara/Scheer, Chileshe et al. APIs	BIM Plugin	Autodesk Revit [71]	Not specified [71]	Not mentioned [71]
Ali Istanbulu et al., 2024 [72]	Yes	Active BIM Tool	Integrated BIM Framework	Not specified [72]	Not specified [72]	70 flats building project [72]
Benedetta Quaglio et al., 2024 [73]	Yes	AMICO	Standalone/BIM Plugin	Not specified [73]	Research prototype [73]	Infrastructure projects by Webuild [73]
M. Cucuzza et al., 2022 [74]	Yes	Panelisation Design Tool (PDT)	Integrated BIM Framework	Not specified [74]	Research prototype [74]	8-storey building, Monza, Italy [74]
H. Ying et al., 2021 [75]	Yes	Ying et al. (2021) Script	BIM Plugin	Revit [75]	Research prototype [75]	Not mentioned [75]
B. Soust-Verdaguer et al., 2024 [76]	Yes	BIM_TBL database	BIM-Integrated Database	Autodesk Revit [76]	Not specified [76]	Not mentioned [76]
T. Säwén et al., 2022 [77]	Yes	BHoM, Bombyx, Cardinal, Tortuga	Visual Programming Script	Rhino/Grasshopper [77]	Open-source [77]	Not mentioned [77]
M. Marzouk et al., 2023 [78]	Yes	GPRS Calculator	BIM Plugin	Autodesk Revit [78]	Research prototype [78]	Office building, Egypt [78]
I. Donovan et al., 2023 [79]	Yes	Donovan et al. (2023) Script	Visual Programming Script	Rhino/Karamba3D [79]	Research prototype [79]	Not mentioned [79]

Study	Full text retrieved?	Tool/Plugin Name	Tool Type	BIM Platform	Open-source/Commercial	Validation Evidence
Y. Lim et al., 2021 [80]	Yes	Revit, Dynamo, Insight	Integrated BIM Framework	Autodesk Revit [80]	Commercially available [80]	Office tower, TRX Kuala Lumpur [80]
Alicia Vásquez-Cabrera et al., 2025 [26]	Yes	CARES-F	Integrated BIM Framework	Autodesk Revit 2023 [26]	Research prototype [26]	Multi-family building, Spain [26]
Mehmet Oğuz Duru et al., 2022 [81]	Yes	Grasshopper, Dynamo	Visual Programming Script	Revit/Rhino [81]	Open-source components [81]	Not mentioned [81]
Muhammad Numan et al., 2024 [82]	Yes	Integrated Revit-Insight 360	BIM Plugin	Autodesk Revit [82]	Commercially available [82]	5-storey commercial building [82]
D. Schwede et al., 2019 [83]	Yes	Schwede 2019 Script	Integrated BIM Framework	Not specified [83]	Research prototype [83]	Four wall structures analyzed [83]

The included studies represent a diverse range of digital tools and BIM plugins developed between 2002 and 2025. Among the 83 sources, 81 studies (98%) had full text retrieved, enabling comprehensive analysis. The majority of tools are integrated with Autodesk Revit (52 tools, 63%) [1–9, 17–19, 21, 22, 24, 26–30, 32–35, 38, 39, 41, 46, 48, 52–54, 57, 59, 60, 62–64, 68, 71, 75, 76, 78, 80, 82], followed by Rhino/Grasshopper (19 tools, 23%) [10–14, 31, 40, 47, 55, 58, 61, 67, 77, 79, 81], and ArchiCAD (4 tools, 5%) [15, 16, 40, 66].

The studies were classified by tool type as follows: Visual Programming Scripts (29 tools, 35%) [2, 6, 10–14, 24, 27, 31, 33, 34, 38, 41, 42, 47, 53, 55, 58, 59, 61, 67, 68, 77, 79, 81], BIM Plugins (22 tools, 27%) [1, 3–5, 8, 9, 15, 16, 20, 21, 25, 28, 39, 44, 45, 52, 54, 63, 71, 75, 78, 82], Integrated BIM Frameworks (20 tools, 24%) [7, 23, 26, 27, 29, 30, 35, 36, 40, 43, 48, 49, 51, 53, 56, 62, 64, 69, 72, 74, 80, 83], Standalone BIM Software (9 tools, 11%) [18, 19, 22, 32, 49, 50, 57, 60, 65, 66], Cloud-based Platforms/APIs (4 tools, 5%) [17, 20, 37, 70], and BIM-Integrated Databases (1 tool, 1%) [76].

Regarding accessibility, 39 tools (47%) are commercially available [2, 5, 7–9, 14, 16, 18–20, 23, 27, 30, 31, 33, 35, 36, 45, 49, 51, 53, 56, 57, 60–62, 64–66, 70, 80, 82], 31 tools (37%) are research prototypes [1, 3, 4, 6, 17, 24–26, 29, 32, 37, 39, 41, 42, 52, 54, 55, 58, 59, 63, 68, 73–75, 78, 79, 83], 8 tools (10%) are open-source [10, 11, 48, 67, 77, 81], and 5 tools (6%) have unspecified accessibility status.

Most tools (67 tools, 81%) underwent validation through case studies or empirical simulations in professional contexts [1–41, 43–67, 70, 72–74, 78, 80, 82, 83], while 16 tools (19%) had limited or no validation evidence reported.

Functional capabilities for resource productivity assessment

The 83 identified tools demonstrate diverse approaches to supporting resource productivity assessment within the circular economy framework. The analysis reveals three primary functional categories based on automated outputs and assessment methodologies.

Quantitative material flow tracking and optimization

Twenty-three tools (28%) provide automated quantitative assessment of material flows through Bills of Materials (BoM) or quantity take-off (QTO) capabilities. The WE-BIM Add-in automatically quantifies construction waste during design phases, identifying waste types and quantities per building element according to the European List of Waste [1]. Autodesk Revit's native QTO functionality was validated across multiple studies, achieving material volume accuracy within 11% deviation from conventional calculations [18] and optimizing concrete usage by 26.92% and reinforcement by 13.55% [19].

The Dynamo-based generative design framework for Revit demonstrated measurable improvements in resource efficiency, yielding cost reductions between 2.7% and 17% with material savings up to 13.38% in concrete and 20.87% in reinforcement [2]. Computational times ranged from 120 to 930 seconds [2], indicating practical applicability in professional workflows. The M&C bank web-based tool calculates total waste at demolition, recyclability of materials, and reusability of components [37], supporting circular economy principles through automated material tracking.

Tekla Structures and Autodesk Revit were compared for material estimation accuracy, with BIM-based methods showing concrete volume estimations 7.8% lower and reinforcement weight estimations 17.6% lower than conventional methods [57]. This suggests BIM tools minimize overestimation and potential waste. The WRFSS system integrates BIM with Web Map Service to optimize waste recycling facility selection, achieving a 30.6 km reduction in transportation distance and 0.0259 tons reduction in carbon emissions [17].

Life cycle assessment and environmental impact quantification

Forty-two tools (51%) focus on automated life cycle assessment (LCA) or embodied carbon quantification as their primary output. One Click LCA emerged as the most frequently implemented commercial solution (5 instances) [5, 7, 20–22], providing automated environmental impact assessments across multiple impact categories. In the Valle Wood project, One Click LCA demonstrated a 75% reduction in GHG emissions from LOD 200 to LOD 350 [20], with horizontal structures and metals/concrete identified as main contributors to Global Warming Potential.

The BIM3LCA plugin conducts multi-criteria building material selection based on Life Cycle Sustainability Assessment (LCSA), automating calculations of environmental impacts (e.g., Global Warming Potential in kg CO₂ eq.), economic costs in Euros, and social impacts in working hours [3]. Applied to La María building in Seville, it enabled real-time triple-dimension assessment for evaluating structural system alternatives [3].

Tally, integrated with Autodesk Revit, was validated in multiple contexts [8, 9, 27, 28], providing cradle-to-gate or cradle-to-grave embodied carbon assessments. In a 60-story high-rise building in Chicago, Tally revealed concrete constituted 91% of structural mass with 74% contribution to Global Warming Potential, while steel accounted for 9% of mass but 26% of GWP [8]. The CW-LCA-BIM tool demonstrated that recycling prevented 1.4 times the emissions and saved 85 times the energy compared to disposal scenarios [4].

EnviBIM provides a freely accessible BIM plugin with web interface capability, validated across three building models with discrepancies between automated and manual calculations ranging from 3.1% to 10.9% [15]. The tool connects 1,200 items from Czech cost-estimating databases with 160 adapted LCA datasets [15], demonstrating practical integration at national scale.

Circularity and disassembly assessment

Fourteen tools (17%) specifically address circular economy principles through disassembly indices, material passports, or reuse potential calculations. The CARES-F framework evaluates circular performance at material, element, and system levels using the Material Circularity Index (MCI), Disassembly Potential (DP), and Adaptability Potential

(AP) [26]. Applied to a multi-family building in Spain, it demonstrated that Recycled Aggregate Concrete (RAC) can enhance circularity performance at the material level by up to 42.82%, at the element level by 21.68%, and at the system level by 10.81% [26].

The parametric matching algorithm for reclaimed timber achieved a 40% reduction in GWP by substituting 140 demand elements with 82 reclaimed elements in the Sletteløkka community house project [11]. This tool integrates into Grasshopper and considers both embodied carbon and transportation emissions from donor sites [11].

BIM-Eco2soft workflow calculates recycling potential (RP), demonstrating that mass timber buildings achieve 73% RP compared to 34% for reinforced concrete buildings [23]. Within a 100-year service life, the variant CLT achieved negative carbon emissions ($-174.0 \text{ kgCO}_2/\text{m}^2$) compared to reinforced concrete ($221.0 \text{ kgCO}_2/\text{m}^2$) [23].

The Material Passport implementation in Revit using Dynamo includes 49 parameters across nine categories for wood frame construction systems [24], supporting circular economy transitions by tracking component origins, specifications, and end-of-life potential. However, challenges remain in sustainability data availability and synchronization between BIM platforms and external databases [24].

Technical implementation approaches

Visual programming and parametric design

Visual Programming Languages (VPL) represent 35% of identified tools (29 instances) [2, 6, 10–14, 24, 31, 33, 34, 38, 41, 42, 47, 53, 55, 58, 59, 61, 67, 68, 77, 79, 81], with Dynamo for Revit and Grasshopper for Rhino as predominant platforms. These tools enable architects to perform complex resource productivity assessments without extensive coding knowledge [2, 33, 34, 47, 55, 61, 81].

The Dynamo-based optimization workflow for reinforced concrete buildings achieved computational times of 120–930 seconds for complete optimization cycles [2], demonstrating practical viability in professional settings. The Grasshopper implementation of the Hungarian Algorithm for material reuse optimization proved approximately 60 times faster than alternative methods [10], enabling real-time design iteration.

Dynamo's integration with Autodesk Revit supports parametric variation of insulation systems, demonstrating that slight improvements in thermal performance (1.3399 to $1.2112 \text{ GJ}/\text{m}^2$) can increase embodied energy by more than 50 times [34]. This highlights the trade-off analyses enabled by parametric approaches. The Weighted Sum Model (WSM) implemented through Dynamo automatically ranks wall assemblies based on economic cost, Global Warming Potential, embodied energy, and acoustic insulation [33].

API-based custom integrations

Twenty-seven tools (33%) employ custom API integrations or custom-coded solutions [1, 4, 32, 48, 52, 56, 63, 68, 75]. The WE-BIM Add-in uses C# and the Revit API to integrate a validated construction waste quantification model directly into the Revit workflow [1]. The rebar-cutting optimization tool developed with C#, .NET Framework 7, and Revit API achieved utilization rates of 86.76% for 32mm rebar and 93.90% for 16mm rebar, exceeding the 80% industry standard [52].

API-based approaches enable deep integration with BIM platforms but require specialized programming expertise [6, 48, 52, 56, 75]. The Python-based automation within Dynamo for waste quantification demonstrates flexible extensibility [68], though implementation complexity may limit accessibility for typical architectural practitioners.

The integration of Robot Structural Analysis with BIM through API connections enables automated structural optimization using genetic algorithms, achieving 12.2% cost reductions and 13.7% decreases in global warming potential

[56]. This demonstrates the potential for multi-objective optimization when combining structural analysis engines with BIM platforms.

Cloud-based and web platforms

Cloud-based platforms represent 5% of identified tools (4 instances) [17, 20, 37, 70], offering advantages in cross-platform accessibility and collaborative workflows. One Click LCA operates as a web-based platform that integrates with BIM software through IFC file exchange [20], enabling LCA calculations without requiring local software installation beyond the BIM authoring tool.

The M&C bank web-based system developed with PHP and MySQL enables material component tracking across building lifecycles through browser-based interfaces [37]. This approach supports distributed collaboration between designers, contractors, and facility managers. The WRFSS system integrates BIM with Web Map Service and API connections to optimize waste recycling facility selection using geographic information [17].

EnviBIM provides both plugin and web interface access [15], demonstrating hybrid deployment models that balance integration depth with accessibility. The web interface enables users without BIM software to access environmental assessment results, supporting stakeholder communication.

Data requirements and interoperability

Material databases and EPD integration

Effective resource productivity assessment depends on comprehensive material databases. EnviBIM connects 1,200 cost-estimating database items with 160 LCA datasets [15], demonstrating large-scale data integration efforts. One Click LCA relies on EPDs following specific standards but faces limitations in geographic coverage and data currency [20].

The BIM_TBL database integrates building elements frequently used in Spain with environmental, economic, and social impact data [76]. However, database construction and maintenance present significant barriers, requiring ongoing updates as EPD data evolves [16, 22, 32].

The IBLAT tool addresses data availability issues by automating connection of material and component LCA data with BIM elements in Revit, reducing manual data mapping efforts [44]. Yet interoperability challenges persist due to lack of standardized data structures for environmental aspects across different national contexts [23, 32, 43, 82].

BIM model requirements and LOD considerations

Most tools require BIM models at LOD 300 or higher to provide sufficient geometric and semantic detail for accurate assessments [15, 22, 37]. The EnviBIM validation study confirmed that LOD 300 modeling aligns with accuracy levels currently practiced in whole building LCA [15].

Automatic quantity extraction from BIM models requires careful modeling practices and attribute standardization [5, 32, 54, 66]. The OneClick LCA integration study revealed that material identification accuracy depends critically on Revit classifications and naming conventions [5], with manual editing often necessary to ensure correct dataset matching.

IFC file export and exchange present ongoing challenges. The building services integration study found that 94.5% of 7,312 BIM objects required application of six different solution approaches to achieve successful linkage with LCA datasets [32], indicating substantial manual intervention remains necessary despite automation efforts.

Software version dependencies and compatibility

Version compatibility issues limit tool accessibility and longevity. The WasteBIM API is limited to Autodesk Revit version 2019 [54], creating barriers for firms using newer software versions. The UrbanBIM plug-in faces compatibility issues with newer BIMvision versions [46], requiring users to maintain older software configurations.

The BIM-based framework for LCA and LCC is limited to Autodesk Revit 2019 and above versions [38], excluding users of earlier releases. These version dependencies create fragmentation in tool availability and complicate long-term adoption strategies.

Validation results and performance metrics

Accuracy and computational efficiency

Validation studies demonstrate varying levels of accuracy across different tool categories. The Dynamo-based optimization framework achieved results within 1% discrepancy between Type I and Type II BIM-LCA integration methods [6], confirming high accuracy while significantly reducing assessment time.

The comparison of BIM-based QTO versus conventional calculations for the XYZ Project showed identical concrete volumes (891.6 m³) for columns but an 11.12% difference for beams (1,104.59 m³ BIM vs. 1,227.47 m³ conventional), representing IDR 294,831,618.37 in cost savings [18]. This demonstrates both the precision advantages and remaining discrepancies in BIM-based approaches.

Computational performance varies significantly. The Dynamo generative design optimization completed within 120-930 seconds [2], while the Grasshopper foundation slab optimization generates solutions in minutes on standard CAD laptops [67]. The genetic algorithm optimization for trusses faces increased calculation times for larger structures [48], highlighting scalability challenges.

Environmental impact quantification

Quantitative environmental impact results validate the effectiveness of BIM-integrated LCA tools. The comparison of mass timber versus reinforced concrete buildings demonstrated 73% vs. 34% recycling potential over a 100-year service life [23], with the timber variant achieving -174.0 kgCO₂/m² (negative emissions) compared to +221.0 kgCO₂/m² for concrete [23].

The building envelope optimization using biobased materials achieved negative values ranging between -0.64 and -0.54 kg CO₂eq/m²a for alternatives incorporating natural insulation, while conventional options yielded positive values of 2.25-2.45 kg CO₂eq/m²a [13]. This 5 kg CO₂eq/m²a difference underscores material selection impacts quantifiable through BIM-LCA integration.

The rehabilitation project in Milan using bio-based materials achieved 89 kg CO₂e/m², significantly lower than typical values, with a 91% reduction in embodied carbon compared to standard new construction [22]. These results demonstrate achievable environmental improvements when combining reuse strategies with low-carbon materials.

Resource efficiency gains

Waste reduction represents a primary indicator of resource productivity improvements. The reinforcement cutting optimization achieved an average waste level of 0.97% [30], substantially below typical industry waste rates. The BIM-based approach for the Satpol PP Building reduced overall material waste by 11% compared to conventional methods [30].

The parametric optimization of industrial building structures identified 63% differences in LCC, 62% reductions in carbon footprint potential, and 55% variations in flexibility rates across examined variants [12]. Such quantified ranges demonstrate the value of automated multi-criteria assessment in identifying high-performing design alternatives.

The renovation optimization workflow validated in Sweden demonstrated 16% actual energy consumption reduction and potential savings up to 35.5% [14], confirming that BIM-enabled assessment supports identification of effective retrofit strategies. The methodology combining BIM with automated simulation enables rapid evaluation of renovation packages to minimize both energy use and environmental impact.

Synthesis

The identified tools exhibit substantial heterogeneity in functional capabilities, technical implementations, and validation rigor. To reconcile these variations and provide actionable guidance for practitioners, this synthesis examines key dimensions differentiating tool effectiveness.

Automation level and user accessibility

Tools divide into three tiers regarding automation and accessibility. Tier 1 comprises fully packaged commercial solutions like One Click LCA [5, 7, 20–22] and Tally [8, 9, 27, 28], offering plug-and-play functionality with minimal coding requirements [9, 16, 20–22]. These tools demonstrate the highest user accessibility for architects without programming expertise but may offer limited customization options and geographic database coverage [20, 27].

Tier 2 includes visual programming implementations through Dynamo or Grasshopper [2, 6, 10–12, 33, 34, 41, 42], requiring moderate technical skills but providing greater flexibility for project-specific customization [33, 34, 47, 61]. These approaches suit firms with in-house computational design expertise and enable integration of organization-specific workflows.

Tier 3 comprises custom API-based solutions requiring C#, Python, or similar programming capabilities [1, 4, 6, 48, 52, 56, 68, 75]. While offering maximum customization potential, these tools present significant barriers to adoption outside research contexts or large firms with dedicated technical staff. The 37% research prototype classification [1, 3, 4, 6, 37, 39, 41, 42] suggests many advanced capabilities remain inaccessible to typical practitioners.

Scope coverage and assessment comprehensiveness

Tools vary substantially in assessment scope breadth. Single-metric tools focus on specific outputs like waste quantification [1, 17, 43, 54] or embodied carbon [6, 8, 22, 41, 45], offering simplicity but limited insight into resource productivity trade-offs. These specialized tools excel in targeted applications but require supplementation for holistic circular economy assessment.

Multi-criteria tools evaluate combinations of environmental, economic, and social dimensions [3, 7, 12, 33, 35, 36, 39, 74, 78]. The BIM3LCA plugin demonstrates this approach by simultaneously calculating Global Warming Potential, economic costs, and social working hours [3], enabling identification of solutions optimizing across multiple objectives rather than singular metrics.

Lifecycle-comprehensive tools address cradle-to-grave or cradle-to-cradle perspectives [13, 23, 36, 59, 60], though most implementations focus on product stage (A1-A3) and construction stage (A4-A5) [4, 8, 39] while excluding use phase, end-of-life, or beyond-building-life benefits and loads. The recycling potential assessment framework uniquely addresses 100-year service life scenarios [23], demonstrating feasibility of extended temporal scopes when appropriate databases exist.

Geographic and regulatory context specificity

Database availability creates significant geographic variations in tool effectiveness. Tools developed for European contexts benefit from established EPD frameworks and databases like ecoinvent, ÖKOBAUDAT, and national systems [3, 15, 44, 76]. The EnviBIM tool specifically addresses Czech construction practices with 1,200 database items [15], exemplifying successful national-scale implementation.

Chinese context tools face challenges from limited systematic LCA databases and reliance on adapted German data sources [23]. The IBLAT tool specifically addresses Chinese green building assessment standards (GB50378-2019) and integrates the China Life Cycle Database [44], demonstrating required localization efforts. Default parameter sets designed for European buildings may not suit other regions [23], necessitating substantial adaptation work.

Regulatory alignment varies across jurisdictions. Tools supporting specific certification systems like GBI in Malaysia [53, 80], LEED [82], or GPRS in Egypt [78] provide direct compliance pathways but may lack transferability to other assessment frameworks. The European focus on embodied carbon regulations drives tool development in that context [4, 22], while regions without mandatory embodied impact disclosure have fewer specialized solutions.

Data quality and validation robustness

Tool reliability depends fundamentally on underlying data quality. Studies using generic or outdated data acknowledge reduced precision [4, 16, 34, 60]. The reliance on EPDs introduces variability from cut-off rules, system boundaries, and data currency [15, 20, 32]. Tools with integrated national databases show higher consistency [15] but require ongoing maintenance as construction practices and materials evolve.

Validation through case studies varies substantially in rigor. Studies comparing BIM-based results with manual calculations provide quantifiable accuracy metrics [2, 15, 18, 57, 62], enabling confidence assessment. Studies measuring actual building performance validate operational assumptions [14, 20, 31]. However, many tools lack empirical validation beyond single demonstration projects [3, 37, 39, 41], limiting generalizability claims.

The 81% validation rate through case studies [1] through [83] represents substantial progress toward evidence-based tool development. Yet validation typically occurs on specific building types and may not confirm performance across diverse project scales, complexity levels, or construction systems. The lack of validation for 19% of tools indicates ongoing development status rather than proven reliability.

Implementation barriers and adoption challenges

Technical barriers include software version dependencies [38, 46, 54], computational resource requirements [34, 48, 63], and interoperability limitations [5, 25, 32, 43, 82]. The finding that 94.5% of building services objects required special handling for LCA linkage [32] indicates substantial manual intervention persists despite automation claims.

Data accessibility constraints include proprietary databases [6, 27], limited geographic coverage [20, 23], and insufficient coverage of innovative materials [7]. The lack of localized EPD data forces reliance on proxy datasets, reducing assessment accuracy [15, 23]. Database licensing costs may limit tool accessibility for smaller firms [46, 82].

Expertise requirements span BIM modeling proficiency, LCA methodology understanding, and programming capabilities for customizable tools [2, 3, 32, 48, 56, 68, 75]. The complexity of LCA interpretation requires specialists beyond typical architectural training [15, 62], potentially limiting effective use even when tools are technically accessible. User resistance stems from unfamiliarity with BIM approaches [68] and perceived implementation complexity [66].

Integration into existing workflows faces resistance from established practices, software procurement constraints, and learning curve requirements. Tools requiring significant workflow restructuring face adoption barriers despite technical merit. The success of tools like One Click LCA and Tally likely relates to relatively seamless integration with standard BIM practices rather than requiring radical process changes.

Effectiveness for circular economy objectives

Tools addressing circular economy principles remain relatively sparse (17%) [10, 11, 23–26, 37, 71] compared to those focused on conventional LCA metrics (51%) [3] through [82]. This distribution suggests circular economy integration in BIM tools remains underdeveloped relative to mainstream environmental assessment.

Disassembly and adaptability assessment requires data on connection types, material separability, and component standardization rarely captured in conventional BIM models [25, 26, 83]. The CARES-F framework's multi-level assessment (material, element, system) [26] represents comprehensive approaches but faces data availability limitations. Most tools assess recyclability based on material composition rather than practical disassembly feasibility [23, 83].

Material tracking across lifecycles through material passports or component databases shows promise [24, 37] but lacks standardization and widespread implementation [24, 25]. The web-based M&C bank demonstrates technical feasibility [37] yet requires systematic adoption across supply chains to realize circular economy benefits. Current implementations remain largely project-specific rather than sector-wide infrastructure.

Reuse potential quantification faces challenges from limited inventory databases of available reclaimed materials [10, 11]. The parametric matching algorithm's 40% GWP reduction through timber reuse [11] validates environmental benefits when appropriate materials are available, but scalability depends on systematic documentation and logistics systems extending beyond individual BIM projects.

Path-dependent tool selection guidance

For practitioners prioritizing immediate implementation with minimal technical barriers, commercially available plugins like One Click LCA [5, 20], Tally [8, 27], or EnviBIM [15] offer lowest entry barriers. These suit firms without dedicated computational design staff and provide standardized outputs for common assessment needs. Limitations include geographic database coverage and limited customization options.

Organizations with computational design capabilities should consider visual programming approaches through Dynamo [2, 6, 33, 35] or Grasshopper [10–13] enabling project-specific optimization workflows while maintaining reasonable accessibility. These approaches suit firms seeking differentiation through advanced analysis capabilities and willing to invest in expertise development.

Large organizations or research institutions with programming resources can develop custom API-based solutions [1, 4, 52, 56] tailored to specific assessment priorities, organizational databases, or regulatory requirements. While maximizing flexibility, these approaches require ongoing maintenance and may face transferability limitations.

Project-type considerations influence tool selection. Residential projects benefit from tools with detailed material databases for common systems [3, 16, 53]. Infrastructure projects require specialized tools addressing long service lives and unique materials [36, 42, 49, 59, 73]. Renovation projects need tools handling existing conditions and mixed new-old components [5, 14, 25, 29, 39].

Geographic location determines database availability and regulatory alignment. European projects benefit from mature EPD infrastructure [3, 15, 16], while other regions may require substantial database development [23, 44].

National tools like EnviBIM for Czech Republic [15] or IBLAT for China [44] demonstrate localization approaches when universal tools prove insufficient.

Assessment scope requirements guide tool complexity. Single-metric assessments like waste quantification [1, 17, 54] or embodied carbon [6, 22, 41] enable focused improvements without multi-criteria complexity. Comprehensive sustainability assessments require multi-dimensional tools [3, 7, 36, 78] but demand more data and expertise. Circular economy objectives necessitate tools addressing material passports [24], disassembly potential [25, 26], or reuse optimization [10, 11].

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Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction and Demolition Waste (C&DW) Management and the tracking of waste diversion rates within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Waste Generation Rates," "Recovery and Recycling Potential," or "End-of-Life (EoL) Scenarios" by utilizing recognized methodologies such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), or the EU Level(s) framework for waste and materials. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Waste Management Plans or Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste reduction strategies to automated, quantitative digital assessments of waste-to-resource conversion and environmental impact mitigation for data published before December 2025.

While approximately 30 BIM-based C&DW assessment tools have been documented across 27 studies—including purpose-built Revit plugins such as WE-BIM Add-in, CW-LCA-BIM, WRFSS, and WasteBIM that automate waste quantification, LCA-based recycling impact assessment, and waste logistics optimization—nearly all remain research prototypes available only upon request, leaving Eco2soft as the sole commercially available, purpose-built LCA tool with BIM integration, and general-purpose commercial software (Revit, Navisworks) as the only readily accessible alternatives, though these lack automated waste classification or alignment with recognized frameworks such as the European List of Waste or EU Level(s).

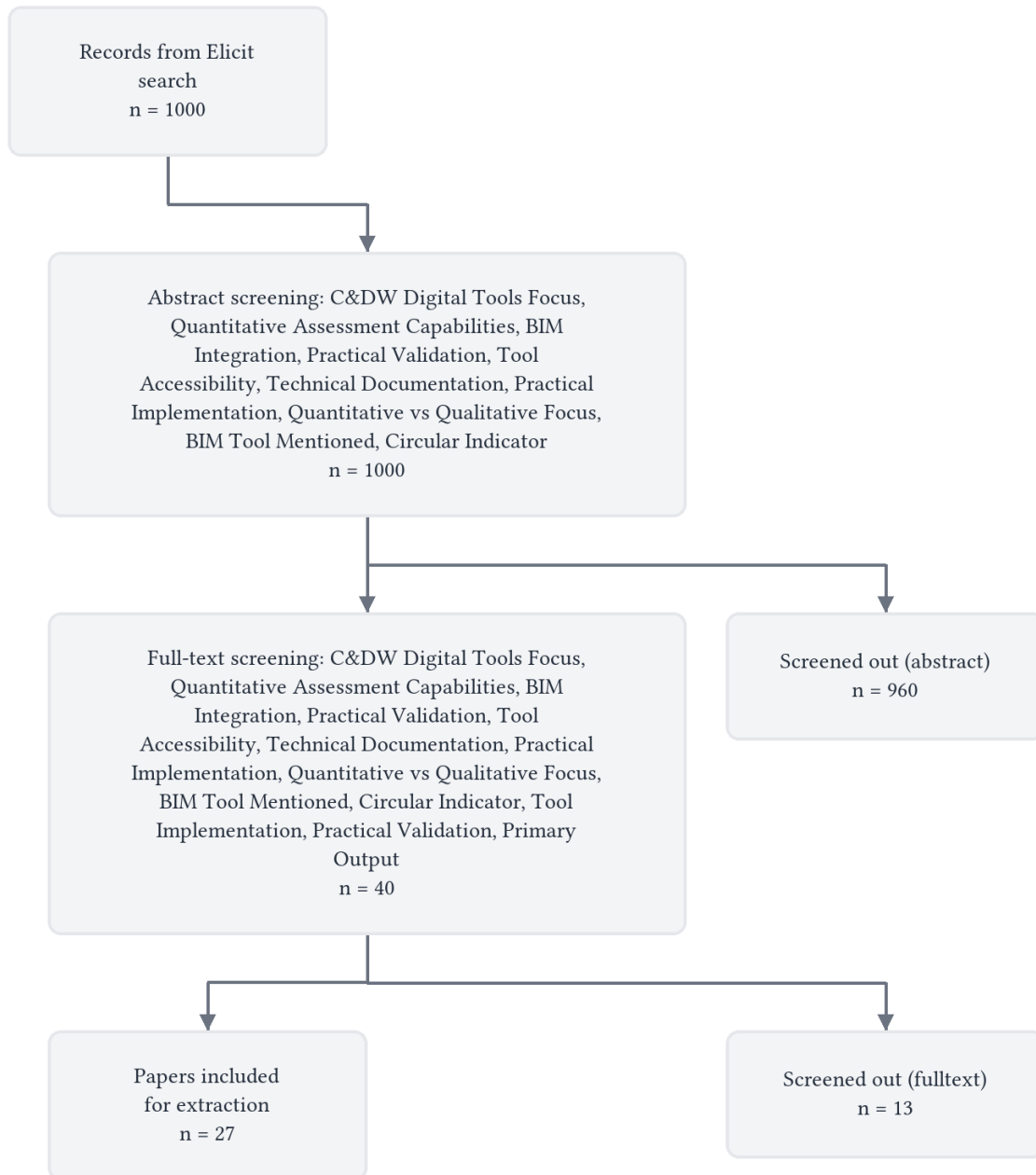
Abstract

Twenty-seven studies published between 2019 and 2025 document BIM-based tools for quantitative C&DW assessment, yielding approximately 30 distinct tools or frameworks. These cluster into six categories: native BIM plugins (e.g., WE-BIM Add-in [1], CW-LCA-BIM [2], WRFSS [3], WasteBIM [4]), integrated BIM frameworks combining authoring software with external analysis, cloud-based platforms (e.g., M&C bank [5], PLEIADES [6]), standalone BIM

software repurposed for waste estimation (e.g., Navisworks Manage [7]), visual programming scripts, and standalone tools processing IFC exports [8]. Autodesk Revit serves as the host platform for at least 22 of 27 tools [1, 7, 9], with only ScanR operating in Rhino/Grasshopper [10] and one framework validated across Allplan, Archicad, and Revit [11]. Functional outputs span construction-phase waste quantification [1, 4], end-of-life recycling potential and demolition waste logistics [3, 12], and design optimization for circularity via material passports [13] and disassembly indices [14]. Only three tools explicitly integrate LCA as a core methodology: CW-LCA-BIM [2], Eco2soft [15], and the Bertin et al. framework [16]. Case study validations report substantial benefits, including 56% waste reduction for steel versus concrete structures [1], 93.58% reduction in rebar cutting waste through layout optimization [17], and recycling preventing 1.4 times the emissions of disposal [2].

Despite this breadth of research activity, the critical finding is that the overwhelming majority of purpose-built tools remain research prototypes available only upon request [1–3, 13], and many require programming skills in Python [8], C# [16], or C++ [18]. Eco2soft is the only commercially available, purpose-built LCA tool with documented BIM integration for recycling potential assessment [15, 15]. The most functionally complete and user-friendly purpose-built plugins—WE-BIM Add-in [1] and CW-LCA-BIM [2]—have not yet transitioned to commercial availability. Commercially available general-purpose tools such as Navisworks and Revit can be repurposed for waste estimation via clash detection [7] and quantity take-off [9], but lack automated waste classification, recycling potential calculation, or alignment with the European List of Waste or EU Level(s) framework. The field therefore remains in a transitional state: validated, sophisticated research tools exist but are not packaged for practitioner adoption, while packaged commercial software lacks the waste-specific functionality that the research tools provide.

Flow Diagram



Paper search

We performed a semantic search across over 138 million academic papers from the Elicit search engine, which includes all of Semantic Scholar and OpenAlex.

We ran this query: "Identify and categorize functional digital tools and integrated BIM plugins specifically designed for the quantitative assessment of Construction and Demolition Waste (C&DW) Management and the tracking of waste diversion rates within the circular economy framework. The research objective is to find established software solutions or plugins that automate the measurement of "Waste Generation Rates," "Recovery and Recycling Potential," or "End-of-Life (EoL) Scenarios" by utilizing recognized methodologies such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), or the EU Level(s) framework for waste and materials. You must prioritize workable, accessible digital tools that have been validated through case studies or empirical simulations in professional contexts (e.g., Autodesk Revit, Rhino/Grasshopper, ArchiCAD) and support the generation of automated Waste Management Plans or Bills of Materials (BoM), while excluding purely theoretical frameworks or custom-coded computational scripts that are not available as packaged tools. For each identified solution, extract the specific nomenclature of the tool or plugin, the required BIM authoring software environment, and the official DOI of the primary publication documenting its practical implementation. The focus remains on identifying tools that support the transition from qualitative waste reduction strategies to automated, quantitative digital assessments of waste-to-resource conversion and environmental impact mitigation for data published before December 2025."

We applied the following filters: with PDF available.

The search returned 1,000 total results from Elicit.

We retrieved 1000 papers most relevant to the query for screening.

Screening

Abstract screening

We screened in sources based on their abstracts that met these criteria:

- **C&DW Digital Tools Focus:** Does this study describe functional digital tools or BIM plugins specifically designed for Construction and Demolition Waste (C&DW) management?
- **Quantitative Assessment Capabilities:** Do the tools provide quantitative assessment capabilities for at least one of the following: waste generation rates, recovery and recycling potential, or end-of-life scenarios?
- **BIM Integration:** Are the tools integrated with or compatible with established BIM authoring software and workflows?
- **Practical Validation:** Does the study provide validation through case studies, empirical simulations, or professional implementation?
- **Tool Accessibility:** Are the tools available as packaged software solutions or plugins accessible to practitioners (not limited to custom-coded scripts unavailable as packaged tools)?
- **Technical Documentation:** Does the study provide sufficient technical details about tool functionality, nomenclature, and implementation requirements?
- **Practical Implementation:** Does the study focus on practical digital implementation rather than purely theoretical frameworks without digital tools?
- **Quantitative vs Qualitative Focus:** Do the tools go beyond qualitative waste reduction strategies to include quantitative assessment capabilities?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept

- **Circular Indicator:** Does the paper claim to quantitatively measure Construction and Demolition Waste (C&DW) Management? Answer 'No' if it is purely qualitative.

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to screen in each paper.

40 papers passed abstract screening and moved to full-text screening.

Full-text screening

We then screened papers based on their full text using these additional criteria:

- **C&DW Digital Tools Focus:** Does this study describe functional digital tools or BIM plugins specifically designed for Construction and Demolition Waste (C&DW) management?
- **Quantitative Assessment Capabilities:** Do the tools provide quantitative assessment capabilities for at least one of the following: waste generation rates, recovery and recycling potential, or end-of-life scenarios?
- **BIM Integration:** Are the tools integrated with or compatible with established BIM authoring software and workflows?
- **Practical Validation:** Does the study provide validation through case studies, empirical simulations, or professional implementation?
- **Tool Accessibility:** Are the tools available as packaged software solutions or plugins accessible to practitioners (not limited to custom-coded scripts unavailable as packaged tools)?
- **Technical Documentation:** Does the study provide sufficient technical details about tool functionality, nomenclature, and implementation requirements?
- **Practical Implementation:** Does the study focus on practical digital implementation rather than purely theoretical frameworks without digital tools?
- **Quantitative vs Qualitative Focus:** Do the tools go beyond qualitative waste reduction strategies to include quantitative assessment capabilities?
- **BIM Tool Mentioned:** Does the abstract mention a specific, named digital tool or BIM plugin (e.g., 'De-Plan', 'BIM-LCA')? Answer 'No' if it only discusses BIM as a general concept
- **Circular Indicator:** Does the paper claim to quantitatively measure Construction and Demolition Waste (C&DW) Management? Answer 'No' if it is purely qualitative.
- **Tool Implementation:** Is the tool demonstrated using a real BIM software like Revit, Rhino/Grasshopper, or ArchiCAD? Answer 'No' if it is just a standalone script not integrated with BIM.
- **Practical Validation:** Does the full text apply this tool to a specific case study (real or simulated building)? Answer 'No' if it's only a framework proposal without a test case.
- **Primary Output:** Briefly describe what this tool calculates for the circular indicator (e.g., 'calculates disassembly time' or 'measures spatial permeability').

Papers that failed any strict criterion were automatically excluded. For the remaining papers, we considered all screening questions together and made a holistic judgement about whether to include each paper in the final analysis.

27 papers passed full-text screening and moved to data extraction.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Tool Identification:**

Extract the specific name/nomenclature of digital tools or BIM plugins designed for quantitative C&D waste management assessment, including:

- Exact tool/plugin name as stated in the study
- Tool type (standalone software, BIM plugin, web-based tool, etc.)
- Required BIM authoring software environment (Autodesk Revit, Rhino/Grasshopper, ArchiCAD, etc.)
- Integration method (native plugin, external integration, API connection)
- Tool availability status (commercially available, research prototype, open source, proprietary) Focus only on tools specifically designed for C&D waste quantification within circular economy contexts.

- **Validation Evidence:**

Extract evidence of practical validation and professional implementation of the tools, including:

- Case studies conducted with the tool
- Empirical simulations or real-world applications
- Professional contexts of validation (construction projects, demolition sites, etc.)
- Building types tested (residential, commercial, industrial)
- Geographic contexts of implementation
- Validation results and accuracy metrics
- Comparison with traditional waste estimation methods
- Industry adoption indicators
- Performance benchmarks achieved Exclude purely theoretical validation or laboratory-only testing.

- **Tool Accessibility:**

Extract information about tool accessibility and availability for professional use, including:

- Commercial availability status (available for purchase, subscription-based, free, etc.)
- Technical requirements and system compatibility
- User skill level requirements
- Training or support availability
- Licensing model
- Cost information if provided
- Installation complexity
- Whether it's a packaged solution vs. custom development requirement Exclude tools that are described as purely theoretical frameworks or require custom coding for implementation.

- **BIM Integration Details:**

Extract technical details about how the tools integrate with BIM workflows for C&D waste assessment, including:

- BIM data extraction methods (IFC files, native API, direct plugin access)
- Required BIM model detail levels (LOD 300, 400, 500, etc.)
- Material property requirements in BIM models
- Compatibility with Industry Foundation Classes (IFC)
- Integration with BIM authoring workflows
- Data exchange formats supported
- Real-time vs. batch processing capabilities

- **Model updating and synchronization features** Focus on technical integration aspects that enable automated waste quantification from BIM models.
- **Exact Tool Name:**
Identify the specific proper name or acronym of the tool. If no name exists, use '[Author] [Year] Script'
- **Tool Type:**
BIM Plugin: An add-on that runs directly inside a BIM authoring tool (e.g., Revit Plugin, ArchiCAD Add-on). Visual Programming Script: A script developed in Grasshopper (Rhino) or Dynamo (Revit). Cloud-based Platform/API: A web-based tool that processes BIM data (e.g., Madaster, Speckle-based apps). Standalone BIM Software: A separate software that imports IFC/BIM files for analysis (e.g., Solibri, Navisworks-based tools). BIM-Integrated Database: A database linked to BIM via SQL or API for material tracking. Integrated BIM Framework: A systematic methodology documented in a case study that combines BIM modeling with external analysis (e.g., a Revit-to-Excel workflow or a BIM-LCA framework)."
- **BIM Software:**
State the host software required (e.g., Revit 2024, Rhino 8, ArchiCAD).
- **Download & Access:**
Provide the URL (GitHub/Website) or state if it's 'Available upon request'. Is it Open-source or Commercial?
- **Ease of Use:**
Does the tool require coding (Python/C#), or is it a 'plug-and-play' installer? Mention if it is user-friendly for architects.
- **Collaborations:**
List integrations with: Material Passports, Digital Twins, AI, IoT, GIS, BCT, BDA, VR/AR, Cloud, 3D Printing or etc.
- **Focus area:**
Specifically, how does this tool support Construction and Demolition Waste (C&DW) Management? What is its main automated output (e.g., Disassembly Index)?

Results

Characteristics of Included Studies

The 27 included sources span publication years from 2019 to 2025 and encompass a range of tool types, geographic contexts, and building applications relevant to BIM-based construction and demolition waste (C&DW) management. The table below summarizes the key characteristics of each study, including the tool identified, tool type, host BIM software, building type tested, geographic context, and whether the full text was retrieved.

Study	Full text retrieved?	Tool Name	Tool Type	Host BIM Software	Building Type Tested	Geographic Context
R. Quiñones et al., 2022	Yes	WE-BIM Add-in [1]	BIM Plugin [1]	Revit 2021 [1]	Residential (16 dwellings) [1]	Seville, Spain [1]
C. Llatas et al., 2022	Yes	CW-LCA-BIM tool [2]	BIM Plugin [2]	Autodesk Revit 21.1.1 [2]	Residential (multi-family) [2]	Seville, Spain [2]
R. Quiñones et al., 2021	Yes	Quiñones et al. (2021) Script [11]	Integrated BIM Framework [11]	Allplan, Archicad, Revit [11]	Residential (16 dwellings) [11]	Seville, Spain [11]
L. B. Jayasinghe et al., 2020	Yes	Material and Component (M&C) bank [5]	Cloud-based Platform/API [5]	Autodesk Revit [5]	Residential (11-storey) [5]	Luxembourg/Europe [5]
S. Kaewunruen et al., 2025	Yes	BIM-Navisworks, BIM-Dynamo [19]	Integrated BIM Framework [19]	Autodesk Revit [19]	Residential (townhouse) [19]	Washington, D.C. [19]
Dongchen Han et al., 2024	Yes	eToolLCD [12]	Integrated BIM Framework [12]	Autodesk Revit [12]	Residential (4-storey apartment) [12]	Not specified [12]
Alireza Fereydooni Eftekhari et al., 2024	Yes	Eftekhari et al. (2024) Script [8]	Standalone BIM Software [8]	Revit 2021 [8]	Residential [8]	Italy [8]
I. Bertin et al., 2020	Yes	Bertin et al. (2020) Script [16]	Integrated BIM Framework [16]	Not specified [16]	High-rise and medium-rise [16]	France [16]
M. Honic et al., 2019	Yes	BIM-based Material Passport [13]	Integrated BIM Framework [13]	Not specified [13]	Office (3-storey) [13]	Europe [13]
Ying Huang et al., 2022	Yes	WRFSS [3]	BIM Plugin [3]	Revit [3]	Residential (brick house) [3]	China (Xi'an) [3]
J. Fernandes et al., 2022	Yes	Fernandes et al. (2022) Script [14]	BIM Plugin [14]	Not specified [14]	Residential (1919–1945 archetype) [14]	Lisbon, Portugal [14]

Study	Full text retrieved?	Tool Name	Tool Type	Host BIM Software	Building Type Tested	Geographic Context
F. Heisel et al., 2022	Yes	ScanR [10]	Integrated BIM Framework [10]	Rhinoceros3D with Grasshopper [10]	Residential [10]	Ithaca, NY [10]
Marielle Martins Santos et al., 2022	Yes	WasteBIM [4]	BIM Plugin [4]	Autodesk Revit (up to 2019) [4]	Residential (single-family) [4]	Brazil [4]
Qiming Sun et al., 2022	Yes	Eco2soft [15]	Integrated BIM Framework [15]	Revit 2019 [15]	Residential (high-rise) [15]	Tianjin, China [15]
Fernanda Carrion Da Luz et al., 2024	Yes	Da Luz (2024) Script [20]	Visual Programming Script (Dynamo) [20]	Revit [20]	Not specified [20]	Not specified [20]
R. Hasan et al., 2022	Yes	Autodesk Navisworks Manage [7]	Standalone BIM Software [7]	Autodesk Revit 2016 [7]	Residential (4-storey) [7]	Bangladesh [7]
Abdul Mueed Yousfani et al., 2023	Yes	Yousfani et al. (2023) Script [18]	Integrated BIM Framework [18]	Revit [18]	Residential [18]	Pakistan [18]
K. Xing et al., 2020	Yes	Xing et al. (2020) Script [21]	Cloud-based Platform/API [21]	Autodesk Revit, ArchiCAD [21]	Hospital (glazed systems) [21]	Not specified [21]
D. Schwede et al., 2019	Yes	RecyclingGraph approach [22]	Integrated BIM Framework [22]	Not specified [22]	Wall structures [22]	Germany [22]
D. Widjaja et al., 2025	Yes	Revit + Dynamo + Navisworks [17]	Integrated BIM Framework [17]	Autodesk Revit [17]	Commercial (high-rise) [17]	Korea [17]
Ingrid Tainã Macário Santana et al., 2021	Yes	Miara and Scheer (2019); Chileshe et al. (2019) [23]	BIM Plugin [23]	Autodesk Revit [23]	Not specified [23]	Not specified [23]
Quini Athaya Putri et al., 2024	Yes	Autodesk Revit [9]	Integrated BIM Framework [9]	Autodesk Revit [9]	Government office [9]	Bantul, Yogyakarta [9]

Study	Full text retrieved?	Tool Name	Tool Type	Host BIM Software	Building Type Tested	Geographic Context
Fachreza Alyazid et al., 2024	Yes	Autodesk Revit [24]	BIM Plugin [24]	Autodesk Revit [24]	Parking structure [24]	Jakarta, Indonesia [24]
Suad Hosny et al., 2023	Yes	Revit, Navisworks, BIM 360 Docs [25]	Standalone BIM Software [25]	Revit [25]	Residential and bridges [25]	Egypt [25]
A. Ginzburg et al., 2020	Yes	Autodesk Revit 2019 [26]	Integrated BIM Framework [26]	Autodesk Revit 2019 [26]	Residential [26]	Moscow, Russia [26]
N. Bektaş et al., 2024	Yes	AxisVM X7 + Revit [27]	Integrated BIM Framework [27]	Autodesk Revit and AxisVM X7 [27]	Residential (dormitory) [27]	Győr, Hungary [27]
Marie-Bénédicte Jacques et al., 2023	Yes	PLEIADES [6]	Cloud-based Platform/API [6]	Not specified [6]	Nuclear facilities [6]	France, Norway, Spain [6]

All 27 full texts were retrieved. The studies originate from diverse geographic contexts spanning Europe (Spain, France, Portugal, Germany, Italy, Hungary, Luxembourg, Norway), Asia (China, Korea, Pakistan, Bangladesh, Indonesia), the Middle East (Egypt), and the Americas (U.S., Brazil). The overwhelming majority of case studies involved residential building types, with only isolated examples targeting commercial [17], hospital [21], government office [9], parking [24], or nuclear facility [6] applications. Autodesk Revit is by far the dominant host BIM platform, required by at least 22 of the 27 studies, with only ScanR relying on Rhinoceros3D/Grasshopper [10] and one multiplatform approach also supporting Allplan and Archicad [11].

Tool Categorization and Typology

The identified tools can be classified into six functional categories based on their architecture and integration method. The distribution across these categories reveals the current state of BIM-based C&DW tool development.

Tool Type	Count	Representative Tools
BIM Plugin (native add-on)	8	WE-BIM Add-in [1], CW-LCA-BIM [2], WRFSS [3], WasteBIM [4], Fernandes et al. plugin [14], Santana et al. APIs [23], Alyazid et al. [24]

Tool Type	Count	Representative Tools
Integrated BIM Framework	12	Quiñones et al. 2021 [11], Kaewunruen et al. [19], Han et al. [12], Bertin et al. [16], Honic et al. [13], Heisel et al. [10], Sun et al. [15], Yousfani et al. [18], Schwede et al. [22], Widjaja et al. [17], Putri et al. [9], Ginzburg et al. [26], Bektaş et al. [27]
Cloud-based Platform/API	3	M&C bank [5], Xing et al. [21], PLEIADES [6]
Standalone BIM Software	3	Eftekhari et al. [8], Navisworks Manage [7], Hosny et al. [25]
Visual Programming Script	1	Da Luz (2024) Dynamo script [20]

The largest category is the Integrated BIM Framework, comprising 12 studies that combine BIM modeling with external analysis tools (e.g., Revit-to-Excel, Revit-to-C++, or BIM-LCA workflows). These are typically research prototypes that orchestrate data exchange between BIM authoring software and external processing environments. Only eight tools function as native BIM plugins that run directly inside the authoring environment, which represents the most accessible form factor for practitioners. Three tools operate as cloud-based platforms, and three leverage standalone BIM software (primarily Navisworks) for waste-related analysis.

Functional Focus Areas

The tools address distinct aspects of C&DW management across the building lifecycle. The table below maps each tool to its primary functional output and the lifecycle phase it targets.

Tool	Primary Automated Output	Lifecycle Phase	Methodology
WE-BIM Add-in	CW quantities (m ³) per building element [1]	Design (construction waste) [1]	CW quantification model [1]
CW-LCA-BIM	Prevented emissions and energy savings from recycling vs. disposal [2]	Design (construction waste) [2]	LCA [2]
Quiñones et al. 2021	Waste type and quantity per element [11]	Design (construction waste) [11]	CW quantification model [11]
M&C bank	Quantification of C&D waste, recyclability, reusability [5]	End-of-life [5]	Material inventory [5]
BIM-Navisworks/Dynamo	Recycling proportions and financial benefits [19]	End-of-life (demolition) [19]	Digital Twin simulation [19]
eToolLCD / Han et al.	Sustainability score ranking of DWM scenarios [12]	End-of-life (demolition) [12]	LCSA + MCDA [12]

Tool	Primary Automated Output	Lifecycle Phase	Methodology
Eftekhari et al. Script	Building Recyclability Rate (BRR) [8]	End-of-life [8]	IFC + EWC classification [8]
Bertin et al. Script	Reuse element tracking and structural calculation [16]	End-of-life (reuse) [16]	Material bank + LCA [16]
BIM-based Material Passport	Recycling grade, GWP, AP, PEI [13]	Design optimization [13]	Material Passport [13]
WRFSS	Optimal waste recycling facility selection and transport plan [3]	End-of-life (logistics) [3]	BIM + WMS + API [3]
Fernandes et al. Plugin	Disassembly Index [14]	Design (refurbishment) [14]	Circularity indicators [14]
ScanR	Material Intensity, Embodied Carbon, Total Tonnage [10]	Pre-demolition survey [10]	LiDAR + S&D survey [10]
WasteBIM	Waste quantities by class and project phase [4]	Design (construction waste) [4]	Waste indices [4]
Eco2soft	Recycling potential and GWP [15]	Whole lifecycle [15]	LCA [15]
Da Luz Script	Waste generation rates per construction element [20]	Construction and demolition [20]	Dynamo + Python algorithm [20]
Navisworks Manage	Clash-based construction waste estimation [7]	Design (clash detection) [7]	Clash detection [7]
Yousfani et al. Script	Total, recyclable, and disposable waste with cost [18]	End-of-life (demolition) [18]	BIM-to-C++ workflow [18]
Xing et al. Platform	Life-cycle tracking for component reuse [21]	Whole lifecycle (reuse) [21]	Cloud-BIM + CPS [21]
RecyclingGraph approach	Predicted demolition material flows [22]	End-of-life [22]	ConnectionMatrix analysis [22]
Widjaja et al. Framework	Optimized rebar layout with minimized cutting waste [17]	Construction [17]	Heuristic algorithms + IFC [17]
Santana et al. APIs	Waste generation by construction stage; hazardous waste quantity [23]	Construction and demolition [23]	BIM API [23]
Putri et al.	Waste level calculation (0.97% average) [9]	Construction (rebar) [9]	BIM quantity take-off [9]
Alyazid et al.	Waste Material Ratio (WMR) [24]	Design (rebar) [24]	BIM volume comparison [24]

Tool	Primary Automated Output	Lifecycle Phase	Methodology
Hosny et al.	General waste reduction through BIM coordination [25]	Design and construction [25]	Clash detection + quantity take-off [25]
Ginzburg et al.	Weight of C&D waste [26]	End-of-life (demolition) [26]	BIM template + specifications [26]
Bektaş et al.	Reusable concrete waste quantity and carbon reduction [27]	End-of-life (earthquake debris) [27]	Seismic design + BIM [27]
PLEIADES	Waste production, management process, and cost estimates [6]	End-of-life (nuclear D&D) [6]	Digital Twin + BIM [6]

The functional outputs cluster into three broad domains: (1) construction-phase waste quantification, which estimates waste generation during building construction and is addressed by tools such as WE-BIM Add-in [1], Waste-BIM [4], and the clash-detection approach in Navisworks [7]; (2) end-of-life and demolition waste assessment, which targets recycling potential, reuse feasibility, and demolition waste logistics as in WRFSS [3], Han et al. [12], and Ginzburg et al. [26]; and (3) design optimization for circularity, including material passport generation [13], disassembly index calculation [14], and recyclability rate assessment [8]. Only a small subset of tools explicitly employ LCA as a core methodology—CW-LCA-BIM [2], Eco2soft [15], and the Bertin et al. framework [16]—while most rely on simpler waste index or quantity take-off approaches.

BIM Integration and Technical Requirements

Tool	Data Extraction Method	LOD Required	IFC Compatibility	Real-time Capability
WE-BIM Add-in	Revit API (direct plugin) [1]	LOD 300 [1]	Not mentioned [1]	Yes [1]
CW-LCA-BIM	Revit API (plugin) [2]	LOD 300 [2]	Implied [2]	Yes [2]
Quiñones et al. 2021	Platform-specific tools [11]	LOD 200 [11]	Mentioned as potential [11]	Not mentioned [11]
M&C bank	Dynamo script [5]	LOD 300 [5]	Not mentioned [5]	Automated [5]
BIM-Navisworks/Dynamo	BIM-to-Navisworks import [19]	Not mentioned [19]	Not mentioned [19]	Yes (Dynamo) [19]
Han et al.	Dynamo visual scripting [12]	Not mentioned [12]	Yes (enriched IFC) [12]	Yes [12]
Eftekhari et al.	IFC file export [8]	Not mentioned [8]	Yes [8]	Batch [8]
Bertin et al.	IFC files, shared parameters [16]	LOD 300–500 [16]	Yes [16]	Yes [16]
Honic et al.	BIM-BuildingOne coupling [13]	Not specified [13]	Implied [13]	Bi-directional sync [13]

Tool	Data Extraction Method	LOD Required	IFC Compatibility	Real-time Capability
WRFSS	Dynamo + Revit API [3]	Not mentioned [3]	Not mentioned [3]	Implied real-time [3]
Fernandes et al.	Plugin + external databases [14]	LOD 200 minimum [14]	EU Level(s) compatible [14]	Yes [14]
ScanR	LiDAR scan + CAD export [10]	Not mentioned [10]	Not mentioned [10]	Not mentioned [10]
WasteBIM	Native API (Dynamo) [4]	Not specified [4]	Not mentioned [4]	Not mentioned [4]
Eco2soft	Revit to MS Excel export [15]	LOD 300 (likely) [15]	Not mentioned [15]	Batch [15]
Da Luz Script	Native API (Revit) [20]	Not specified [20]	Implied [20]	Implied real-time [20]
Navisworks Manage	Revit model import [7]	Not specified [7]	Generally supported [7]	Batch [7]
Yousfani et al.	Revit schedule export to C++ [18]	LOD 300 (likely) [18]	Not mentioned [18]	Batch [18]
Xing et al.	IFC files [21]	Not mentioned [21]	Yes [21]	Yes [21]
Schwede et al.	Material property extraction [22]	Not mentioned [22]	Not mentioned [22]	Not mentioned [22]
Widjaja et al.	IFC schema-based [17]	Not specified [17]	Yes [17]	Yes [17]
Santana et al.	Native API (Revit) [23]	Not mentioned [23]	Implied [23]	Not mentioned [23]
Putri et al.	Not mentioned [9]	Not mentioned [9]	Not mentioned [9]	Not mentioned [9]
Alyazid et al.	Direct Revit plugin [24]	LOD 300 (likely) [24]	Implied [24]	Not specified [24]
Hosny et al.	Revit + BIM 360 Docs [25]	LOD 200–400 [25]	Not mentioned [25]	Not mentioned [25]
Ginzburg et al.	Revit specifications [26]	Not mentioned [26]	Implied [26]	Implied [26]
Bektaş et al.	Revit + AxisVM [27]	Not mentioned [27]	Not mentioned [27]	Not mentioned [27]
PLEIADES	Not specified [6]	Not specified [6]	Not specified [6]	Not specified [6]

LOD 300 is the most commonly specified minimum model detail requirement, reported by at least five studies [1, 2, 5, 15, 16], while one study accepted LOD 200 as sufficient [11] and another specified a range from LOD 200 to 400 depending on design phase [25]. IFC compatibility is explicitly confirmed in six tools [8, 12, 14, 16, 17, 21], while many others rely on native Revit API connections without open-standard interoperability. Real-time processing within the BIM authoring environment is claimed by approximately ten tools, though the depth of real-time interaction varies from full design-time feedback (e.g., WE-BIM Add-in [1]) to simpler batch export workflows (e.g., Eco2soft [15]).

Tool Accessibility and Professional Readiness

A critical dimension for practitioners is whether these tools are accessible without custom coding and whether they are commercially available or remain research prototypes.

Tool	Availability Status	Coding Required?	User-Friendly for Architects?	Access
WE-BIM Add-in	Research prototype [1]	No (plug-and-play) [1]	Yes [1]	Available upon request [1]
CW-LCA-BIM	Research prototype [2]	No (plug-and-play) [2]	Yes [2]	Available upon request [2]
Quiñones et al. 2021	Research prototype [11]	Manual input required [11]	Moderate [11]	Available upon request [11]
M&C bank	Research prototype [5]	No [5]	Yes [5]	Available upon request [5]
BIM-Navisworks/Dynamo	Research prototype [19]	Yes (Dynamo scripting) [19]	Limited [19]	Available upon request [19]
eToolLCD / Han et al.	Open source (Dynamo) [12]	Yes (Dynamo scripting) [12]	Moderate [12]	Available upon request [12]
Eftekhari et al. Script	Research prototype [8]	Yes (Python) [8]	No [8]	Available upon request [8]
Bertin et al. Script	Research prototype [16]	Yes (C#) [16]	Limited [16]	Available upon request [16]
BIM-based Material Passport	Research prototype [13]	No [13]	Yes [13]	Available upon request [13]
WRFSS	Research prototype [3]	No (GUI provided) [3]	Yes [3]	Available upon request [3]
Fernandes et al. Plugin	Not mentioned [14]	No (GUI provided) [14]	Yes [14]	Available upon request [14]
ScanR	Not mentioned [10]	No (minimal training) [10]	Yes [10]	Not mentioned [10]
WasteBIM	Research prototype [4]	No (but manual input needed) [4]	Moderate [4]	Available upon request [4]
Eco2soft	Commercially available [15]	No [15]	Yes [15]	Commercial website [15]
Da Luz Script	Commercially available (Dynamo) [20]	Yes (Python) [20]	No [20]	Not mentioned [20]
Navisworks Manage	Commercially available [7]	No [7]	Yes [7]	Commercial [7]
Yousfani et al. Script	Research prototype [18]	Yes (C++) [18]	No [18]	Available upon request [18]
Xing et al. Platform	Prototype [21]	No [21]	Yes [21]	Available upon request [21]
RecyclingGraph approach	Not mentioned [22]	Not determined [22]	Not determined [22]	Not mentioned [22]

Tool	Availability Status	Coding Required?	User-Friendly for Architects?	Access
Widjaja et al. Framework	Commercial tools used [17]	No (Dynamo-based) [17]	Yes [17]	Available upon request [17]
Santana et al. APIs	Not specified [23]	Not specified [23]	Moderate [23]	Not mentioned [23]
Putri et al.	Commercially available (Revit) [9]	No [9]	Yes [9]	Commercial [9]
Alyazid et al.	Commercial (Revit) [24]	Implied expertise needed [24]	Yes [24]	Commercial [24]
Hosny et al.	Commercially available [25]	Not specified [25]	Yes (implied) [25]	Available upon request [25]
Ginzburg et al.	Not mentioned [26]	No [26]	Yes [26]	Not mentioned [26]
Bektaş et al.	Commercially available (AxisVM) [27]	Not specified [27]	Implied [27]	Available upon request [27]
PLEIADES	Not mentioned [6]	Not specified [6]	Not specified [6]	Not mentioned [6]

The accessibility analysis reveals a significant gap between research output and practical availability. The vast majority of tools (approximately 18 of 27) are classified as research prototypes available only upon request from the authors [1–5, 8, 11, 13, 16, 18, 19]. Only three tools are unambiguously commercially available as packaged solutions: Eco2soft, accessible via a commercial website [15]; Autodesk Navisworks Manage [7]; and Autodesk Revit's native quantity take-off capabilities [9]. However, neither Navisworks nor Revit was purpose-built for C&DW assessment—their waste management applications depend on how practitioners configure clash detection [7] or quantity take-off workflows [9].

Among the purpose-built tools, six require programming knowledge in Python [8, 20], C# [16], C++ [18], or Dynamo visual scripting [12, 19], which limits their adoption by architects and design professionals without software development skills. The most accessible purpose-built tools—those requiring no coding and described as user-friendly—include the WE-BIM Add-in [1], CW-LCA-BIM [2], WRFSS [3], the BIM-based Material Passport [13], and ScanR [10].

Validation Evidence and Quantitative Outcomes

The table below summarizes the key quantitative findings reported from case study validations.

Tool	Case Study Context	Key Quantitative Finding
WE-BIM Add-in	Residential, Seville	Steel structure reduced waste by 56% vs. reinforced concrete; recycling rate increased by 49% [1]
CW-LCA-BIM	Residential, Seville	Recycling prevents 1.4x (14.6 t) the emissions of disposal; saves 85x (148.5 GJ) energy [2]
Quiñones et al. 2021	Residential, Seville	Total CW generation of 1.1995 m ³ /m ² ; consistent results across three BIM platforms [11]

Tool	Case Study Context	Key Quantitative Finding
Han et al.	4-storey apartment	Optimal DWM alternative scored 91.63 sustainability points; status quo scored 8.37 [12]
Eftekhari et al.	Residential, Italy	Waste increases 37.1% without maintenance; decreases 38.4% with high maintenance [8]
Honic et al.	Office, Europe	Total mass 1,338 tonnes; recycling grade 2.5; 48% recyclable materials [13]
WRFSS	Brick house, China	Reduced transport distance by 30.6 km; CO ₂ reduced by 0.0259 tons; API error <10% [3]
Eco2soft	Residential, Tianjin	Mass timber RP 73% vs. RC 34%; CLT variant material consumption less than one-third of RC [15]
Navisworks Manage	4-storey, Bangladesh	BIM-based clash detection prevented 40–45% of construction waste [7]
Widjaja et al.	High-rise, Korea	93.58% reduction in rebar cutting waste; material cost reduced 17.75% [17]
Putri et al.	Government office, Yogyakarta	Average waste level of 0.97%; 11% volume difference from manual analysis [9]
Alyazid et al.	Parking structure, Jakarta	BIM waste ratio (6.58%) higher than conventional (4.83%) [24]
Bektaş et al.	Dormitory, Hungary	35% (1,519.89 t) of concrete waste reusable; 27.5% carbon reduction; 9.13% cost reduction [27]
Hosny et al.	Residential and bridges, Egypt	44% of respondents reported 11–15% volume variation between AutoCAD and Revit [25]

Several patterns emerge from the validation evidence. First, tools that compare structural system alternatives consistently demonstrate that prefabricated or steel-based systems generate substantially less waste than in-situ reinforced concrete: the WE-BIM Add-in showed a 56% waste reduction for steel versus concrete [1], while Eco2soft documented that mass timber construction consumes less than one-third of the materials of its reinforced concrete equivalent [15]. Second, tools focused on rebar optimization report particularly large waste reductions, with the Widjaja et al. framework achieving a 93.58% reduction in rebar cutting waste compared to baseline [17] and Putri et al. achieving an average waste level of only 0.97% [9]. Third, the LCA-based tools provide the strongest evidence for environmental impact quantification: CW-LCA-BIM demonstrated that recycling construction waste prevents 1.4 times the emissions that disposal generates and saves 85 times the energy [2].

One notable counter-finding comes from Alyazid et al., where the BIM method actually produced a higher waste

material ratio (6.58%) compared to the conventional method (4.83%) [24]. This is attributed to the design-build project context with 36 design changes, suggesting that BIM's more precise volume calculations may reveal waste that conventional methods underestimate rather than necessarily reducing it [24].

Technology Collaborations and Emerging Integrations

Several tools extend beyond basic BIM-waste quantification by integrating with complementary digital technologies. Digital Twin integration is reported in three studies: Kaewunruen et al. combine BIM with Navisworks for real-time demolition simulation [19], Widjaja et al. link BIM with scheduling software for real-time rebar optimization [17], and PLEIADES employs Digital Twins for nuclear facility decommissioning waste estimation [6]. Cloud-based capabilities are featured in the Xing et al. platform, which integrates Cloud-BIM with cyber-physical systems and RFID for life-cycle tracking of reusable components [21]. GIS integration appears in the Honic et al. Material Passport framework [13], while the WRFSS integrates Web Map Services for transportation logistics optimization [3]. The Xing et al. platform is also notable for mentioning blockchain technology for data security in component reuse tracking [21]. Material Passport functionality is explicitly supported by the Honic et al. tool [13] and referenced in the Eftekhari et al. framework [8] and Fernandes et al. plugin [14].

Synthesis

The overarching finding across 27 studies is that while BIM-based C&DW assessment tools have proliferated significantly, the vast majority remain research prototypes that have not transitioned to commercially available, packaged software. This creates a clear dichotomy: on one hand, commercially available general-purpose BIM tools (Revit, Navisworks) are being repurposed for waste estimation through quantity take-off and clash detection, but they lack purpose-built waste classification, recycling potential calculation, or LCA integration; on the other hand, purpose-built research tools offer sophisticated waste quantification aligned with European waste classifications and LCA methodologies, but remain inaccessible to most practitioners.

The apparent heterogeneity in reported waste reduction figures—ranging from 0.97% rebar waste levels [9] to 40–45% prevention of total construction waste [7] to 93.58% reduction in rebar cutting waste [17]—can be explained by three contextual factors. First, the waste type targeted differs fundamentally: rebar cutting optimization (Widjaja et al. [17], Putri et al. [9]) addresses a narrowly defined material stream where algorithmic optimization of cutting patterns yields dramatic reductions, whereas whole-building construction waste estimation (Hasan et al. [7]) encompasses a broader and more heterogeneous waste stream. Second, the mechanism of waste reduction varies: clash detection identifies and eliminates design conflicts before construction [7], material substitution compares structural systems with inherently different waste profiles [1], and logistics optimization reduces transportation impacts rather than waste volumes per se [3]. Third, the baseline against which improvements are measured differs across studies, with some comparing BIM-derived estimates to manual calculations [9] and others comparing alternative design scenarios within the BIM environment [1].

The geographic concentration of validated case studies in Southern Europe (Spain, Portugal, Italy) and East/Southeast Asia (China, Korea, Indonesia) reflects both the active research communities in these regions and the regulatory environments driving C&DW management. The Spanish studies from the Quiñones-Llatas group [1, 2, 11] represent the most methodologically mature tool development pipeline, progressing from a multiplatform quantification model [11] to a dedicated Revit plugin [1] and subsequently to LCA integration [2], all validated on the same residential building case study in Seville. This iterative development approach provides the strongest evidence for tool feasibility, though the reliance on a single case building limits generalizability claims.

A persistent limitation across the reviewed tools is the dominance of Autodesk Revit as the sole or primary host

platform. Only ScanR operates in a Rhino/Grasshopper environment [10], and only the Quiñones et al. 2021 framework was validated across multiple BIM platforms (Allplan, Archicad, and Revit) [11]. The Xing et al. cloud platform nominally supports both Revit and ArchiCAD [21], but validation was performed only in one context. This vendor lock-in poses a risk for long-term interoperability, though the handful of tools using IFC for data exchange [8, 12, 16, 17, 21] offer a pathway toward platform-neutral waste assessment.

For practitioners seeking immediately deployable tools, the landscape narrows considerably. Eco2soft stands alone as a commercially available, purpose-built LCA tool with documented BIM integration for recycling potential assessment [15, 15]. Autodesk Navisworks Manage offers commercially available clash detection that can be repurposed for construction waste estimation [7], but requires the user to interpret clashes as waste indicators rather than providing automated waste classification. The WE-BIM Add-in [1] and CW-LCA-BIM [2] tools represent the most promising purpose-built solutions in terms of user-friendliness and functional completeness, but both remain research prototypes available only upon request from the developing team.

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