

Optimizing Building Sustainability: A Systematic Review of BIM-Based Decision Support Systems

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Abstract

In light of the climate protection goals of the Paris Agreement, optimizing the sustainability of planning processes is becoming increasingly important. Building Information Modeling (BIM) centralizes planning information for interdisciplinary evaluation, enabling sustainable decision-making. This paper presents a systematic review of BIM-based decision support approaches for building sustainability. Following vom Brocke's five-phase model and the PRISMA 2020 standard, 70 studies were analyzed to identify current methods, their respective strengths and limitations, and future research needs. The findings reveal a highly dynamic but fragmented field of research. Assessment-Based Optimization and multi-criteria decision-making (MCDM) methods dominate. However, the holistic integration of ecological, economic and social indicators remains rare, with social sustainability receiving the least attention. Most approaches rely on proprietary BIM environments, while open BIM applications and interoperable data standards remain underdeveloped. Standardized data sources, such as Environmental Product Declarations (EPDs), are well established for ecological assessments, but are largely lacking for the economic and social dimensions. The review highlights the urgent need for interoperable data formats, standardized evaluation methods, and accessible databases to enable scalable and comparable BIM-based sustainability optimizations. Advancing these foundations will be essential for achieving consistent, holistic sustainability optimization in the construction industry.

Keywords: BIM; IFC; sustainability optimization; Decision Support Systems (DSS); Multi-Criteria Decision-Making (MCDM); Life Cycle Assessment (LCA); Environmental Product Declarations (EPD); open BIM



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1. Introduction

1.1. Motivation

Under the 2015 Paris Climate Agreement, 195 countries, have committed themselves under international law to limiting global warming to well below 2 °C, ideally to 1.5 °C, compared to pre-industrial levels [1]. With around 37% of global greenhouse gas emissions coming from the construction sector, it is one of the most resource-intensive industries worldwide and a major contributor [2]. Therefore, the planning of a building has a particularly strong influence on its overall environmental performance [3].

Nevertheless, sustainability measures are often not implemented or only applied retrospectively at considerable cost [4,5]. When sustainability is considered, research to date has focused primarily on ecological sustainability. However, economic and social aspects,

as well as correlations with building physics, have only been considered sporadically [6]. This stands in contrast to a holistic approach, as is increasingly demanded by sustainability certificates, for example [7].

One way to determine sustainability is to perform a life cycle assessment (LCA) and calculate life cycle costs (LCC). These are usually based on material names and quantities. This information can be obtained in the traditional way from 2D plans or using the Building Information Modeling (BIM) method from a digital building model. BIM is a method that enables different stakeholders to collaborate on a digital building model. In the context of sustainability, BIM also offers the possibility of centrally recording object-related sustainability information [8]. This information can be stored in the building model and used for evaluations. In addition, it is possible to carry out semi-automated testing processes with regard to sustainability criteria that must be met [9].

At the same time, the increasing use of BIM and the availability of life cycle assessment data such as environmental product declarations (EPDs) provide new digital foundations for the data-based integration of material-related sustainability information [10,11]. However, existing data sources are often not linked to each other due to a lack of standardized interfaces, automation options and user-friendly tools [12].

In BIM-based planning, the open data exchange format Industry Foundation Classes (IFC) is becoming increasingly important for the digital description of building models. On the one hand, it improves interoperability between software solutions, and on the other hand, it facilitates the integration of sustainability data. The automated linking of digital building models with sustainability data is therefore a key requirement for the data-based evaluation and optimization of sustainable planning variants [13].

The BIM methodology can be applied to a wide range of disciplines within the planning and construction process. In particular, it allows the possibility of centrally bundling, evaluating and utilizing cross-disciplinary data. This requires the structured collection, processing and interpretation of this information in order to be able to derive accurate insights into the optimization of sustainability-related aspects at an early stage of planning.

1.2. Purpose and Structure

Given the background outlined above, this paper aims to identify and compare scientific approaches within the framework of a systematic literature analysis to identify research gaps in BIM-based decision support for optimizing the sustainability of building construction. While most previous BIM-LCA studies focus primarily on assessment, the main focus of this study is on optimization. It examines all sustainability dimensions and explores the different ways in which optimization is approached, providing a comprehensive overview of strategies for enhancing sustainability through BIM-based decision support. To achieve this goal, one fundamental question and three research-guiding questions are posed:

- Main research question:
 - What scientific approaches to BIM-based decision support for optimizing the sustainability of building structures exist, and how do they differ?
- Sub-research questions:
 - Which sustainability indicators and associated data sources are used in the literature to record ecological, economic and social sustainability aspects, and how do they differ in terms of standardization and availability?
 - How are sustainability data integrated into digital planning processes from a technical and methodological perspective, and what differences exist in terms of the software environments, interfaces and degrees of automation used?

- What methodological approaches are used to evaluate integrated sustainability data and how do they support decision-making processes relating to sustainable building structures?

2. Methodology

The methodological approach of the paper is based on the five-phase model developed by Brocke et al. [14]. This model enables systematic literature analyses to be carried out in a structured and transparent manner (Figure 1). In the first phase, the objective of the analysis is defined and the thematic and temporal scope of the search is determined. The second phase involves the conceptual structuring of the field of investigation, for example, by defining key terms, categories and perspectives. On this basis, a systematic literature search is carried out in the third phase, which is typically database-supported and supplemented by methods such as snowball searching in order to increase the relevance and completeness of the results. [15] In the fourth phase, the identified contributions are analyzed in terms of content, compared and sorted by topic in order to identify patterns and research gaps. The fifth phase serves to derive further research needs [14].

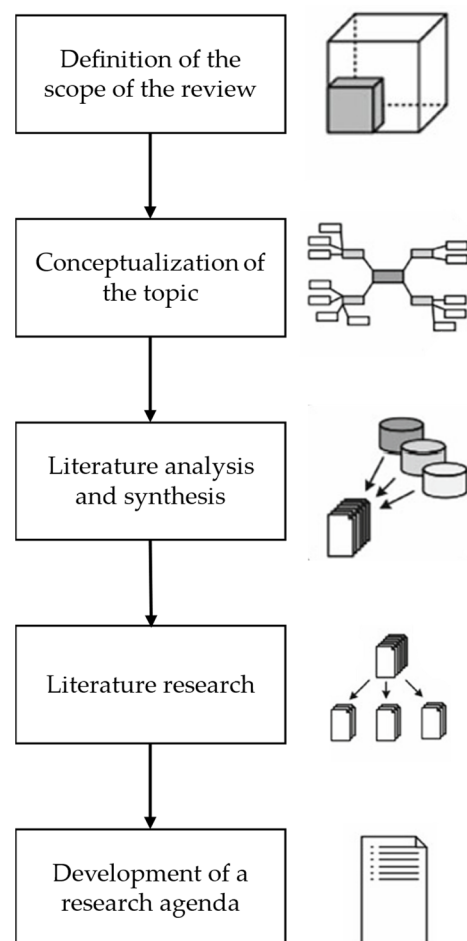


Figure 1. Five-phase model approach based on Jan vom Brocke et al. [14].

For transparent documentation of the search and analysis process, the PRISMA 2020 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is used. PRISMA is an internationally recognized reporting standard that ensures systematic reviews are described in a complete, transparent and comprehensible manner [16]. In this paper, PRISMA serves not only as a formal guide, but also as a methodological framework for the systematic presentation of all decisions in the review process: from determining

the search strategy and defining inclusion criteria to the transparent presentation of the literature that was reviewed, included and excluded. In the interest of transparency and completeness, all evidence of compliance with the PRISMA guidelines is documented in the official checklist in Table S1 [16].

2.1. Search and Selection Strategy (Literature Research)

The search was conducted in January 2025 across four major scientific databases: Scopus, Web of Science, ScienceDirect, and IEEE Xplore. These databases were selected to ensure comprehensive coverage of both construction management and technology-oriented literature [17]. To capture the broadest possible range of relevant sources, no restrictions were applied regarding publication type. Peer-reviewed journal articles, conference papers, book chapters, and other academic publications were all considered. Additionally, no temporal limitations were imposed, meaning that publications from all years were eligible for inclusion. This decision was made to avoid excluding potentially fundamental or early contributions to the field of research and to cover a wide range of publications. This inclusive approach aligns with recommendations to avoid selection bias and ensure that practically oriented contributions are not excluded [18].

The search string was defined based on a preliminary keyword analysis and specified as:

("BIM" OR "IFC") AND ("sustainability assessment" OR "sustainable" OR "LCA") AND ("process" OR "framework") AND ("decision" OR "optimization").

Searches were performed within the fields of titles, abstracts, and keywords. Only publications written in English were included, as English is the dominant language in scientific communication and facilitates international comparability while minimizing translation errors [19]. Moreover, only Open Access publications were considered in order to ensure full accessibility and transparency. This decision is grounded in the FAIR principles, which emphasize that digital research objects, such as datasets and publications, should be Findable, Accessible, Interoperable and Reusable. This facilitates the long-term discoverability, usability and machine-actionable integration of scientific knowledge [20].

After the initial search, duplicates were removed. The remaining records were screened manually through a three-stage process: title screening, abstract evaluation, and full-text review. Studies were excluded if they lacked sufficient relevance to BIM, sustainability, or planning processes, or if they did not meet formal inclusion criteria such as language or accessibility. The entire selection process was documented in accordance with the PRISMA guideline using a flow diagram.

In addition to keyword searches in scientific databases, snowball searches were also used in this study. This involves identifying further relevant sources via the reference lists of suitable works or through references within the literature. This form of research complements systematic searches in a meaningful way, as it often refers to articles that cannot be found using keyword searches alone [15]. All steps of the review and data collection were checked by several reviewers.

2.2. Synthesis Methods (Literature Analysis)

Systematic literature reviews make an important contribution to scientific foundations, as they structure existing knowledge and highlight gaps in research. Particularly in subject areas with a large number of publications, there is a risk of losing track or overlooking important contributions [21].

A standardized scheme was developed for the extraction of bibliographic metadata for the systematic analysis of the included literature. The following data were recorded: title, first author, year of publication, DOI, publication type, and author-supplied keywords.

To further analyze these metadata, a bibliometric visualization was conducted using the software VOSviewer version 1.6.20 [22]. This included the mapping of author collaboration networks and keyword co-occurrence patterns to identify dominant research topics and methodological clusters within the field.

The available data is considered to be qualitative. Therefore, the studies are analyzed according to the principles of qualitative content analysis according to Kuckartz & Rädiker [23]. The difference to quantitative data lies in the data form. Quantitative data consists exclusively of numerical data, whereas qualitative data includes all other data formats such as texts, interviews or recordings [23]. The studies are structured according to concept, as in Webster & Watson, using categories [21]. The categories are formed using a deductive-inductive approach: first, deductive categories are defined based on theoretical knowledge of BIM and sustainability. These are then supplemented and refined through an inductive, text-analytical evaluation. The iterative process leads to a final, inductive-based category system. For each study, content categories were created in Excel version 2512. Frequencies were aggregated per category and visualized using tables and figures to enable comparative analysis across studies.

Subsequently, the focus was on the identified optimization methods, the sustainability dimensions addressed (ecological, economic, social) and the underlying data sources. In addition, the studies were examined with regard to the linking techniques used to integrate sustainability data into BIM models—for example, standardized interfaces, data exchange formats or proprietary tools. Furthermore, it was documented whether an open BIM approach (e.g., based on IFC) or a closed BIM environment was used and which software tools were employed. Open BIM approaches rely on standardized, vendor-neutral data formats to enable interoperability between different software tools. In contrast, closed BIM environments typically rely on proprietary formats and workflows within a single software ecosystem.

3. Results

3.1. Study Selection Overview

The selection process for relevant studies is illustrated in Figure 2. A total of 812 L sources were identified across four databases: ScienceDirect ($n = 136$), Web of Science ($n = 157$), Scopus ($n = 496$), IEEE Xplore ($n = 15$) and through a supplementary snowball system ($n = 8$). After removing duplicates ($n = 108$), 706 unique entries remained. Subsequently, all 706 sources were selected for in-depth content review. However, unrestricted full-text access (open access) could not be established for 346 articles. The remaining 360 studies were subjected to a detailed review based on the defined inclusion and exclusion criteria. A total of 288 studies were excluded: 154 based on the title, 82 after evaluation of the title and abstract, and 52 after complete review of the title, abstract and content. Frequent reasons for exclusion related to deviations in content from the focus of the study. For example, numerous studies conducted a life cycle assessment but did not link it to specific decision-making processes or optimization steps in the planning and design phase. Studies addressing the operational or deconstruction phases were excluded, as this work focuses exclusively on the planning of new buildings. Additionally, studies on civil engineering structures (e.g., bridges and infrastructure facilities) and studies primarily examining the optimization of building services systems (e.g., HVAC) without considering construction or material selection as design elements were excluded. All in all, 70 studies met all the formal and content-related selection criteria and were included in the final qualitative synthesis. Although most studies focus on small-scale or idealized buildings, they provide insights that are transferable to the implementation of BIM-based sustainability practices in complex real-world projects.

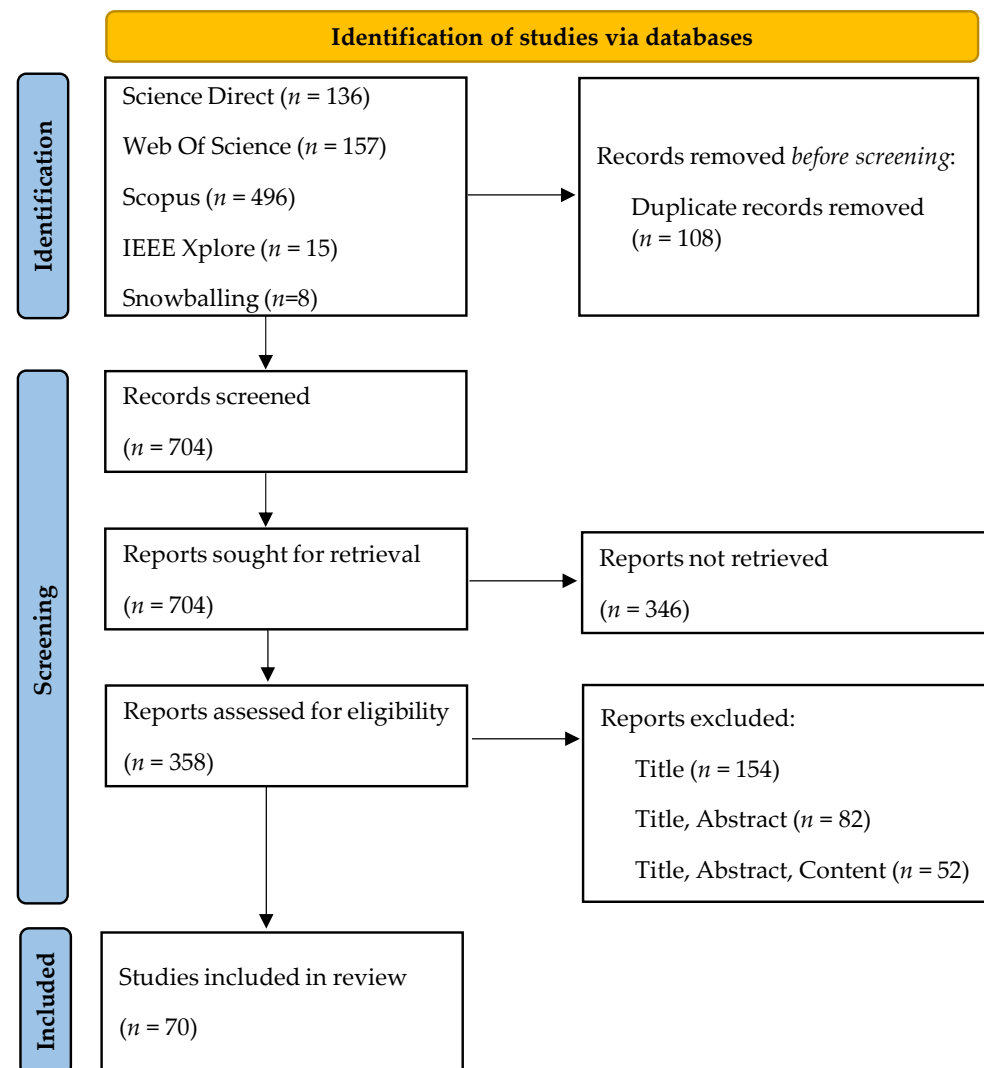


Figure 2. Flowchart for the Identification of studies.

3.2. Study Characteristics

The publications considered in this categorization were identified through the systematic literature review. A complete list of these papers is provided in Appendix A [24–93].

3.3. Results of Individual Studies

3.3.1. Years of Publication

The distribution of publication years for the studies included is shown in Figure 3. No time restrictions were imposed during the selection process; the earliest contributions considered date from 2011, and the most recent from 2024.

The development shows an overall upward trend, which is illustrated by the dotted regression line. Until the beginning of 2015, only a few relevant studies were published each year. From 2015 onwards, a significant increase can be seen, with a first peak in 2019 ($n = 10$) and the highest value to date in 2023 ($n = 13$). Despite slight fluctuations in the meantime, publication activity remains at a comparatively high level, which may indicate the increasing relevance and dynamism of the research field. The slump in 2022 can possibly be attributed to delayed publication processes or project-related cycles, and may also be explained by delays in academic publishing following the COVID-19 pandemic. The data indicate that the integration of BIM and LCA as well as the development of

sustainability-oriented assessment methods in building design have become a greater focus of scientific research, particularly in the last five years.

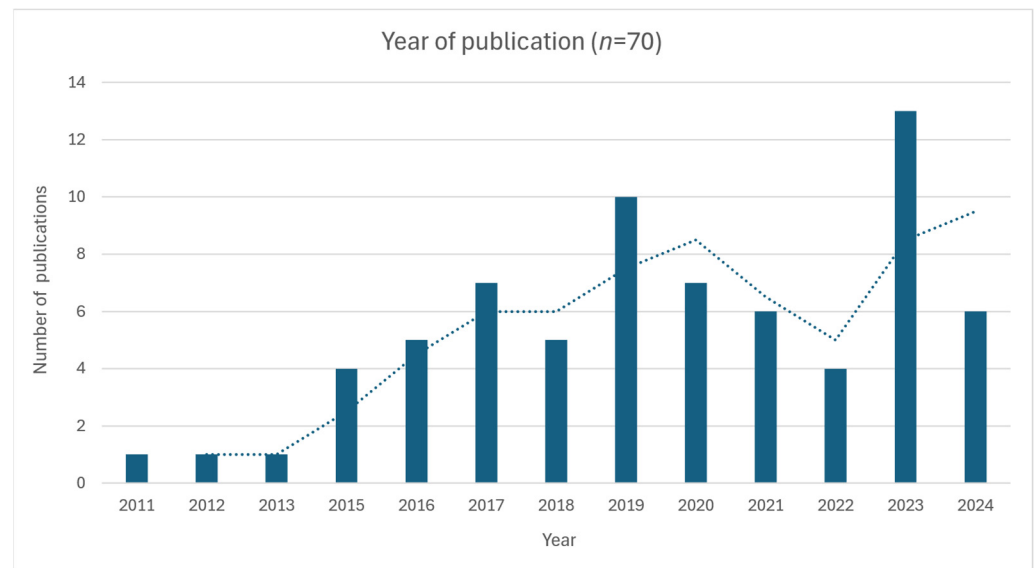


Figure 3. Distribution of publications by year.

3.3.2. Origin of Publication

The geographical analysis of the 70 publications on BIM-based decision support is based on the country of origin of the first author. Figure 4 shows the percentage distribution by continent. There are at least three publications from each inhabited continent. The lowest number is attributable to Africa ($n = 3$), Australia ($n = 4$) and South America ($n = 5$). North America is represented with ten publications, Asia (including Turkey) with 17 sources. Europe has the largest share with 31 publications (44%) and thus plays a dominant role.

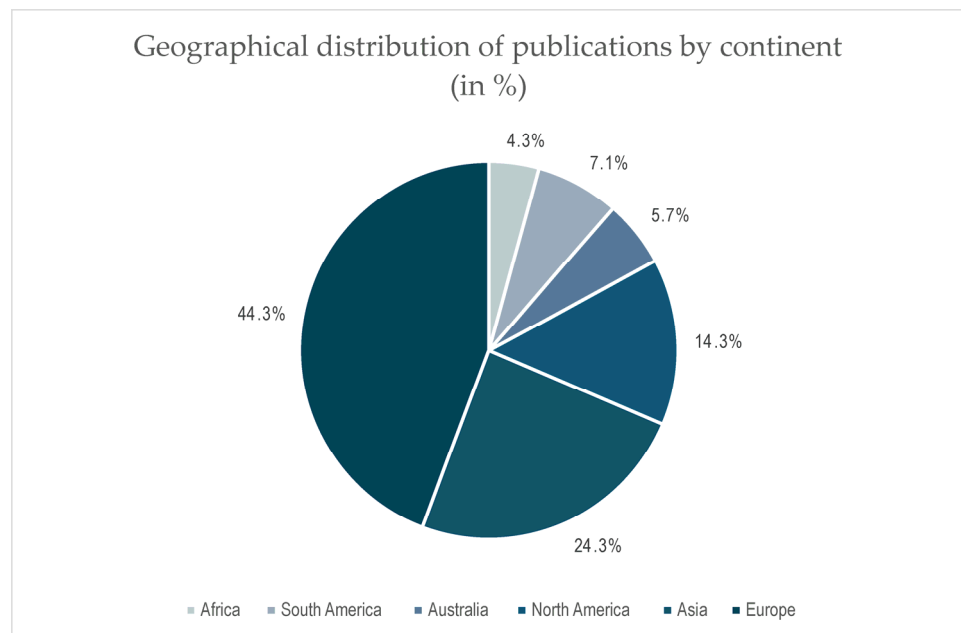


Figure 4. Geographical distribution of publications by continent (in %).

Overall, the sources come from 24 countries. The United Kingdom (8 publications), the USA, Germany and China have particularly high publication numbers. The numerous publications from the United Kingdom could be attributed to its national BIM strategy,

which has been in place since 2007. This strategy specifically promotes the use of BIM methodology to reduce costs and greenhouse gas emissions in the construction sector [94].

The figures show that research activity in this field is highly concentrated in certain regions. Europe, North America and selected Asian countries are the main players, while large parts of Africa, South America and Oceania are only represented in isolated cases.

3.3.3. Bibliometric Analysis

An author network analysis using VOSviewer is used to analyze the scientific collaboration between authors in the field of BIM-based sustainability optimization. The visualization shows which authors publish together and how strong these collaborations are. Each node represents an author, the node size indicates the number of publications in the analyzed study base, and the edges represent co-authorships. The author network is shown in Figure 5.

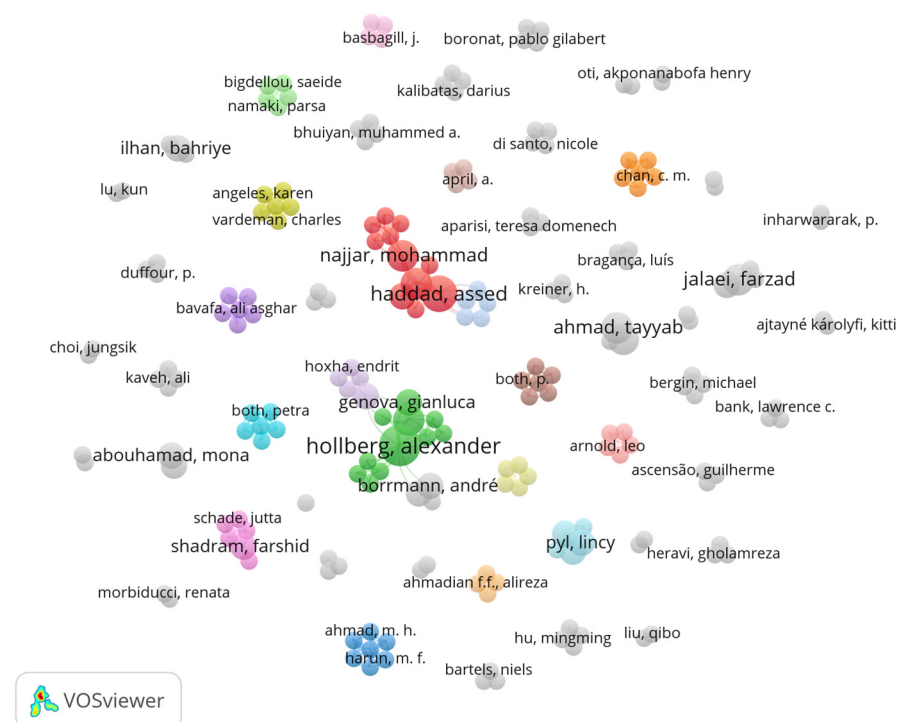


Figure 5. Author network analysis with VOSviewer.

A total of 199 authors contributed to the 70 publications analyzed. The analysis shows that several smaller groups of authors have emerged, each focusing on specific issues. The publications are grouped into 54 isolated clusters, which indicates a low degree of interdisciplinary and supraregional networking within the study base examined. On average, each cluster comprises 1.3 publications; however, the majority consist of individual studies whose authors are not represented in any of the other publications analyzed. The integration of LCA into digital planning processes and the development of data-based tools to support ecological design decisions are particularly frequent topics of focus [24].

A recurring pattern is the formation of project-related teams that focus specifically on topics such as decision support systems [25], parametric environmental assessment in the early design phase [95] or the combination of life cycle assessment and energy analysis of buildings [26].

It is striking that broad, interdisciplinary cooperation networks have been the exception rather than the rule to date. Instead, the field is characterized by many independent groups of authors, each with their own methodological focus. This struc-

ture points to a dynamic and thematically still highly fragmented field of research in which central methodological lines are emerging, but without far-reaching institutional or international networking.

3.3.4. Keywords

To classify the studies examined thematically, the paper performs a keyword co-occurrence analysis using VOSviewer. Only keywords assigned by the authors that appear in at least two publications are taken into account. The visualization shows which topics are addressed particularly frequently in the field of research and how closely they are linked. The nodes represent individual terms, whose size corresponds to their relative frequency. The connecting lines represent their combined use in publications.

The network shown in Figure 6 reveals clusters that highlight different thematic focuses within the literature. At the center of the visualization is the term “BIM”, which is closely linked to a number of other key terms and serves as an overarching reference point. In particular, there is a strong connection to the term “LCA”, suggesting that the use of BIM is often associated with life cycle-related environmental assessments.

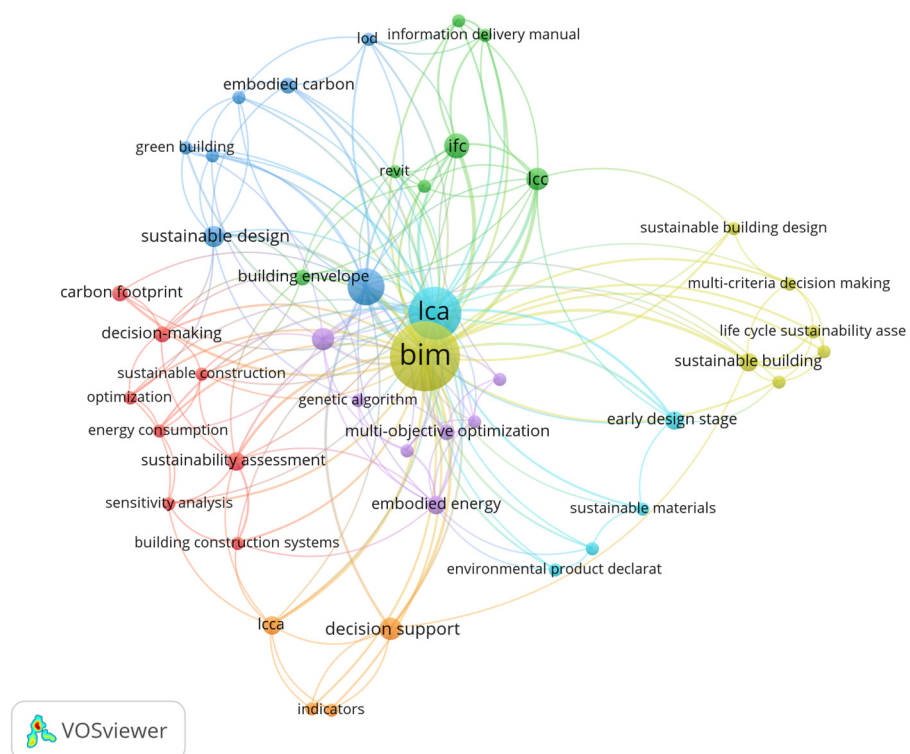


Figure 6. Keyword co-occurrence analysis using VOSviewer.

In addition, methodologically oriented terms such as “optimization”, “sensitivity analysis”, and “sustainability assessment” can be assigned to another cluster that refers to computer-based approaches for evaluating and improving planning decisions. These are complemented by terms such as “decision support”, “LCA” and “indicators”, which refer to strategic evaluation frameworks and overarching decision-making processes in the context of sustainability.

An additional theme relates to early planning phases and material-related sustainability aspects, as indicated by terms such as “early design stage”, “sustainable materials”, and “environmental product declaration”. The analysis shows that the field of research is strongly influenced by the interconnection of technical, ecological, and planning perspectives. The combination of digital planning models, automated environmental assessments,

and structured decision-making processes is reflected in the structural composition of the network.

3.4. Results of Syntheses

3.4.1. Sustainability Indicators

First, an analysis is conducted to determine which data sources are available to the studies examined in order to take sustainability into account in the planning process. The focus here is on how the ecological, economic, and social dimensions of sustainability are captured and operationalized. The studies examined address different dimensions of sustainability. Several studies incorporate both ecological and economic aspects into their assessment and optimization approaches. The social dimension is the least represented. Figure 7 visualizes the distribution of the sustainability dimensions considered.

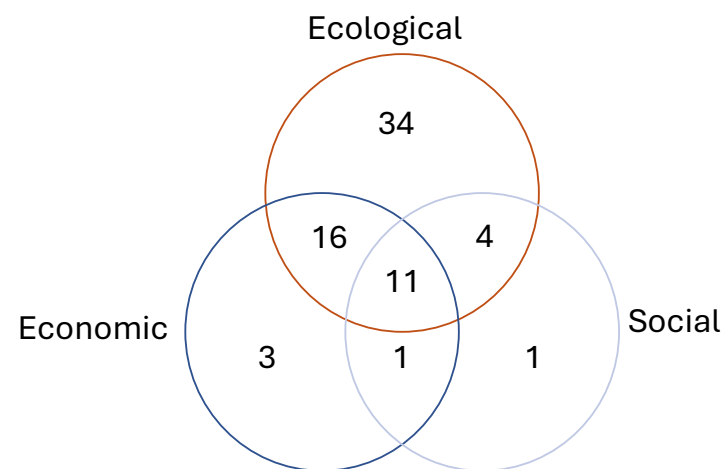


Figure 7. Sustainability dimensions addressed.

The ecological level is the most frequently considered dimension in the studies examined. A total of 65 publications, corresponding to approximately 93% of the sources analyzed, integrate ecological indicators into their concepts. In 34 of these studies, the analysis is based exclusively on ecological indicators. It should be noted that it is not always possible to clearly distinguish between the ecological and economic levels, as both dimensions are closely interrelated, particularly in the context of energy simulations. The economic level is the second most frequently considered dimension after the ecological one. In three publications, the optimization approaches for buildings are based exclusively on economic indicators.

About a quarter of the studies analyzed take social indicators into account. This means that the social dimension of sustainability is the least frequently considered aspect in the optimization of buildings. Only one study considers social indicators exclusively. Its authors emphasize that an isolated assessment based on social criteria is not sufficient to achieve sustainable improvements and point to the need for further research that includes ecological and economic aspects.

For an in-depth analysis of the individual sustainability dimensions, the evaluation is based on the indicators used in the publications.

At the **ecological** level (Figure 8), analysis of the publications examined reveals which indicators are particularly frequently considered. The most relevant of these are energy consumption, full LCA, resource consumption, and waste generation. Aspects from the LCA are also considered specifically, such as global warming potential, gray emissions, gray energy, and local environmental impacts. Land and water consumption and the use of

passive energy appear less frequently. Overall, the analysis shows that energy, resource, and emission aspects are the main focus of the ecological assessment.

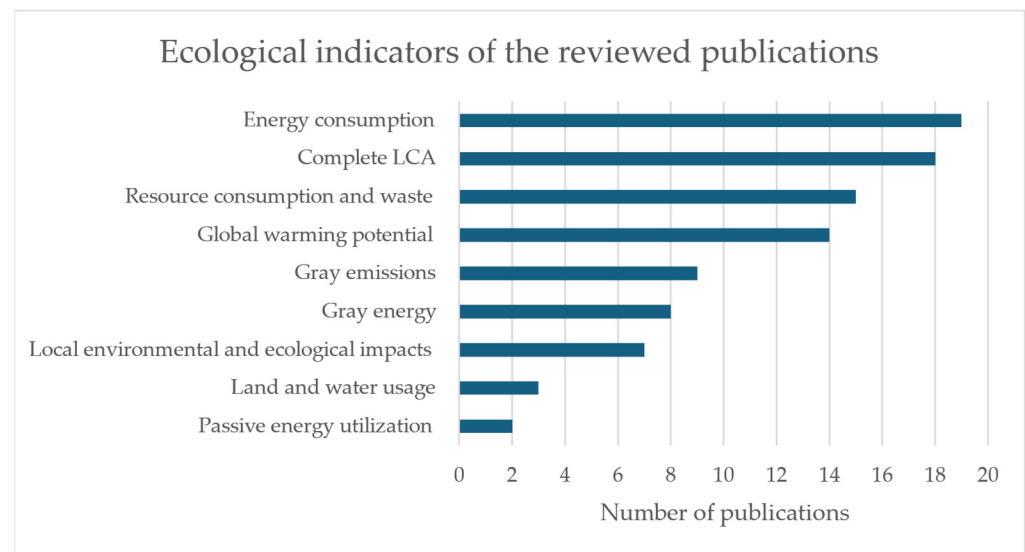


Figure 8. Ecological indicators of the reviewed publications.

The ecological assessment of the studies examined is based primarily on EPDs, which quantify the material footprint and specific indicators such as complete LCA, global warming potential, gray emissions, and gray energy. As can be seen in Figure 9, the focus is primarily on the early life cycle phases (A1–A3: raw material extraction, transport and manufacturing). This suggests that priority is given to those phases for which the most and most reliable data is available in the EPDs, while downstream phases such as use (B), disposal (C), or reuse (D) are included much less frequently.

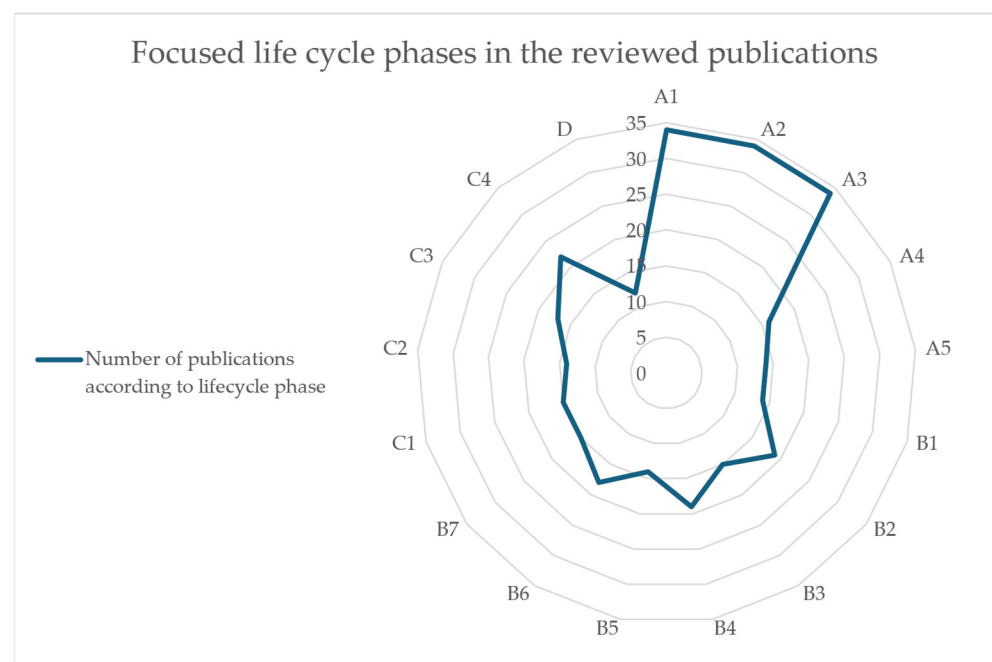


Figure 9. Focused EPD-life cycle phases in the reviewed publication taken into account.

The analysis shows that **economic** assessments primarily focus on construction costs and full life cycle costs (LCC), as these are the most frequently considered indicators (Figure 10). Other aspects, such as value development, operating and energy costs, mainte-

nance and repair costs, certification costs and deconstruction costs, are rarely addressed. The focus remains on construction costs, while economic impacts are only partially considered. The following figure shows this correlation.

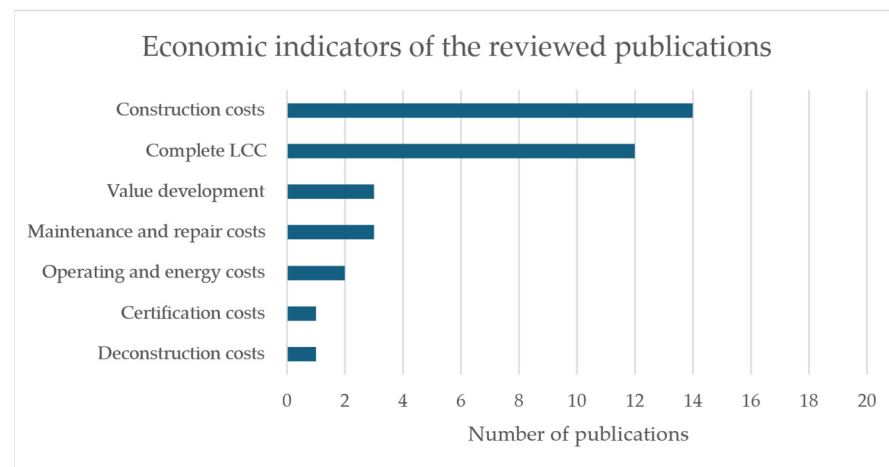


Figure 10. Economic indicators of the reviewed publications.

In terms of the social dimension (Figure 11), user satisfaction was the most frequently applied indicator category, encompassing aspects such as indoor air quality and comfort. This was followed by design and functionality, including aesthetics, as well as health and infrastructure connections, such as accessibility to public transport and essential services. Less frequently applied, but still relevant, were indicators addressing income fairness, support for regional development, the societal impact of CO₂ emissions and teamwork. These indicators capture fair labor conditions, contributions to local economies, climate-related societal costs and collaboration during planning and construction processes.

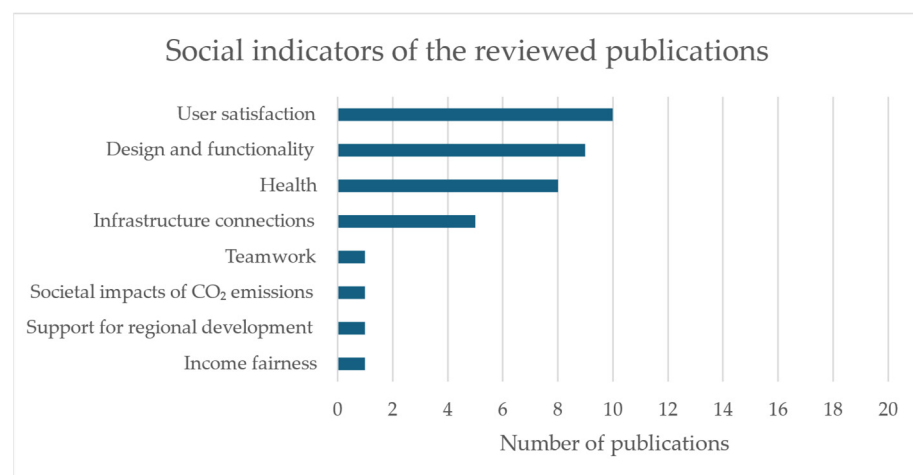


Figure 11. Social indicators of the reviewed publications.

3.4.2. Sustainability Databases

Different data sources are used to identify the ecological, economic, and social impacts of building designs and for optimization, depending on the sustainability dimensions of the studies.

EPDs are the most frequently used source of information for **ecological** assessments. Numerous studies, such as [27–29], use these data to determine equivalent CO₂ emissions, environmental impacts, and material characteristics. National and international life cycle

assessment databases are also used, particularly the Inventory of Carbon and Energy (ICE) database, which provides CO₂ emission factors for building materials [30,31].

For **economic** assessments, external tools such as the “CYPE Cost Estimator” are used [32]. In other cases, economic assessments are based on cost data related to the project from tender documents. For example, Hollands and Korjenic use material and quantity information from a digital building model combined with cost parameters from manufacturer catalogs to evaluate different façade greening systems [33].

The **social** dimension is addressed comparatively rarely to the other dimension. It is based predominantly on qualitative or system-integrated assessment approaches. In several cases, social criteria are considered via qualitative criteria from certification systems, such as the German Sustainable Building Council (DGNB) and the Austrian Sustainable Building Council (ÖGNI). These systems establish indicators such as user comfort, quality of stay and accessibility [34,35]. Significantly more standardized data sources are available for ecological impacts, particularly CO₂ emissions and the environmental impact of materials, than for economic or social aspects. While life cycle assessment databases such as EPDs or ICE are publicly accessible and can often be used for ecological assessments, comparable structured databases for economic and, above all, social criteria are lacking.

3.4.3. System Architecture for Optimization Within BIM

Following the data collection, the next step is to examine how sustainability information can be integrated into digital planning processes. The studies analyzed describe various methods for integrating ecological, economic, and social parameters into digital building models. The focus is on methodological differences regarding the timing of integration, the degree of automation, and the data formats, software, and interfaces used. Both internal model enrichment processes and methods for external post-processing in analytical environments are examined.

A key step in sustainability-focused building design is linking environmental, economic, and social aspects with digital building models. The papers analyzed in this study present methods for integrating sustainability data into design processes. These methods differ in terms of integration timing, automation level, and data formats used.

To ensure systematic categorization of publications, the division follows the workflow proposed by Wastiels and Decuyper [96]. Their approach distinguishes two fundamental stages: first, integrating sustainability-related data into the digital model and second, processing this information. The strength of this workflow lies in the universality of the first stage. Data integration is a necessary step, whether the objective is assessment or optimization. Although it was originally developed for LCA, the resulting data structure is not limited to evaluation purposes. In fact, it also provides a robust foundation for optimization tasks, such as exploring material alternatives or generating design recommendations. Thus, the methodological framework extends beyond assessment to include optimization-oriented applications.

The following section derives and presents five workflows for optimization based on digital building models and sustainability data. Subsequently, the identified papers are assigned to these workflows according to their focus.

Quantities and Volumes Export

This approach relies on the manual extraction of mass and quantity data from the BIM model. This quantitative information is then transferred to external assessment software, where it is manually linked to the corresponding sustainability datasets (Figure 12). The present literature review identified this workflow in nine publications. Despite its high

degree of manual effort, its frequency suggests that it remains an established method in practice, especially in contexts where specialized, automated interfaces are not available.

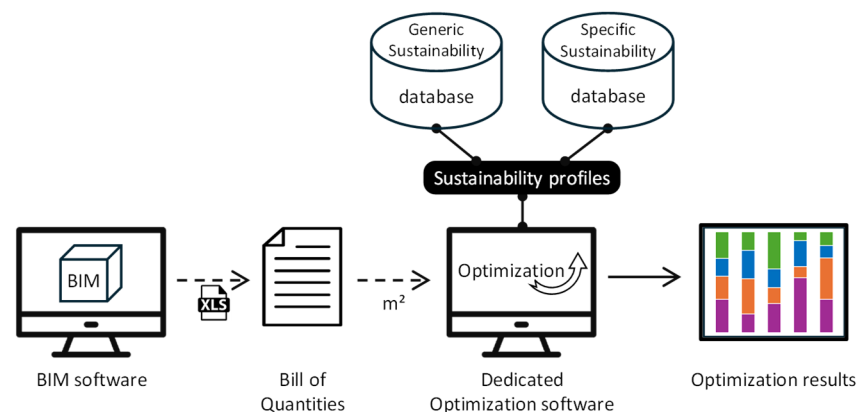


Figure 12. Workflow Quantities and volumes export, based on Wastiels and Decuypere [96].

Geometric IFC Model Import

The export of the entire BIM model as a geometric IFC format represents an alternative approach. In this workflow, the complete model is imported into external software, where the assignment of geometry and component-related information to sustainability data is performed (Figure 13). With only six mentions in the literature review, this method appears to be less frequently used. This could be attributed to the complexity and increased post-processing effort required to enable a comprehensive analysis of the model data.

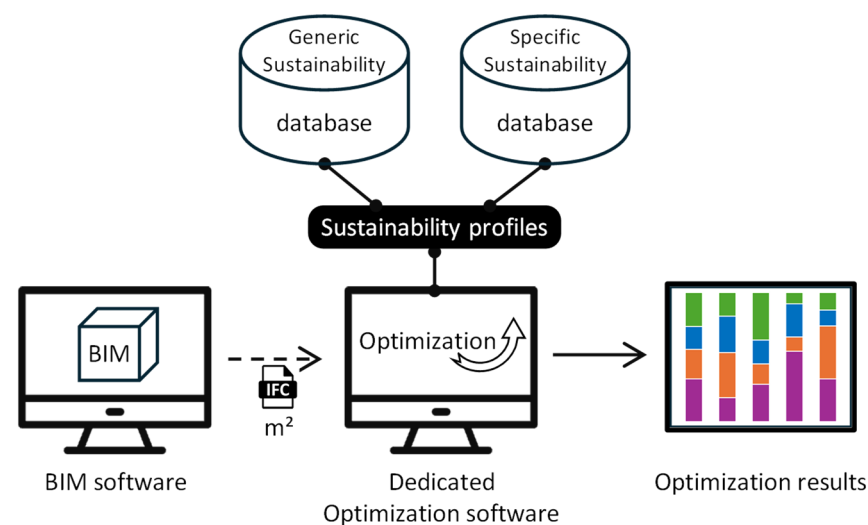


Figure 13. Workflow geometric IFC Model Import, based on Wastiels and Decuypere [96].

BIM Tool for Sustainability Data Linking

This workflow uses specialized tools to act as an intermediary between the BIM model and the assessment software. These tools allow BIM objects to be linked to sustainability datasets in a 3D environment. This attribution process is conducted by the user and is therefore not fully automated. This approach ensures consistency in the assignment process and maintains the connection between geometry and datasets. The detailed LCA calculation is then performed in the dedicated assessment software (Figure 14). The high number of 16 mentions in the review confirms the significant relevance of this approach as an established solution for bridging the data gap between BIM and external analysis.

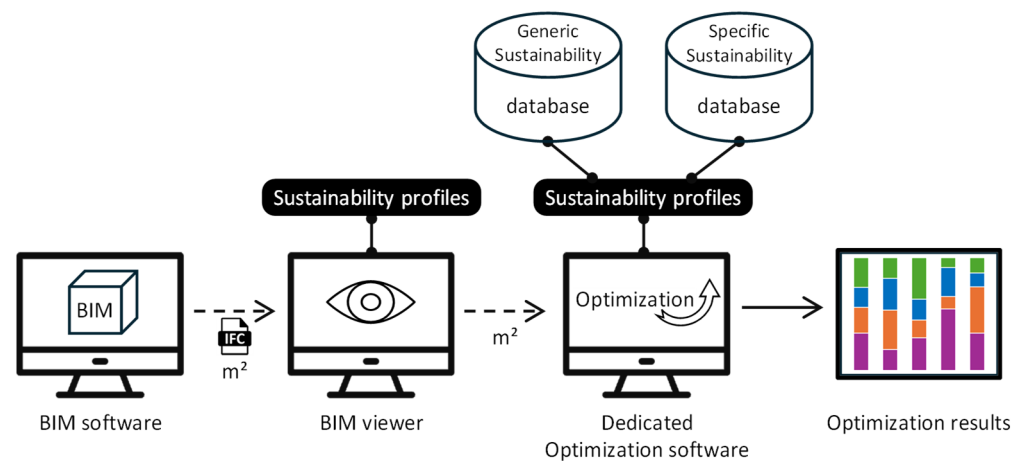


Figure 14. Workflow BIM Tool for Sustainability Data Linking, based on Wastiels and Decuyper [96].

BIM Sustainability Plugin

Integrating sustainability assessment functionalities directly into the native BIM software environment via plug-ins allows for automated data linking and analysis within the modeling environment (Figure 15). With 26 mentions, this approach is the most frequently identified workflow and is considered the most efficient and widespread method in current research and practice. While it does not use an Open BIM approach with an open data structure such as IFC, creating and using sustainability assessments is simple.

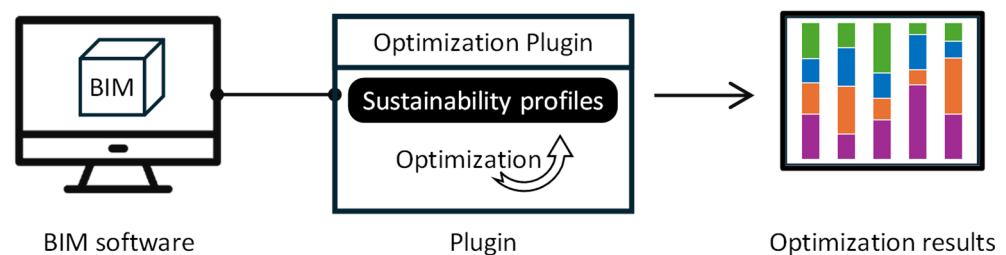


Figure 15. Workflow BIM Sustainability Plugin, based on Wastiels and Decuyper [96].

Sustainability-Enriched BIM Objects

This progressive approach involves storing sustainability data directly in the attributes of BIM objects (Figure 16). The linking is therefore inherent and automated, enabling continuous and early assessment that can be performed either via a plugin or by exporting the enriched model. The BIM objects may contain the LCA data themselves or, alternatively, a reference to an external profile stored in a dedicated database or tool. Although this approach is documented less frequently, with eight mentions in the review, it represents the highest degree of integration and has the potential to significantly maximize the efficiency of sustainability assessment in future construction processes.

It appears that six sources cannot be assigned to any specific approach. Reasons include a focus on the development and weighting of sustainability assessment criteria rather than on the workflow itself ($n = 2$), an imprecise description of the workflow ($n = 2$), only optional integration of the developed tool using digital building models ($n = 1$), or a focus on the practical application of existing systems ($n = 1$). Two additional sources indicate that their applications could not yet be implemented using the BIM method at the time of publication; however, since the workflow is sufficiently explained, these sources can still be classified. One further source can be assigned to two workflows, as both are conceptually developed.

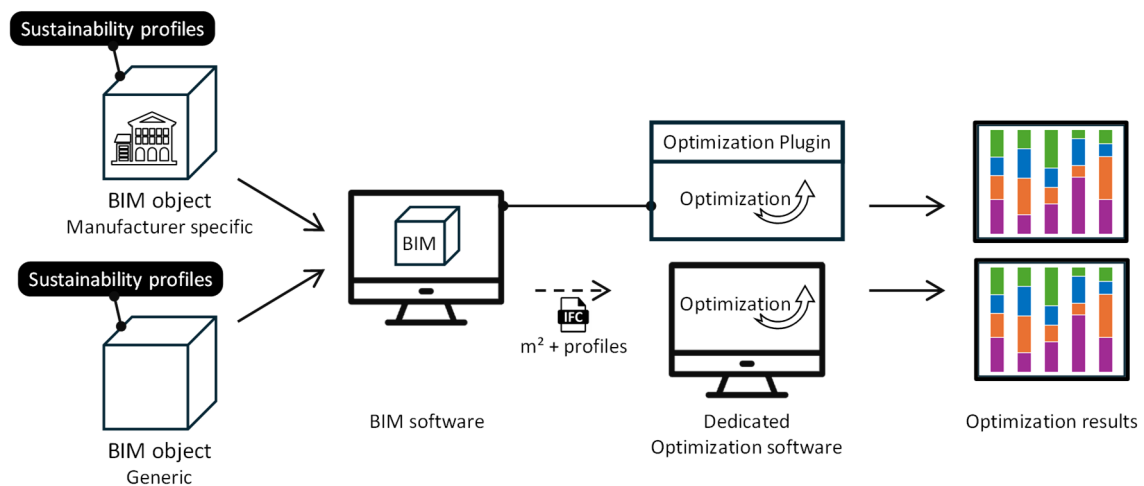


Figure 16. Workflow Sustainability-Enriched BIM Objects, based on Wastiels and Decuyper [96].

It can be observed that the publications focus almost on the BIM Sustainability plugin. This dominance may stem from several factors: the plugin is a well-established piece of software, it offers good data interoperability and it consolidates various functions within a single platform. Programs with user-friendly interfaces and extensibility features will likely attract researchers and practitioners due to their ability to easily integrate sustainability assessments into BIM workflows.

Figure 17 provides a synthesized representation of all identified workflows.

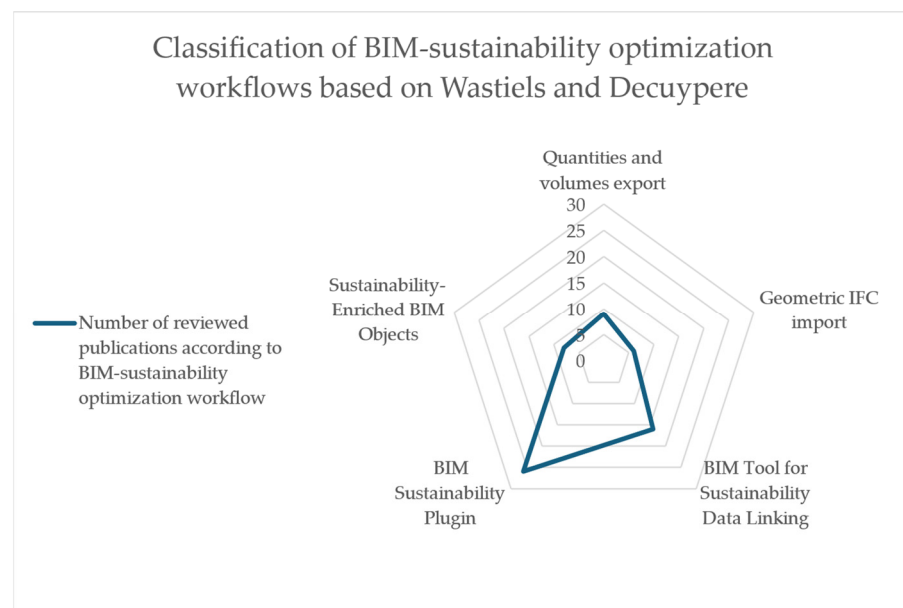


Figure 17. Classification of BIM-sustainability optimization workflows based on Wastiels and Decuyper [96].

In evaluating sustainability strategies in digital planning processes, it is crucial to consider the underlying BIM information exchange strategies for extracting information from a model. There are two types of information exchange strategy: Closed BIM, where data exchange takes place within proprietary software environments, and Open BIM, which relies on interoperable, vendor-neutral formats such as IFC. The examined studies show a clear predominance of Closed BIM systems: according to the quantitative evaluation shown in Figure 18, around 66 percent of contributions are based on Closed BIM, while only around 23 percent use Open BIM. For approximately 11 percent of the studies, the

method of data extraction from the models is not specified, so no clear statement can be made.

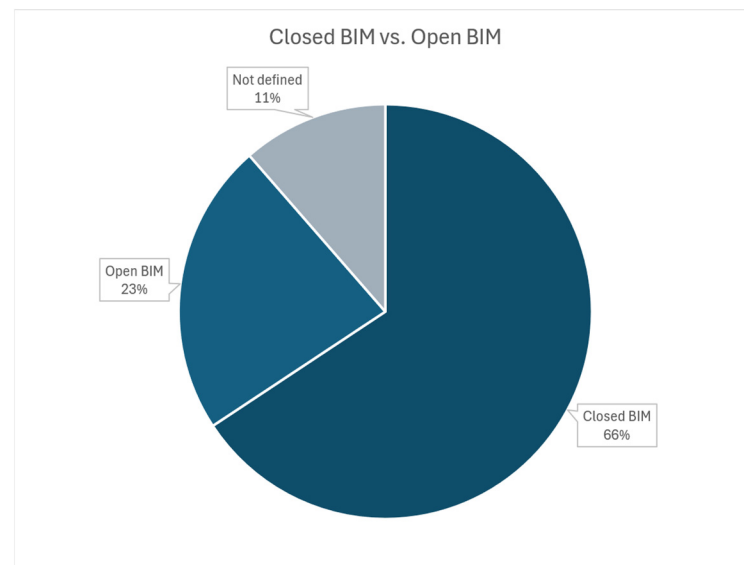


Figure 18. BIM Information exchange strategies.

The analysis shows that Autodesk Revit is the most frequently used modeling platform. In closed BIM workflows, Revit is often supplemented by tools such as Dynamo. Dynamo enables rule-based automation and the integration of external data sets [32,36,37]. The LCA plugin Tally, which is integrated into Revit, is often used for LCA analyses [38–40,42–44]. Other tools such as Power Pivot, Excel, or Power BI support data evaluation, for example, in the aggregation of environmental indicators or comparative presentations [27,28].

Software-based LCA and LCC tools are also increasingly being used in proprietary BIM workflows. Several studies use external platforms such as OneClick LCA [42] or CYPE [33,43] to assess environmental impacts and life cycle costs. These tools are usually connected to the modeling environment via interfaces, perform the analysis, and forward the results to the planning system via data links or export functions. In some cases, platforms such as Grasshopper are also used as a visual programming approach, e.g., for the parametric generation of geometric variants [33,43].

In contrast, Open BIM-oriented work relies on the use of open standards for interoperability. The IFC format is primarily used here to transfer model-based information such as geometry, component characteristics, or material assignments to other applications [44,45]. The aim is to enable manufacturer-independent data exchange between different software solutions throughout the planning and evaluation process. Although IFC provides a standardized basis for cross-model sustainability assessments, the studies analyzed show that practical implementation is often limited to one-way export.

3.4.4. Optimization Methodology

In a further evaluation step, the methodological approaches to decision-making used in the studies are examined. The aim is to identify procedures that support planning decisions in terms of sustainability optimization. The methods are categorized inductively on the basis of content analysis procedures. The resulting six categories form the methodological basis for the interpretation of content and are shown in Figure 19.

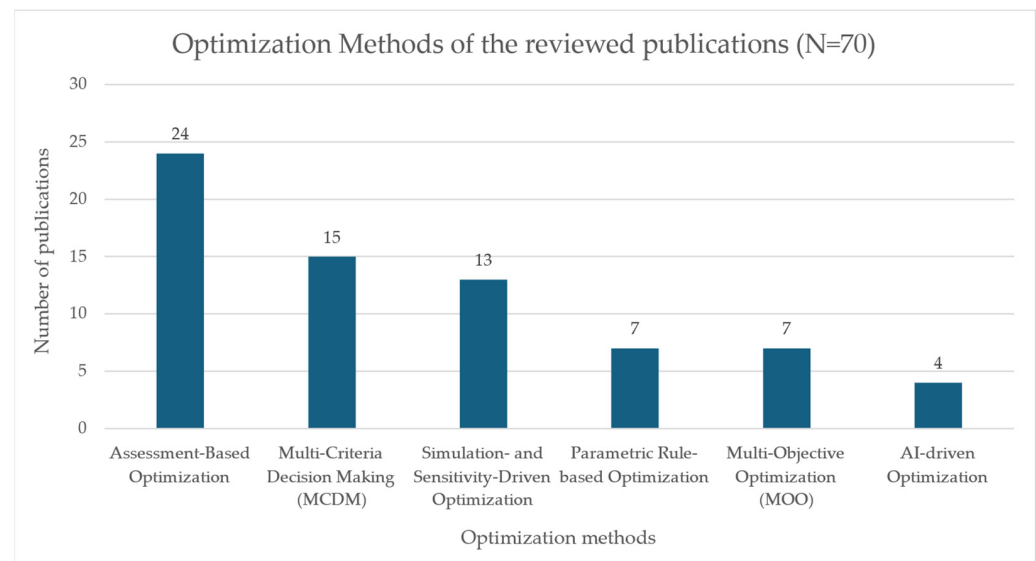


Figure 19. Optimization Methods.

The most frequently identified category is **assessment-based optimization**, which are used in 24 of the studies examined. This method serves to support decision-making processes in the planning process. The specific characteristics range is from classic cost-benefit approaches to more complex decision-making models. Several studies utilize LCA-based or combined LCA + LCC approaches to systematically evaluate ecological and economic impacts [27,42,46]. Other contributions integrate certification frameworks (e.g., BREEAM, LEED, or DGNB) into decision-making or use process-economic modeling to evaluate the economic efficiency of construction projects [47]. Visualizations are also used to increase decision-making transparency and make complex sustainability data intuitively presentable [48].

The next largest category includes 15 studies on **multi-criteria decision-making (MCDM)** methods. These methods enable the simultaneous evaluation of multiple criteria from different areas. Hierarchical evaluation methods were used most frequently, in particular the Analytic Hierarchy Process (AHP) [41]. This enables complex decision-making problems to be systematically subdivided into objectives, criteria, and solution alternatives. In several studies, the AHP was combined with other methods such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) or the Weighted Additive Model (WAM) to enable the prioritization of competing sustainability criteria [30,49]. Other contributions used uncertainty-robust MCDM approaches, for example, by using fuzzy set theory or Bayesian decision models to systematically integrate subjective assessments, incomplete information, or uncertainties into the decision-making process [38,45].

Simulation- and sensitivity driven optimization were used in 13 studies to evaluate sustainability-related design decisions. Among other things, these methods serve to quantify factors influencing energy consumption, emissions, or environmental impacts. For example, Basbagill used a sensitivity analysis in the early planning phase to identify the building components with the greatest reduction potential [50]. Tushar et al. combined a simulation-based energy and environmental assessment with BIM and LCA data to select suitable building materials [51]. Choi et al. developed an alternative assessment model based on simulation-supported variant comparisons [44].

Seven contributions followed the **multi-objective optimization (MOO)** approach. This approach allows for the simultaneous optimization of several target variables, for example, to minimize CO₂ emissions and costs. Among other things, evolutionary algorithms

such as NSGA-II were used. An example that is a BIM-based optimization framework to simultaneously optimize energy consumption and daylight utilization [52]. Another study used an ϵ -constraint method to identify optimal building envelope materials in terms of energy consumption and environmental impact [39].

Seven studies used **parametric rule-based optimization** approaches for the automated evaluation and optimization of sustainability-related design decisions.

One approach is the parametric BIM framework for structural concept optimization, which uses visual programming to generate and compare structural variants based on geometric efficiency parameters [53]. Gianluca Genova developed a optimization tool that calculates the environmental impact of individual BIM elements in real time. The tool links material and geometry data with LCA databases and provides visual guidance to support sustainable design decisions throughout the planning process [54]. Another approach created a rule-based planning logic for evaluating green facades, in which the environmental impacts were determined directly from the model behavior [33].

Four studies used **AI-based optimization** methods to improve planning decisions. One paper presents a dual AI-driven approach to low-carbon architectural design: a machine learning model predicts the building's carbon footprint based on parametric inputs, while a large language model (LLM) offers text-based suggestions for material substitutions to further reduce environmental impact [55]. Another study combined genetic algorithms with BIM data to optimize sustainable construction methods by comparing variants [56]. Another study developed an evolutionary metaheuristic with the help of AI to target the optimization of construction-related sustainability indicators [57].

4. Discussion

4.1. General Interpretation of the Results

The results of this systematic literature analysis reveal a dynamically growing but still highly fragmented field of research in the area of BIM-based sustainability optimization. As the results show, the predominant focus in the **sustainability dimension** is on ecological aspects. The observed imbalance between the different dimensions of sustainability can partly be explained by the existence of clearer climate targets and evaluation metrics. This has resulted in a greater emphasis on environmental factors in research and practice, with social and economic aspects being comparatively underdeveloped. In order to better integrate social sustainability into BIM-based decision support systems, it is necessary to develop methods that quantify social aspects. This would also enhance transparency in the assessment process. Linking these indicators to existing frameworks, such as Social Life Cycle Assessment (SLCA), would allow social sustainability to be included alongside environmental and economic dimensions, providing more comprehensive decision support.

At the same time, differences in **data** availability and quality present additional challenges. Standardized information sources such as EPDs or the national database have been established for ecological assessments. However, there is a lack of comparable bases for economic and social criteria. Access to publicly available, structured, and reliable data sources is essential to enable automated sustainability assessments. In practice, this asymmetry means that planners continue to rely heavily on individual expertise, the respective project context, and manual data collection.

Another key finding is the strong focus on closed BIM environments in the **system architectures**. Around three-quarters of the studies use proprietary software solutions such as Revit in combination with tool sets such as Tally, Dynamo, or OneClick LCA. Although these tools often enable the functional integration of sustainability data into the planning process, they are usually not interoperable and tie users to specific providers. Open BIM approaches are in the minority and are often limited to data exchange. As a

result, the potential of open interfaces to promote interoperability and reduce barriers to entry remains largely untapped. These observations that closed BIM is the predominant approach are also illustrated by the identified workflows. Sustainability data is usually integrated via BIM sustainability plugins that are directly embedded in the modeling environment. While this enables seamless evaluation within proprietary platforms, it also limits the interchangeability of vendor-independent data and promotes isolated solutions, hindering progress toward standardization.

In view of the variety of **optimization methods** applied in the literature, the range of approaches identified is broad, extending from classic assessment based optimization and MCDM methods to AI-based optimization approaches. On the one hand, this diversity is an expression of a high degree of innovation, but on the other hand, it leads to limited comparability of study results and makes it difficult to establish standardized procedures.

Methodologically, AHP- and TOPSIS-based MCDM methods dominate, as do assessment based optimization methods, which are mainly used in combination with LCA or LCC. They allow for a structured evaluation of competing target variables such as CO₂ emissions, costs, or functional requirements. Nevertheless, many approaches remain limited to considering only a few criteria. Holistic evaluation models that also systematically integrate social, health-related, or usage-oriented indicators are still the exception.

All in all, there is a methodological trend toward partially automated decision support in the early planning phases. This support is often combined with visualization and simulation to raise awareness and aid in qualitative decision-making. However, full optimizations that systematically identify the best solution among many alternatives are rarely achieved, and modeling often remains exploratory or heuristic. Nevertheless, these approaches lay the groundwork for more advanced, AI-based optimization that could integrate multiple sustainability dimensions, systematically evaluate alternatives, and remain simple enough to be applied in practice.

4.2. Limitations Related to the Review Procedures and Their Outcomes

The review process was subject to several limitations that potentially restrict the completeness and generalizability of the results. First, only English-language and open-access publications were considered. As a result, relevant contributions, especially from non-English-language specialist contexts or sources that are not freely accessible, may have been excluded.

Second, the distinction between pure sustainability assessment and actual optimization was not always clear, as the objectives were only implicitly formulated in many studies. This made it difficult to apply the inclusion criteria consistently and led to uncertainties in categorization.

In addition, the entire screening and evaluation process was carried out manually. While this allows for a differentiated analysis of content, it also carries the risk of subjective selection decisions and limited reproducibility.

Despite the large number of approaches identified, the studies included in the analysis reveal several limitations in terms of content, which restrict the significance and comparability of the results. One problem is the methodological heterogeneity. The studies follow very different objectives and evaluation procedures and use different data sources. This makes it difficult to compare the results on an equal basis and it is hardly possible to make generalizable statements about the effectiveness of individual methods. Another limitation is the often limited depth of content in many case studies.

Most contributions are limited to small demonstration projects or idealized model cases, whose complexity often does not correspond to reality. Aspects such as the building location, type of use, or legal framework are rarely systematically included. As

a result, it remains unclear how well the methods described work in real, complex construction projects.

The quality of the evidence is limited because many studies quantify ecological impacts, but treat economic and social indicators only qualitatively or ignore them completely. This represents a considerable deficit, particularly with regard to the integral assessment of sustainability. The uneven availability of data, with an overemphasis on ecological parameters, distorts the weighting of the results.

4.3. Implications for Practice, Policy, and Future Research

The results of the analysis show that the holistic integration of sustainability assessments into digital planning processes has so far only been implemented to a limited extent. In many cases, ecological, economic, or social criteria are evaluated in parallel with the design process, but are not considered an integral part of the digital model. In practice, this means that optimization potential often remains unused and decisions continue to be made largely based on experience.

In order to seamlessly integrate sustainability information into digital building models, there is a central need for action in the development of standardized interfaces and interoperable data formats. Open BIM approaches play a key role in this area, especially for small and medium-sized companies without proprietary software solutions. The promotion of open standards can thus contribute to broader application and comparability.

At the same time, centrally available, structured, and quality-assured data sources are required. EPDs currently provide a valid basis for ecological assessment, while comparable foundations for economic and social criteria are largely lacking. Future developments should therefore also promote open-source databases for comprehensive sustainability indicators.

Once a sufficient amount of data is available, the next step is to efficiently leverage it within BIM-based decision support processes. Intelligent, AI-based linking mechanisms can significantly simplify the assignment of materials to their corresponding sustainability data. Currently, the connection between elements in digital building models and sustainability indicators is hindered by the lack of standardized data structures and naming conventions. AI methods can address these challenges by enabling flexible, data-driven matching and inference. This creates a more robust, scalable integration of sustainability values within digital building models. Beyond data linking, AI-based decision-making could enable predicting a building's overall sustainability performance. However, this requires large, well-prepared datasets with reliably matched material information and corresponding sustainability values. This underscores the importance of extensive data preparation and matching processes.

In the field of research, there is a need to standardize evaluation and optimization methods and make them available in modular, scalable tools. Furthermore, the methods should be applicable not only to ideal model projects, but also to complex real-world construction projects. In particular, the social dimension, which has been underrepresented to date, must be addressed in greater depth in order to meet the requirements of integral sustainability.

Overall, it is shown that there is a fundamental basis for digital sustainability optimization. However, its implementation is hindered by a lack of integration into planning processes, insufficient interoperability, and an incomplete database. To address this issue, the development of common standards is of central importance. Only through uniform evaluation methods, interoperable data formats, and standardized interfaces can sustainability assessments be implemented in a scalable, comparable, and practical manner. This requires coordinated progress in research, software development, and regulation in order to

create the technical, organizational, and normative foundations for consistent and holistic sustainability optimization in the construction industry.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18052341/s1>. Table S1: The PRISMA guideline.

Author Contributions: Conceptualization, S.R.; methodology, S.R.; validation, S.R. and E.H.; formal analysis, S.R.; investigation, S.R. and E.H.; resources, S.R.; data curation, S.R. and E.H.; writing—original draft preparation, S.R.; writing—review and editing, S.R., E.H., S.M. and K.K.-A.; visualization, S.R. and E.H.; supervision, S.R.; project administration, S.R.; funding acquisition, S.R. and K.K.-A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that supports the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of the analyzed papers.

Author	Year	Title	DOI
AbouHamad & Abu-Hamd	2019	Framework for construction system selection based on life cycle cost and sustainability assessment	[58]
AbouHamad & Abu-Hamd	2021	Life Cycle Assessment Framework for Embodied Environmental Impacts of Building Construction Systems	[59]
Ahmad et al.	2017	BIM-based Iterative Tool for Sustainable Building Design: A Conceptual Framework	[25]
Ahmad & Thaheem	2017	Developing a residential building-related social sustainability assessment framework and its implications for BIM	[60]
Ahmad & Thaheem	2018	Economic sustainability assessment of residential buildings: A dedicated assessment framework and implications for BIM	[49]
Ahmadian F.F. et al.	2017	BIM-enabled sustainability assessment of material supply decisions	[30]
Ajtayné Károlyfi & Szép	2023	A Parametric BIM Framework to Conceptual Structural Design for Assessing the Embodied Environmental Impact	[53]
Alasmari et al.	2024	Utilising BIM on LCC to Enhance the Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia	[61]
Angeles et al.	2021	Advancing the Design of Resilient and Sustainable Buildings: An Integrated Life-Cycle Analysis	[62]
Atik et al.	2023	The Opportunities and Challenges of Using LCA-Based BIM Plugins in Early-Stage Building Design: An Industry Expert Perspective	[63]
Ayman Mohamed et al.	2023	Automation of embodied carbon calculation in digital built environment-tool utilizing UK LCI database	[64]
Bagul & Katare	2023	Comparative Analysis of Various Walling Materials for Finding Sustainable Solutions Using Building Information Modeling	[65]

Table A1. Cont.

Author	Year	Title	DOI
Bank et al.	2011	Decision-making tools for evaluating the impact of materials selection on the carbon footprint of buildings	[66]
Bartels et al.	2023	Life cycle-oriented decision making based on data-driven building models	[67]
Basbagill et al.	2013	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	[50]
Carvalho et al.	2021	Assessing Life Cycle Environmental and Economic Impacts of Building Construction Solutions with BIM	[32]
Choi & Lee	2023	A Suggestion of the Alternatives Evaluation Method through IFC-Based Building Energy Performance Analysis	[44]
Cornely et al.	2024	A Case Study on Integrating an Eco-Design Tool into the Construction Decision-Making Process	[27]
Di Santo et al.	2023	Holistic Approach for Assessing Buildings' Environmental Impact and User Comfort from Early Design: A Method Combining Life Cycle Assessment, BIM, and Active House Protocol	[68]
Dupuis et al.	2017	Method to Enable LCA Analysis through Each Level of Development of a BIM Model	[69]
Ebertshäuser et al.	2019	Sustainable building information modeling in the context of model-based integral planning	[70]
Ebertshäuser et al.	2018	BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives	[71]
Figueiredo et al.	2021	Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP	[40]
Filho et al.	2022	Sustainability Assessment of a Low-Income Building: A BIM-LCSA-FAHP Based Analysis	[38]
Forth et al.	2023	Calculation of embodied GHG emissions in early building design stages using BIM and NLP-based semantic model healing	[72]
Forth et al.	2023	BIM4EarlyLCA: An interactive visualization approach for early design support based on uncertain LCA results using open BIM	[48]
Gan et al.	2018	Holistic BIM framework for sustainable low carbon design of high-rise buildings	[73]
Gardezi et al.	2016	A multivariable regression tool for embodied carbon footprint prediction in housing habitat	[74]
Genova	2019	BIM-Based LCA throughout the Design Process: a Dynamic Approach	[54]
Haruna et al.	2021	Building information modelling application for developing sustainable building (Multi criteria decision making approach)	[75]
Hollands & Korjenic	2021	Evaluation and Planning Decision on Façade Greening Made Easy—Integration in BIM and Implementation of an Automated Design Process	[33]
Horn et al.	2020	The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning	[76]
Hunt & Osorio-Sandoval	2023	Assessing Embodied Carbon in Structural Models: A Building Information Modelling-Based Approach	[36]

Table A1. Cont.

Author	Year	Title	DOI
Ilhan & Kog	2020	BIM and Sustainability Integration: Multi-agent System Approach	[45]
Ilhan & Yaman	2016	Green building assessment tool (GBAT) for integrated BIM-based design decision	[47]
Inharwararak & Stravoravdis	2023	Building information modelling-based life cycle assessment (BIM-LCA) for housing estates in Thailand	[29]
Jalaei & Jrade	2015	Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings	[26]
Jalaei et al.	2022	A framework for specifying low-carbon construction materials in government procurement: A case study for concrete in a new building investment	[46]
Jrade & Jalaei	2013	Integrating building information modelling with sustainability to design building projects at the conceptual stage	[77]
Khanzadi et al.	2015	Optimization of Building Components with Sustainability Aspects in BIM Environment	[57]
Kreiner et al.	2015	A new systemic approach to improve the sustainability performance of office buildings in the early design stage	[35]
Lim et al.	2018	BIM and genetic algorithm optimisation for sustainable building envelope design	[56]
Lim et al.	2017	BIM-based sustainable building design process and decision-making	[78]
Liu & Wang	2022	Green BIM-based study on the green performance of university buildings in northern China	[43]
Lu & Wang	2019	Estimation of Building's Life Cycle Carbon Emissions Based on Life Cycle Assessment and Building Information Modeling: A Case Study of a Hospital Building in China	[79]
Masoumi-Hajiagha et al.	2025	Development of a Framework for Optimal Selection of Sustainable Building Envelope using BIM	[31]
Mowafy et al.	2023	Parametric BIM-based life cycle assessment framework for optimal sustainable design	[37]
Najjar et al.	2019	Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings	[39]
Najjar et al.	2017	Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building	[24]
Najjar et al.	2019	Integrating Parametric Analysis with Building Information Modeling to Improve Energy Performance of Construction Projects	[80]
Namaki et al.	2024	An Integrated Building Information Modeling and Life-Cycle Assessment Approach to Facilitate Design Decisions on Sustainable Building Projects in Canada	[41]
Naneva et al.	2020	Integrated BIM-Based LCA for the Entire Building Process Using an Existing Structure for Cost Estimation in the Swiss Context	[81]
Oti & Tizani	2015	BIM extension for the sustainability appraisal of conceptual steel design	[82]

Table A1. Cont.

Author	Year	Title	DOI
Ozcan-Deniz & Rodovalho	2024	Towards carbon-neutral construction: Integrating BIM and energy analysis for sustainable design decision-making	[83]
Peng	2016	Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling	[84]
Płoszaj-Mazurek & Ryńska	2024	Artificial Intelligence and Digital Tools for Assisting Low-Carbon Architectural Design: Merging the Use of Machine Learning, Large Language Models, and Building Information Modeling for Life Cycle Assessment Tool Development	[55]
Rahmani Asl et al.	2015	BPOpt: A framework for BIM-based performance optimization	[52]
Rezaei et al.	2019	Integrating building information modeling and life cycle assessment in the early and detailed building design stages	[85]
Röck et al.	2018	LCA and BIM: Visualization of environmental potentials in building construction at early design stages	[86]
Sadeghifam et al.	2016	Energy Analysis of Wall Materials Using Building Information Modeling (BIM) of Public Buildings in the Tropical Climate Countries	[87]
Santos et al.	2020	Development of a BIM-based Environmental and Economic Life Cycle Assessment tool	[42]
Santos et al.	2019	Integration of LCA and LCC analysis within a BIM-based environment	[88]
Scherz et al.	2022	A hierarchical reference-based know-why model for design support of sustainable building envelopes	[34]
Serrano-Baena et al.	2023	Optimising LCA in complex buildings with MLCAQ: A BIM-based methodology for automated multi-criteria materials selection	[89]
Shadram et al.	2016	An integrated BIM-based framework for minimizing embodied energy during building design	[28]
Shadram & Mukkavaara	2018	An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy	[90]
Tushar et al.	2021	An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development	[51]
Vilutiene et al.	2020	Assessing the Sustainability of Alternative Structural Solutions of a Building: A Case Study	[91]
Vite & Morbiducci	2021	Optimizing the Sustainable Aspects of the Design Process through Building Information Modeling	[92]
Zanni et al.	2019	Developing a Methodology for Integration of Whole Life Costs into BIM Processes to Assist Design Decision Making	[93]

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