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A New Building Information Modelling-Based Approach to Automate Recyclability Rate Calculations for Buildings

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Abstract: To address environmental challenges, the Architecture, Engineering, Construction, and Operations (AECO) industry, which is known for its high resource consumption and waste production, needs to switch to a circular economy (CE). This approach focuses on reducing, recycling, and reusing materials to narrow, slow, and close material loops. However, one of the main problems which the AECO industry is still facing is the lack of common, standardized, and automated procedures to consider the recyclability and presence of hazardous materials. To address this problem, this study focuses on extending the recyclability rate from the material to building scale, considering the presence of hazardous materials based on the European Waste Catalogue (EWC), hence defining a new KPI. It adopts Building Information Modelling (BIM) and Industry Foundation Classes (IFCs) and integrates them with bespoke programming in Python to develop a standardized and automated procedure that complies with Italian regulations. The new KPI will help clients and designers to rate the overall recyclability of a building and to choose the best combination of materials and components. The procedure includes data acquisition, transmission, and data/model integration, resulting in practical and trackable measures that could be globally scalable. Scenario analyses are also developed to consider the impact of maintenance attitude on waste production.

Keywords: circular economy; maintenance; building information modelling; industry foundation classes; life-cycle analysis

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Citation: Fereydooni Eftekhari, A.; Khodabakhshian, A.; Iuorio, O.; Re Cecconi, F.; Daniotti, B. A New Building Information Modelling-Based Approach to Automate Recyclability Rate Calculations for Buildings. *Buildings* **2024**, *14*, 1521. https://doi.org/10.3390/buildings14061521

Academic Editor: Pei Huang

Received: 28 March 2024
Revised: 18 May 2024
Accepted: 22 May 2024
Published: 24 May 2024

1. Introduction

The construction sector is a pivotal component of global infrastructure development, and is at the forefront of addressing pressing environmental and economic challenges arising from its substantial waste generation and resource consumption [1]. Amidst a rapidly increasing global population projected to reach between 9.4 and 10.1 billion by 2050, and an ensuing demand for approximately 230 billion square meters of new building space, the urgency for sustainable construction practices has never been more pronounced [2]. This expansion, primarily fueled by urbanization, exacerbates the environmental footprint of the Architecture, Engineering, Construction, and Operation (AECO) industry in the European Union (EU), which is responsible for producing 850 million tons of waste annually, amounting to 35% of the EU's total waste generation [3]. This industry also accounts for about 50% of the raw materials consumption, significant energy use, and contributes 5–12% of the total greenhouse gas emissions due to material extraction, products manufacturing, and construction and renovation of buildings [4,5].

Traditional construction methodologies, characterized by linear "take–make–consume–dispose" models, further complicate the situation by failing to implement circular economy (CE) strategies effectively, leading to inefficient resource use and high levels of waste, much of which ends up in landfills without plans for recovery or recycling [6,7]. CE strategies, characterized by the reduction, reuse, and recycling of materials, aim to extend the lifespan of products and close material loops, thereby enhancing economic prosperity and environmental quality [7–10]. Despite existing initiatives such as the Circular Economy Action Plan (CEAP) and the EU Green Deal, the construction sector's material reuse and recycling rates remain suboptimal [11,12].

Two main pillars of CE in AECO are the recovery and recycling process of materials and the maintenance management of the built assets; these help save the remaining value of building materials before complete deterioration of their physical condition [8]. With the vision to escalate the recycling rate of non-hazardous materials in Europe up to 70%, CE is becoming mainstream in construction research [9]. However, the lack of standardized design methodologies and procedures to better utilize construction and demolition waste hinders the realization of such a number [13]. Moreover, though the concept of component management, including maintenance and waste management at the building component level, is gaining more attention in the literature [14], the full assessment of recyclability indicators contributing to CE goals has been limitedly studied. Given the intricate nature of construction processes and the diverse materials involved, the need for a systematic approach to assess and improve waste management and material recyclability is paramount.

This paper examines the factors hindering CE in construction projects and proposes a Building Information Modelling (BIM)- and Industry Foundation Classes (IFCs)-based procedure for improving waste management practices in terms of recyclability through systematic data extraction and consideration of the waste classification (hazardous or not). By adopting a comprehensive, systematic approach, this study scrutinizes the current state of waste management within the construction sector, evaluates the lifecycle sustainability of building materials, and assess the recyclability rate of buildings possibly penalized by the presence of hazardous material. The methodology is articulated into three layers of data acquisition, transmission, and data/model integration and is implemented in an automated way through a bespoke tool in Python. The method is validated through a case study on a residential building.

The methodology builds upon European codes for materials' waste categories, Italian regulations, and Life Cycle Analysis (LCA) databases for extending circularity from the material to building scale. It subsequently integrates advanced computational tools through bespoke programming in Python with established environmental guidelines to offer novel insights into material management, emphasizing the critical role of early-stage decision making in reducing waste production. Utilizing BIM and IFCs, this research facilitates a detailed analysis of construction materials, assessing their end-of-life recyclability and overall sustainability impact.

BIM-based tools are being widely studied for sustainable design, construction, and operation phases of built assets. BIM and Digital Twin (DT) technologies are pivotal in construction, offering a detailed digital representation for decision making across a building's lifecycle and providing a real-time virtual model for analysis and monitoring [15]. There are some remarkable studies such as the one conducted by Jayasinghe and Waldmann (2020), which introduced novel BIM-based concepts such as Material and Component (M&C) banks to manage recycling and reuse of materials and components, facilitating a sustainable construction industry [16]. However, despite their potential to enhance waste management through precise planning and real-time simulations, the adoption of BIM and DT in reducing construction waste is still in its early stages, hindered by the absence of standardized procedures.

Therefore, this study's main objective is to present a methodology and define a new KPI which extends the definition of recyclability rates from materials to buildings, including the contribution of hazardous materials. Moreover, it aims to automate and facilitate the implementation of such a methodology and evaluate the impact of different maintenance attitudes on waste production through a scenario analysis.

The novelty of the methodology is that it builds upon European codes for materials' waste categories, Italian regulations, and Life Cycle Analysis (LCA) databases for extending circularity from the material to building scale and defines a new KPI. Subsequently, it integrates advanced computational tools through bespoke programming in Python with established environmental guidelines to offer novel insights into material management, emphasizing the critical role of early-stage decision making in reducing waste production. Utilizing BIM and IFCs, this research facilitates a detailed analysis of construction materials, assessing their end-of-life recyclability and overall sustainability impact. Moreover, the impact of various maintenance attitudes on waste production is another important aspect which is considered in this study.

By bridging the gap between theoretical frameworks and practical applications, this research contributes to the ongoing discourse on sustainability, offering actionable insights for enhancing recyclability and waste management. This paper addresses the technical challenges associated with the transition from the recyclability of materials to the recyclability of buildings, and ultimately contributes to the body of knowledge in the field of CE in the AECO industry.

This paper is organized into the following sections: Section 2 is devoted to a literature review about CE, recyclability and waste management, maintenance interventions, and digital technologies. This section aims to showcase state-of-the-art technology and the possible research gaps. Afterward, in Section 3, the methodology of the research explains the overall procedure that was followed and describes each step in more detail to clarify the formulae which were used for calculation, how BIM and IFCs were implemented for quantity takeoff, how the procedure integrates with national and international regulations, the required information and their related resources, and how the scenario analysis was developed. Section 4 presents the results and discussion about the building recyclability rate of a selected case study, how different maintenance attitudes affect waste production, and how a further sensitivity analysis was performed to evaluate the impact of parameter changes for building design life on the overall waste production. The conclusions are provided in Section 5 to highlight the contribution of this study and indicate future developments.

2. Literature Review

CE is a major focus of research in construction and design. The frequent pairing of BIM with sustainability and design with CE shows a trend towards integrating CE principles with BIM technologies and design practices, as captured in the bibliometric analysis mapping shown in Figure 1. The literature review also highlights the importance of demolition waste, energy, and LCA for sustainable resource management.

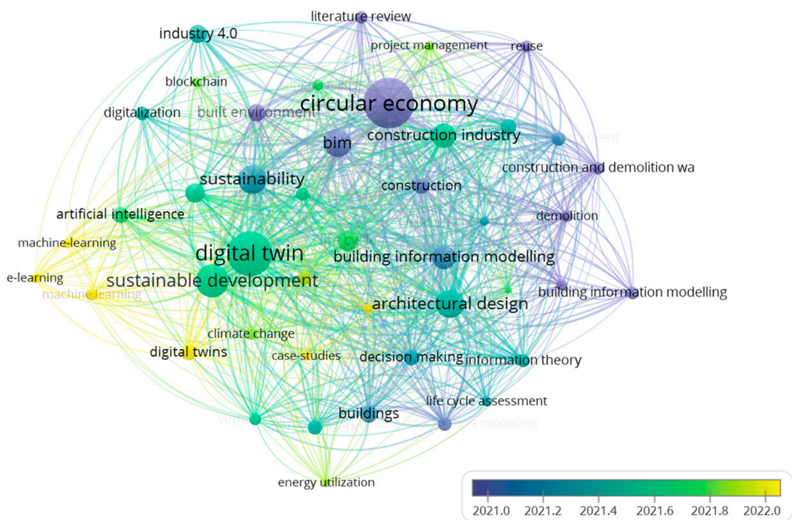


Figure 1. Bibliometric analysis mapping: Co-occurrence diagram of keywords in source papers.

Studies in the literature suggest further avenues for research, including the integration of CE principles into construction, the exploration of advanced BIM functionality for sustainability, and the development of sustainable design methodologies. These studies form the basis of a proposed BIM-based model for assessing recyclability rates and waste management efficiency. A more in-depth analysis of the state-of-the-art topics related to the present research is presented in the following sub-sections.

2.1. Waste Management and Recyclability in CE

Recycling and material reuse in construction vary in difficulty, facing challenges like technological requirements, legal assurances for quality, and insufficient market demand [17]. The sector also struggles with data fragmentation and inefficient communication among stakeholders, leading to delays and financial losses [18]. To mitigate these issues, researchers advocate for comprehensive waste management and CE strategies, focusing on integrating LCA and emphasizing the importance of systematic approaches for material sustainability among various phases of a building's life cycle [17].

Studies have highlighted the importance of urban mining for e-waste management and sustainable resource exploitation [19], as well as a CE's potential in reducing construction and demolition waste (CDW) [20,21]. Furthermore, Schützenhofer et al. (2022) analyzed dismantling, recovery, and recycling processes in the AECO industry to assess material sustainability and eco-indicators [22]. The findings emphasize the need to quantify construction and demolition waste from the early design phase to align with CE principles to ensure sustainable construction practices [23].

2.2. Circular Indicators of Building Materials

Assessing circularity has become crucial for stakeholders, researchers, and organizations, highlighted by entities such as the European Commission (EC) and ISO, despite the challenges in proving its effectiveness [17]. To tackle this, some methods involving circularity indicators (C-indicators) have been developed, offering a way to gauge circularity at various levels from nano (material) to macro (city or nation) [24], incorporating both qualitative and quantitative measures. Recognizing the diversity of CE scenarios, the introduction of decision support tools, which integrate the Building Circularity Index (BCI) with material costs, is pivotal to guide decision makers through various alternatives [25].

Rahla et al. (2021) provided a comprehensive review of the selection criteria for building materials and components in line with the CE principles, grouping these criteria into nine groups: (a) recycled or recovered content, (b) recyclability, (c) reusability, (d) ease of deconstruction, (e) maintainability, (f) durability, (g) energy recoverability, (h) upcycling potential, and (i) biodegradability. Recyclability was the most applied technique in the literature and in practice [26].

Cottafava and Ritzen (2021) developed the BCI and Predictive BCI (PBCI), combining the Material Circularity Indicator (MCI) with Embodied Energy and CO_2 analyses [27]. Steinmann et al. (2019) proposed a material quality indicator based on the energy use of recycled products to assess circularity in the economy [28]. Other researchers have explored tools, such as material flow models and circularity scoring methods [29], for assessing circularity and material selection in the built environment, as well as setting up circularity strategies as early as the design stage [30]. However, a major research gap is in defining and implementing CE indicators that can also account for the presence and the impact of hazardous materials, which can undermine the recyclability capacity of construction materials.

2.3. Application of Digital Technologies in CE

With the increasing focus on sustainability, the application of BIM and digital technologies has been identified as a promising approach to enhance Construction Waste Management (CWM) and to promote CE [31]. BIM is a concept which is implemented in the real-world AECO projects globally [32]. It can facilitate cooperation and information sharing among stakeholders across the design and construction processes. All this information can be updated and refined during different project phases by their designated stakeholders [33]. The information is easily accessible through the IFCs and Construction Operations Building Information Exchange (COBie) using plugins in BIM [18].

By leveraging BIM and relevant concepts like LCA integrated with other advanced technologies, such as predictive analytics and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), maintenance can be proactively scheduled, and materials can be efficiently reused or recycled, aligning with CE principles [10,34]. For instance, Akinadé and Oyedele (2019) developed a BIM-based tool that predicts construction waste, facilitating material optimization and waste reduction, which are essential for circularity [35]. Additionally, Charef and Emmitt (2020) identified BIM uses that support CE approaches by managing end-of-life building materials, promoting recycling and reuse [7].

Thus, while significant strides have been made towards integrating CE in the construction industry, there remains an open question regarding the practical, systematic adoption of these principles across all stages of the construction lifecycle. Further research is essential to address these gaps, standardize methodologies, and fully harness the potential of digital technologies in promoting a CE in the built environment. In particular, the literature review highlighted the lack of KPIs that measure recyclability at the building level and not just at the material or component level, as is now the case in most cases, and the poor integration of currently used KPIs with the tools that digitization has brought to the construction sector, particularly BIM.

3. Materials and Methods

This paper presents a procedure to assess the recyclability of buildings, with a transition from the material to building scale, and considers the classification of materials in terms of being hazardous or not. This procedure is based on automated implementation of BIM and IFCs through a bespoke programming in Python (version 3.12.0, Python Software Foundation, Wilmington, DE, USA) to perform quantity takeoff, automated classification and codification of wastes, computation of recyclability rates of buildings, and perform a scenario analysis to evaluate the impact of different maintenance attitudes on the overall material consumption in a case study of a residential building.

This procedure consists of three layers: data acquisition, data transmission, and data/model integration, and each layer benefits from some tools. The first layer gathers various types of data from various resources, such as databases, the literature, and regulations, including information about RSL, material recyclability rates, and waste classification. In addition, the BIM model provides data about the building's materials and components. Regarding the scope of the study, the data are not dynamic in a time-dependent manner. Moreover, the size of data is too low which makes them easy to use (all the data, including the BIM model and other required information, are less than 5 MB in size). Because these data are of varying types, it is critical to transmit and exchange them in a way that facilitates interpretation. For this reason, in the second layer, the model is exported to an IFC (version 4.0.2.1, buildingSMART, Hertfordshire, UK) making all these data easier to integrate.

The paper's main contribution begins in the third layer, where a bespoke Python tool is used to provide a material inventory from the IFC file. This material inventory is then utilized in the calculation tool. This tool assigns waste classification (hazardous/non-hazardous) and waste codification to the materials based on the European Waste Catalogue (EWC) [36]. This subsequently calculates each material's recyclable amount and ESL. The use of this tool results in the calculation of the Building Recyclability Rate (BRR), which is proposed in this study and will be further explained in the next sub-sections.

Finally, a scenario analysis was performed to determine the impact of three levels of maintenance intervention (no maintenance, normal maintenance, and good maintenance) on a case study building's waste production. Each step will be explained in the following sub-sections, and the figure below shows the general process (Figure 2).

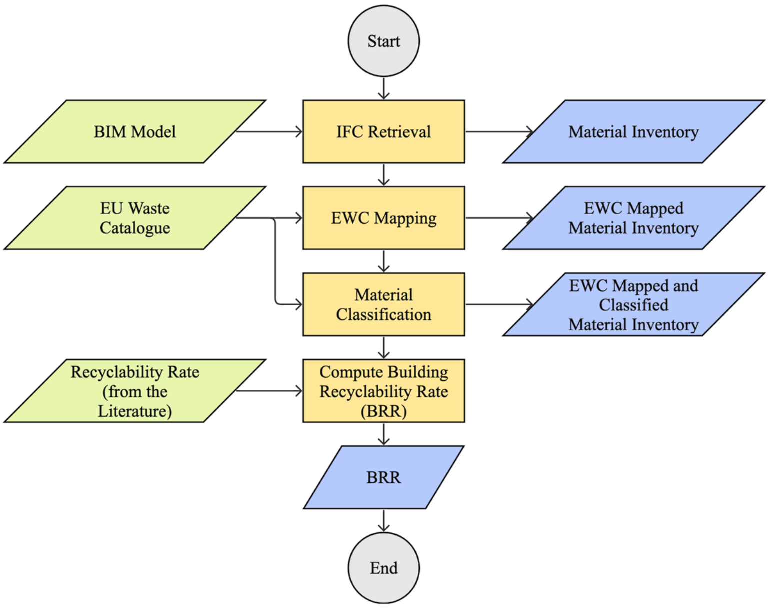


Figure 2. Flowchart of the proposed procedure, indicating the steps to follow, inputs, and outputs.

3.1. BIM Model and IFC for Material Inventory

As previously stated, the first layer involves data collection. For this purpose, a hypothetical case study model of a common residential building was created that includes information about material quantities. This model consists of a two-story building with a concrete structure, insulated external brick walls, and gypsum wallboard for internal partitions. The modelling of the study considers the structural and architectural elements of the buildings and does not include the systems like elevators or piping. Hence, it is possible to consider the model at a Level of Detail (LOD) of 200.

The generated Revit (version 2021, Autodesk, San Francisco, CA, USA) model can automatically provide the BoM. However, for the purpose of this study, it was exported to an IFC to automate the integration with EWC, recycling rate, and RSL data. The IFC file integrated with bespoke programming by Python was used to obtain information from the model including the elements and components, their assigned materials, and the related quantities such as volume. Figure 3 shows the exported model in the openIFC Viewer from four different angles.

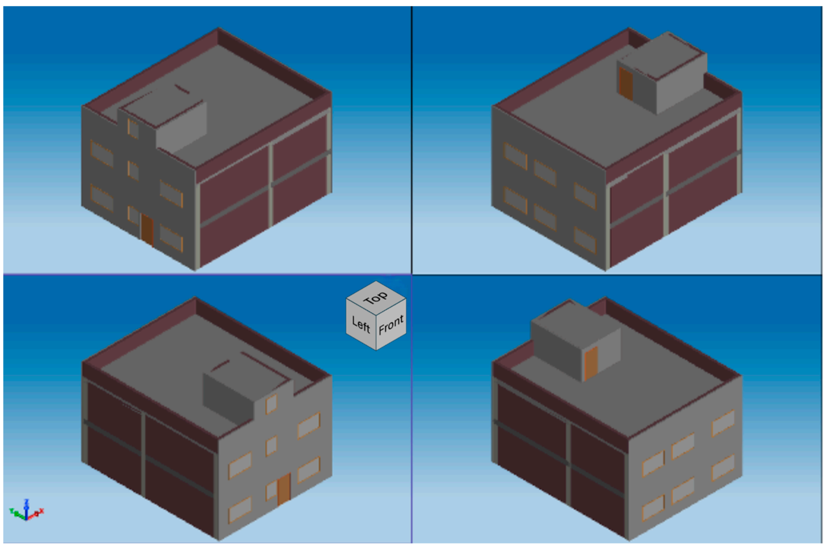


Figure 3. BIM model of the generated case study building exported in an IFC.

3.2. Inventory Integration with the European Waste Catalogue (EWC)

The material inventory needs to be classified in a standard manner based on its final purpose. The EWC is useful for waste management because it classifies materials as hazardous or not. Furthermore, it assigns a six-digit code that indicates the type of waste. Chapter 17 of the EWC document is titled "Construction and Demolition Wastes (Including Excavated Soil from Contaminated Sites)" and is used to categorize waste in this study.

The process of waste classification and assignment of the related codes in this study was automatically performed via integration with the programming tool. This process involves checking the query of material names in the EWC and automatically assigning the most relevant one using the predefined libraries in Python. The accuracy of the tool was verified by the authors' double check.

3.3. Recyclability Rate of Each Material

Once the material inventory is developed and the classification is performed based on EWC, it is possible to add more information to this database in terms of RSL and recyclability rates of materials. These features provide more quantitative information and results in the developed tool. The first kind of information is the recyclability rate of materials when they reach the end of their life. This information was retrieved from the literature and technical reports for common building materials in different countries. Indeed, there is no global and common standard to define the materials' recyclability rates, and data can significantly vary across countries. However, for this study, the closest rate to Italian conditions and standards were chosen. Table 1 summarizes the considered recyclability rates.

Table 1. Recyclability rate of common building materials.

No.	Material	Recyclability Range	Recyclability Rate Considered for Case Study	Reference
1	Brick	0–85%	36%	[9,37,38]
2	Gypsum wall	2–10%	4%	[39,40]
3	Rigid insulation	46%	46%	[41]
4	Wood	10–15%		[42,43]
5	PVC	11–100%	50%	[44,45]
6	Steel	59%		[46]
7	Aluminum	33%		[46]
8	Copper	37%		[46]
9	Concrete	40–98%	75%	[47,48]
10	Glass	35–74%	70.9%	[49,50]
11	Sash	80%	80%	[44,51]
12	Asphalt shingle	10–70%	70%	[52,53]
13	EPDM membrane	70–100%	96%	[52,54]

The recyclability rates for different materials mentioned earlier can be integrated with information about hazardous materials from the material inventory to generate a new KPI to measure the recyclability rate of the building, as follows:

$$BRR = \frac{\sum_m^M R_m . V_m}{\sum_m^M V_m} \times \frac{\sum_m^M V_{m,\ non-hazardous}}{\sum_m^M V_m} \quad (1)$$

where

BRR: Building Recyclability Rate

R_m: recyclability rate of material "m"

V_m: volume of the installed material "m"

$V_{m,non-hazardous}$: volume of the non-hazardous material "m"

M: number of materials in the building

The BRR is calculated by multiplying two factors, each ranging from zero (indicating a worse condition) to one (indicating the best condition). The former (the left side of the equation) reflects the recyclability of the materials used in construction. A value of one signifies that all materials are fully recyclable, while a value of zero indicates that none of the materials can be recycled. The latter is influenced by the presence of hazardous materials within the building. A value of one indicates the absence of hazardous materials, while zero implies that all materials are hazardous. Considering the presence of hazardous materials is crucial when assessing the recyclability of a building for several reasons:

1. Health and safety: Hazardous materials can pose significant risks to human health and the environment if not handled and disposed of properly. By identifying these materials early in the recyclability assessment process, appropriate safety measures can be put in place to protect workers, occupants, and the surrounding community.
2. Regulatory compliance: The EWC provides a legal framework to classify and manage waste materials. Buildings that contain hazardous materials are subject to specific regulations regarding their demolition, deconstruction, and recycling in different countries.
3. Environmental protection: The improper disposal of hazardous materials can have severe environmental consequences, including contamination of soil, water, and air. By identifying these materials and ensuring their safe disposal or recycling, ecosystems can be protected, and sustainable development is promoted.

Therefore, considering the presence of hazardous materials is essential for ensuring health and safety, regulatory compliance, resource recovery, environmental protection, and adherence to CE principles. In Equation (1), by multiplying the weighted average of materials' recyclability rates (left multiplier) by the percentage of non-hazardous materials (right multiplier), the former is lowered by a quantity proportional to the volume of hazardous materials installed in the building.

Assessing a building's recyclability rate can be a laborious and time-consuming task, even for a relatively small-scale building like the one used in this study. However, the evaluation process outlined in Figure 2 has been streamlined through automation, significantly reducing the required time and removing constraints associated with the size of the building under assessment. This automated approach allows for efficient application of the proposed methodology, regardless of the building's scale.

3.4. Reference Service Life (RSL)

The RSL of building materials and components is another type of data that needs to be added to the database of the study. Table 2 provides a summary of the data used in this study to determine the RSL.

Table 2. RSLs of different materials used in this study.

No.	Material	RSL 1 (Years) [55]	RSL 2 (Years) [56]	RSL 3 (Years) [57]	RSL 4 (Years) [58]	RSL 5 (Years) [59]	RSL 6 (Years) [60]	RSL 7 (Years) [61]	Average (Years)
1	Brick	N/A	25	+35	+60	20	N/A	25–40	34.5
2	Gypsum wall	40	40	35	60	25	N/A	20–30	37.5
3	Rigid insulation (exterior)	38	35	35	60	25	N/A	30–40	38
4	Rigid insulation (interior)	38	35	35	60	N/A	N/A	30–40	40.6
5	Wood (exterior)	40	40	35	30	N/A	20–30	30–40	34
6	Wood (interior)	40	40	35	60	N/A	20–30	30–40	39
7	Concrete	N/A	75	+35	60	N/A	15–20	80	53
8	Glass	30	30	30	30	N/A	N/A	25–30	29.5
9	Sash	30	30	20	30	N/A	N/A	N/A	27.5
10	Asphalt shingle	30	30	30	50	15–20	20–30	40–50	32.5
11	EPDM membrane	30	30	35	25	15–20	10–15	20	24
12	Ceiling, plaster	30	35	N/A	25	N/A	25–30	25–40	30
13	Oak flooring	N/A	35	N/A	60	N/A	15–20	15–20	32.5

N/A stands for Not Available.

3.5. Scenario Analysis

Following the study's contributions, a scenario analysis was conducted to evaluate the effects of various maintenance attitudes on waste generation throughout the building's life cycle. For the purpose of this analysis, the building's design life was assumed to be 60 years based on the literature and standards like the 7543:2015 standard [62]. Every building component has an Estimated Service Life (ESL), which is dependent on use-specific conditions, according to the standard ISO 15686-8:2008 [63]. The ISO standard provides an explanation and classification of these conditions, and the Factor Method is used to modify the RSL to determine the relevant ESL. The inherent performance level (A), design level (B), work execution level (C), indoor and outdoor environment (D), usage conditions (F), and maintenance level (G) are these factors. Every factor is an RSL modification; ISO 15686-8 suggests some preferable values between 0.8 and 1.2 that, respectively, take into account the range of the worst and best conditions. Below is the formula needed to calculate the ESL:

$$t_{ESL} = t_{RSL} \times \varnothing_A \times \varnothing_B \times \varnothing_C \times \varnothing_D \times \varnothing_E \times \varnothing_F \times \varnothing_G \quad (2)$$

Since this study just considers the impact of maintenance, the values for all the factors would be equal to 1, except factor G. Three different scenarios are as follows: Scenario (1): the project without any maintenance (worst situation, G = 0.8), Scenario (2): the project with minimum required maintenance (medium situation, G = 1), and Scenario (3): the project with the best maintenance (best situation, G = 1.2). These maintenance attitudes affect the ESL of the components so that a higher level of maintenance leads to a longer ESL. Based on these three scenarios, it is possible to understand the impact of maintenance interventions on waste production in two cases of waste related to primary construction, and waste related to construction and maintenance. Finally, the total volume of the materials used in all the cycles could be computed.

4. Results and Discussion

With an emphasis on waste production and the recyclable nature of building materials, the proposed methodology refines the materials' recyclability rates at the building scale, including the negative effect of hazardous materials as identified by the EWC [36]. Considering the presence of hazardous materials is essential for ensuring health and safety, regulatory compliance, resource recovery, environmental protection, and adherence to circular economy principles. Hazardous materials can pose significant risks to human health and the environment if not handled and disposed of properly. Moreover, identifying hazardous materials in a building can help to optimize resource recovery and reduce waste. The improper disposal of hazardous materials can have severe environmental consequences, including contamination of soil and water.

4.1. Building Recyclability Rate

Information about the recyclability of a building is required by clients and non-technical stakeholders. Therefore, a graphical interface has been provided to communicate BRR results in an accessible way to any stakeholder. A good and communicative graphical representation of a KPI is essential for facilitating understanding, enhancing communication, increasing engagement, enabling data-driven decision making, and supporting transparency and accountability in a research project where many stakeholders with different backgrounds and education are involved.

A clear and concise graphical representation of a KPI can help stakeholders quickly grasp the meaning and significance of the data, regardless of their background or level of expertise, thus facilitating understanding. This is especially important in applications where stakeholders may have different areas of specialization and varying levels of familiarity with the project's technical details. A well-designed graphical representation of a KPI can capture stakeholders' attention and interest, making them more likely to engage with the project and its findings. This is especially important in applications where stakeholders have competing priorities and limited time to devote to the project. Moreover, graphical representations of KPIs can help stakeholders make data-driven decisions by providing a clear and objective picture of project performance. By presenting data in a visual format, stakeholders can more easily identify areas where corrective action is needed.

Figure 4 shows the BRR applied to the case study together with its two components: the weighted average of materials' recyclability rates (left multiplier in Equation (1)) and the percentage of non-hazardous materials (right multiplier in Equation (1)). Of note, there is an almost 20% volume decrease in hazardous materials, and the weighted average of the materials' recyclability rates decreases by nearly 10%.

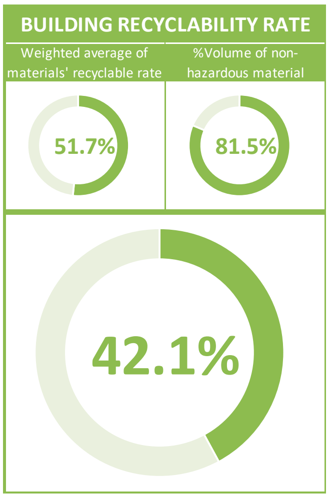


Figure 4. Graphical interface to communicate the building recyclability rate and its two components: the weighted average of materials' recyclability rates and the percentage of non-hazardous materials.

Results from Figure 4 also depict that the weighted average of material's recyclability is comparable to the average recyclability rate of the Italian construction sector, which is 50.6% [64]. Based on this result, it can be inferred that the impact of hazardous materials is somehow neglected in the recyclability of materials in the AECO industry.

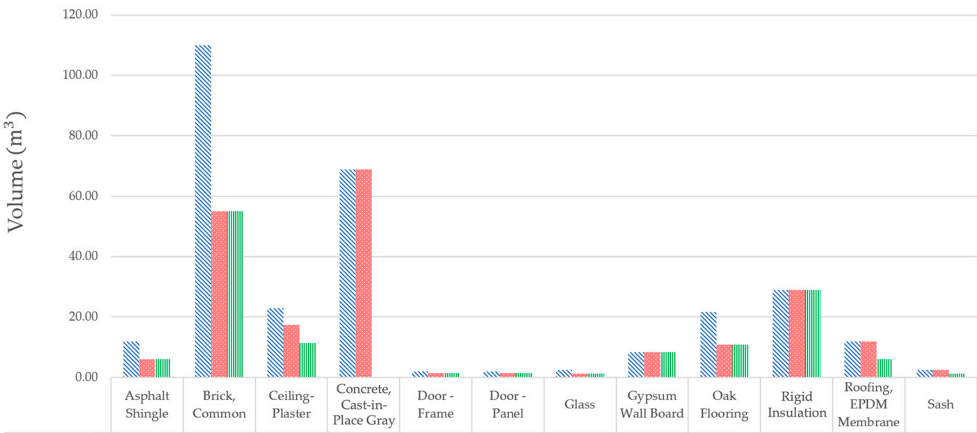
Moreover, based on the BRR calculated in the case study, which is based on the average of the Italian construction sector, it can be understood that the sector is still far away from the goal of a 70% recycling rate of non-hazardous materials in Europe. It emphasizes the importance of further considerations for the use of materials with higher possibilities of being recycled and the use of fewer hazardous materials.

4.2. Scenario Analysis

The impact of the maintenance interventions on the ESL of components and materials is very important, since it would in turn lead to changes in the amounts of consumed materials, the produced waste, and number of use cycles of materials in the whole life cycle of a building. This impact would play a role in a CE by reducing material consumption.

Utilization of such a procedure results in calculation of the additional required materials to perform the maintenance interventions during the life cycle of the project. Therefore, it will be feasible to assess which maintenance action can have a bigger influence on the building's overall waste production. The scenario analysis of those maintenance interventions is made easier by the integration of BIM and IFCs into a bespoke Python programming tool.

Figure 5 displays the main findings of the scenario analysis in terms of the amount of additional material required due to material refurbishment in each scenario after reaching the building's end of life. For instance, in the case where no maintenance has been performed on asphalt shingles, an extra 12 cubic meters of material will be needed for any future refurbishments. Nevertheless, just 6 cubic meters of extra material are needed in two additional minimum and best maintenance scenarios. What is significant about the findings is that the maintenance attitude has no effect on the required materials in certain situations, such as rigid insulation and gypsum wall board. It is because the ESLs of those materials in all scenarios are between 30 and 60 years; therefore, they will be refurbished just once during the life cycle of building, regardless of the maintenance condition. However, in the case of ceilings, improving the maintenance attitude will result in a reduction in the quantity of materials needed. Furthermore, there are situations where low maintenance is sufficient, such as with bricks and oak floors, and there is no need to maintain it at a higher level. However, in other cases, such as EPDM membranes, there is no difference between the scenarios of performing low maintenance and none at all, indicating that high maintenance is necessary if we wish to reduce the amount of materials required.



	Asphalt Shingle	Brick, Common	Ceiling-Plaster	Concrete, Cast-in-Place Gray	Door - Frame	Door - Panel	Glass	Gypsum Wall Board	Oak Flooring	Rigid Insulation	Roofing, EPDM Membrane	Sash
Scenario 1 (m^3)	12.00	109.93	22.88	68.89	1.92	1.92	2.45	8.31	21.76	28.90	12.00	2.45
Scenario 2 (m^3)	6.00	55.07	17.44	68.89	1.42	1.42	1.23	8.31	10.88	28.90	12.00	2.45
Scenario 3 (m^3)	6.00	55.07	11.44	0.00	1.42	1.42	1.23	8.31	10.88	28.90	6.00	1.23

Figure 5. Amount of additional required materials for maintenance interventions, shown in three scenarios (1: without maintenance, 2: with minimum required maintenance, and 3: with best maintenance) by volume (cubic meters).

Overall, as shown in Figure 6, the amount of additional materials required for maintenance interventions in Scenario (1) will be 146% greater than that required for construction. The amounts for Scenarios (2) and (3) will be 107% and 66%, respectively. Further analysis revealed that using Scenario (2) instead of Scenario (1) results in 27% less material consumption, hence, less waste production. However, using Scenario (3) instead of Scenario (2) has a greater impact on waste production, resulting in 38% less material consumption. As a result, changing the attitude from low to high maintenance will have a greater impact than implementing low maintenance rather than no maintenance.

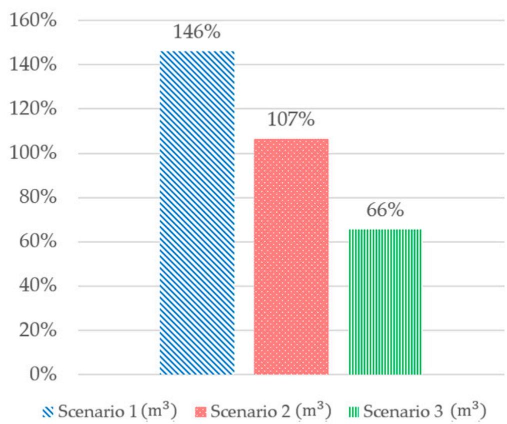


Figure 6. Percentage of overall required material for each maintenance scenario in comparison with the required materials for construction.

4.3. Sensitivity Analysis

A sensitivity analysis is of great importance to determine the impact of a parameter on the results. It was conducted to better understand the impact of building design life on the overall material consumption and waste production across every scenario. For this kind of analysis, three states were considered: the baseline with 60 years of building life cycle, and two other cases with a ±20% change in the baseline, i.e., 48 and 72 years.

Figure 7 shows the cumulative additional required material for refurbishments in each scenario during the years. Analysis of this figure depicts that in the case of "Baseline − 20%", at the end of a building's life at year 48, the difference between the required material of Scenario (3) with respect to Scenario (2) is −8%, which is the minimum difference between these two scenarios among various states. On the other hand, in this year, the difference between Scenario (1) with respect to Scenario (2) is the maximum one, which is 67%.

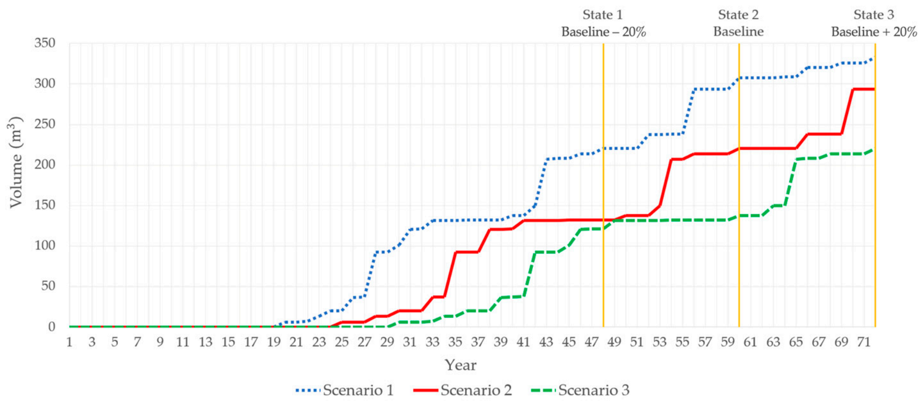


Figure 7. Figure to show how the material consumption varies across three scenarios over the years, including three states of "Baseline − 20%", "Baseline", and "Baseline + 20%".

In the second state, which is the "Baseline" in year 60, the differences between Scenarios (3) and (2) and between Scenarios (1) and (2) are almost the same in absolute value, which are −38% and 39%, respectively. In the last state in year 72 ("Baseline + 20%"), differences between Scenarios (3) and (2) and between Scenario (1) and (2) are −25% and 14%, respectively. In this state, the minimum difference between Scenarios (1) and (2) occurs.

Considering these numbers, it can be inferred that in the state of "Baseline − 20%", there is no significant difference between low and high maintenance, which means that in order to decrease the material consumption, it is not necessary to perform high levels of maintenance. However, in the third state ("Baseline+20%"), the situation is exactly the opposite, which means that in order to have a significant change in the materials consumption, it is required to have high levels of maintenance. Finally, it is important that during the analysis and interpretation of the results, the building design life should be considered carefully, since it can affect the results significantly.

5. Conclusions

Enhancing the CE in the AECO sector through better understanding of the recyclability potential of buildings is the main objective of this paper. To this end, this paper proposes a novel KPI, the Building Recyclability Rate (BRR), and an automated procedure to assess it. The BRR, which is based on the recyclability rates of materials and takes into account the impact of hazardous materials, will help stakeholders to make informed decisions when designing the recyclability of buildings. Hazardous materials can pose significant health and environmental risks, such as soil and water contamination, if not managed and disposed of correctly. Instead, having a tool that can help in understanding and quantifying the presence of hazardous materials in a building can optimize resource recovery and waste reduction.

The proposed automated procedure integrates Building Information Modelling (BIM) and Industry Foundation Classes (IFCs) into a bespoke programming in Python to perform the quantity takeoff, automate the materials' waste classifications, and compute the recyclability rate of a building. This procedure enhances the efficiency of waste management based on materials' recyclability and indicates the percentage of hazardous materials, which have been defined in accordance with the European Waste Catalogue (EWC).

The results of the study are beneficial for the AECO industry since they provide a standardized, common, and automated procedure for waste management, and ultimately can enhance sustainability of the sector in terms of a CE. Using a BRR in the early stages of building design could support design choices towards the selection of the most optimized option in terms of a CE. Furthermore, the proposed indicator is presented in a graphical form to be easily understandable by a variety of users.

The proposed procedure has been tested on a case study of a residential building and the results highlight the controversy in retrieving information on recyclability rates and RSLs of the materials, especially in Italy. This barrier was solved for the application to the presented case study by adopting an average estimation and approximation based on the existing data. The evaluation of the BRR on the case study showed that a 20% presence of hazardous materials can reduce the BRR by about 10%.

The scenario analysis shows that without maintenance, the waste would increase by 37.1% at the end of life, while with high maintenance, the amount of waste would decrease by 38.4%. Moreover, the sensitivity analysis, which considered a 20% shorter and a 20% longer service life, showed that for longer design lives, a high level of maintenance can significantly reduce the amount of building waste generated.

In the future, the presented automated procedure could be applied to models with higher Level of Information Need (LOIN) and to case studies of greater complexity. The procedure includes and can collaborate with a Materials Passport (MP) in terms of data acquisition, transmission, processing, and integration with models and standards. Moreover, this procedure is boosted through the application of digital technologies to automate material quantification, waste codification and classification, service life prediction, and further analysis for maintenance attitude scenarios. This automation can lead to waste management and optimization from the early stages of design. In conclusion, the results of the study underscore the importance of the application of digital technologies and Industry 4.0 solutions into the sustainable practices to enhance circularity in the AECO, especially in terms of recyclability.

Author Contributions: Conceptualization, software, visualization, and methodology, A.F.E.; formal analysis and validation, A.K.; writing—original draft preparation and validation, A.F.E., A.K., F.R.C. and O.I.; writing—review and editing, A.K., O.I. and F.R.C.; supervision, F.R.C., O.I. and B.D.; project administration, F.R.C., O.I. and B.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author due to privacy concerns.

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

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