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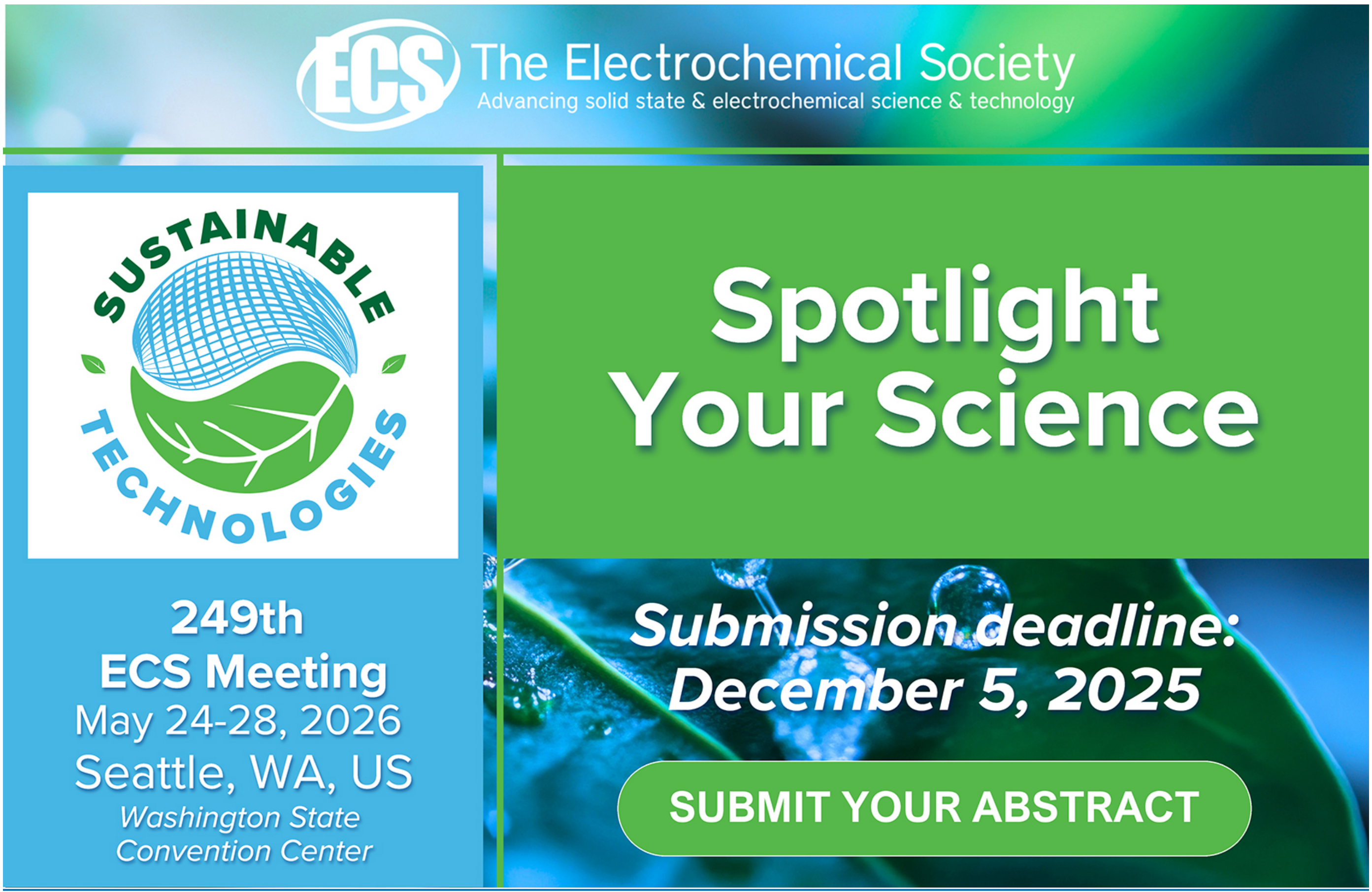

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Improving Circularity in Construction Through a BIM-Based Waste Management Framework

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Abstract. The Architecture, Engineering, and Construction (AEC) industry, known for its significant resource consumption and waste production, requires a shift to a Circular Economy (CE) to address environmental challenges, focusing on reducing, recycling, and reusing materials to narrow, slow, and close material loops. The impact of CE in the AEC industry is directly associated with the existing buildings' potential to be a source of raw materials for future construction projects. The waste management process necessitates detailed information on material composition, connections, availability, future uses, and quality. Urban Mining, facilitated by digital technologies and Industry 4.0 solutions, aims to provide answers to the abovementioned questions. This study, focusing on the Italian building sector, utilizes BIM and IFC platforms to establish a standardized procedure aligned with Italian regulations. The procedure encompasses data acquisition, transmission, integration, and application, resulting in practical and trackable measures stored in IFC files. Notably, this procedure is scalable globally. The results of this study are important from a managerial point of view to have a comprehensive and standardized procedure, improving waste management and decreasing the environmental impacts of the construction sector. Moreover, it contributes to enhancing the cost-benefit efficiency of the industry through enhancing circularity.

Keywords: Circular Economy (CE), Construction Waste Management, Building Information Modelling (BIM), Recyclability, Industry Foundation Classes (IFC)

Introduction

Construction and demolition activities of the Architecture, Engineering, and Construction (AEC) industry in European Union cause to generate 850 million tons of annual waste generation, as the highest waste producing sector with 35% of the total waste [1], consumption of approximately 50% of raw materials, natural resources, and energy [2] , and 5-12% of total GHG emission [3]. This waste, which usually comes in the form of concrete, bricks, timber beams, metals, glass, and tiles, is usually disposed of in landfills or used for backfilling operations (about 40 to 60% [4]) without any recovery or recycling plans, wasting huge amount of capital, and raising critical economic and environmental concerns.

These issues are mainly due to the traditional design strategies that are based on resource consumption linearly [5]. Therefore, to address these environmental and economic challenges stemming from the prevailing Linear Economy model of "take-make-consume-dispose," the construction industry

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requires a shift toward Circular Economy (CE) [6] [7], and must adopt new and improved building strategies for waste management. CE strategies enable saving the remaining value of these materials and components before the deterioration of their physical condition [7] and can escalate the current 47% re-use, recovery, and recycling rate of non-hazardous materials across Europe up to 70% [8].

The Circular Economy (CE) is commonly defined as a system combining the 'reduce, reuse, and recycle' principles to achieve economic prosperity and environmental quality [6] [9]. It aims to minimize resource input, waste, emissions, and energy loss by narrowing, slowing, and closing material and energy loops [10]. Among all these categories, the main focus of CE is to extend the lifetime of the products as much as possible and close the loop, especially in terms of recycling and reuse at the end of life of project [11].

The recycling rate of construction and demolition waste within the EU exhibits significant variations, ranging from less than 10% to over 90% [12]. However, due to the absence of standardized definitions among EU countries and lack of appropriate design methodologies to make a better use of construction and demolition waste, the recycling rates remain far from the 70% target of European Waster Framework [13]. In 2021, the average recycling rate of municipal waste in the EU was estimated at 49.6% with Germany having the highest municipal waste recycling rate, estimated at 71.1% [14]. In Italy, the construction waste recycling rate increased from 17.6% in 2004 to 51.4% in 2020 [15].

However, although there are many initiatives to promote the CE goals, such as the Circular Economy action plan [16] and EU green deal [17], the reuse and recycling rate of building materials is relatively low. Out of the 40% of municipal solid waste which is generated by construction and demolition activities, merely 20–30% are recycled. A major part of the recycled construction waste is concrete, asphalt and wood, with 15%, 12% and 8% of the total construction waste, respectively [18]. Another report by Arup claims that only 6% of construction materials are reused in an industry responsible for 40% of CO_2 emissions [19].

A main reason for the low recycling rate of construction waste is the lack of exact information on the type of materials and their recyclability in demolished buildings, which is caused by the poor and unstructured documentation throughout the building lifecycle. To tackle this issue, one solution is to use the Industry 4.0 technologies and digitalization. Using digital development tools and data-driven services brings the AEC industry towards digitalization and making the Metaverse-like environment [20], enabling real-time and structured data storing and retrieving for decision-making purposes.

Building Information Modelling (BIM) and Digital Twin (DT) are important technologies in this field. BIM is a digital representation of physical and functional characteristics of a facility or building, providing a shared knowledge source for decisions during its life cycle from earliest conception to demolition [21]. A Digital Twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process, used for various purposes including analysis, simulation, and monitoring [22]. BIM provides detailed information and quantity take-offs on materials and construction processes, aiding in minimizing waste through precision and planning, while Digital Twins offer real-time monitoring and simulation capabilities to manage and reduce waste during the construction and operational phases. However, although all their capabilities, the application of these technologies for construction waste management is still nascent and faces many challenges, especially in terms of lack of a standardized and common procedure to follow.

This study proposes a BIM and IFC-based framework for systematic data extraction on materials and their quantities in an automated ways form building digital models and integrates them with Italian national codes for materials' waste categories. As a result, an automated quantity take-off on materials and components could be generated, which is a necessity in Italian construction sites, since it is necessary to fill the construction site waste forms. Moreover, the classification of materials in terms of being hazardous or non-hazardous is of great importance and can be achieved through this tool. Finally, the building circularity can be evaluated in terms of recyclability index which will be calculated based on the quantity of each material and its recyclability rate.

1. Literature Review

The systematic literature review (SLR) was done based on two databases of Scopus and Web of Science, filtered by resources in English. The keywords and search string are as follows:

("BIM" OR "IFC") AND ("Circularity" OR "circular economy" OR "Recycle" OR "Recyclability") AND ("Waste" OR "Waste management") AND ("building" OR "construction")

Figure 1 presents the SLR process conducted by the study.

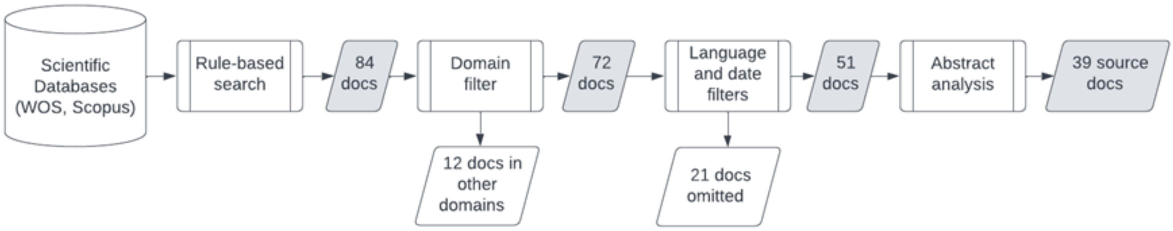


Figure 1. SLR process of the study and determination of source papers

1.1. Bibliometric Analysis

According to the bibliometric analysis that has been done on the results of literature review, as presented in Figure 2, the trend in scientific publication has shifted from conventional demolition and waste management methods to the integration CE, DT, and BIM. Figure 2 presents the co-occurrence diagram of the keywords in source papers, indicating the foci of their publication periods. The reviewed studies indicate a growing interest in applying CE principles to the construction sector. They highlight the potential of design strategies, material selection, digital technologies, and waste management practices to transform the way buildings are constructed and deconstructed, thereby reducing environmental impact and contributing to more sustainable built environments.

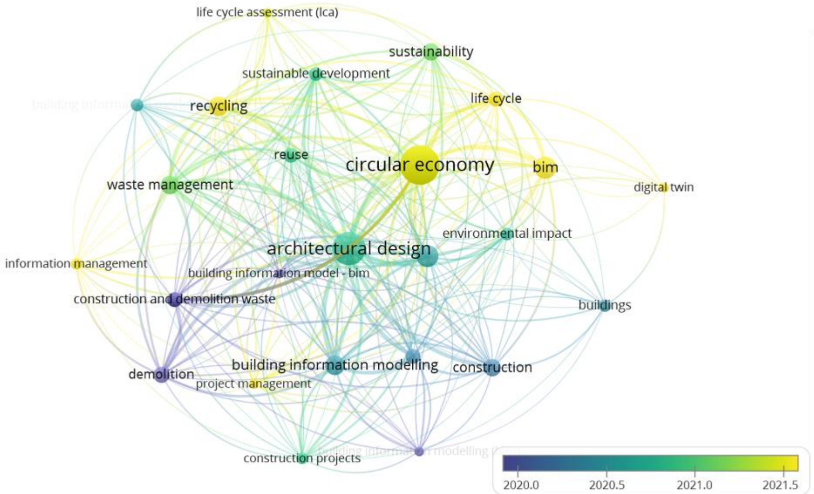


Figure 2. Co-occurrence diagram of keywords in source papers, indicating the foci of their publication periods

As CE and waste management are huge umbrella terms, this study focuses mainly on the application of BIM and DT technologies for assessing the recyclability of buildings. There are remarkable previous studies on the application of digital technologies in overcoming the challenges and barriers achieving circular economy goals in the construction sector [23] as well as other relevant sectors like transportation [24].

1.2. Circular Economy and Waste Management and Recycling Materials

Recycling and reuse of materials faces some challenges like the specific technology requirements, the legal warranties for the quality of reused or recycled components, and lack of sufficient market demand to use them in future projects [25]. Another important challenge in the construction industry is the data fragmentation and lack of sufficient connection among different stakeholders; hence, the traditional of data registration and sharing may lead to delays and waste of capital [26].

To address these issues, previous researchers tried to propose holistic frameworks for waste management and CE. For example, De Gregorio et al. (2023) tried to define and implement a circular process to manage the valuable materials in the rehabilitation process and use the selective demolished materials in future projects or in the building itself [27]. Minunno et al. (2023) discuss strategies for applying the circular economy to prefabricated buildings. They underline the potential of these building types to reduce construction waste and increase the reuse and recycling of materials, thereby contributing to a more circular construction sector [28]. Schützenhofer in 2022 emphasizes the importance of construction waste management for material reuse in achieving environmental sustainability and circular economy goals, highlighting the need for a holistic approach and linking relevant parameters for assessing material sustainability [29].

1.3. Circular Indicators of Building Materials

Evaluating the circular performance has had a great importance for project stakeholders, researchers and organizations like European Commission (EC) and ISO, even though validating the effectiveness of circularity is not easy [25]. Hence, C-indicators are proposed to measure and monitor the circularity of a building, which can be classified in nano (material) [30], micro (building, product, company) [31] [32] [33] [34], meso (neighbourhood, industrial park), and macro (city, nation) levels, based on the scale of measurement. These indicators can be both qualitative and quantitative [5]. Since there are different scenarios to opt for CE, it is essential to have a decision support tool that can be combined with Building Circularity Index (BCI) and material prices to help decision-makers to choose among alternative scenarios [31].

Struck (2023) provided insights into measuring recyclability and reusability, a key factor for resource efficiency evaluation, proposing the concept of recycling rate as an indicator of the proportion of a waste fraction that can be recycled based on national waste statistics. The current postconsumer recycling rates of building materials range from 0% (e.g., mineral wool) to 88% (metals) in the European Union [35]. The author argued for the importance of indicators that measure potential recyclability of buildings at the design stage, an aspect echoed in the work of Roithner et al. (2022), which introduces a recyclability assessment at the building design stage based on statistical entropy. That study used the “Relative product-inherent recyclability” (RPR) assessment method to evaluate the recyclability of buildings, considering buildings’ material composition and structure (assembly). It offers an innovative way to assess the potential of different building materials for recycling, thereby supporting the design of buildings that are more aligned with the CE principles [36].

1.4. BIM and IFC

A BIM-based system framework can integrate the concept of CE into construction waste management, enabling visualization, direct quantity take-off, sorting, cost estimation, and monitoring [37] [38]. Importance of BIM in achieving the concepts of CE and sustainability is clearer in case of Green BIM which tries to move towards Net Zero Energy buildings. The integration of BIM and Industrial Foundation Classes (IFC) to promote sustainability in the AEC sector through quality certification by LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), and CESBA (Common European Sustainable Built Environment Assessment) has been widely studied [39]. Furthermore, a database framework was introduced by Göswein et al. (2022) which is called CirBIM, that aims to provide robust data for circularity assessments throughout the building's life cycle, addressing data inconsistencies and interoperability issues [40]. Bakchan et al. (2019) presented a seven-dimensional automated construction waste quantification and management framework that leverages BIM to integrate waste management with project and site planning, enabling strategic alignment and cost savings through reuse and recycling [41].

By creating detailed virtual models of buildings, BIM allows for more accurate planning and estimation, which can minimize over-ordering and overproduction of materials [42]. Moreover, BIM facilitates better collaboration among stakeholders, which can lead to more efficient design and construction processes, further reducing waste [43]. The use of BIM for tracking and monitoring material usage on-site can help identify waste streams and enable more effective segregation and collection of CDRs [44]. This can improve the recycling rates of materials and contribute to a more circular economy in the construction sector. Recent literature underscores the importance of recycling construction materials, assessing the environmental impact of waste recycling versus disposal, and the application of life cycle assessment (LCA) and building information modelling (BIM) tools in the design stage to optimize resource use [45].

While the potential of BIM and digital technologies in CWM is evident, there are challenges to their widespread adoption. These include the need for standardization in data management, interoperability among different digital tools, and the upskilling of the workforce to use these technologies effectively [8]. However, the opportunities outweigh the challenges. BIM and digital technologies can enable a more proactive approach to CWM, where waste is not just managed but actively designed out of the construction process. They also open up new avenues for material recovery and recycling, contributing to the sustainability goals of the construction industry [42].

2. Methodology

The general procedure that the paper follows is composed of four layers of Data Acquisition, Data Transmission, Data/Model Integration, and Application as it can be seen in figure below. At the first layer, BIM model is used to get the data which include data about the components and their related layers. Then it will be exported to the IFC format at layer 2 for further analysis. This data will be processed in layer 3 through a bespoke program in Python and this tool will help us to get the components composition, materials quantities, assign EWC code to each material and classification of materials (hazardous or non-hazardous) in order to have an inventory of materials. The contribution of this tool is important from the point of view of facilitating and automating the process of materials take-off, since it is a process which needs to be done in Revit manually. The outcome of these three steps will be used for the calculation of recyclability of materials, considering that a part of materials can be hazardous and their amount should be evaluated for the specific required treatments. The rest of materials which are not hazardous will be considered to compute the circularity of the building, specifically in terms of recyclability. Finally, the number of materials which are neither hazardous nor possible to recycle, would be considered the residual waste that will go to energy recovery or landfilling and so forth. The flowchart below shows the layers, activities and tools in more detail to give a better understanding of the procedure.

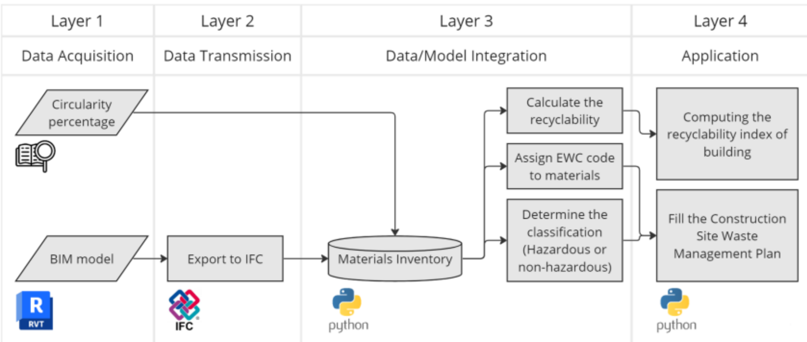


Figure 3. The diagram of methodology containing the details on steps to follow, layers and tools which are used

2.1. Italian Construction Site Standards

The proposed procedure is common and applicable to different scales of projects, as well as different countries. Specifically in Italy, the Construction Waste Management Plan ("*Piano di gestione dei rifiuti di cantiere"*) [46] is used to develop a plan for waste management on construction sites, providing the operational methods to be adopted in organizing and optimizing the management of different types of waste in construction site. The plan defines and identifies the different types of waste that are produced by construction site activities, their related management activities, technical indications for the correct management, and evaluation of related impacts. This plan is necessary to avoid incurring non-compliance with legal obligations. Moreover, it should be presented, in support of related demolition/construction projects, at the time of project approval. Figure 4 shows the template for construction site waste management plan and its required information. As can be seen, filling this form is a time-consuming process that may raise the number of faults due to human errors. The proposed tool in this paper can be used to provide such data and filling these forms easily, with no errors, and rapidly.

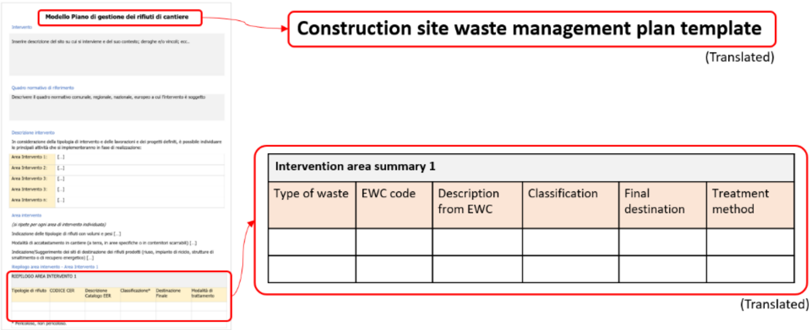
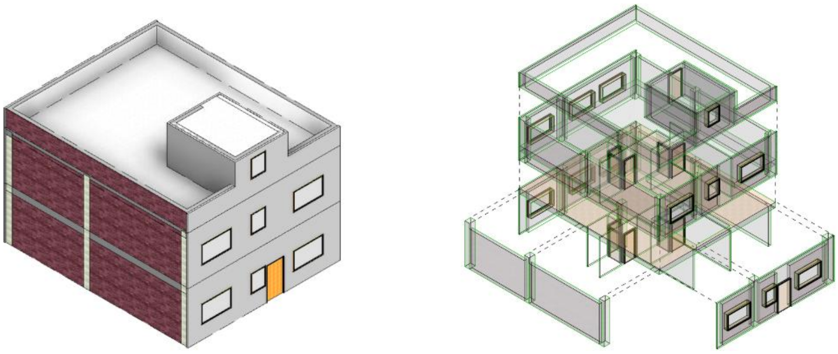


Figure 4. Construction site waste management plan template

2.2. BIM model creation, Quantity take-offs

The proposed procedure is applied to a hypothetical model in order to evaluate the feasibility of the procedure, its accuracy, and its potential advantages and disadvantages. The model is a two-story building with concrete structure. The figure below shows the 3D view of the model itself and exploded model to show better overview of the components. The figure shows also the internal partitions and columns.



(a) (b)

Figure 5. BIM model of building in Revit (a), and exploded-view drawing of building to show the components (b)

The analysis of exported model in IFC will result in an inventory of materials in the building that can be achieved through a tool which is bespoke programming in Python.

2.3. Integrating BIM/IFC data with standards (EWC)

In order to have a better categorization of wastes, the European Waste Catalogue (EWC) [47] has been used in this paper. It provides a list of wastes divided into 20 chapters connected to a six-digit code. The chapter 17 entitled “Construction and Demolition Wastes (Including Excavated Soil from Contaminated Sites)”. Using this catalogue, not only makes it easy to categorize the waste by different materials, but also determines the hazardous materials in the building.

2.4. Recyclability Rate of each material (the process of data acquisition)

To have a quantitative sense of the recyclability of the produced waste in each building after demolition, the recyclability rate of common building materials in different countries were extracted from literature

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and technical reports. These ranges were so broad as there are no global standards and procedures for recycling of building materials. Therefore, the closest rate to the Italian conditions and standards were selected, as presented in Table 1. Hence, extracting the volume of each material in a building, based on its BIM model, it is possible to multiply it to its recyclability rate and understand how much of each has the potential to be recycled, so that waste production can be minimized.

Table 1. Recyclability rate of common building materials.

No	Material	Recyclability range	Closest Recyclability rate	References
1	Brick	0-85%	36%	[48] [49] [8]
2	Gypsum wall	2-10%	4%	[50] [51] [52]
3	Rigid insulation (Expanded polystyrene EPS)	46%	46%	[53]
4	Wood	10-15%		[54] [55]
5	PVC	11-100%	50%	[56] [57]
6	Steel	59%		[42]
7	Aluminium	33%		[42]
8	Cooper	37%		[42]
9	Concrete	40-98%	75%	[58] [59] [60] [61]
10	Glass	35-74%	70.9%	[62] [63]
11	Sash	80%	80%	[64] [56]
12	Asphalt shingle	10-70%	70%	[65] [66] [67]
13	EPDM membrane	70-100%	96%	[66] [68] [69] [70]

2.5.Calculating the Recyclability Index of the building

Regarding the above-mentioned recyclability indices for different materials, it would be possible to integrate them with the material inventory to calculate the amount of recyclable materials. Later on, the average recyclability index of the building can be calculated by dividing the sum of the recyclable volume of materials by the sum of the volume of the materials as indicated be formulae below:

$$Recyclability\ index = \frac{\sum (Recyclable\ materials\ volume)}{\sum (Materials\ volume)} \quad (1)$$

3. Results

The presented model tries to integrate the BIM to leverage the CE, specifically through the enhancement of circularity in buildings in terms of waste management and recyclability. The results of the application of such procedure reveal how much of the materials volume can be recycled, based on the recyclability percentages which were achieved from previous studies. The primary results can be shown in the table below. It is worth noting that this is just a part of the table for the sake of providing an insight into the outcomes.

Table 2. Part of results show the assigned EWC code, classification, quantities and recycled volume.

ID	Component	Material	EWC code	Classification	Volume (m3)	Area (m2)	Perimeter (m)	Recyclability (%)	Recyclable Volume (m3)
1	Walls : Basic Wall : A-Exterior	Brick, Common	170102	Non-Hazardous	2.84	14.20		37%	1.05
2	Walls : Basic Wall : A-Exterior	Gypsum Wall Board	170801	Hazardous	0.21	14.20		4%	0.01
3	Walls : Basic Wall : A-Exterior	Brick, Common	170102	Non-Hazardous	1.44	7.20		37%	0.53
4	Walls : Basic Wall : A-Exterior	Gypsum Wall Board	170801	Hazardous	0.11	7.20		4%	0.00
5	Walls : Basic Wall : A-Exterior	Brick, Common	170102	Non-Hazardous	3.64	18.20		37%	1.35
6	Walls : Basic Wall : A-Exterior	Gypsum Wall Board	170801	Hazardous	0.27	18.20		4%	0.01
7	Walls : Basic Wall : A-Exterior insulation	Rigid insulation	170601	Hazardous	3.43	34.34		46%	1.58
8	Walls : Basic Wall : A-Exterior insulation	Rigid insulation	170601	Hazardous	3.20	32.03		46%	1.47
9	Walls : Basic Wall : A-Interior	Gypsum Wall Board	170801	Hazardous	0.22	14.75		4%	0.01
10	Walls : Basic Wall : A-Interior	Rigid insulation	170601	Hazardous	1.03	14.75		46%	0.47

As it can be seen in the above table, the outcome of the procedure will be in form of a table containing the list of components in the building, the components composition and materials, the related EWC code, the classification of the materials (if they are hazardous or not), the quantities (volume, area, perimeter), the recyclability percentage, and the recyclable volume. The summary of the above table can be seen in the figure below that shows the percentage of construction waste and of recyclable construction waste in volume by type for the different materials used in this model.

As it can be understood from the figure, concrete, brick, and insulation have the most share of volume among the materials with amount of 34%, 27%, and 14%, respectively. The part of figure about the recycled materials shows the same result in terms of the materials with higher share of volume, with amounts of 50%, 20%, and 13%, respectively again for concrete, brick, and insulation. It is important to notice that the share of concrete after recycling has been increased tremendously and it covers half of the recycled materials.

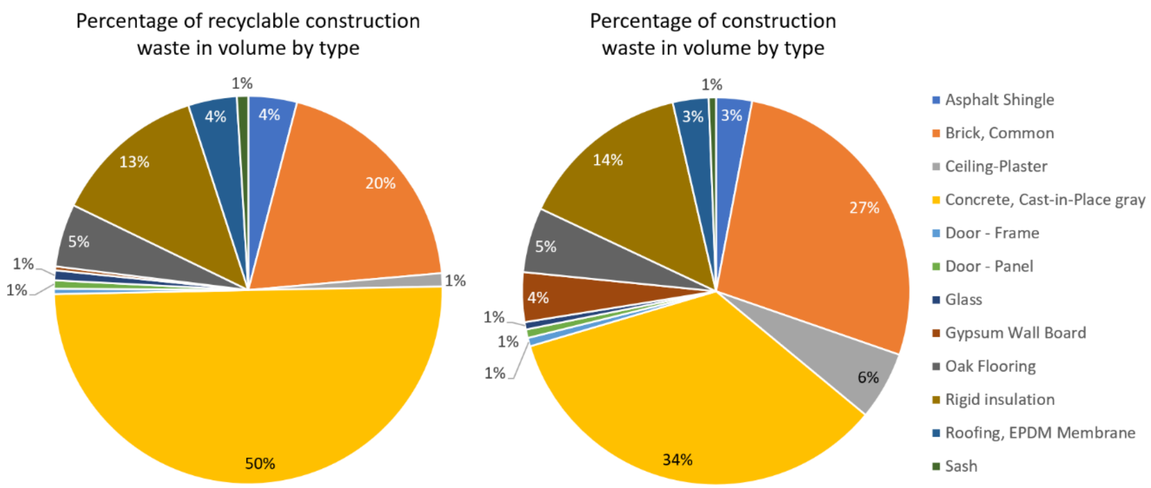
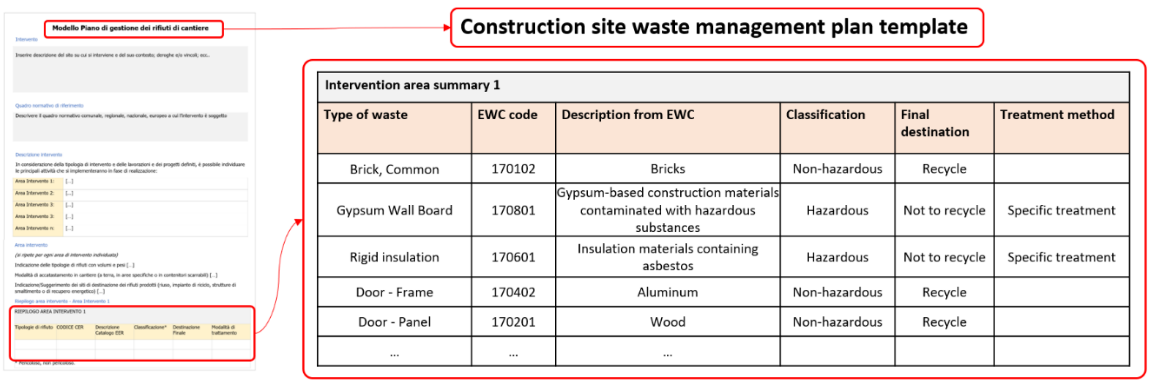


Figure 6. Share of construction waste in volume by type, before and after recycling

Another consequence of the result will lead to fill the construction site waste management plan as it can be seen in the figure below. This is the result of the tool which facilitates the completion of such plan easily and causes the decrease in the possibility of occurring errors in such procedure which is time-consuming and needs human resources to do.



Intervention area summary 1					
Type of waste	EWC code	Description from EWC	Classification	Final destination	Treatment method
Brick, Common	170102	Bricks	Non-hazardous	Recycle	
Gypsum Wall Board	170801	Gypsum-based construction materials contaminated with hazardous substances	Hazardous	Not to recycle	Specific treatment
Rigid insulation	170601	Insulation materials containing asbestos	Hazardous	Not to recycle	Specific treatment
Door - Frame	170402	Aluminum	Non-hazardous	Recycle	
Door - Panel	170201	Wood	Non-hazardous	Recycle	
...	...	...			

Figure 7. Sample of auto-filled construction site waste management plan

Finally, considering the above-mentioned formulae to calculate the overall recyclability index of the building, it was found that the overall recyclability index of the building is 51.7%. Although the value for the recyclability index of the evaluated case study is very close to the ones of Italian average which is 50.6%, there is still a large gap to achieve the final goal of EU legislative decree that requires at least 70% of recovery rate.

4. Conclusion

This study presents a comprehensive approach to enhance sustainability in the Architecture, Engineering, and Construction (AEC) industry. It emphasizes the transition from a linear to a circular economy model, focusing on maximizing the reuse and recycling of construction materials. Utilizing Building Information Modelling (BIM) and Industry Foundation Classes (IFC), the paper proposes a robust framework for efficient waste management in construction projects. The methodology involves a detailed process for creating a Materials Passport, encompassing aspects such as data collection, processing, and integration with regulatory standards, particularly in the Italian context. This approach facilitates automated material quantification and classification, significantly aiding in waste reduction and resource optimization. By calculating the recyclability index of building materials, the study demonstrates how digital technologies can be leveraged to achieve environmental sustainability, reduce waste, and enhance the economic feasibility of construction projects. This innovative strategy underscores the importance of integrating advanced digital tools and sustainable practices to foster circularity in the construction sector.

The main limitation of the study was the lack of specific information on the reuse and recycling rate of building materials in Italy, which was substituted by an approximate rate based on EU statistics. Moreover, the Level of Detail (LOD) in the BIM file was in a low grade and the data extraction process was not fully automated, given the nature of this study. However, as future research directions, the proposed framework can be implemented on various case studies with higher BIM model LOD for a more accurate result; moreover, the entire data extraction and calculation processes can be fully automated by the help of Machine Learning.

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