

Article

Upcycling Strategies for Resilience Reconstruction Goals: A Case Study of an Italian Public Building

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Abstract

This study examines the economic and financial implications of the upcycling process and Design for Disassembly (DfD) applied to an “authorial” building. The objective is to examine the economic benefits deriving from the reuse of construction materials by quantifying the savings obtained through the reduction of disposal costs and CO₂ emissions in comparison with a traditional linear economic model. The methodological approach has been developed with the aid of Building Information Modeling (BIM) in order to provide an accurate estimation of both costs and environmental impacts related to the disassembly and reuse of materials. The financial analysis is based on local market prices to assess the savings associated with the reuse of building components compared to their disposal in landfills. The case study demonstrates the feasibility of this approach under real conditions, underscoring the transformative potential of upcycling in the construction industry, highlighting how this strategy can simultaneously improve economic efficiency and reduce environmental impact. The research offers a significant contribution to the debate on sustainable building practices and may serve as a starting point for future investigations.

Keywords: circular economy; upcycling; avoided costs; financial analysis; economic analysis



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1. Introduction

In recent decades, the growing evidence of the effects of climate change has been making the urgent need for a drastic reduction in global greenhouse gas (GHG) emissions increasingly clear. The Paris Agreement represents the main reference in this regard, as it establishes long-term objectives that have been directing all countries to significantly reduce global GHG emissions in order to keep the rise in global temperatures well below 2 °C above pre-industrial levels and to strive to limit the increase to a maximum of 1.5 °C, recognizing that achieving this objective would considerably reduce the risks and impacts of climate change [1].

In this scenario, mitigation and adaptation strategies must necessarily involve the sectors most responsible for emissions, including the construction sector, which plays a crucial role. In the 1990s, buildings accounted for approximately 40% of global material consumption and one-third of energy consumption [2].

Two decades later, the sector has continued to represent the main global user of raw materials, absorbing about 60% of the extracted resources [3,4], with particularly significant incidences concerning aggregates (around 65%) and metallic materials (around 20%) [5]. At the same time, it has been estimated that the building sector has still been

contributing significantly to global energy consumption and CO₂ emissions [6,7], as well as to the production of about one-third of global waste. These values have been constantly increasing due to new construction and refurbishment activities [8].

Emissions from the construction sector mainly derive from two sources: operational carbon, associated with the management of the building during the use phase (heating, cooling, lighting, and ventilation), and embodied carbon, which includes the emissions generated throughout the entire life cycle of construction materials, from the extraction and production phase up to demolition and disposal [9]. In current practice, attention has been focusing predominantly on the reduction of operational carbon, an approach that has already proved insufficient to significantly reduce the overall environmental impact [10]. The embodied component has been assuming an increasingly greater weight in terms of environmental impact [11], making urgent a revision of the processes of procurement, management, and recovery of materials.

Despite the growing global emphasis on sustainability, most construction and demolition waste (CDW) has been continuing to be disposed of rather than reused or recycled, thereby aggravating resource depletion and environmental degradation [12].

The traditional linear model “take–make–dispose”, which has still been dominating the sector, has been exacerbating these critical issues by favoring extraction and disposal over reuse. With global urbanization on the rise, the pressure for a transition towards sustainable waste management practices has never been so cogent. In this perspective, the development of strategies for managing CDW generated in the end-of-life phase of buildings and the improvement of the recovery rate of materials represent central actions for reducing embodied carbon. Although several studies have highlighted that demolition may prove economically more convenient than deconstruction [13], research on the actual costs of deconstruction has remained limited and often confined to conceptual evaluations, despite the environmental benefits of selective demolition being widely acknowledged. However, it is foreseeable that the economic competitiveness of traditional demolition is destined to decrease in the future, following the evolution of the regulatory framework towards more stringent recovery targets.

In this regard, at the national level there has been a growing attention to the reuse of materials deriving from construction activities, in line with European guidelines on circular economy. Legislative Decree No. 152 of 3 April 2006 (Environmental Consolidated Act) constitutes the reference framework for waste management, including construction and demolition waste. In particular, Article 179 establishes the waste hierarchy, assigning priority to reuse and recycling over disposal, while Article 183 regulates the concept of temporary storage at the place of production, a crucial aspect for site logistics in selection and recovery operations. A technical reference of primary importance is represented by UNI/PdR 75:2020 [14], which defines a methodology for selective deconstruction, articulated into operational phases—from preliminary investigation to executive management—aimed at the upstream separation of recoverable materials and their subsequent reintegration into the supply chain. These guidelines are complementary to the Minimum Environmental Criteria (CAM) introduced by Ministerial Decree No. 256 of 23 June 2022, which are mandatory for public procurement. In particular, paragraph 2.6.2 of the CAM document has been promoting selective demolition practices, material traceability, and the preparation of environmental management plans oriented towards the recovery of building components. A further significant element is the recent Ministerial Decree No. 127 of 28 June 2024, which defines the criteria for the cessation of waste status (End of Waste) for construction and demolition aggregates. The measure establishes the technical and environmental conditions for their reuse as recovered aggregates, recognizing selective demolition as the preferential

practice to ensure the quality of recycled materials and, in fact, promoting the creation of a national supply chain of secondary construction materials.

In the light of these premises, it has become necessary to develop a methodology capable of supporting strategic decisions in the management of the end-of-life of buildings by integrating financial and environmental-economic aspects [15]. In particular, the adoption of processes able to quantify the benefits deriving from selective deconstruction, compared with traditional demolition and disposal practices, constitutes a key factor in directing both public and private investments towards material recovery and reuse processes. This approach is framed within a broader transition towards the circular economy in the construction sector, in line with European and national policies, and constitutes the basis for increasing efficiency in the use of resources and reducing embodied carbon emissions. The present work aims to outline a methodological process which, embedded within the broader framework of resource optimization in the construction sector, is directed towards the conception of regenerated building components, deriving from the dismantling and selective deconstruction of an existing building, through actions attributable to the practices of Design for Disassembly (DfD) and upcycling. This approach has been developed according to the cradle-to-cradle principles [16] and has been articulated through a critical reinterpretation of the concept of tectonics: no longer understood solely as the “art of assembly”, but, in this specific case, reinterpreted as the “art of disassembly”, aimed at maximizing the recovery and valorization of building components. The primary objective of the research is twofold: (i) on the one hand, to verify the technical and design feasibility of disassembling structural and envelope components through an analysis applied to the original construction system, with particular attention to their preservation, transportability, and reconfigurability (see phases I, II, and III in the following sections); and (ii) on the other hand, to evaluate—through economic and financial indicators—the effectiveness of upcycling actions compared with conventional alternatives of demolition and landfill disposal (see phase IV in the following sections).

From this perspective, the proposed study aims to construct an initial operational framework, useful for shaping intervention strategies on the industrialized building stock, with potential methodological and heuristic implications that can be extended to similar contexts. The methodology has been applied to the field of school buildings of the second half of the twentieth century through an emblematic case study. Although not originally conceived according to DfD principles, the building constitutes an opportunity to test, under real conditions, advanced strategies for the regeneration and reuse of prefabricated steel building components.

2. Materials and Methods

In recent years, numerous studies have been exploring the possibility of reusing structural and non-structural components of decommissioned buildings [17,18], and the technical and managerial practices that make such reuse possible fall within the principles of DfD, or Design for Deconstruction, which promote selective dismantling and the re-employment of building elements in analogous contexts.

Compared with conventional demolition or recycling, dismantling and reuse present multiple advantages: they preserve the embodied energy in components, extending their useful life; they significantly reduce costs, energy consumption, and carbon emissions resulting from demolition, recycling processes, and transport to landfills or treatment plants. The synthesis of these advantages is reflected in the concept of upcycling, which is aimed at producing higher-value output than the original material while preserving as much as possible of the intrinsic characteristics and minimizing additional costs [19].

In line with these principles, the methodological framework developed in this research has been applied to a specific case study. The building selected—ITIS “Alessandro Volta” (Figure 1), located in Tivoli (a municipality within the Metropolitan City of Rome in the Lazio region)—belongs to a small series of schools constructed by the Roman company Tecnosider in the 1960s, within the framework of national programs for industrialized school building promoted and coordinated by the Ministry of Public Education. The Tecnosider construction system, based on a steel frame and lightweight prefabricated panels, was designed by the architects Pietro Barucci, Beata Di Gaddo, and Ugo Sacco, gathered in the BDS office, with the collaboration of the architect Giovanni Barucci.



Figure 1. Photo of the case study: (a) the school’s entrance; (b) main facade of the gymnasium. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

A distinctive feature of the system is the special assembly joint (Figure 2) for the facade panels, protected by a patent filed in 1962: four extruded metal profiles, which can be coupled together and provided with molded shapes enabling the “snap-fit” fastening of the wall panels. The steel load-bearing structure, composed of standardized elements, also displays authorial features, including a special bolted and demountable joint for the connection between columns and beams, as well as corrugated steel floor slabs made up of modular assemblable elements. The entire system is organized according to a rigorous dimensional coordination based on a 1.20-m module, corresponding to the width of the wall panel. The load-bearing structure, fully exposed on the facade, plays a central role in defining the architectural image of the envelope, emphasized by the design of the joints that visually restore the vertical continuity of the columns. These constructional features, characterized by lightweight prefabrication and modular composability, make the building particularly suitable for testing advanced strategies of deconstruction and reuse of building components, in line with the principles of DfD and upcycling.

Starting from these premises, the methodological process developed has been articulated into four sequential phases (Figure 3):

1. Site analysis and organization of the construction site area;
2. Knowledge of the building through surveys and BIM modeling, aimed at redesigning and studying the load-bearing structure and the envelope;
3. Dismantling the design and prefiguration of the reassembly modes of the components following an upcycling process;
4. Economic and financial analysis of the operation, aimed at comparing the deconstruction strategy with the conventional approach of demolition and disposal.
5. The following subsections describe each of these phases in detail.



Figure 2. Beam-to-column joints of the main facade. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

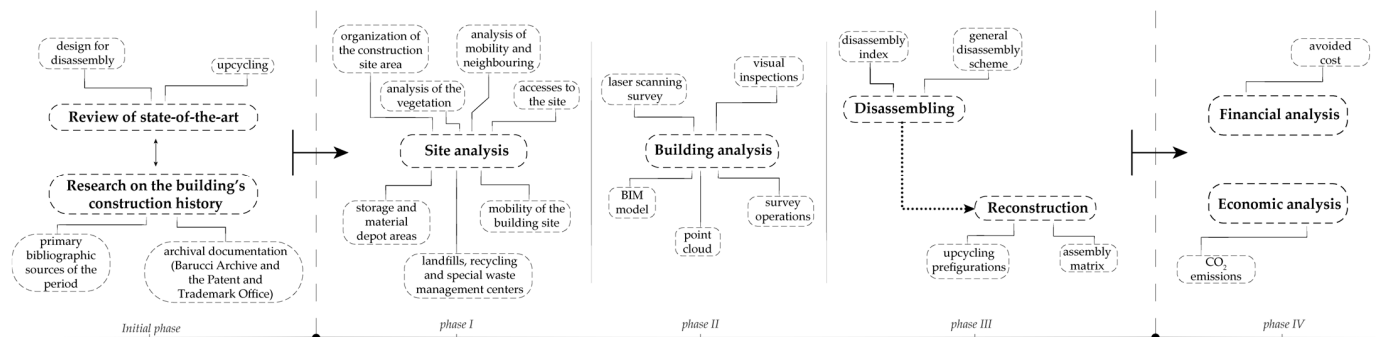


Figure 3. Flowchart of the methodological process, illustrating the sequential progression across the macrophases—Study, Analysis, and Output—as denoted by the directional arrows.

2.1. Phase I

The first phase concerned the preliminary analysis of the site and its surrounding areas, aimed at defining the logistical and operational conditions for the subsequent dismantling activities. This step is fundamental in any deconstruction-oriented process, since site constraints strongly influence both the feasibility and the efficiency of selective dismantling operations. In particular, accessibility, safety conditions, and the availability of maneuvering spaces are critical variables that determine the choice of equipment, the sequencing of operations, and the allocation of temporary storage areas.

2.2. Phase II

The definition of a sustainable deconstruction strategy requires the assessment of a structured set of parameters that affect overall costs, energy consumption, and carbon emissions. A typical building comprises thousands of components, each characterized by specific physical and technological properties that determine its potential for reuse or recycling. Consequently, it is essential to establish, already at the preliminary stage, a structured information system that allows such data to be systematically stored and consulted.

In this perspective, the study has initiated its methodological path with a historical reconstruction of the building's design practices, aimed at accurately understanding the construction techniques and materials employed. The investigation has been carried out through the analysis of bibliographical sources of the period and archival documentation, including the Barucci Fund and the Patent and Trademark Office Fund preserved at the Central State Archive in Rome, as well as the archive of the institute itself.

At the same time, a Building Information Model (BIM) has been developed, containing a comprehensive dataset relating to the building, including geometry, spatial relationships, geographical information, quantities and properties of the components, and the materials employed. In recent years, one particular aspect of BIM has attracted considerable academic interest: its potential use not only in the phases of design, construction, and management, but also in those of selective demolition, recovery, and reuse of building components, with the aim of systematically addressing issues related to sustainability and the reduction of environmental impacts [20,21].

2.3. Phase III

Building disassembly has increasingly attracted the attention of scholars in recent years [22–24]. According to ISO 20887, disassembly is defined as the non-destructive separation of construction works or constructed assets into constituent materials or components, and several studies have adopted this standard as a benchmark for assessing the disassembly potential of buildings [25–27]. Several Green Building Councils have also promoted research on DfD [28], with emblematic experiments such as the “Het Centrum” circular building, designed to be dismantled five years after its construction in order to evaluate its effective disassembly capacity [29]. The scientific debate has progressively expanded, highlighting not only the structural or historical features that may limit reuse potential but also the role of specific building components. In particular, the “SCI P427 protocol” has been developed for steel components, providing an operative benchmark for their reuse and recycling potential [30,31].

Through a combination of insights from the literature with the adoption of international standards (ISO 20887) [32], national regulations (Legislative Decree No. 42 of 22 January 2004) [33], and sector-specific guidelines (SCI P427) [34], a set of measurable “disassembly parameters” (Table 1) has been identified to assess the disassembly potential of both structural and non-structural components. These parameters, organized by element typology and consistent with the classes defined by the Industry Foundation Classes (IFCs) standards [35], have been integrated into the BIM model, thereby ensuring coherent classification and the straightforward accessibility of information. Their combination has made it possible to define a synthetic indicator, referred to as the disassembly index, which quantitatively expresses the ease of disassembly and can be applied both to the present case study and, more generally, to similar building types.

The proposed framework includes six macro-categories: site, space plan, structure, skin, space partitions, and shared heritage (the latter referring to the preservation of “authorial” architectural features). Each category comprises several parameters relating to accessibility, versatility, weight, stratification, and other relevant factors. To ensure comparability, each parameter has been assigned a discrete score from 0 (low) to 2 (high). For example, within the skin category, the parameter “Weight” (weight of the component for construction site disassembly activities) is given a score of 0 (low disassembly index) when the weight exceeds 50 kg, 1 if it ranges between 20 and 50 kg, and 2 when it is below 20 kg. In addition, a parameter concerning safety (safety of disassembly), as defined in ISO 20887, has been introduced across all categories. A negative assessment of this parameter entails the resetting of the disassembly index in order to safeguard operational feasibility and the safety of workers [36].

From the knowledge phase, the process of dismantling has therefore been defined and conceived as a reverse reconstruction of the original assembly operations. The analysis has led to the adoption of a top-down approach, articulated as follows: (i) cutting of the slab at the beam junctions and removal of the panels while preserving the stratigraphy; (ii) removal of the facade panels from the interior; (iii) cutting and removal of the beams at

the joints; (iv) cutting and removal of the columns at the joints [36]. Although the building was constructed with dry-assembly techniques, the degradation and painting of the bolts make direct dismantling impracticable, while the historical value of the patented joints suggests preserving their integrity. It was therefore decided to cut the steel elements in proximity to the joints, keeping them intact.

Table 1. Excerpt from the “disassembly parameters” table, aimed at providing a detailed assessment of the factors related to the dismantling potential of structural and non-structural components. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

Categories	Parameters	Definition	Score		
			0—Low	1—Medium	2—High
Site	Accessibility (construction site installation)	The position of the building allows the access for the transport of the building components off-site. The parameter is measured considering the % value of accessible area/total area of the site	0–20%	20–60%	>60%
Space plan	Expandability	The building features the possibility to be expanded, facilitating the addition of new spaces (ISO 20887). The parameter is measured considering the % value of direct expandable area/total area of the building floors	0–20%	20–60%	>60%
Structure	Signs of fire exposure	Proven through a visual inspection. Components exposed to uncontrolled flames cannot be reused (SCI P427)	exposed	not exposed	
Skin	Obsolescence	Express the % damage area/total area of the element, considering visible damages	>60%	20–60%	0–20%
Space partitions	Reversible connection	Connections that can be disconnected or disassembled (ISO 20887)	Light welding (corner welding)	Fixed metallic connection (rivets)	Disassemble metallic connection (bolt)
Shared heritage (authorial contribution)	Documentary heritage	Presence of documents proving links with historical and technological background (Legislative Decree No. 42 of 22 January 2004)	Authorial design proven by original drawings	Authorial design proven by original drawings, literature of the time	Authorial design proven by original drawings, literature of the time, and industrial patents

In line with the objectives of the research, two complementary dismantling perspectives have been considered:

- Efficiency scheme, aimed at recovering the largest possible number of simple elements to be reintroduced into the market;
- Heritage valorization scheme, aimed at preserving and recovering composite elements (e.g., facade modules) that reflect the original architectural identity.

These are not conceived as dual or alternative strategies, but rather as two converging approaches that reinforce one another. Their integration makes it possible to reconcile the requirements of economic efficiency with the protection of historical and cultural value, thereby enhancing the overall effectiveness of the upcycling process and demonstrating how, although not originally conceived for disassembly, the building displays constructional characteristics intrinsically favorable to such operations.

Following this process, several design preconfigurations have been developed with the aid of an Assembly Matrix, aimed at facilitating the reciprocal integration of reused components. Some examples will be presented in Sections 3 and 3.3.

2.4. Phase IV

2.4.1. Financial Analysis

The current economic system remains largely anchored to a linear paradigm, in which the life cycle of products unfolds according to the sequence take–make–use–dispose. This model, characterized by an intensive use of virgin raw materials and a strong dependence on non-renewable energy sources, is proving increasingly unsustainable on a planet with finite resources. In addition to causing a constant depletion of natural resources, it generates significant quantities of waste, which, through processes of accumulation and dispersion, contribute to the degradation of terrestrial and marine ecosystems.

In contrast, the circular economy proposes a production system oriented towards waste prevention, the reduction of resource consumption, and the maximization of reuse and recycling, with the ultimate aim of preserving natural capital. Within this framework, selective deconstruction can be regarded as an operational tool for enhancing the value of materials deriving from the end-of-life of a building, while at the same time reducing environmental impacts and generating tangible economic benefits for stakeholders across the supply chain.

The financial analysis has therefore aimed to quantify the financial benefit derived from avoided costs, i.e., the reduction of production activity through technically and functionally comparable alternatives. In this sense, the financial benefit has been identified in the reuse of building components, which can be understood as the reduction of overall expenditures when compared with the traditional option of demolition and landfill disposal.

For this purpose, the building elements have been grouped into seven macro-categories (Tables 2 and 3), defined according to functional and material criteria, in order to provide a coherent and systematic reading of the entire building system.

Table 2. Classification of building elements and parameters of the financial analysis, excluding hazardous materials.

Building Elements	Disposed Elements		Recovered Elements	
	[€]	Cost Share [%]	[€]	Cost Share [%]
External walls	−46,345.80	8.85	9854.26	1.88
Internal walls	−14,571.07	2.78	-	-
Joints	-	-	2768.14	0.53
Slabs	−197,165.97	37.64	140,257.56	26.78
Roofing	-	-	16,477.86	3.15
Load-bearing structure	-	-	37,574.42	7.17
Frames	-	-	58,797.89	11.22
Total	−258,082.84	49.27	265,730.12	50.73

- External walls: including cladding facade panels, curtain wall systems, perimeter walls, glazed surfaces, and reinforced concrete shear walls.
- Internal walls: including partitions and lightweight non-load-bearing walls.
- Structural joints: comprising metal connections, articulated into bolts and fasteners, short steel profiles, and connecting plates or flanges.

- Slabs: represented by selected portions of slabs suitable for reuse, elements composed of flooring and corrugated steel sheets, ground-floor pavements, and reinforced concrete slabs.
- Roofing: consisting of corrugated steel panels.
- Load-bearing structure: including the main supporting elements, namely beams and columns.
- Frames: including doors and windows.

For each category, materials destined for recovery were distinguished from those directed to disposal, with a further separation between hazardous and non-hazardous waste, according to the European Waste Catalogue (EWC). For each element, divided into disposed and recovered components, weight, volume, and the costs associated with loading, transport, treatment, and disposal operations were calculated, including landfill fees and any additional charges, such as long-distance transport. The estimates were developed by adopting the items listed in the *Tariffa dei Prezzi Regione Lazio 2023* and in the *Prezzi tipologie edilizie 2024* [37], and in compliance with current regulations.

The data shown in Table 2, further detailed below, have been implemented and re-processed into graphical representations in order to provide an immediate and intuitive overview of the results. Moreover, the quantitative and analytical data have been integrated into the BIM model, allowing precise identification—also in visual form—of which components contribute most or least to the formation of avoided costs and which, on the contrary, generate the most significant disposal costs. From this process, the following findings emerge.

2.4.2. Economic Analysis

The environmental impact of the construction sector can be mitigated, while at the same time generating economic benefits, through the implementation of circular economy principles. Within this paradigm, value does not stem from an ever-growing consumption of resources but is instead created by eliminating waste and reducing the use of raw materials through the extension of product longevity and the strengthening of reuse processes [38].

Recent literature documents a growing interest in the application of these principles to the construction sector, as well as in the identification of suitable tools to address the emerging challenges in the transition from a linear to a circular economy [39–41]. Nevertheless, despite these efforts, the level of global circularity remains extremely low, with only 9% of materials actually recovered in some form [42]. The construction sector, through demolition alone, is responsible worldwide for about 50% of the waste generated by the construction and infrastructure industries [43], with significant environmental and social impacts. From this perspective, increasing the share of materials that are reused, valorized, or recycled becomes a necessary condition for improving the overall sustainability of the sector.

This phase of the study therefore focuses on the assessment of the benefits, in terms of both carbon emission reduction and economic savings associated with carbon credits, deriving from deconstruction processes oriented towards upcycling. Unlike traditional practices, based on the linear demolition–landfill model, the adoption of management strategies structured according to a life-cycle approach makes it possible to reduce GHG emissions and to generate a measurable economic return. It is well established that the reuse of materials and components provides superior advantages in terms of energy efficiency and carbon savings [44], with positive effects not only for the environment but also for the economic system as a whole [45].

For the accounting of GHG emissions, the analysis has been carried out using the software SimaPro version 9.6.0, applying the methodology of the GHG Protocol, the

international reference standard for GHG reporting. Developed and issued by the GHG Protocol Initiative, it provides guidance to be used as a benchmark in the process of data collection and processing for the assessment of emission impacts. Quantification was based on specific, publicly available emission factors, as well as on datasets modeling the emissions generated by a given process, available in the Ecoinvent database, one of the most comprehensive international sources.

For each construction element the parameter Fossil CO₂eq has been considered, expressed in kilograms of CO₂ equivalent (kgCO₂eq). This indicator represents the global warming potential associated with fossil carbon dioxide emissions. The coefficient—derived from SimaPro and the reference databases (in particular Ecoinvent 3)—has been multiplied by the previously calculated weight of each material. In this way, the specific carbon footprint and, consequently, the total embodied emissions of each element have been determined, providing a quantitative basis for the comparative evaluation between recovery and disposal scenarios.

On this basis, the assessment allowed the quantification of avoided CO₂ emissions. Specifically, if a material is recovered and reintroduced into the production cycle, the corresponding amount of CO₂ emissions associated with its primary production is avoided. Conversely, if the same material is disposed of in a landfill, these emissions are not avoided and are therefore considered as definitively lost in environmental terms. This approach makes it possible to highlight the environmental benefit of recovery and reuse operations, which directly translates into a reduction of the building's carbon footprint.

The study also considered the carbon credit market regulated in Europe through the European Union Emissions Trading System (EU ETS), the main instrument adopted by the EU to achieve CO₂ reduction targets, introduced and governed by Directive 2003/87/EC [46]. For monetization purposes, the reference unit cost of carbon emissions for Italy in 2024 was assumed, amounting to 57.03 €/tCO₂eq [47].

The accounting of embodied carbon was aggregated by macro-category and distinguished between disposed and recovered components (Table 3).

Table 3. Classification of building elements and parameters of the economic analysis, excluding hazardous materials.

Building Elements	Disposed Elements		Recovered Elements	
	[tCO ₂ eq]	% CO ₂	[tCO ₂ eq]	% CO ₂
External walls	−70.89	2.51	116.76	4.14
Internal walls	−125.38	4.44	-	-
Joints	-	-	29.87	1.06
Slabs	−958.74	33.95	755.32	26.75
Roofing	-	-	199.45	7.06
Load-bearing structure	-	-	473.05	16.75
Frames	-	-	94.16	3.33
Total	−1155.01	40.91	1668.61	59.09

3. Results

This section presents the results obtained from the different phases of the research, providing both quantitative evidence and qualitative insights derived from the methodological steps previously outlined. To ensure clarity and coherence, the results have been

organized in accordance with the sequential phases of the methodological framework described above.

3.1. Phase I

The case study building is located about 700 meters from Tivoli railway station and has a single main access, both pedestrian and vehicular, from Via di S. Agnese, through a ramp approximately 3.0 m wide. The intervention area provides an available surface of about 60 m², which can be used for handling operations and for the temporary on-site storage of materials.

Based on a territorial analysis extended to a radius of approximately 30 km (Figure 4), the main infrastructures relevant to the management of material flows were identified: a plant 14 km away for the disposal of asbestos-containing panels; a depot 10 km away for the storage of elements and components subject to the upcycling project; and a landfill 28 km away for the disposal of non-recoverable debris. This logistical mapping constitutes an essential preliminary step to ensure the efficiency of site operations and the proper management of costs.

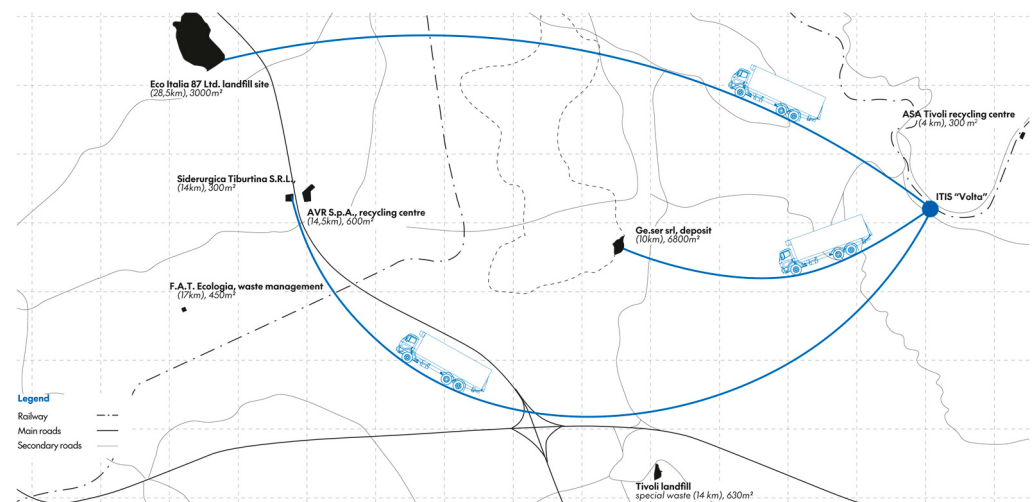


Figure 4. Territorial analysis. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

3.2. Phase II

The methodological work carried out in the second phase has led to the development of a comprehensive digital model of the building. This model provides both an accurate geometric and material reconstruction of the case study and a reliable tool for extracting measurable and comparable data.

The data extracted from the model have been organized according to two main criteria:

- By material (concrete, steel, Petralit, etc.), as reported in Table 4;
- By component (columns, beams, slabs, etc.), as reported in Table 5.

This meta-representation, comparable to a “mass spectrometry” of the building, makes it possible to quantify and qualify with precision the available resources. Such information has a strategic value both in the logistical planning of dismantling operations and in the subsequent upcycling design phase, as it clearly defines “what is available and in what quantity.” Moreover, this approach provides the basis for an integrated evaluation that encompasses architectural outcomes, environmental impacts, and economic-financial sustainability (examined in Phase IV).

Table 4. Quantity of materials by weight. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

Material	Quantity [t]
Concrete	1340
Steel	317
Siporex	109
EPS-Petralit	30
Glass	23
PVC	6
Other	9

Table 5. Quantity of components by weight. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

Components	Quantity [t]
Slabs	2664
Internal walls	230
Beams	150
External walls	120
Columns	65
Windows and doors	37
Joints	11

3.3. Phase III

The information acquired so far has made it possible to accurately outline both the surrounding context and the characteristics of the building. In order to move towards the deconstruction phase, it has been necessary to identify, through the combination of several factors assessed for each element—as reported in Table 1 and described in the previous chapter—those components with the greatest potential to undergo dismantling processes. The outcome of this evaluation has been synthesized in the disassembly index (for the methodological framework, see Sections 2 and 2.3).

As an illustrative example, and in order to demonstrate how the disassembly index has been constructed for each element, Table 6 compares a structural steel joint (reported as “Joint”)—characterized by a high disassembly index—with an asbestos–cement panel (reported as “Panel”), which, due to its hazardous composition, displays a very low disassembly index.

The disassembly index has been incorporated into the digital model (as illustrated in Figure 5), alongside the other data previously collected, thus creating a unified repository of knowledge on the building and its components, which serves as a basis for subsequent analyses and decision-making.

From the dismantling process, the research progressed to the subsequent stage of reassembly, focusing on the possible joints and connections between the various components. In this initial phase of experimentation, attention has been limited to the exploration of how individual elements can be coupled, giving rise to new composite and reusable configurations.

Within this framework, an Assembly Matrix has been defined, understood as a guiding tool capable of providing design indications on the potential coupling of one or more elements in order to generate configurations composed entirely, or partly, of disassembled components (Figure 6). This approach lies at the very core of the concept of upcycling, demonstrating how the dismantling of individual elements can give rise to new bi- or three-dimensional compositions with both structural and architectural value.

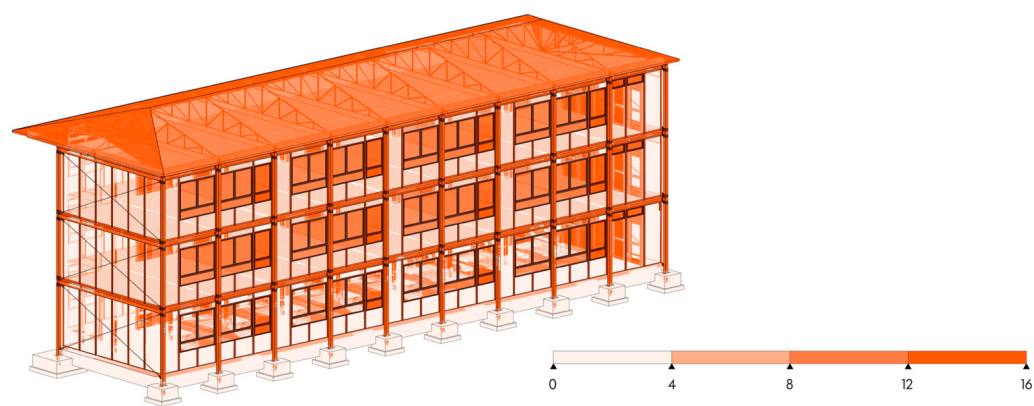


Figure 5. Schematic representation of the disassembly index for each component in the axonometric view. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

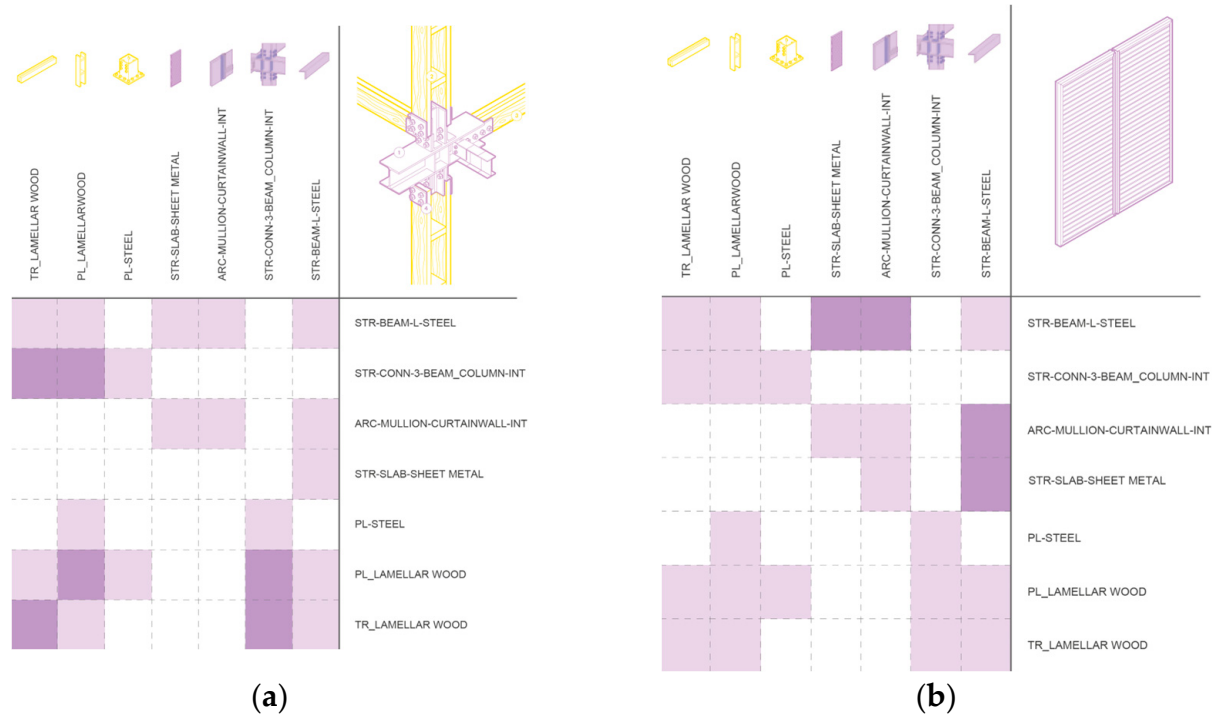


Figure 6. Extract from the broader Assembly Matrix, illustrating the gradient from light tones—representing elements with lower assembly attitude—to dark violet tones—indicating elements with higher assembly attitude. The Figure focusing, through the examination of individual elements, on two different configurations: **(a)** Node + Beam/Pillar prefiguration, a configuration partly composed of disassembled elements, characterized by good potential for new assembly and a high degree of versatility; **(b)** Facade module assembly, obtained by joining two or more facade panels through the reuse of the original disassembled omega profiles. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

Table 6. Excerpt comparing the disassembly index applied to two elements. Source: Upcycling Architecture in Italy. Design Workshop. Risultati/Results, 2024.

Parameters	Values	
	Joint	Panel
Ease of access	2	1
Independence	2	2
Reversible connection	1	2

Table 6. Cont.

Parameters	Values	
	Joint	Panel
Standardization	2	2
Weight	1	2
Obsolescence	1	2
Steelwork erected after 1970	0	-
Significant section loss due to corrosion	2	-
Signs of fire exposure	1	-
Evidence of plasticity observed in the steel surface or corrosion protection	2	-
Steelwork objects to fatigue	1	-
Safety of disassembly	2	0
Consistency of original design principle to DfD principle:	2	2
Disassembly index	13	-

3.4. Phase IV

The preceding steps have served to address the first research objective, namely the verification of the technical and design feasibility of disassembly applied to the case study. The final phase is therefore devoted to a different but complementary dimension: the evaluation of the economic and financial implications of the proposed strategy. This phase assesses the effectiveness of upcycling actions in comparison with the conventional alternatives of demolition and landfill disposal. The results of this analysis, which complete the overall framework of the research, are presented and discussed in the following subsections.

3.4.1. Financial Analysis

The financial assessment has been undertaken with the purpose of estimating avoided costs through the classification of building components into two categories: those deemed suitable for reuse and those destined for landfill. This approach has made it possible to quantify the economic savings generated when compared with the conventional linear-economy scenario, thereby highlighting the potential contribution of upcycling strategies to the transition towards a circular economy.

With reference to the recovered elements, Figure 7 illustrates the contribution of each category to the determination of avoided costs, that is, the components identified as potentially reusable on the basis of the analyses previously carried out. These include cladding facade panels, glazed facade panels, all structural joints, selected portions of reinforced concrete slabs, corrugated steel roofing sheets, the load-bearing structure composed of beams and columns, and the frames.

The color scales represent the level of savings achieved: darker shades indicate greater savings on disposal costs, whereas lighter shades denote less significant benefits. Elements without color are not included in the computation of avoided costs, since they are considered non-reusable and are therefore destined for landfill disposal.

The analysis highlights, for each category, an avoided unit cost, expressed in €/kg, and a percentage contribution with respect to the overall cost (given by the sum of avoided costs, disposal costs, and the costs related to the management of hazardous materials). Slabs, although showing a relatively low unit value (0.33 €/kg), generate total savings of 140,257.56 €, corresponding to 26.78% of the total, as a result of the significant mass

involved. Frames, by contrast, display a considerably higher unit cost (1.88 €/kg), with a percentage contribution of 11.22%, equal to 58,797.89 €, confirming the greater economic valorization associated with the reuse of materials. The load-bearing structure generates savings of 37,574.42 €, corresponding to 0.38 €/kg and 7.17%, whereas the roofing accounts for 16,477.86 € (0.19 €/kg; 3.15%). More limited values are recorded for external walls (9854.26 €; 1.11 €/kg; 1.88%) and for structural joints (2768.14 €; 0.65 €/kg; 0.53%).

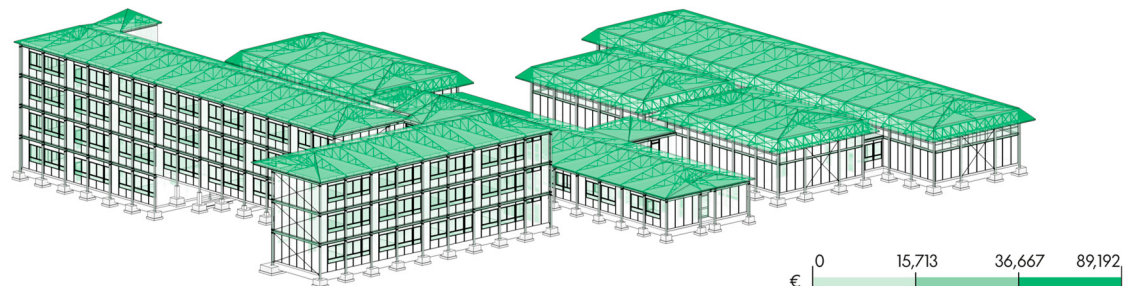


Figure 7. BIM model highlighting elements contributing to the reduction of disposal costs.

With regard to the elements destined for landfill disposal, these comprise the external reinforced concrete walls, the internal Siporex partitions, the reinforced concrete slabs, and the external curtain wall panels containing asbestos. The latter are subject to specific remediation procedures, including removal, transport, and disposal in authorized landfills. Figure 8 presents the BIM-based elaboration of the extent of costs. The color scale allows their contribution to be grasped immediately: more intense shades indicate higher costs, whereas lighter shades denote lower values. Components without color are not included in the computation.

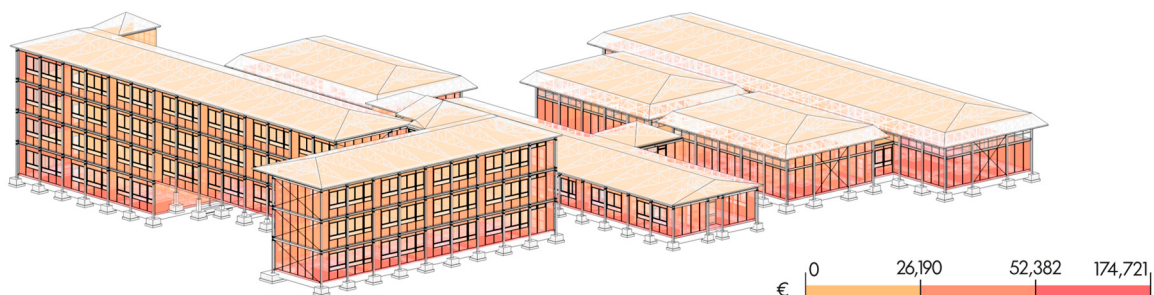


Figure 8. BIM model highlighting elements associated with disposal costs.

The unit disposal costs, derived from official sources such as regional price lists—specifically that of the Lazio Region—and the DEI price list, display a considerable variability. They range from approximately 80.00 €/ton for steel disposal to 0.87 €/kg for plastic materials and 0.61 €/kg for glass, while for concrete the reference parameter amounts to 13.55 €/ton. As illustrated in Figure 4, different disposal facilities have been identified, entailing additional transport expenses which, for distances exceeding 10 km, amount to 1.1 €/ton. Furthermore, the regulatory distinction established at the European level between hazardous and non-hazardous waste determines differentiated landfill fees, which vary according to both the type of material and the regional context.

The analytical data associated with the graphical elaboration show a more significant contribution for the reinforced concrete slabs, with a cost of 197,165.97 €, corresponding to 37.64% of the total cost, and a unit cost of 1.11 €/kg. These are followed by the external walls, whose disposal entails an expenditure of 46,345.80 € (8.85% of the total) with a higher unit cost (1.27 €/kg), confirming the greater impact due to their material characteristics

and the related logistics of management. By contrast, the contribution of the internal walls is more limited, amounting to 14,571.07 € (2.78%) with a unit cost of 0.12 €/kg.

In detail, the elaborations make it possible to highlight, through an analytical approach, the financial benefits deriving from the so-called avoided costs and the actual expenditure to be borne, namely the burden on the enterprise or the private actor. To facilitate the interpretation of these values, they have been represented through two graphical tools: the Hierarchical Chart (Figure 9a), which distinguishes the overall disposal costs for each macro-category, highlighting at the upper level the savings associated with reusable elements and at the lower level the expenses related to materials destined for landfill; and the Bubble Chart (Figure 9b), in which the total disposal cost (x-axis) and the unit cost (y-axis) are represented for each macro-category. In this case, the points located in the positive quadrant indicate avoided costs, while those in the negative quadrant represent the costs incurred. The size of the points reflects the percentage contribution of each category to the total cost.

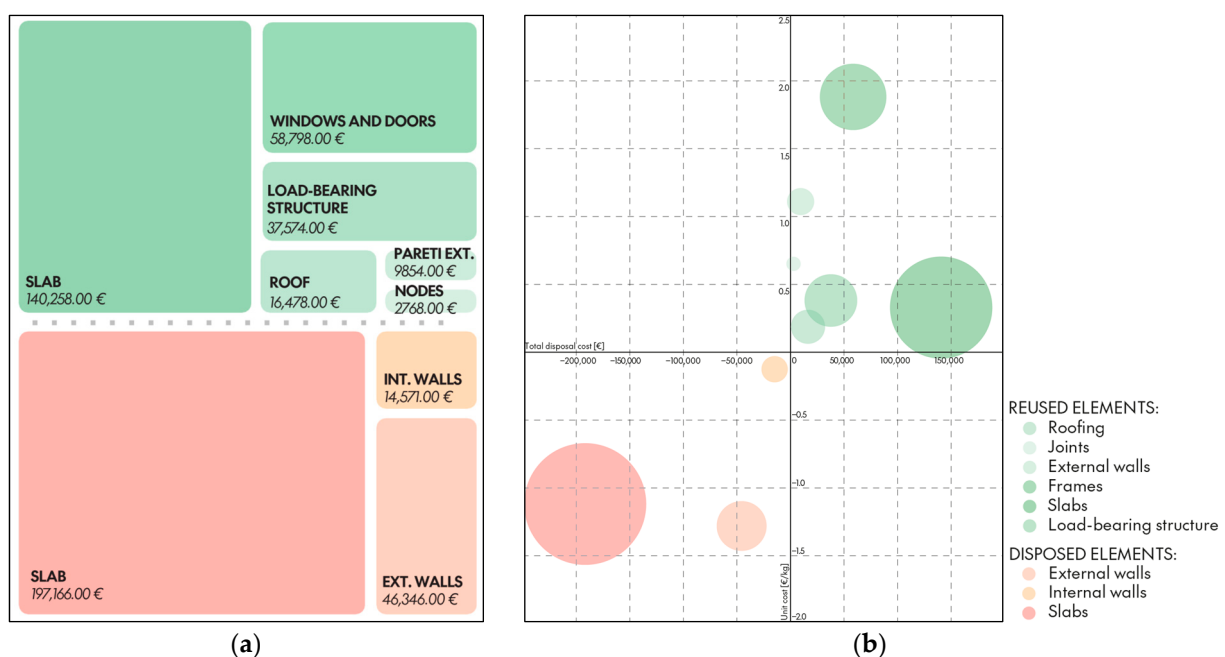


Figure 9. (a) Hierarchical Chart; (b) Bubble Chart, illustrating the results of the Financial Analysis.

Furthermore, Figure 10 presents an extract from the BIM model that relates, for each building element, the disposal costs and the benefits deriving from reuse, thus providing in a single representation the overall economic balance. The color scale allows the different impacts to be immediately distinguished: red indicates the costs incurred, green represents the avoided costs, while the intensity of the shades expresses their percentage weight with respect to the total. It should be emphasized that materials classified as hazardous—in particular, panels containing asbestos—involve an additional disposal cost of 32,062.05 €, exerting a significant impact on the overall financial feasibility of the operation.

In conclusion, the financial analysis indicates that the reuse of the selected materials would generate avoided costs—that is, a financial benefit—amounting to 265,730.12 €, corresponding to savings of 51% with respect to the total investment cost. This result confirms the viability of selective deconstruction as an integrated end-of-life management strategy for buildings, capable of combining economic efficiency with environmental sustainability.

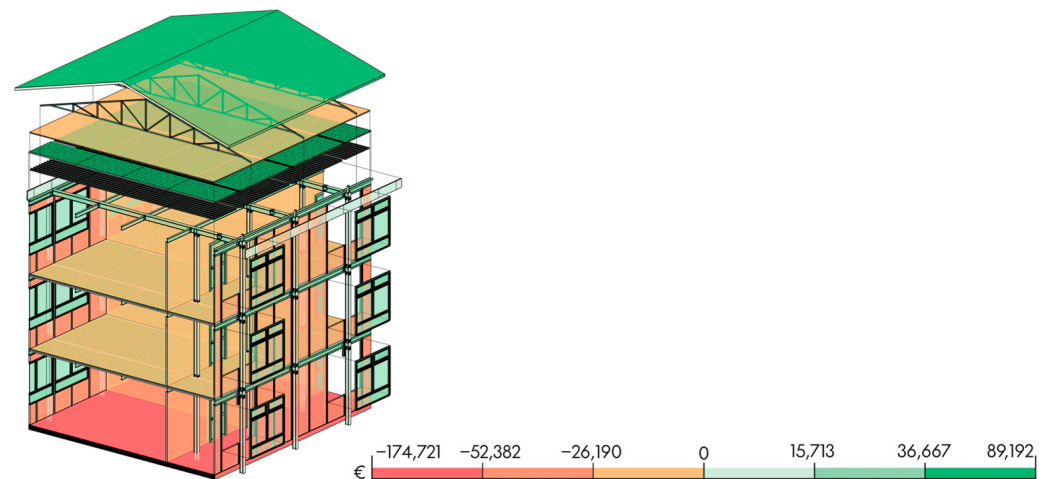


Figure 10. Extract from the BIM model, illustrating the disposal cost associated with each building element.

3.4.2. Economic Analysis

The economic assessment has quantified the CO₂ emissions associated with the different components, with the aim of highlighting the avoided emissions resulting from their reintegration into the production cycle, in line with the principles of the circular economy as opposed to the conventional linear model.

With regard to the recovered elements, Figure 11 provides the BIM-based elaboration, highlighting the components that contribute most significantly to the mitigation of CO₂ emissions. The adopted color scale allows for an immediate interpretation of the results: more intense shades indicate higher values of avoided tCO₂eq and thus a greater contribution to the overall reduction, whereas lighter shades denote reductions of more limited magnitude.

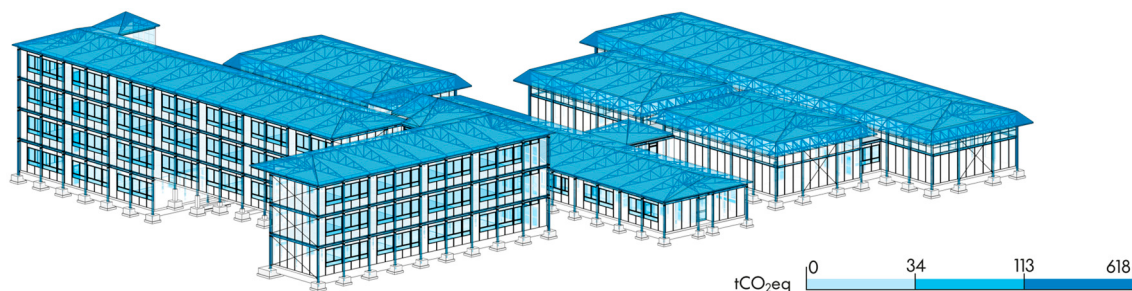


Figure 11. BIM model highlighting elements contributing to CO₂ emission avoidance.

The analysis of the data highlights that the slabs represent the largest share of avoided emissions, with 755.32 tCO₂eq, equivalent to 43,076.04 €, accounting for 26.75% of the total. The load-bearing structure contributes 473.05 tCO₂eq (26,978.13€; 16.75%), followed by the roofing with 199.45 tCO₂eq (11,374.56 €; 7.06%). More limited values are recorded for the external walls (116.76 tCO₂eq; 6658.78 €; 4.14%), the frames (94.16 tCO₂eq; 5369.91 €; 3.33%), and the structural joints (29.87 tCO₂eq; 1703.65 €; 1.06%).

With regard to the elements directed to disposal, Figure 12 presents the BIM-based elaboration, highlighting the components that contribute most significantly to CO₂ emissions generated by landfill disposal. The color scale enables an immediate interpretation of the results: darker shades indicate higher levels of emitted tCO₂eq, whereas lighter shades denote more limited contributions.

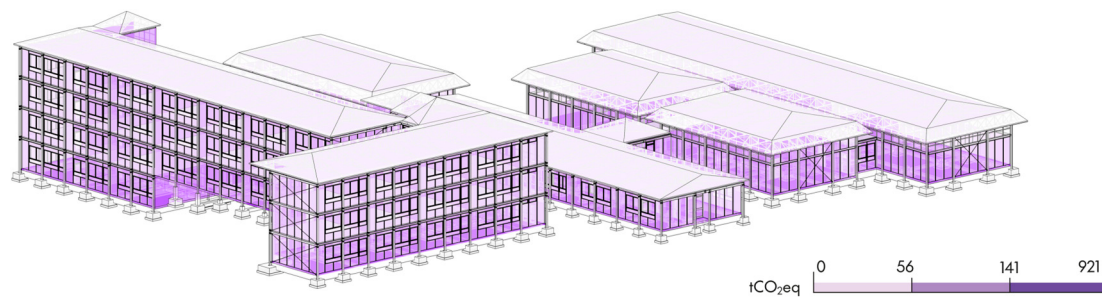


Figure 12. BIM model highlighting elements contributing to CO₂ emissions (disposed elements).

For the aforementioned elements directed to landfill, GHG emissions are expressed as negative values, since they cannot be attributed to recovery processes but are directly connected to the linear end-of-life cycle of materials. In this case, the most significant impact is attributable to the reinforced concrete slabs, which account for $-958.74 \text{ tCO}_2\text{eq}$ (33.95% of the total), corresponding to an estimated cost of $-54,676.78 \text{ €}$. These are followed by the internal walls, with $-125.38 \text{ tCO}_2\text{eq}$ (4.44%; -7150.65 €), and the external walls, with $-70.89 \text{ tCO}_2\text{eq}$ (2.51%; -4042.70 €).

These values, unlike the positive ones associated with the recovered elements, do not represent an environmental benefit but rather a net cost, since landfill disposal marks the definitive exit of the material from the production cycle and precludes any opportunity for circular valorization.

In this case as well, two graphical representation tools have been developed to facilitate the interpretation of the data. It should be noted in advance that the reported values represent the monetization of carbon credits, calculated by assuming a shadow price of CO₂ of approximately $57 \text{ €/tCO}_2\text{eq}$, implicit in the elaborated data.

The Hierarchical Chart (Figure 13a) illustrates the overall costs of CO₂ emissions associated with each macro-category. The boxes located in the upper section highlight the avoided costs deriving from the emissions saved through the recovery and reuse of elements; those in the lower section, on the other hand, represent the costs attributable to the emissions generated by the elements directed to disposal.

The Bubble Chart (Figure 13b) relates, for each macro-category, the total disposal cost (x-axis) with the total cost of CO₂ emissions (y-axis). The points located in the positive quadrant indicate the avoided costs, whereas those positioned in the negative quadrant represent the costs actually incurred. The size of the bubbles reflects the percentage contribution of the emitted CO₂ to the total emissions, allowing the relative weight of each category to be immediately assessed.

Furthermore, Figure 14 provides an extract from the BIM model that relates, for each building element: (i) the CO₂ emissions avoided through reuse (blue) and (ii) those generated by the elements not reintegrated into circular economy cycles (purple). This representation enables the overall environmental performance balance to be immediately understood, offering an integrated view of the effects resulting from the different end-of-life management strategies.

In conclusion, the economic analysis highlights that the material reuse strategy has made it possible to avoid a total of $1668.61 \text{ tCO}_2\text{eq}$, corresponding to 59.09% of the overall emissions considered. The monetization of this result, carried out on the basis of the shadow price of CO₂ ($57 \text{ €/tCO}_2\text{eq}$), corresponds to an economic benefit of $95,161.07 \text{ €}$ in terms of carbon credits. From an environmental perspective as well, therefore, selective deconstruction confirms its validity as an end-of-life management strategy for buildings, capable of integrating the reduction of greenhouse gas emissions.

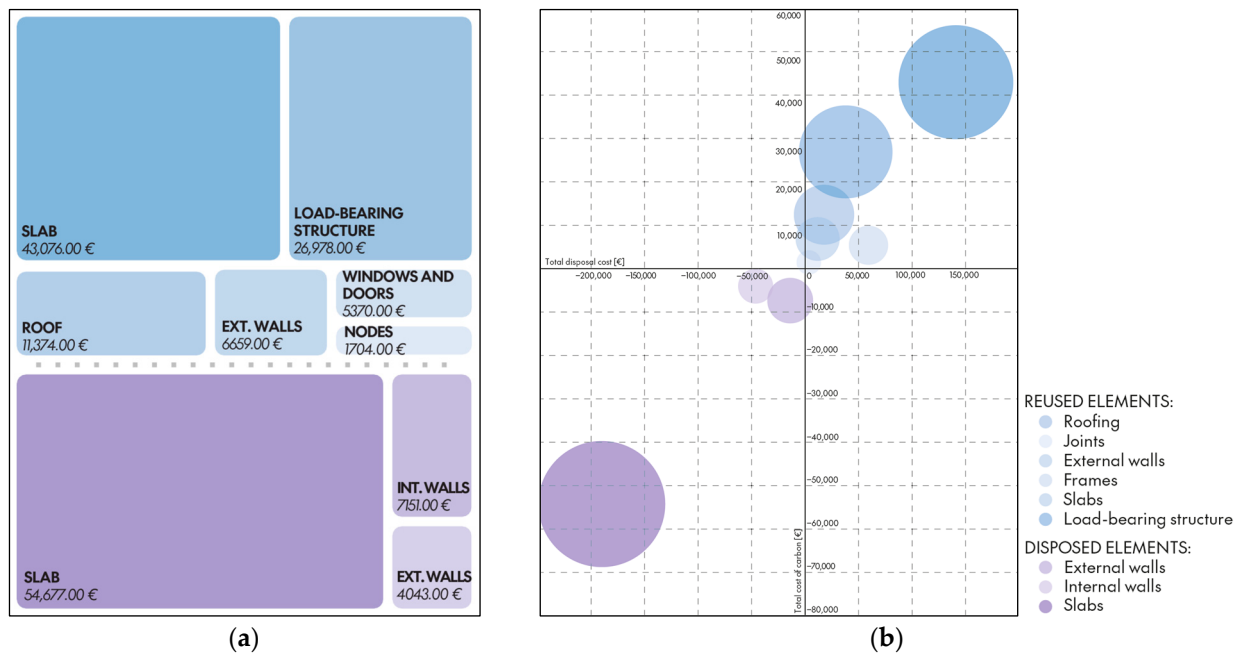


Figure 13. (a) Hierarchical Chart; (b) Bubble Chart, illustrating the results of the Economic Analysis.

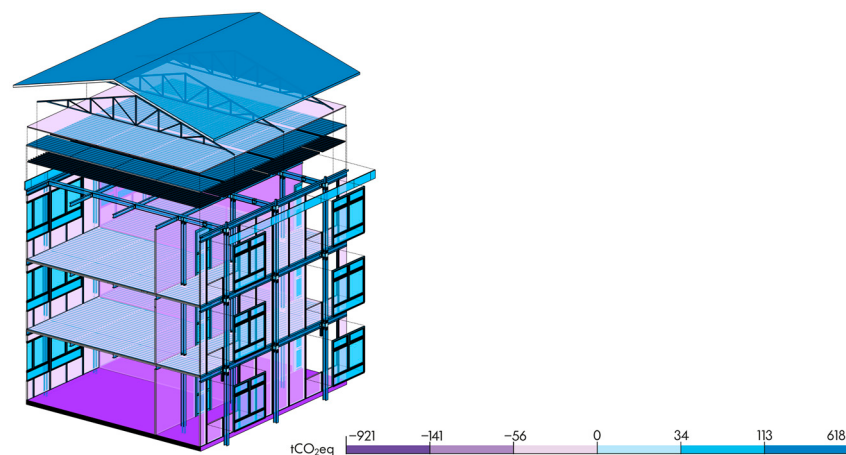


Figure 14. Extract from the BIM model, illustrating tCO₂eq emissions in accordance with the GHG Protocol.

4. Discussion and Conclusions

As illustrated in the previous sections, the comparative assessment between demolition and deconstruction requires the consideration of a plurality of factors that equally affect the determination of overall costs. Among these are the intrinsic characteristics of the building—such as size, project complexity, and number of above-ground and underground floors [48]—as well as its location, accessibility, the presence of hazardous materials [49], and the availability of technical information [50]. Exogenous variables such as the work schedule, weather conditions, regulatory requirements, disposal fees, and the resources available [51] can, in turn, significantly influence the total costs of the intervention. The cost of demolition is generally easier to estimate [49], also thanks to the availability of well-established tools on the market. On the other hand, the estimation of deconstruction costs presents greater complexity, primarily due to the uncertainty concerning the amount of labor-intensive work required [52].

Against this backdrop, the present research provides a meaningful contribution to the debate on circular strategies in the construction sector. The financial analysis has been de-

liberately confined to the estimation of avoided costs, focusing on a reuse scenario—where components are dismantled and only theoretically considered for potential reassembly—compared with complete demolition and landfill disposal. The quantitative evidence demonstrates avoided costs of 265,730.12 €, corresponding to approximately 51% of the expenditure that would otherwise be incurred under a conventional linear model. The case study demonstrates the feasibility of the proposed methodological pathway under real conditions and indicates that the research objective has been effectively achieved. The results show that selective deconstruction, when supported by upcycling strategies—even in their most essential form—can generate financial advantages that make it a credible alternative to demolition.

In addition to addressing financial aspects, the regulatory and political debate, in line with environmental sustainability objectives, is aiming at a shift from the consolidated linear economy towards a circular economy, which seeks to eliminate waste and reduce the consumption of raw materials, with particular attention to material flows. In this context, “recycling” [53] represents one of the most historically consolidated strategies for the management of CDW, reducing the demand for new resources through the use of waste that would otherwise be sent to landfill.

The environmental and economic benefits of CDW recycling are widely documented [54] and justify its adoption as a more sustainable practice [55] compared with traditional demolition and landfill disposal, thanks to the reduction of costs and energy consumption associated with disposal, as well as to the decrease in the extraction of new raw materials. However, recycling presents intrinsic limitations, since recovered materials are often destined for downcycled applications compared with the original use, with a consequent partial loss of the embodied energy invested in their initial production [56], to which must be added the energy required for treatment processes.

Alternatively, at the end-of-life of the building, its components can be reused for identical or similar applications to those of the original components; and considering the constant increase in the costs of materials and construction services, it is plausible that such components may acquire a higher value at the time of deconstruction compared with that of their initial production.

The findings further confirm how the adoption of a circular economy approach, centered on the reintegration of dismantled components into new elements or design solutions, can prevent the embodied CO₂ released during their original production from being wasted. By reintroducing these components into the production cycle, the need for manufacturing equivalent new elements is reduced, thereby avoiding the additional emissions that such processes would inevitably generate. This dynamic has been expressed through the concept of avoided CO₂ emissions, which, in the present case study, corresponds to a reduction of nearly 60% of the total embodied emissions.

In line with the international debate, the findings of this study provide further evidence of the potential benefits of selective deconstruction and upcycling strategies, corroborating previous research that has emphasized the financial and environmental advantages of circular practices in the construction sector [57,58]. However, international literature has predominantly focused on residential buildings in timber or hybrid systems [44], while little attention has been devoted to *authorial* buildings, where the preservation of distinctive elements—such as patented inventions—represents a crucial challenge. In this respect, the case study aligns with the debate explored by Rotor Deconstruction [59], which highlights the dual challenge of reconciling efficiency with heritage valorization. In addition, the study confirms how selective deconstruction, unlike conventional demolition, maximizes the recovery of components and reduces waste, thereby fostering reuse and regeneration [60,61]. Within this framework, the contribution of the present research lies in extending the

application of circular economy principles to buildings not originally conceived with disassembly in mind [62,63], opening up new perspectives for the regeneration of the industrialized building stock.

Nevertheless, the research also reveals certain limitations: (i) the analysis has been deliberately restricted to the avoided costs associated with a “first-stage” reuse scenario, without considering the additional treatments required to reintroduce components into new projects; (ii) the estimates are highly dependent on local market conditions, disposal fees, and the other costs, which may vary across geographical contexts.

Future research should therefore expand the methodological framework in at least three directions: (i) the inclusion of life-cycle costing approaches that account for the full range of processes required for reuse and upcycling; (ii) the application of the model to a wider set of building typologies and construction systems in order to assess its scalability; and (iii) the integration of advanced digital tools—such as GIS-based spatial analysis and artificial intelligence—that can refine financial and environmental estimations and facilitate the transferability of results obtained in one context to others worldwide. Finally, closer alignment with evolving regulatory frameworks and incentive schemes will be essential to fully exploit the transformative potential of upcycling strategies for sustainable urban regeneration.

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References

1. Delbeke, J.; Runge-Metzger, A.; Slingenberg, Y.; Werksman, J. The Paris Agreement. In *Towards a Climate-Neutral Europe*; Routledge: London, UK, 2019; pp. 24–45. ISBN 978-92-76-08256-9.
2. Rees, W.E. The Built Environment and the Ecosphere: A Global Perspective. *Build. Res. Inf.* **1999**, *27*, 206–220. [\[CrossRef\]](#)
3. Çimen, Ö. Construction and Built Environment in Circular Economy: A Comprehensive Literature Review. *J. Clean. Prod.* **2021**, *305*, 127180. [\[CrossRef\]](#)
4. Zabalza Bribián, I.; Valero Capilla, A.; Aranda Usón, A. Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-Efficiency Improvement Potential. *Build. Environ.* **2011**, *46*, 1133–1140. [\[CrossRef\]](#)
5. Ajayabi, A.; Chen, H.-M.; Zhou, K.; Hopkinson, P.; Wang, Y.; Lam, D. REBUILD: Regenerative Buildings and Construction Systems for a Circular Economy. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 225, p. 012015. [\[CrossRef\]](#)
6. Licciardello, D.; Spatafora, S.L.; Vizzini, L.; Martelli, C.; Martelli, C.F.V. Carbon Dioxide Balance of Wooden Structures: Circular Economy in the Ecological Building Industry. *Procedia Environ. Sci. Eng. Manag.* **2017**, *4*, 199–205.
7. Liddo, F.D.; Amoruso, P.; Tajani, F.; Morano, P.; Stara, F. Urban Redevelopment and Decarbonization Challenges. An Overview from the Real Estate Market Perspective. *Energy Build.* **2025**, *343*, 115914. [\[CrossRef\]](#)
8. Pomponi, F.; Moncaster, A. Circular Economy for the Built Environment: A Research Framework. *J. Clean. Prod.* **2017**, *143*, 710–718. [\[CrossRef\]](#)
9. Lei, B.; Yang, W.; Yan, Y.; Zaland, S.; Tang, Z.; Dong, W. Carbon-Saving Benefits of Various End-of-Life Strategies for Different Types of Building Structures. *Dev. Built Environ.* **2023**, *16*, 100264. [\[CrossRef\]](#)

10. Pomponi, F.; Moncaster, A. Embodied Carbon Mitigation and Reduction in the Built Environment—What Does the Evidence Say? *J. Environ. Manag.* **2016**, *181*, 687–700. [\[CrossRef\]](#)
11. Ibn-Mohammed, T.; Greenough, R.; Taylor, S.; Ozawa-Meida, L.; Acquaye, A. Operational vs. Embodied Emissions in Buildings—A Review of Current Trends. *Energy Build.* **2013**, *66*, 232–245. [\[CrossRef\]](#)
12. Swarnakar, V.; Khalfan, M. Circular Economy in Construction and Demolition Waste Management: An in-Depth Review and Future Perspectives in the Construction Sector. *Smart Sustain. Built Environ.* **2024**; *ahead of print*. [\[CrossRef\]](#)
13. Hoang, N.H.; Ishigaki, T.; Watari, T.; Yamada, M.; Kawamoto, K. Current State of Building Demolition and Potential for Selective Dismantling in Vietnam. *Waste Manag.* **2022**, *149*, 218–227. [\[CrossRef\]](#) [\[PubMed\]](#)
14. UNI/PdR 75:2020; Decostruzione selettiva—Metodologia per la decostruzione selettiva e il recupero dei rifiuti in un’ottica di economia circolare. UNI-Ente Italiano di Normazione: Milano, Italy, 2020.
15. Torre, C.M.; Morano, P.; Locurcio, M.; Anelli, D. Comparing Environmental Values and CO₂ Values in Geographical Contexts. In *Computational Science and Its Applications—ICCSA 2023 Workshops*; Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M., Eds.; Lecture Notes in Computer Science; Springer Nature Switzerland: Cham, Switzerland, 2023; Volume 14106, pp. 523–533, ISBN 978-3-031-37110-3.
16. McDonough, W.; Braungart, M. *Cradle to Cradle: Remaking the Way We Make Things*; North Point Press: Berkeley, CA, USA, 2010; ISBN 1-4299-7384-6.
17. Chilton, J. Designing Structures for Deconstruction. *Constr. Inf. Q.* **2009**, *11*, 121–126.
18. Webster, M.; Costello, D. Designing Structural Systems for Deconstruction. In *Proceedings, Greenbuild Conference*; U.S. Green Building Council: Atlanta, Georgia, 2006.
19. Altamura, P. *Costruire a Zero Rifiuti: Strategie e Strumenti per la Prevenzione e L’upcycling dei Materiali di Scarto in Edilizia*; FrancoAngeli: Milano, Italy, 2015; ISBN 978-88-917-2567-7.
20. Akbarnezhad, A.; Ong, K.C.G.; Chandra, L.R. Economic and Environmental Assessment of Deconstruction Strategies Using Building Information Modeling. *Autom. Constr.* **2014**, *37*, 131–144. [\[CrossRef\]](#)
21. Krygiel, E.; Nies, B. *Green BIM: Successful Sustainable Design with Building Information Modeling*; John Wiley & Sons: Hoboken, NJ, USA, 2008; ISBN 0-470-39046-8.
22. Järvelä, H.; Lehto, A.; Pirlä, T.; Kuittinen, M. Metrics for Building Component Disassembly Potential: A Practical Framework. *B&C* **2025**, *6*, 634–653. [\[CrossRef\]](#)
23. Ottenhaus, L.-M.; Hernández-Aldaz, M.; Davies, A.; Cabrero, J.M. Evaluating the Disassembly Potential of Timber Buildings: Development of Calculation Tool and Proof of Concept. *Wood Mater. Sci. Eng.* **2025**, *20*, 881–909. [\[CrossRef\]](#)
24. Gaute-Alonso, A.; Garcia-Sanchez, D.; O’Connor, A. Structural Safety Assessment Criteria for Dismantling Operations of Unique Structures. San Mames Roof Arch Experience. *J. Build. Eng.* **2024**, *84*, 108617. [\[CrossRef\]](#)
25. Sandin, Y.; Cramer, M.; Sandberg, K. How Timber Buildings Can Be Designed for Deconstruction and Reuse in Accordance With ISO 20887. In *Proceedings of the World Conference on Timber Engineering (WCTE 2023)*, Oslo, Norway, 19–22 June 2023; pp. 3558–3567.
26. Khanalizadehtaromi, S. Design for Disassembly and Reuse: Developing an Indicator System for Volumetric Timber Structures Based on Case Studies. Master’s Thesis, Luleå University of Technology, Department of Engineering Sciences and Mathematics, Wood Science and Engineering, Luleå, Sweden, 2023.
27. Anastasiades, K.; Goffin, J.; Rinke, M.; Buyle, M.; Audenaert, A.; Blom, J. Standardisation: An Essential Enabler for the Circular Reuse of Construction Components? A Trajectory for a Cleaner European Construction Industry. *J. Clean. Prod.* **2021**, *298*, 126864. [\[CrossRef\]](#)
28. Attia, S.; Al-Obaidy, M.; Mori, M.; Campain, C.; Giannasi, E.; Van Vliet, M.; Gasparri, E. Disassembly Calculation Criteria and Methods for Circular Construction. *Autom. Constr.* **2024**, *165*, 105521. [\[CrossRef\]](#)
29. Al-Obaidy, M.; Courard, L.; Attia, S. A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. *Sustainability* **2022**, *14*, 3370. [\[CrossRef\]](#)
30. Bartsch, H. Reuse of Reclaimed Steel Components in Construction: A Systematic Review of Potential, Challenges and Future Directions. *Structures* **2025**, *80*, 110057. [\[CrossRef\]](#)
31. Kanyilmaz, A.; Birhane, M.; Fishwick, R.; Del Castillo, C. Reuse of Steel in the Construction Industry: Challenges and Opportunities. *Int. J. Steel Struct.* **2023**, *23*, 1399–1416. [\[CrossRef\]](#)
32. ISO 20887:2020; Sustainability in Buildings and Civil Engineering Works—Design for Disassembly and Adaptability—Principles, Requirements and Guidance. International Organization for Standardization (ISO): Geneva, Switzerland, 2020.
33. Ministero per i Beni e le Attività Culturali. *Italian Legislative Decree No. 42 of 22 January 2004. Code of Cultural Heritage and Landscape, in Accordance with Article 10 of the Law No. 137 of July 6, 2002*; Ministero per i Beni e le Attività Culturali: Roma, Italy, 2004.
34. Pimentel, R.; Brown, D.; Sansom, M. *SCI P427-Structural Steel Reuse: Assessment, Testing and Design Principles*; The Steel Construction Institute: Ascot, UK, 2019; ISBN 978-1-85942-243-4.

35. ISO 16739-1:2024; Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries Part 1: Data Schema. International Organization for Standardization (ISO): Geneva, Switzerland, 2024.
36. Bologna, A.; Garcia-Fuentes, J.M.; Giannetti, I.; Neri, G. *Upcycling Architecture in Italy—Design Workshop—Risultati/Results*; Upcycling Architecture in Italy: Torino, Italy, 2024; ISBN 979-12-81583-09-2.
37. DEI. *Prezzi Tipologie Edilizie*; DEI: Roma, Italy, 2024; ISBN 979-12-5505-137-4.
38. Ellen MacArthur Foundation. *Cities in the Circular Economy: An Initial Exploration*; Ellen MacArthur Foundation: Isle of Wight, UK, 2017.
39. Benachio, G.L.F.; Freitas, M.D.C.D.; Tavares, S.F. Circular Economy in the Construction Industry: A Systematic Literature Review. *J. Clean. Prod.* **2020**, *260*, 121046. [CrossRef]
40. Guerra, B.C.; Leite, F. Circular Economy in the Construction Industry: An Overview of United States Stakeholders' Awareness, Major Challenges, and Enablers. *Resour. Conserv. Recycl.* **2021**, *170*, 105617. [CrossRef]
41. Mahpour, A. Prioritizing Barriers to Adopt Circular Economy in Construction and Demolition Waste Management. *Resour. Conserv. Recycl.* **2018**, *134*, 216–227. [CrossRef]
42. Economy, C. The Circularity Gap Report 2023. Available online: <https://www.circularity-gap.world/2023> (accessed on 13 August 2025).
43. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*; John Wiley & Sons: Hoboken, NJ, USA, 2016; ISBN 1-119-05517-2.
44. Zaman, A.U.; Arnott, J.; McIntyre, K.; Hannon, J. Resource Harvesting through a Systematic Deconstruction of the Residential House: A Case Study of the 'Whole House Reuse' Project in Christchurch, New Zealand. *Sustainability* **2018**, *10*, 3430. [CrossRef]
45. Chileshe, N.; Rameezdeen, R.; Hosseini, M.R.; Martek, I.; Li, H.X.; Panjehbashi-Aghdam, P. Factors Driving the Implementation of Reverse Logistics: A Quantified Model for the Construction Industry. *Waste Manag.* **2018**, *79*, 48–57. [CrossRef] [PubMed]
46. Directive-2003/87-EN-EUR-Lex. Available online: <https://eur-lex.europa.eu/eli/dir/2003/87/oj/eng> (accessed on 3 October 2025).
47. World Bank Group. Available online: <https://carbonpricingdashboard.worldbank.org/compliance/price> (accessed on 26 August 2025).
48. Shin, D.-W.; Cho, K.-M.; Lee, U.-K.; Kim, T.-H. Analysis of the Factors Influencing the Demolition Costs. *J. Korea Inst. Build. Constr.* **2018**, *18*, 499–506.
49. Tatiya, A.; Zhao, D.; Syal, M.; Berghorn, G.H.; LaMore, R. Cost Prediction Model for Building Deconstruction in Urban Areas. *J. Clean. Prod.* **2018**, *195*, 1572–1580. [CrossRef]
50. Hradil, P.; Talja, A.; Ungureanu, V.; Koukkari, H.; Fülöp, L. 21.03: Reusability Indicator for Steel-framed Buildings and Application for an Industrial Hall. *Ce/Papers* **2017**, *1*, 4512–4521. [CrossRef]
51. Akinade, O.O. BIM-Based Software for Construction Waste Analytics Using Artificial Intelligence Hybrid Models. Ph.D. Thesis, University of the West of England, Bristol, UK, 2017.
52. Mollaei, A.; Bachmann, C.; Haas, C. Estimating the Recoverable Value of In-Situ Building Materials. *Sustain. Cities Soc.* **2023**, *91*, 104455. [CrossRef]
53. Mohammed, M.; Shafiq, N.; Abdallah, N.; Ayoub, M.; Haruna, A. *A Review on Achieving Sustainable Construction Waste Management through Application of 3R (Reduction, Reuse, Recycling): A Lifecycle Approach*; IOP Publishing: Bristol, UK, 2020; Volume 476, p. 012010.
54. Tam, V.W.; Tam, C.M. *Re-Use of Construction and Demolition Waste in Housing Developments*; Nova: Hauppauge, NY, USA, 2008; ISBN 1-60456-362-1.
55. Anelli, D.; Morano, P.; Tajani, F.; Di Liddo, F.; Locurcio, M. Environmental Impacts and Housing Deprivation: A Study of the Effects of Industrial Polluting Sites in the Italian Context. In *Computational Science and Its Applications—ICCSA 2025 Workshops*; Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Faginas Lago, M.N., Scorza, F., Braga, A.C., Eds.; Lecture Notes in Computer Science; Springer Nature Switzerland: Cham, Switzerland, 2026; Volume 15889, pp. 381–392, ISBN 978-3-031-97602-5.
56. Akbarnezhad, A.; Ong, K.C.G.; Tam, C.T.; Zhang, M.H. Effects of the Parent Concrete Properties and Crushing Procedure on the Properties of Coarse Recycled Concrete Aggregates. *J. Mater. Civ. Eng.* **2013**, *25*, 1795–1802. [CrossRef]
57. Bayram, B.; Greiff, K.; Gerlich, L.; Luthin, A.; Hildebrand, L.; Traverso, M. Environmental and Economic Implications of Selective Demolition and Advanced Recycling of Construction Waste. *Sustain. Prod. Consum.* **2025**, *57*, 61–79. [CrossRef]
58. Antunes, A.; Martins, R.; Silvestre, J.D.; Do Carmo, R.; Costa, H.; Júlio, E.; Pedroso, P. Environmental Impacts and Benefits of the End-of-Life of Building Materials: Database to Support Decision Making and Contribute to Circularity. *Sustainability* **2021**, *13*, 12659. [CrossRef]
59. Deconstruction (Volume N° 51) | Rotor. Available online: <https://rotordb.org/en/projects/deconstruction-volume-ndeg-51> (accessed on 23 September 2025).
60. Addis, B. *Briefing: Design for Deconstruction*; Thomas Telford Ltd.: London, UK, 2008; Volume 161, pp. 9–12.
61. Guy, B.; Shell, S.; Esherick, H. Design for Deconstruction and Materials Reuse. *Proc. CIB Task Group* **2006**, *39*, 189–209.

62. Coelho, A.; De Brito, J. Economic Analysis of Conventional versus Selective Demolition—A Case Study. *Resour. Conserv. Recycl.* **2011**, *55*, 382–392. [[CrossRef](#)]
63. Bertino, G.; Kisser, J.; Zeilinger, J.; Langergraber, G.; Fischer, T.; Österreicher, D. Fundamentals of Building Deconstruction as a Circular Economy Strategy for the Reuse of Construction Materials. *Appl. Sci.* **2021**, *11*, 939. [[CrossRef](#)]

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