



GRAĐEVINSKI
**MATERIJALI I
KONSTRUKCIJE**

BUILDING
**MATERIALS AND
STRUCTURES**

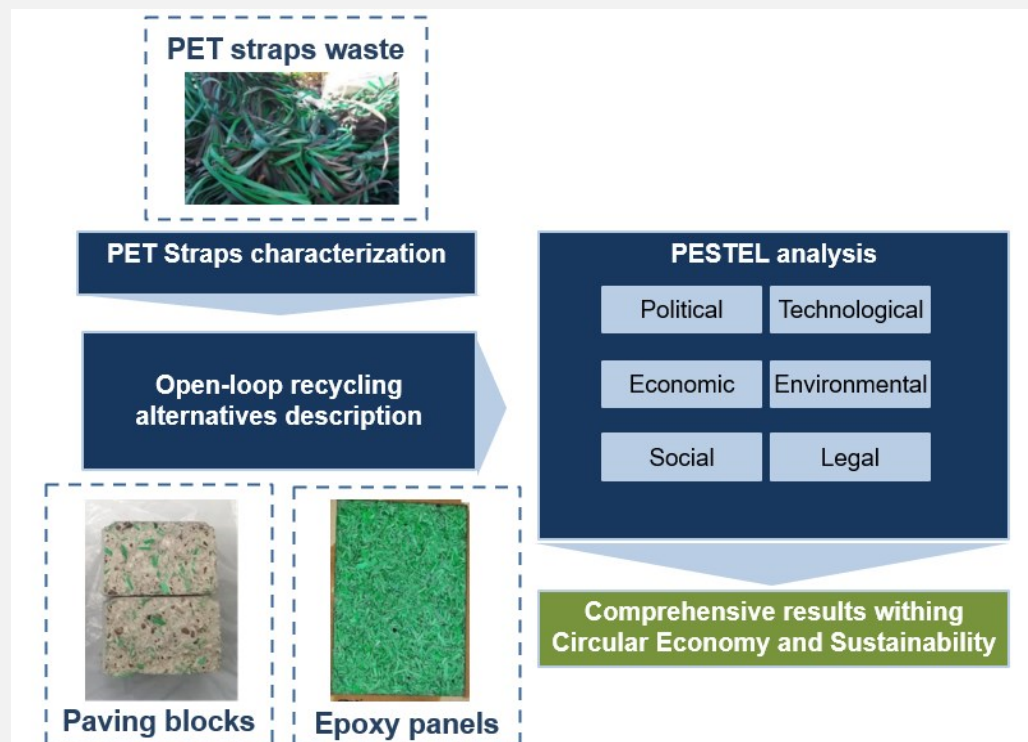
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**Innovative Circular Materials and Solutions for Sustainable
Buildings and Structures**

Guest Editors: Luis Bragança, Meri Cvetkovska, Mirjana Malešev, Mirjana Laban, Rand Askar



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Aims and scope

Building Materials and Structures aims at providing an international forum for communication and dissemination of innovative research and application in the field of building materials and structures. Journal publishes papers on the characterization of building materials properties, their technologies and modeling. In the area of structural engineering Journal publishes papers dealing with new developments in application of structural mechanics principles and digital technologies for the analysis and design of structures, as well as on the application and skillful use of novel building materials and technologies.

The scope of Building Materials and Structures encompasses, but is not restricted to, the following areas: conventional and non-conventional building materials, recycled materials, smart materials such as nanomaterials and bio-inspired materials, infrastructure engineering, earthquake engineering, wind engineering, fire engineering, blast engineering, structural reliability and integrity, life cycle assessment, structural optimization, structural health monitoring, digital design methods, data-driven analysis methods, experimental methods, performance-based design, innovative construction technologies, and value engineering.

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EDITORIAL

Special Issue: Innovative Circular Materials and Solutions for Sustainable Buildings and Structures

The construction industry is undergoing a pivotal transformation, driven by the need to respond to climate change, resource scarcity and environmental degradation. This Special Issue, Innovative Circular Materials and Solutions for Sustainable Buildings and Structures, brings together research that advances resource efficiency, reduces waste and supports low-carbon building practices. The ten papers gathered here tackle circularity from multiple angles: novel materials that close resource loops, digital tools and design strategies that keep components in service longer, and the assessment, management and governance instruments that turn principles into practice.

This Special Issue emerged from COST Action CA21103, Implementation of Circular Economy in the Built Environment (CircularB), which connects researchers, practitioners and policymakers from over fifty countries. CircularB addresses a persistent practical gap: although European policy places circularity at the center of the construction agenda, implementation is held back by fragmented definitions, heterogeneous assessment methods and limited attention to the existing building stock.

To overcome these barriers, the Action is developing a common circularity framework for new and existing buildings, built on adaptable Key Performance Indicators. A central output is the Roadmap towards Circularity in the Built Environment, which identifies twenty priority topics across materials, design strategies, digitalisation, business models and policy. The papers in this issue populate several of these priority areas. (Readers interested in the full body of work may consult the edited volumes Circular Economy Design and Management in the Built Environment, 2025, and Shaping Circular Transitions in the Built Environment, 2026.)

A first group of papers concerns the materials that close resource loops. One study develops a low-carbon binder that uses municipal solid waste incineration bottom ash as the sole precursor of an alkali-activated cement, and validates it in a full-scale pedestrian paving element with low metal leaching and adequate strength. Another evaluates two open-loop routes for recycling discarded PET straps into construction products through a PESTEL analysis, finding paving blocks ready for immediate use and resin-bound panels promising but less mature. The first part of a two-part review systematises the regulations, recycling rates and reuse and recycling practices for steel and timber at the end of their service life. A further contribution assesses silica aerogel plaster as a non-invasive insulation solution for the renovation of cultural heritage, tested through dynamic energy simulation of a protected modernist building.

A second group examines digital technologies and design strategies that enable circularity. A systematic review maps how Building Information Modelling can support design for adaptability and deconstruction, keeping components in use for longer. A qualitative study explores how construction professionals perceive a BIM-based materials passport, identifying the modelling and information-management gaps that still limit its adoption. A conceptual framework combines virtual reality, augmented reality and artificial intelligence to reduce waste and strengthen decision-making across the project life cycle.



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A third group turns to assessment, management and governance, the core of process circularity. One review analyses established sustainability tools such as BREEAM, LEED and DGNB, shows that they still lack specific metrics for material loops, design for disassembly and resource recovery, and proposes an expanded set of indicators. Another explores the synergy between circular economy practices and agile project management, locating the strongest links at the design stage and around flexibility and transparency. A third, reading circular policies through a multi-level governance lens, finds that most initiatives remain focused on end-of-life waste and rarely connect the local, regional and national levels.

Read together, these papers show circularity advancing on several fronts at once: in the materials we produce and recover, in the existing buildings we renovate, in the digital tools that manage information across the life cycle, and in the assessment, management and governance instruments that turn principles into practice. A recurrent insight is that material passports and circularity indicators only deliver value when fed with reliable upstream data – a task for which digital traceability tools, including BIM and AI, are essential. The contributions also confirm the value of sustained transnational cooperation in aligning concepts and connecting researchers across countries and disciplines around a shared goal.



Looking ahead, the contributions collectively point to several priorities: harmonised metrics that capture material loops and design for disassembly, digital traceability supported by artificial intelligence, renovation strategies that respect heritage while improving performance, and business models that turn open-loop recycling into economically attractive routes.

We thank all the authors for their contributions and the reviewers for their careful and timely work. We are grateful to the Editor-in-Chief, Professor Snežana Marinković, and to the editorial team of Building Materials and Structures for hosting this Special Issue and for their support throughout the process. We hope these papers will be useful to researchers, practitioners and policymakers working towards a circular built environment.

On behalf of the Guest Editors,
Luís Bragança, Meri Cvetkovska, Mirjana Malešev, Mirjana Laban, Rand Askar



Low-carbon cementitious material from municipal solid waste incineration bottom ash for street furniture and outdoor paving: A circular economy perspective

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ABSTRACT

This study investigates the feasibility of employing municipal solid waste incineration bottom ash (WBA) as the sole precursor for producing alkali-activated binders (AA-WBA), with the aim of developing low-carbon mortars and concretes for non-structural urban applications within a circular-economy framework. The precursor, originally in the 8-30 mm particle-size fraction reported in previous studies, was milled to obtain material below 125 μm . A series of activation conditions was examined by varying the NaOH concentration, the NaOH-to-sodium-silicate ratio, and the liquid-to-solid ratio, together with three precursor particle-size ranges ($\leq 63 \mu\text{m}$, 90-100 μm , and 100-125 μm). The optimal formulation (1:4/0.6/4 M; 90-100 μm) achieved satisfactory mechanical performance in paste form and developed a dense microstructure characterised by the formation of C-(A)-S-H/N-A-S-H gels, as evidenced by TGA, FT-IR, and SEM analyses. As a proof of concept, this binder was used to manufacture a full-scale concrete pedestrian paving element, which exhibited adequate mechanical performance for outdoor pedestrian use at 28 days. Leaching and ecotoxicity tests indicated low metal release and no significant toxic effects, thereby demonstrating the environmental safety of the material and its potential contribution to more sustainable construction systems.

1 Introduction

Alkali-activated cements offer a lower environmental-impact alternative to conventional cement production. As a result, there is growing interest within the construction sector in materials capable of partially or fully replacing Portland cement (OPC), the manufacture of which is associated with substantial global CO₂ emissions and high primary energy demand.

In the precast sector, particularly in the manufacture of street furniture, outdoor paving units and other non-structural components, the use of municipal solid waste incineration bottom ash (WBA) as a precursor in alkali-activated cements (AA-WBA) promotes a more sustainable production cycle, sourcing raw materials directly from citizen-generated waste. This approach is feasible because incineration is widely regarded as an effective strategy for managing the growing volume of municipal solid waste [1].

The study is framed within the principles of the circular economy, emphasising their relevance in reducing the carbon footprint associated with both binder production and use. This approach not only enhances the sustainability of

cementitious formulations but also valorises waste materials and optimises their management, thereby contributing to a process fully aligned with circular-economy objectives.

The literature review indicates that, although several attempts have been made to optimise AA-WBA systems, studies focusing exclusively on the activation of WBA remain limited [2]. Nevertheless, based on the behaviour reported in previous studies [3–7] and preliminary findings from other authors, there is significant potential to improve the performance of AA-WBA produced solely from WBA. This knowledge gap provides a clear opportunity to further investigate the activation mechanisms and optimise the resulting material properties.

WBA exhibits a wide particle-size distribution [8]. The finer fractions contain the majority of soluble salts and potentially leachable heavy metals (and metalloids), whereas the coarser fractions are predominantly composed of ceramics and glass. Natural weathering over 2-3 months outdoors has been shown to significantly reduce the leaching potential; consequently, in most European countries, WBA is currently classified as non-hazardous waste [9,10]. However, information on the mechanical performance and

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durability of concretes produced with alkali-activated cements remains limited, despite their previous use in various applications. This gap underscores the need to translate laboratory findings into potential industrial-scale applications, particularly when using WBA as the primary precursor for non-structural components.

Considering environmental criteria and the goal of maximising WBA recovery, the 8-30 mm fraction, also characterized by the highest SiO₂ content [11], has been identified as the most suitable for alkaline activation. During the material preparation stage, and in order to evaluate the mechanical performance of the binder (AA-WBA paste) formulated exclusively from WBA, this fraction was milled to produce particle sizes ≤125 μm, following procedures reported in previous studies [12]. However, it is to be expected that particles within this powdered WBA will display heterogeneous reactivity as precursors during alkaline activation. Therefore, it is anticipated that finer particles generally enhance dissolution kinetics and promote the formation of reaction products, which improves mechanical performance. Furthermore, the mineralogical composition of the particles plays a critical role, as more fragile phases tend to concentrate in the finer fractions, thereby increasing the availability of reactive species such as SiO₂ and Al₂O₃. Nevertheless, excessive grinding raises energy consumption and may compromise industrial feasibility. This variability in particle behavior provides an opportunity to evaluate the balance between chemical reactivity, mechanical strength and processing efficiency.

Using the powdered 8-30 mm WBA fraction, the study aims to evaluate the mechanical behavior (compressive strength) of AA-WBA pastes across three particle-size ranges: ≤63 μm, 90-100 μm, and 100-125 μm. The fraction exhibiting the best mechanical performance was subsequently employed in a proof-of-concept test aimed at evaluating potential industrial-scale application, yielding satisfactory results.

2 Materials and methods

The powdered WBA sample was supplied by Escofet S.A., a Barcelona-based company specializing in the design and industrial production of urban furniture and paving elements. The sample was originally obtained from a local waste-to-energy facility, where it was generated during the combustion of municipal solid waste at approximately 950 °C. This was subsequently conditioned to recover valuable materials [4,8] using magnetic and eddy-current separators. The remaining mineral fraction was stored outdoors for 2-3 months to allow chemical stabilization [13], after which the stabilised bottom ash underwent selection, screening and final grinding. Figure 1 presents the processing route, through which an initial 40-tonne batch of stabilised WBA was treated. During the screening stage, approximately 6 tonnes were recovered within the 8-30 mm particle-size fraction. This range was selected because previous studies [3] have reported that the highest SiO₂ availability occurs in fractions larger than 8 mm. In addition, this fraction is less contaminated and contains lower amounts of metallic aluminium, thereby reducing hydrogen generation compared with other fractions studied previously [12]. Once this fraction had been obtained, it was subjected to a grinding process to reduce the particle size to below 1 mm. Prior to undertaking the secondary grinding stage, a crucial step was performed to remove any remaining metallic impurities that could interfere with both the grinding operation and the final properties of the cementitious material. The conditioned material was then subjected to fine grinding in a ball mill, enabling a particle size of less than 125 μm to be achieved. Table 1 presents the elemental composition of the WBA, determined by X-ray fluorescence (XRF) using a Bruker S2 PUMA Light Element Energy Dispersive X-ray Fluorescence Spectroscopy. The results indicate a high proportion of SiO₂ (46.61%) and CaO (27.74%), both of which are essential for the formation of C-A-S-H and (C,N)-A-S-H gels during alkaline activation.

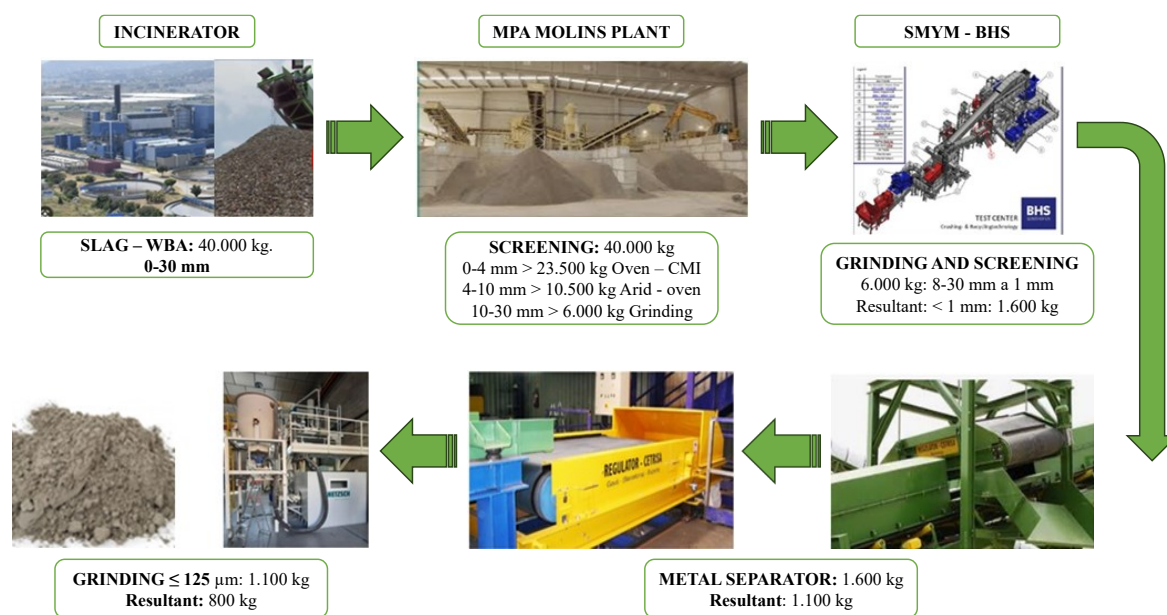


Figure 1. Process of conditioning WBA as a precursor material for alkaline-activated binders

Table 1. Elemental oxide composition of powdered WBA

Major elements	(wt.%)	Minor and traces elements	(wt.%)
SiO ₂	48.61	PbO	0.09
CaO	24.74	MnO	0.09
Al ₂ O ₃	9.23	ZrO ₂	0.09
Fe ₂ O ₃	4.31	Sc ₂ O ₃	0.08
Na ₂ O	4.15	Cr ₂ O ₃	0.07
SO ₃	2.45	BaO	0.06
MgO	2.32	SrO	0.06
K ₂ O	1.44	SnO ₂	0.02
P ₂ O ₅	0.76	NiO	< 0.01
TiO ₂	0.59	Rb ₂ O	< 0.01
Cl	0.5	HfO ₂	< 0.01
ZnO	0.19	MoO ₃	< 0.01
CuO	0.12	Br	< 0.01
LOI (1050°C)	9.36		

This powdered WBA exhibits a density of 2.79 g·cm⁻³, a specific surface area of 4.08 m²·g⁻¹, and an average adsorption pore width of 20.98 Å. The particle size distribution (PSD) is presented in Figure 2. The analyses were performed using a Beckman Coulter LS13320 operating in micro-liquid mode with ethanol as the dispersant. Crystalline phases were identified by X-ray diffraction (XRD) using a PANalytical X'Pert PRO MPD

diffractometer configured in Bragg-Brentano θ/θ geometry with a 240 mm radius. As shown in Figure 3, the material contains numerous mineral phases and a significant fraction of amorphous phases, as evidenced by the angular range from 20 to 35° (2 θ).

For the alkaline activation, a mixture of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) was used. The sodium silicate (waterglass, WG) employed was a commercial solution supplied by Sharlab Laboratories, with a density of 1.37 g·cm⁻³, complete miscibility in water at 20 °C, and a pH of 11-11.5.

2.1 Specimen preparation

All specimens were prepared in 25 mm cubic moulds. For each formulation in the first test series, six specimens were produced for 28-day compressive strength testing using an Incotecnic Multi R-1 universal testing machine, applying a loading rate of 240 kg·s⁻¹ in accordance with UNE 196-1 [13]. The specimens were cured in a humid environment. They were placed in resealable bags containing a small water reservoir for the first three days, then demoulded and maintained under the same conditions at 23 ± 1 °C and 95 ± 5% relative humidity. The formulations varied by changing the NaOH:WG ratio, activator-to-precursor ratio (L/S), and the molarity of the NaOH solution (4M, 6M, 8M, and 10M), as summarised in Table 2. Mixing was carried out in a Labbox OS40-series mixer. During the first 2 minutes at 470 rpm, the activator blend was gradually added to the powdered WBA precursor, followed by a further 3 minutes of mixing at 760 rpm [12]. The mixtures were then discharged, vibrated, and cast into the moulds.

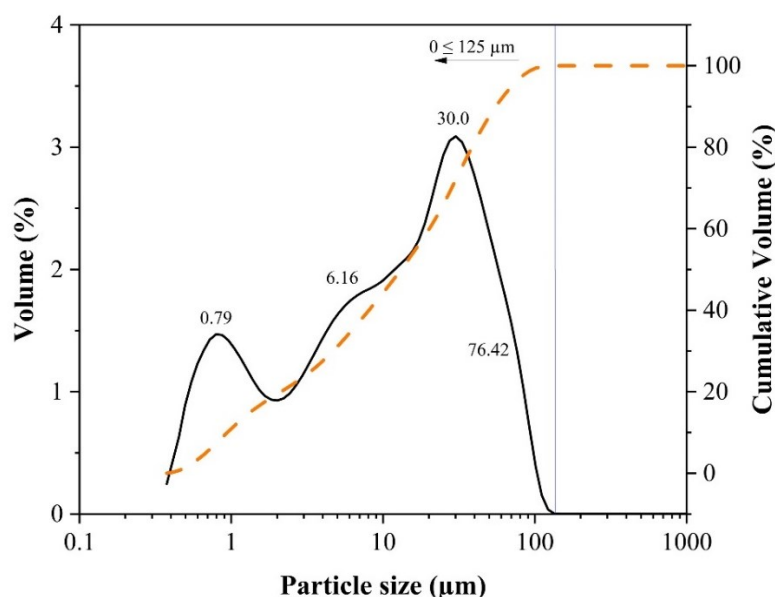


Figure 2. Particle size distribution (PSD) of powdered WBA

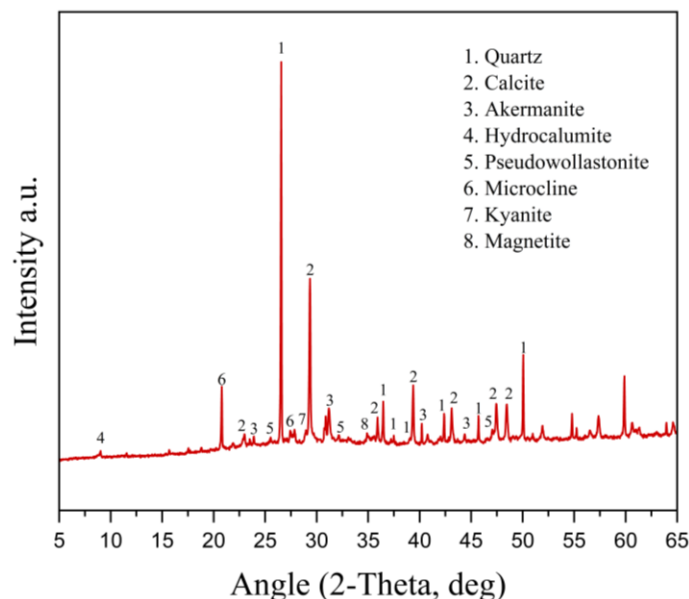


Figure 3. X-ray diffraction (XRD) pattern of powdered WBA

Table 2. Preparation of samples using NaOH:WG combinations with different NaOH molar concentrations

Activator-to-precursor ratio (L/S) 0.5																
NaOH:WG ratio	1:1				1:2				1:3				1:4			
NaOH Molar concentrations	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M
Prepared specimens	-	-	-	-	-	-	x	x	-	-	-	-	-	-	-	-
Activator-to-precursor ratio (L/S) 0.6																
NaOH:WG ratio	1:1				1:2				1:3				1:4			
NaOH Molar concentrations	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M
Prepared specimens	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Activator-to-precursor ratio (L/S) 0.7																
NaOH:WG ratio	1:1				1:2				1:3				1:4			
NaOH Molar concentrations	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M	4M	6M	8M	10M
Prepared specimens	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

x: Formulations with prepared samples

•: Specimens prepared from formulations with high liquid-to-solid ratios and lower compressive strengths

-: Formulations from which specimens could not be prepared due to rapid reactions during mixing

Using the optimal formulation identified in the first test series (employing the full precursor fraction), specimens were prepared for a second experimental stage. In this stage, the powdered WBA precursor was sieved to obtain three particle-size fractions: $\leq 63 \mu\text{m}$, $90\text{--}100 \mu\text{m}$, and $100\text{--}125 \mu\text{m}$. Cubic specimens (25 mm) were cast and cured following the same procedure used in the first stage, in which the precursor comprised the entire particle-size distribution. For each fraction, eight specimens were produced; four were tested after 3 days and four after 7 days.

Finally, the precursor fraction that exhibited the highest increase in compressive strength was used to produce a new set of 25 mm cubic specimens. These were tested at 3, 7, and 28 days using the optimal formulation identified in the

first stage, together with two additional formulations in which the NaOH:WG ratio and the liquid-to-solid ratio were varied.

2.2 Characterization of alkali-activated binder

In accordance with UNE-EN 196-1, the mechanical behaviour of the AA-WBA pastes was evaluated using an Incotecnic MULTI-R1 Lab-Pre S.L. universal testing machine, operating at a loading rate of $240 \text{ kg}\cdot\text{s}^{-1}$ with a 2.5 kN load cell. These conditions were maintained throughout the three test stages. Following the mechanical tests, a microstructural analysis of the AA-WBA pastes formulated with different precursor particle sizes was conducted using a JEOL J-7100FE high-resolution scanning electron

microscope (SEM). In addition, the chemical bonds and functional groups of the reaction products were identified and characterised by Fourier transform infrared spectroscopy (FT-IR) within the 4000–450 cm^{-1} spectral range, using a PerkinElmer Spectrum Two™ spectrometer equipped with an ATR accessory, at a resolution of 4 cm^{-1} and four scans per sample. Thermogravimetric analysis (TGA) was also performed to quantify mass variations during controlled heating in a nitrogen (N_2) atmosphere, using a TGA 550 analyser (TA Instruments), at a heating rate of 10 $^\circ\text{C}\cdot\text{min}^{-1}$ up to a maximum temperature of 1000 $^\circ\text{C}$.

2.3 Determination of environmental impacts

The environmental impact of the concrete used in the proof of concept was assessed, with particular emphasis on the ecotoxicity parameter, in line with European regulations that promote the use of bioassays to evaluate the release of hazardous substances. The luminescence inhibition test using *Vibrio fischeri* was performed in accordance with ISO 11348-3:2007 [14] as a preliminary assay to detect potential toxic effects in aquatic environments. Leachates were prepared following the UNE-EN 12457-4 [15] leaching procedure, with two replicates per sample. This methodology, supported by recent studies and by the CEN (2022) [16] technical guide on ecotoxicity in construction products, enabled a complementary evaluation of the environmental impacts across the material's life cycle.

2.3.1 Leaching test

Leachates were prepared in accordance with UNE-EN 12457-4, using a compliance test with a liquid-to-solid ratio of 10 $\text{L}\cdot\text{kg}^{-1}$ to evaluate the release of compounds associated with ecotoxicity under chemical equilibrium conditions. The granular material, with 95% of particles smaller than 10 mm, was maintained in contact with deionised water for 24 hours in a rotary shaker at 10 rpm. The resulting leachates were then vacuum-filtered through a 0.45 μm cellulose nitrate membrane, after which pH and conductivity were measured. The filtered leachates were stored at 4 $^\circ\text{C}$ for 24 hours prior to bioassay testing. The specific ionic composition of the leachates, including heavy metals, was determined under the same conditions specified in UNE-EN 12457-2. Analyses were conducted using inductively coupled plasma optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS).

2.3.2 Ecotoxicity testing

The ecotoxicological assessment of the proof-of-concept concrete was conducted using a luminescence bioassay with *Vibrio fischeri* (NRRL B-11177) and Microtox LX® equipment. The bacterial strain was supplied in a lyophilised form and

stored at -18 to -20 $^\circ\text{C}$ in 1 mL vials. Tests were performed at concentrations of 0, 5.6, 11.25, 22.5, and 45%, with two replicates per concentration, and the pH was adjusted to between 6.5 and 8.5 using HCl.

3 Results and discussion

3.1 Mechanical behaviour

The formulations employed in this study were designated according to a nomenclature that indicates the NaOH-to-WG ratio, the activator-to-precursor (L/S) ratio, and the molar concentration of NaOH. For instance, a designation such as 1:4/0.6/4M refers to a formulation with a NaOH-to-WG ratio of 1:4, an L/S ratio of 0.6 and a NaOH molarity of 4 M.

According to Table 2, the formulations with a L/S ratio of 0.7, although feasible to prepare and yielding highly fluid mixtures, exhibited low compressive strength values. Within this group, the 1:4/0.7/6M formulation achieved the highest strength, reaching 5.65 MPa. The remaining formulations in this trial, which showed even lower values, were excluded from the analysis due to their poor mechanical performance. For the other mixtures within this range, the test specimens disintegrated upon demoulding as a result of insufficient particle cohesion, displaying a distinctly sandy texture.

Conversely, the formulations with a liquid-to-solid ratio of 0.5 reacted very rapidly during mixing, which prevented the preparation of test specimens for compressive strength testing. In contrast, a liquid-to-solid ratio of 0.6 enabled the production of specimens using a fluid and workable mixture. However, it was observed that as the NaOH molar concentration increased, the mixtures became more fluid but induced swelling in the specimens during the first hours of curing. The presence of metallic aluminium generates hydrogen gas during the reaction, leading to expansion of the mixtures [17–20]. Several studies have confirmed that metallic aluminium derived from waste undergoes intense thermal transformation during the incineration process, resulting in the formation of new aluminium-based metallic phases alloyed with other metals and metalloids (Fe, Si, Mn, Ti, Ca), which are responsible for such expansive deformations in the specimens [18].

Table 3 summarises the highest compressive strength results obtained for formulations prepared with a L/S ratio of 0.6, using the full precursor fraction. The reported range, from 1:3/0.6/4M to 1:4/0.6/10M corresponds to the combination that delivered the best compressive performance. Among these, the 1:4/0.6/4M formulation exhibited the highest mechanical performance, reaching a compressive strength of 11.16 MPa. For this formulation, the activator's $\text{SiO}_2/\text{Na}_2\text{O}$ ratio was 2.7. Within the group of formulations with the highest mechanical performance, the activator modulus varied between 1.89 and 2.7

Table 3. Compressive strength results for all precursor particle sizes

Activator-to-precursor ratio (L/S)	0.6							
	1:3				1:4			
NaOH:WG ratio								
NaOH Molar concentrations	4M	6M	8M	10M	4M	6M	8M	10M
28-day compressive strength (MPa)	10.86	9.76	4.28	2.76	11.16	9	9.65	5.31
$\text{SiO}_2/\text{Na}_2\text{O}$ activator module	2.52	2.23	2.03	1.89	2.70	2.46	2.26	2.13
Ratio a/c total sample*	0.34	0.33	0.32	0.31	0.33	0.32	0.31	0.31

*: Total sample ratio without the solid fraction contained in the activator (Si, Na from WG and NaOH)

This finding is particularly relevant as it highlights that deviations from standard formulations reported in previous studies can substantially affect compressive strength. Several authors have observed that an activator modulus exceeding 2 may adversely impact both the workability and the mechanical performance of the material [21,22]. Other studies [12], however, have demonstrated that this modulus is not the sole parameter influencing strength and workability at an industrial scale. Increasing the proportion of NaOH in the alkaline activating mixture enhances the reactivity with the metallic aluminium present in WBA, which promotes hydrogen generation and, consequently, reduces the mechanical performance. Nevertheless, research on paste formulations has shown that an appropriate balance between high compressive strength and adequate workability can be achieved. Furthermore, both properties can be further optimized through the incorporation of mineral and chemical additives that improve mixture handling, facilitating the production of street furniture and outdoor paving elements.

Based on the results obtained for the best-performing formulation in the first testing stage, in which specimens with a 1:4/0.6/4M ratio exhibited the highest compressive strength, the corresponding mixtures for the second stage were prepared. However, formulations incorporating particles smaller than 63 μm could not be produced, as the mixtures underwent an accelerated reaction during mixing, leading to premature setting. In contrast, mixtures with particle sizes between 90-100 μm and 100-125 μm produced the results shown in Figure 4a, where the formulations

containing 90-100 μm particles and the optimal mixture displayed superior mechanical performance. Nevertheless, when the NaOH:WG ratio was adjusted to 1:2 while using a NaOH molar concentration of 6 M, no favourable results were obtained. For the 100-125 μm particle-size fraction, although specimen fabrication was possible, the samples exhibited substantial porosity, which negatively affected their compressive strength.

In the third testing stage, the optimal formulation (1:4/0.6/4M), combined with the most suitable particle-size fraction (90-100 μm), was selected as the reference for preparing new specimens with comparable mixtures. In these formulations, slight adjustments were introduced to the NaOH:WG ratio and the L/S ratio in order to assess potential variations in both compressive strength and workability. Figure 4b confirms that the previously identified optimal formulation (1:4/0.6/4M), incorporating precursor particles in the 90-100 μm range, delivers the highest compressive strength for this material, reaching values of up to 23.5 MPa.

3.2 Physicochemical characterization

3.2.1 Thermogravimetric (TGA) analysis

Figure 5 presents the thermogravimetric analysis (TGA) results and the corresponding derivative curves (DTG) for the powdered WBA precursor and for the two AA-WBA formulations produced using the two particle-size fractions (90-100 μm and 100-125 μm).

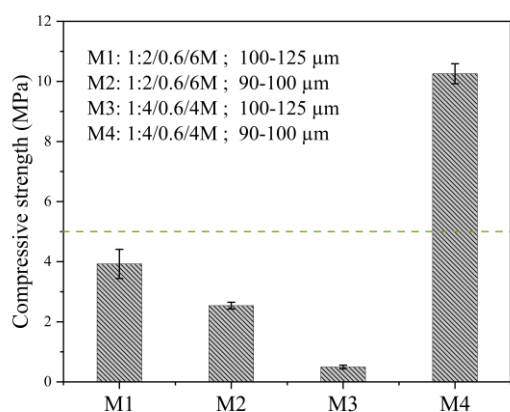


Fig. 4a

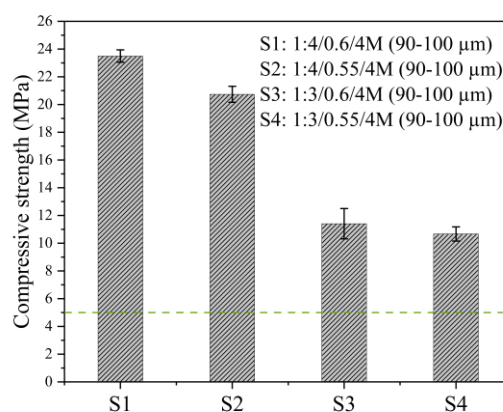


Fig. 4b

Figure 4. a) Compressive strength at 7 days of samples with different particle sizes. b) Compressive strength at 28 days with precursor particle size between 90-100 μm

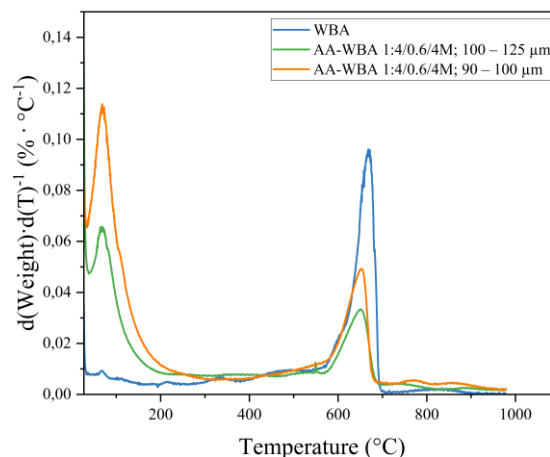
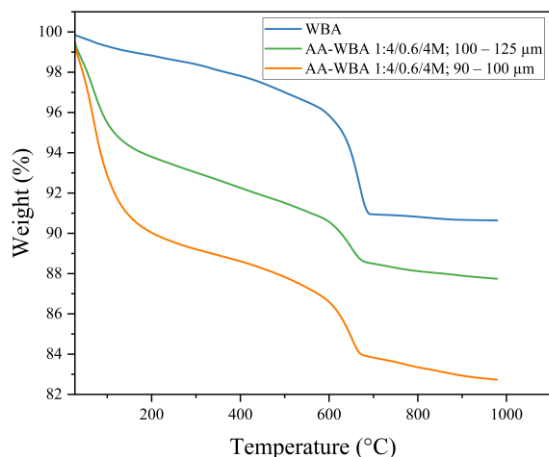


Figure 5. TGA and DTG curves of powdered WBA samples and formulations with higher mechanical strength

In the range of 25–200 °C, all samples exhibit a mass loss associated with the release of physically adsorbed water and structurally bound water. This loss is more pronounced in the AA-WBA formulations (90–100 µm and 100–125 µm) than in the WBA precursor, indicating the formation of hydrated products during the alkaline activation process. The most prominent peaks in the DTG curves, occurring between 110 and 150 °C, are attributed to the dehydration of C-(A)-S-H and/or N-A-S-H gels, consistent with previous findings reported in the literature [23–25].

In the range of 200–400 °C, low-intensity secondary peaks are observed in the activated formulations, which may be associated with the dehydroxylation of hydrotalcite-type phases or hydrated aluminates. In contrast, the powdered WBA precursor shows no significant variations within this interval, confirming its predominantly anhydrous nature. Between 400 and 700 °C, the activated formulations display additional mass losses attributable to the decomposition of carbonates formed on the particle surfaces. The powdered WBA precursor, by comparison, exhibits a pronounced DTG peak around 650–700 °C, corresponding to the thermal decomposition of calcium carbonate (CaCO₃) present in the original material. This behaviour has been previously reported in studies on alkali-activated incineration residues [26,27].

Above 700 °C, all three samples reach a thermally stable region, with no further significant mass loss. The total mass loss up to 1000 °C is approximately 10% for the powdered WBA precursor and between 12% and 14% for the activated formulations, reflecting the higher content of structural water and hydrated phases in the alkaline systems.

Comparatively, the formulation with a particle fraction of 90–100 µm exhibits a more pronounced initial weight loss and a more stable thermal response at elevated temperatures, suggesting a higher degree of reaction and the formation of a denser gel network. This behaviour is consistent with its superior mechanical performance, as a more developed and homogeneous microstructure promotes both the compressive strength and the thermal stability of the final material [28].

3.2.2 Fourier transform infrared (FT-IR) analysis

Figure 6 presents the FT-IR spectra of the powdered WBA and the two alkali-activated formulations (AA-WBA 90–100 µm and AA-WBA 100–125 µm), which exhibit comparable families of bands, albeit with variations in intensity and position that reflect differences in composition and degree of hydration. In the 3400–1650 cm⁻¹ region, associated with the stretching and bending vibrations of -OH groups from adsorbed or structural water, the AA-WBA formulations show broader and more intense bands than the precursor (WBA). This behaviour indicates the presence of bound water within the hydrated gels formed during alkali activation. These signals are consistent with the mass loss observed in the TGA analysis below 200 °C, confirming the presence of both free and structural water in the samples [29,30].

The main bands, attributed to the asymmetric Si-O-(Si/Al) stretching vibrations characteristic of C-(A)-S-H and/or N-A-S-H reaction gels, appear in the 1050–980 cm⁻¹ region. Variations in the position and width of this band among the samples indicate differences in the degree of polymerisation and in the Si/Al ratio of the reaction products. The WBA sample exhibits a more defined signal at 1016 cm⁻¹, whereas the AA-WBA samples show slight shifts and band broadening, consistent with the development of a more

amorphous network typical of alkali-activated materials [25,31]. These features confirm the formation of gel phases associated with the activation process.

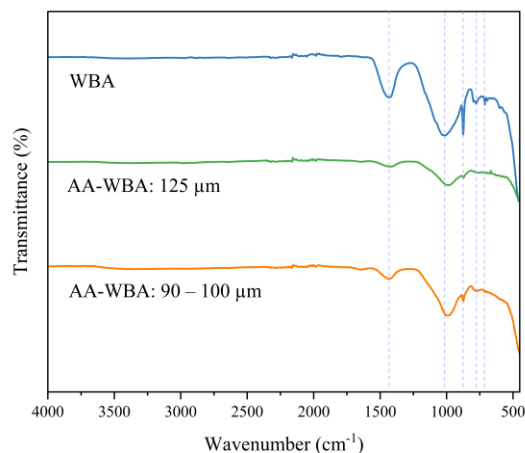


Figure 6. FT-IR spectra of powdered WBA and formulations showing enhanced mechanical performance

The characteristic carbonate bands (1420–1433 cm⁻¹ and 870–875 cm⁻¹) are observed in all three samples, although they appear with greater intensity in the AA-WBA (90–100 µm) formulation. This trend aligns with the TGA/DTG results, in which this sample exhibits the most pronounced mass loss between 500 and 800 °C and a maximum decomposition peak at approximately 600–700 °C, corresponding to the thermal decomposition of carbonates (CaCO₃ → CaO + CO₂). Taken together, these findings indicate a higher carbonate content, or a greater extent of carbonation, in the AA-WBA (90–100 µm) formulation [29,30].

The correlation between the FT-IR and TGA/DTG analyses indicates that the AA-WBA (90–100 µm) formulation exhibits a higher degree of carbonation, as well as distinct variations in the Si-O region that reflect differences in gel polymerization [32]. Overall, the findings demonstrate that particle size and formulation exert a direct influence on carbonation and on the development of C-(A)-S-H and/or N-A-S-H gels.

3.2.3 Scanning electron microscopy (SEM) analysis

Figure 7 presents SEM micrographs of the AA-WBA material acquired using a low-energy secondary electron detector. Images (a) and (b), corresponding to the formulation with a particle size fraction of 100–125 µm, demonstrate that particle size plays a critical role in the resulting microstructure and degree of reaction.

A heterogeneous microstructure is observed, characterised by highly porous regions and the presence of partially dissolved particles remaining after alkali activation. This indicates an incomplete reaction, likely associated with the lower reactivity of the larger particles, possibly due to their glassy nature and the presence of inert oxides. Consequently, voids (pores) are generated between particles that were not fully encapsulated by the reaction gel, a phenomenon that may be exacerbated by hydrogen release from residual metallic aluminium [18].

At a larger scale (Figure 7b), compact and laminar textures can be observed, which are characteristic of C-A-S-H gels and appear to have formed superficially on the

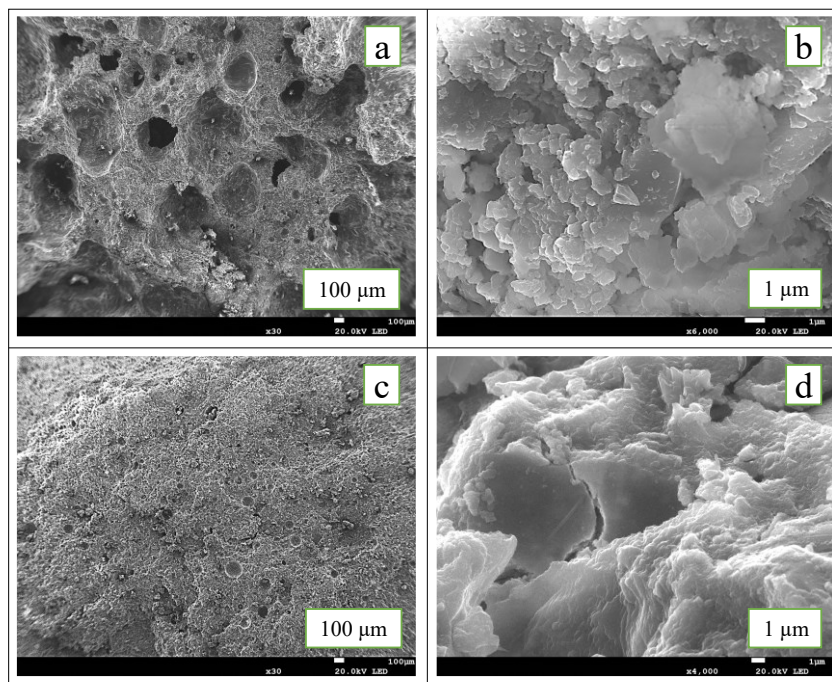


Figure 7. SEM micrographs of AA-WBA samples: a y b) Samples with precursor particle size 125 μm ; c y d) Samples with precursor particle size 90-100 μm

unreacted coarse particles. In this material, the predominant formation of C-A-S-H gels is consistent with the high CaO and Al_2O_3 contents of the slag. Nonetheless, the presence of Na_2O derived both from the sodium silicate activator and from the slag itself suggests the possible coexistence of N-A-S-H phases.

Micrographs (c) and (d), in contrast with the previous images, reveal a more homogeneous and compact microstructure with markedly reduced porosity, indicating a more efficient alkali-activation reaction. This improvement is associated with a more complete dissolution of the precursor particles and the more abundant and continuous formation of the C-A-S-H and/or N-A-S-H binding gels, which correlates with the enhanced mechanical performance of the material. At a larger scale (Figure 7d), a dense and continuous matrix is observed, in which most particles are fully incorporated into the gel phase, demonstrating a more advanced reaction and greater microstructural consolidation.

3.3 Proof of concept

To promote progress within a standardised evaluation framework that assesses the maturity of research, from the conceptual stage to full-scale implementation under real conditions, while considering Technology Readiness Levels (TRL), a proof of concept was undertaken. This approach supports innovation by bridging the transition from laboratory-based conceptual development to practical application, thereby linking theoretical principles with operational performance [13].

To validate the concept, a prototype cover for an inspectable box used in paving was manufactured in collaboration with Escofet by Molins, a world-renowned Barcelona-based company specialising in the design and production of street furniture, paving elements and architectural concrete for public spaces and buildings (Figure 8). The alkali-activated binder was produced using the optimal formulation identified in this study (AA-WBA

1:4/0.6/4M; 90-100 μm), together with the granitic and calcareous aggregates routinely employed by Escofet by Molins in their architectural concrete. The mixture proportions are presented in Table 4. These proportions are based on an appropriate mix design (Fuller–Thompson method), in accordance with the particle size distribution of the available aggregates, as used by Escofet by Molins in its precast elements. The mixture was prepared at the Escofet industrial plant using a vertical-shaft (planetary) mixer with a capacity of 0.33 m^3 per batch (cycle). The dosage of the aggregates was defined as a percentage of the total weight of the sample; in this preliminary test, a 15 kg sample was prepared, which was used to manufacture the proof of concept and several specimens for the control of mechanical behaviour. The resulting concrete displayed a highly compact structure, with a uniform distribution of aggregates within the alkali-activated matrix and excellent overall homogeneity (Figure 9). Strong aggregate-matrix bonding was observed, contributing to the structural integrity and durability of the material. After 28 days of outdoor curing (at

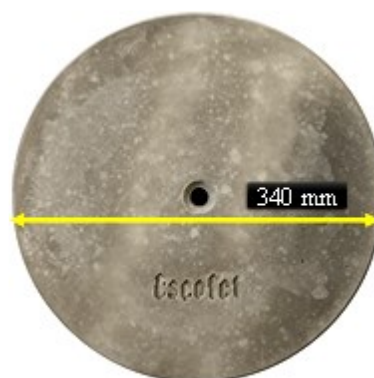


Figure 8. Cover for inspection box in outdoor paving formulated from alkali-activated binder using WBA as the sole precursor

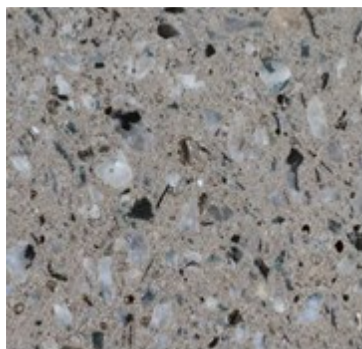


Figure 9. Cross-sectional image of the inspection box cover in concrete formulated for the proof of concept

the Escofet facilities), the prototype was cut into twelve test specimens with average dimensions of 44×44×42 mm for compressive testing. The samples reached an average compressive strength of 14 MPa, meeting the performance requirements for urban pedestrian paving applications.

Proof-of-concept studies from previous research [13] have highlighted that, although initial trials yield promising results, scalability remains a significant challenge. Technical feasibility is largely dependent on production volumes: increasing the liquid content in the mixtures can reduce mechanical performance, affect workability, and necessitate construction methods different from those employed in the

production of Portland cement-based components. Moreover, specific production conditions are required in terms of both labour and equipment. Further research is therefore needed on the use of tailored additives and alternative curing strategies to adapt the casting process for pilot- and industrial-scale production.

3.4 Environmental characterization

Figure 10 presents the dose-response curve for the concrete sample developed in the proof-of-concept study. The luminescence inhibition values represent the average of two replicates of the same sample, with the differences between replicates indicated by error bars. The results demonstrate good reproducibility between replicates. The bacterial luminescence response at the two contact times assessed, 15 and 30 minutes, showed no significant differences. Ecotoxicity was evaluated in accordance with technical report CEN/TS 17459 [16], which specifies that the lowest ineffective dilution (LID), defined as the highest dilution causing the least significant effect on the test organism, must not exceed 8. This parameter is calculated based on the EC_{20} value, corresponding to the leachate concentration that induces a 20% reduction in luminescence, as expressed by the following equation:

$$LID = \frac{1}{\left(\frac{EC_{20}}{100}\right)}$$

Table 4. Material dosing for AA-WBA concrete used in the production of pavement manhole covers

Aggregates	
Arid calcareous 1-3 mm	3750 g
Granitic arid 2-6.3 mm	2143 g
Small granite aggregate 4-12.5 mm	4821 g
Alkali-Activated Binder (AA-WBA) - 1:4/0,6/4M	
WBA (precursor)	4286 g
Sodium silicate (Na_2SiO_3)	2057 g
Sodium hydroxide (NaOH) - 4M	514 g

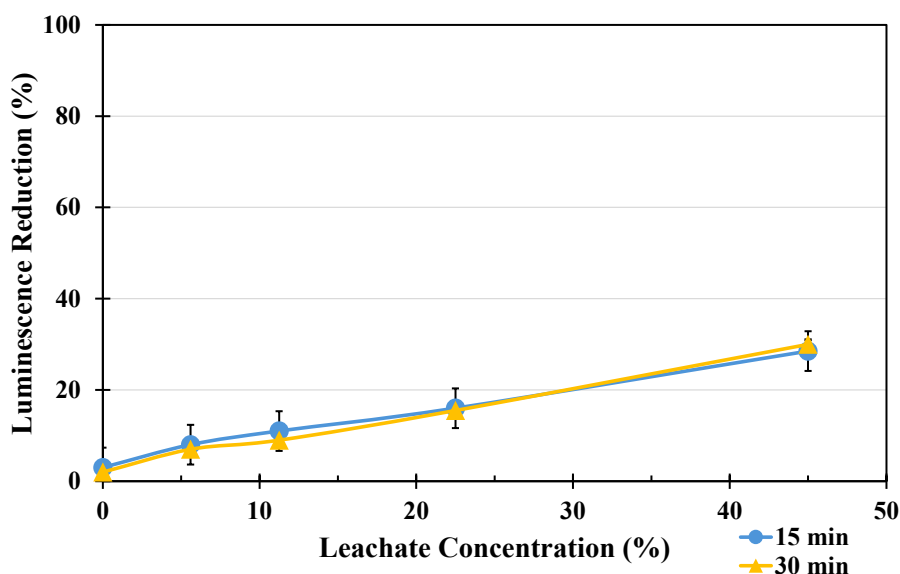


Figure 10. Percentage reduction in luminescence of the concrete samples after 15 and 30 minutes in the proof-of-concept test

For the concrete produced in the proof-of-concept study, the leachate concentration (EC₂₀) was 28.40, corresponding to an LID value of 3.52. This value does not exceed the established limit, indicating that the effect of powdered WBA on bacterial luminescence is reduced following its incorporation into the concrete with the formulated AA-WBA binder.

Table 5. pH and conductivity values of the precursor (powdered WBA) and the concrete in the proof-of-concept test

Specimen	pH	Conductivity (mS·cm ⁻¹)
WBA	9.89 ± 0.06	2.14 ± 0.04
Proof-of-concept concrete	10.36 ± 0.03	3.09 ± 0.98

Table 5 presents the pH and conductivity values of the leachates from the powdered WBA samples (precursor) and the concrete developed in the proof-of-concept study. The results correspond to two replicates, with their respective standard deviations. The measured conductivity values are consistent with the pH of each sample, reflecting the presence of dissolved ions in the leachate. In the alkali-activated concrete (proof-of-concept specimen), no significant changes in leachate pH were observed. These results indicate that the concrete has reached a stabilized phase of ion release, meaning it is no longer undergoing rapid leaching while still exhibiting residual chemical activity. This suggests a reduced risk of generating highly alkaline or ion-rich leachates that could affect receiving waters or soils and demonstrates effective retention and immobilization of alkaline elements, which is a critical consideration when incorporating incineration residues that may contain mobile components.

The results of the specific ionic composition analysis of the leachates (heavy metals) are presented in Table 6. Both the precursor (powdered WBA) and the proof-of-concept concrete exhibit concentrations of most leached metals and metalloids well below the limit for acceptance at landfills as inert waste [33]. For Mo, Sb, and As, the values fall within the thresholds defined for non-hazardous waste. These findings indicate low mobility of potentially hazardous elements and confirm both the environmental safety of the material and its suitability for use in the production of concrete elements.

Table 6. Leached metal concentrations from the precursor (powdered WBA) and the proof-of-concept concrete, compared with the permissible limit values for landfill acceptance according to regulatory thresholds [33]

mg/kg (ppm)	Zn	Cr	Mo	Ni	Cu	Sb	As	Pb	Cd	Hg	Ba	Se
WBA (precursor)	0.09	0.08	0.86	0.02	1.30	0.34	0.00	0.00	0.00	0.00	0.36	0.02
Concept proof concrete	0.18	0.09	0.41	0.02	0.64	0.68	1.00	0.34	0.00	0.00	0.08	0.08
Inert waste	4	0.5	0.5	0.4	2	0.06	0.5	0.5	0.04	0.01	20	0.1
Non-hazardous waste	50	10	10	10	50	0.7	2	10	1	0.2	100	0.5
Hazardous waste	200	70	30	40	100	5	25	50	5	2	300	70

4 Conclusions

The results demonstrate that it is technically feasible to formulate an alkali-activated binder using bottom ash from municipal solid waste incineration (WBA) as the sole precursor. The identified optimal formulation (1:4/0.6/4 M; 90-100 µm) developed a dense microstructure characterised by the coexistence of C-(A)-S-H and N-A-S-H gels, enabling the attainment of competitive compressive strengths. The proof-of-concept concrete reached values of up to 14 MPa, which are suitable for non-structural urban applications.

In comparison with the compressive strengths achieved by the binder (AA-WBA 1:4/0.6/4M, 90-100 µm) under laboratory conditions, the mechanical performance of the proof-of-concept concrete could be further enhanced by adopting manufacturing practices specific to alkali-activated cements. These include the optimisation of mixing protocols, curing regimes, equipment cleaning procedures, control of initial moisture levels, material pre-conditioning, and a work culture adapted to the distinct requirements of alkali-activated systems, which differ from those typically applied to Portland cement-based concretes.

The study demonstrates that the particle-size distribution of the precursor is a critical factor governing the efficiency of alkaline activation. Fractions in the 90-100 µm range produced a higher degree of reaction, lower porosity, and a more cohesive matrix, whereas finer particles (≤63 µm) induced accelerated and uncontrolled reactions, and coarser particles (100-125 µm) resulted in more porous microstructures with limited reactivity. Similarly, the NaOH:WG ratio and the SiO₂/Na₂O modulus exerted a marked influence on both workability and mechanical strength, underscoring the need for precise chemical balance to ensure material stability and performance.

Leaching tests, ecotoxicity assessments, and ionic analyses confirmed that both the WBA and the formulated concrete exhibit low heavy metal mobility, complying with the limits for inert waste for most metal and metalloid, and with non-hazardous waste criteria for Mo, Sb and As. The AA-WBA-based concrete displayed an LID value below the recommended threshold, indicating the absence of significant toxic effects. These results confirm the environmental safety of the material and underscore its potential to contribute to closing material cycles within circular economy frameworks, promoting the use of municipal waste in low-impact urban applications.

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CRedit authorship contribution statement

Fabian Cuspoca: Data Curation, Formal Analysis, Investigation, Methodology, Validation, Writing-Original Draft Preparation. **Jofre Mañosa:** Validation, Writing-Review and Editing. **Joan Ramon Rosell:** Methodology, Supervision, Writing-Review and Editing. **Gerard Faneca:** Funding Acquisition, Resource, Writing-Review and Editing. **Josep Maria Chimenos:** Conceptualization, Funding Acquisition, Methodology, Supervision, Writing-Review and Editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

This manuscript uses the following abbreviations:

AA-WBA	Bottom ash-based alkali-activated material
C-A-S-H	Calcium–aluminium–silicate–hydrate
FT-IR	Fourier Transform Infrared Spectroscopy
LID	Lowest Ineffective Dilution
LOI	Loss on ignition
N-A-S-H	Sodium–aluminium–silicate–hydrate
OPC	Ordinary Portland Cement
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
WBA	Waste-incineration bottom ash (precursor)
wt. (%)	Weight percent

References

- [1] B. Chen, M. Brito van Zijl, A. Keulen, G. Ye, Thermal Treatment on MSWI Bottom Ash for the Utilisation in Alkali Activated Materials, *KnE Engineering* 2020 (2020) 25–35. <https://doi.org/10.18502/keg.v5i4.6792>.
- [2] P.C.D. Tortora, A. Maldonado-Alameda, J. Mañosa, A.C. Quintero-Payan, C. Leonelli, I. Lancellotti, J.M. Chimenos, Effect of Temperature and Humidity on the Synthesis of Alkali-Activated Binders Based on Bottom Ash from Municipal Waste Incineration, *Sustainability* 14 (2022) 1848. <https://doi.org/10.3390/su14031848>.
- [3] A. Maldonado-Alameda, J. Giro-Paloma, A. Svobodova-Sedlackova, J. Formosa, J.M. Chimenos, Municipal solid waste incineration bottom ash as alkali-activated cement precursor depending on particle size, *J Clean Prod* 242 (2020). <https://doi.org/10.1016/j.jclepro.2019.118443>.
- [4] A. Maldonado-Alameda, J. Giro-Paloma, A. Alfocea-Roig, J. Formosa, J.M. Chimenos, Municipal Solid Waste Incineration Bottom Ash as Sole Precursor in the Alkali-Activated Binder Formulation, *Applied Sciences* 10 (2020) 4129. <https://doi.org/10.3390/app10124129>.
- [5] X.C. Qiao, M. Tyrer, C.S. Poon, C.R. Cheeseman, Characterization of alkali-activated thermally treated incinerator bottom ash, *Waste Management* 28 (2008) 1955–1962. <https://doi.org/10.1016/j.wasman.2007.09.007>.
- [6] N. Yamaguchi, M. Nagaishi, K. Kisu, Y. Nakamura, K. Ikeda, Preparation of monolithic geopolymer materials from urban waste incineration slags, *Journal of the Ceramic Society of Japan* 121 (2013) 847–854. <https://doi.org/10.2109/jcersj2.121.847>.
- [7] J. Giro-Paloma, A. Maldonado-Alameda, J. Formosa, L. Barbieri, J.M. Chimenos, I. Lancellotti, Geopolymers based on the valorization of Municipal Solid Waste Incineration residues, in: *IOP Conf Ser Mater Sci Eng*, 2017. <https://doi.org/10.1088/1757-899X/251/1/012125>.
- [8] J.M. Chimenos, M. Segarra, M.A. Fernández, F. Espiell, Characterization of the bottom ash in municipal solid waste incinerator, *J Hazard Mater* 64 (1999) 211–222. [https://doi.org/10.1016/S0304-3894\(98\)00246-5](https://doi.org/10.1016/S0304-3894(98)00246-5).
- [9] B.S. Bandarra, J.L. Pereira, R.C. Martins, A. Maldonado-Alameda, J.M. Chimenos, M.J. Quina, Opportunities and Barriers for Valorizing Waste Incineration Bottom Ash: Iberian Countries as a Case Study, *Applied Sciences* 2021, Vol. 11, Page 9690 11 (2021) 9690. <https://doi.org/10.3390/APP11209690>.
- [10] D. Blasenbauer, F. Huber, J. Lederer, M.J.M.J. Quina, D. Blanc-Biscarat, A. Bogush, E. Bontempi, J. Blondeau, J.M.J.M. Chimenos, H. Dahlbo, J. Fagerqvist, J. Giro-Paloma, O. Hjelm, J. Hyks, J. Keane, M. Lupsea-Toader, C.J.C.J. O'Caollai, K. Orupöld, T. Pająk, F.-G.F.-G. Simon, L. Svecova, M. Šyc, R. Ulvang, K. Vaajasaari, J. Van Caneghem, A. van Zomeren, S. Vasarevičius, K. Wégner, J. Fellner, Legal situation and current practice of waste incineration bottom ash utilisation in Europe, *Waste Management* 102 (2020) 868–883. <https://doi.org/https://doi.org/10.1016/j.wasman.2019.11.031>.

- [11] R. del Valle-Zermeño, J. Gómez-Manrique, J. Giro-Paloma, J. Formosa, J.M. Chimenos, Material characterization of the MSWI bottom ash as a function of particle size. Effects of glass recycling over time, *Science of The Total Environment* 581–582 (2017) 897–905. <https://doi.org/10.1016/j.scitotenv.2017.01.047>.
- [12] A. Maldonado-Alameda, J. Giro-Paloma, J. Mañosa, J. Formosa, J.M.J.M. Chimenos, Alkali-activated binders based on the coarse fraction of municipal solid waste incineration bottom ash, *Bol Soc. Esp. Ceram. Vidr.* In press (2020) 313–324.
- [13] J.M. Chimenos, F. Cuspoca, A. Maldonado-Alameda, J. Mañosa, J.R. Rosell, A. Andrés, G. Faneca, L.F. Cabeza, MSW Incineration Bottom Ash-Based Alkali-Activated Binders as an Eco-Efficient Alternative for Urban Furniture and Paving: Closing the Loop Towards Sustainable Construction Solutions, *Buildings* 15 (2025) 1–24. <https://doi.org/10.3390/buildings15091571>.
- [14] ISO, ISO 11348-3:2007 - Water quality - Determination of the inhibitory effect of water samples on the light emission of *Vibrio fischeri* (Luminescent bacteria test) -- Part 3: Method using freeze-dried bacteria, ISO/TC 147/SC5 - Water Quality/Biological Methods (2018) 21 pp. http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=40518.
- [15] European Committee for Standardization, EN 12457-4: Compliance test for leaching of granular waste materials and sludges. Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction)., (2002).
- [16] European Committee for Standardization (CEN), CEN/TS 17459:2024 EX Construction products: Assessment of release of dangerous substances - Determination of ecotoxicity of construction product eluates, Madrid, 2024.
- [17] X. Tian, F. Rao, C.A. León-Patiño, S. Song, Effects of aluminum on the expansion and microstructure of alkali-activated MSWI fly ash-based pastes, *Chemosphere* 240 (2020) 124986. <https://doi.org/10.1016/j.chemosphere.2019.124986>.
- [18] A. Saffarzadeh, N. Arumugam, T. Shimaoka, Aluminum and aluminum alloys in municipal solid waste incineration (MSWI) bottom ash : A potential source for the production of hydrogen gas, *Int J Hydrogen Energy* 41 (2015) 820–831. <https://doi.org/10.1016/j.ijhydene.2015.11.059>.
- [19] J.E. Aubert, B. Husson, A. Vaquier, Metallic aluminum in MSWI fly ash: quantification and influence on the properties of cement-based products, *Waste Management* 24 (2004) 589–596. <https://doi.org/10.1016/j.wasman.2004.01.005>.
- [20] S.K. Adhikary, T. Luukkonen, M.A.H. Bhuyan, Y. Yu, P. Perumal, A method of pretreating incineration ashes containing metallic aluminium using NaOH to mitigate volume expansion under highly alkaline conditions, *Constr Build Mater* 450 (2024) 138639. <https://doi.org/10.1016/j.conbuildmat.2024.138639>.
- [21] X. Ouyang, Y. Ma, Z. Liu, J. Liang, G. Ye, Effect of the Sodium Silicate Modulus and Slag Content on Fresh and Hardened Properties of Alkali-Activated Fly Ash/Slag, *Minerals* 10 (2019) 15. <https://doi.org/10.3390/min10010015>.
- [22] S. Choi, K.M. Lee, Influence of Na₂O content and Ms (SiO₂/Na₂O) of alkaline activator on workability and setting of alkali-activated slag paste, *Materials* 12 (2019). <https://doi.org/10.3390/ma12132072>.
- [23] C.K. Yip, G.C. Lukey, J.S.J. van Deventer, The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation, *Cem Concr Res* 35 (2005) 1688–1697. <https://doi.org/10.1016/j.cemconres.2004.10.042>.
- [24] B. Pacewska, I. Wilińska, Comparative investigations of influence of chemical admixtures on pozzolanic and hydraulic activities of fly ash with the use of thermal analysis and infrared spectroscopy, *J Therm Anal Calorim* 120 (2015) 119–127. <https://doi.org/10.1007/s10973-014-4334-x>.
- [25] J.L. Provis, S.A. Bernal, Geopolymers and Related Alkali-Activated Materials, *Annu Rev Mater Res* 44 (2014) 299–327. <https://doi.org/10.1146/annurev-matsci-070813-113515>.
- [26] S. Kucharczyk, W. Pichór, The effect of waste-expanded perlite on alkali activation of ground granulated blast furnace slag, *Mater Struct* 56 (2023) 58. <https://doi.org/10.1617/s11527-023-02150-8>.
- [27] S.A. Walling, S.A. Bernal, L.J. Gardner, H. Kinoshita, J.L. Provis, Blast furnace slag-Mg(OH)₂ cements activated by sodium carbonate, *RSC Adv* 8 (2018) 23101–23118. <https://doi.org/10.1039/C8RA03717E>.
- [28] C. Li, H. Sun, L. Li, A review: The comparison between alkali-activated slag (Si + Ca) and metakaolin (Si + Al) cements, *Cem Concr Res* 40 (2010) 1341–1349. <https://doi.org/10.1016/j.cemconres.2010.03.020>.
- [29] A. Sujak, M. Pyzalski, K. Durczak, T. Brylewski, P. Murzyn, K. Piłarski, Studies on Cement Pastes Exposed to Water and Solutions of Biological Waste, *Materials* 15 (2022) 1931. <https://doi.org/10.3390/ma15051931>.
- [30] S.J. Kemp, A.L. Lewis, J.C. Rushton, Detection and quantification of low levels of carbonate mineral species using thermogravimetric-mass spectrometry to validate CO₂ drawdown via enhanced rock weathering, *Applied Geochemistry* 146 (2022) 105465. <https://doi.org/10.1016/j.apgeochem.2022.105465>.
- [31] M.O. Yusuf, Bond Characterization in Cementitious Material Binders Using Fourier-Transform Infrared Spectroscopy, *Applied Sciences* 13 (2023) 3353. <https://doi.org/10.3390/app13053353>.
- [32] C. Marieta, A. Martín-Garin, I. Leon, A. Guerrero, Municipal Solid Waste Incineration Fly Ash: From Waste to Cement Manufacturing Resource, *Materials* 16 (2023) 2538. <https://doi.org/10.3390/ma16062538>.
- [33] Council of the European Union, 2003/33/EC, Council Decision establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC, Official Journal of the European Communities (2003) 27–49.



Original scientific paper

Open loop alternatives for recycling PET straps in construction products: a PESTEL analysis

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ABSTRACT

Polyethylene terephthalate (PET) straps cannot be mechanically recycled in certain regions where the required technology is unavailable or where the scale of operations is insufficient to ensure economic viability. They tend to be accumulated in the recycling chain, from industrial generators, to waste separation plants and even recycling plants and landfills. However, PET straps could be used in construction as aggregates for concrete paving blocks or in panels with epoxy resin binder. This study evaluates two open-loop alternatives for recycling discarded PET straps into construction products considering Political, Economic, Social, Technological, Environmental, and Legal factors of the PESTEL framework. The political, social, and legal conditions were comparable for both alternatives, whereas the economic and environmental assessments favoured the panel-based solution. However, the technological analysis indicated that panel production remains at an early stage of development, introducing uncertainty and potentially delaying its large-scale implementation. In contrast, the manufacturing process for paving blocks is based on established and readily available technology, allowing for immediate implementation under current conditions.

1 Introduction

Plastic waste pollution is a major environmental problem, mainly because it takes a long time to decompose [1]. The amount of plastic pollution has grown to unsustainable levels, polluting land, waterways, and oceans, causing harm to wildlife and ecosystems [2].

Polyethylene terephthalate (PET) straps can be considered single-use plastic products since once used to secure goods, they are usually discarded rather than reused in their original form. This aligns with the definition of single-use plastics, which are intended for one-time use before disposal [3]. PET straps are strong enough to withstand outdoor environmental conditions such as humidity, solar exposure and high temperatures. Although there are many literature reviews regarding the problem of plastic waste and PET waste [4], no specific data on PET straps waste management as a separate waste stream were found, apart from case studies related to valorisation alternatives.

In some places such as Mendoza, Argentina, PET straps are used in construction and wineries, but this province has no facilities for its complete mechanical recycling [5]. Although recycling PET helps to reduce environmental impact, conserve resources, and minimize landfill accumulation, the recycling rate for PET remains relatively

low, and much of it still ends up in landfills or the environment, where it can persist for hundreds of years [4].

Mechanical recycling is not always available due to the lack of appropriate technologies or economies of scale to process PET straps. In those cases it could be considered transporting them to other regions, but it is often economically infeasible and environmentally inconvenient [6]. Two valorisation alternatives related to construction materials have been studied before by the authors: to shred PET straps and use them as aggregates for concrete paving blocks [7], and to mix shredded PET straps with epoxy resin binder to obtain panels [5]. Other alternatives identified in literature are to make welded geogrids [8], to build mechanically stabilized soil structures [9], to reinforce columns with a pre-stressed system [10] and to produce PET strap fibers for concrete reinforcement for pull-out tests [11, 12].

The construction industry could take advantage of the strength and homogeneity of this waste material [12]. Recycling plastic waste can generate environmental benefits in the construction sector, as it supports the transition toward a circular economy in which waste is valorized as a secondary raw material for new products [13]. Circular economy helps to reduce the need for virgin materials, to decrease the environmental impacts associated with their

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extraction and production, and to decouple the economic development from resources consumption [14].

Recent developments regarding the circular economy focus on their relationship with sustainable development through its aims to generate environmental quality, economic development and social equity [15]. Influence of politics, legal and technological developments are also considered relevant for circular economy strategies. Authors have studied some aspects of PET straps waste valorisation, but until now, no systematic and comprehensive analysis has been conducted for this waste stream. The aim of this paper was to analyse and compare two innovative open loop valorisation alternatives for construction applications in terms of political, economic, social, technological, environmental, and legal characteristics. By integrating these dimensions within a single analytical framework, this study provides a structured basis to compare technological maturity, economic feasibility, environmental performance and social conditions, thereby supporting decision-making regarding these alternative pathways for PET straps waste valorisation.

2 Materials and methods

The methodology used in the present study is presented in Figure 1 and described in the following sections.

2.1 PET straps characterization

The PET straps analysed in this study were collected as post-industrial packaging waste from a local company, typically employed for securing industrial loads. According to the manufacturer, the material exhibits a tensile strength ranging from 380 to 500 MPa and an elongation at break exceeding 12%. The elastic modulus of PET ranges between 2,8 and 3,1 GPa [16]. PET typically presents a density of approximately 1,39 g/cm³ and negligible water absorption, which is characteristic of this polymer and relevant for both cement-based and epoxy-based composite applications. For their use as aggregates in paving blocks and panels, the straps were mechanically shredded by a local industry to produce a material with the granulometric distribution shown in Figure 2 [5].

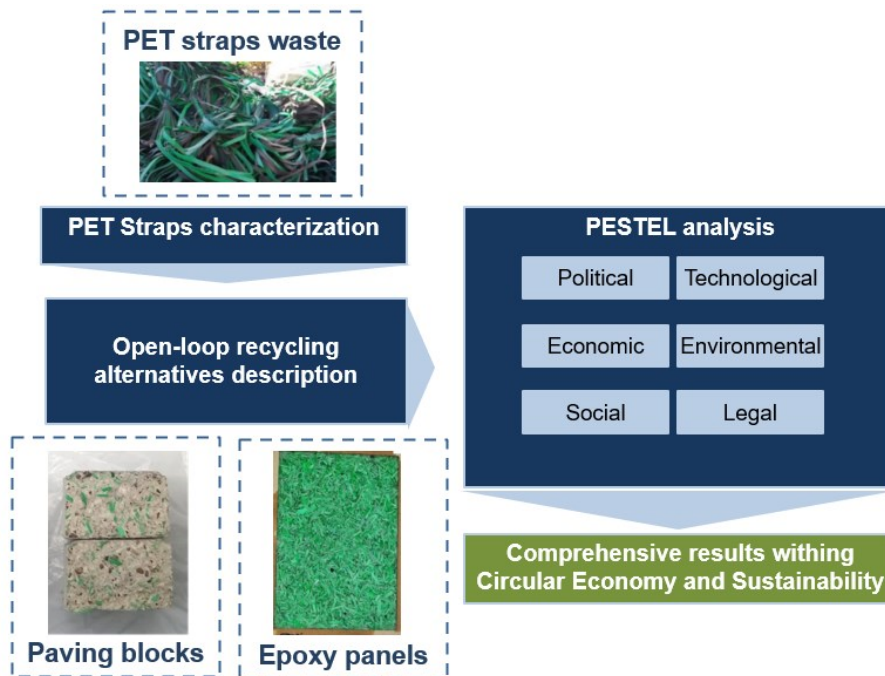


Figure 1. Study design for the PESTEL comparison of construction applications of recycled PET straps

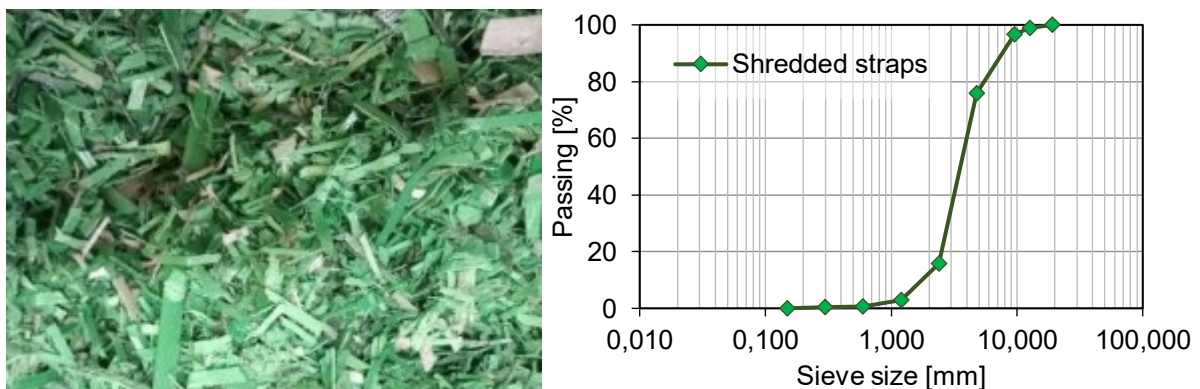


Figure 2. Shredded PET straps (left) and granulometric analysis of shredded PET straps (right)

2.2 Open-loop recycling alternatives description

Two valorisation alternatives were considered from previous studies developed by the authors:

- to use shredded PET straps as aggregates for concrete paving blocks [7],
- to mix shredded PET straps with epoxy resin binder to obtain panels [5].

Many different dosages could be used in both alternatives, but only optimal dosages reported by the authors were considered in this study. Composites for paving blocks were prepared using Portland cement, natural sand, tap water and shredded PET straps. A 1:2 ratio of cement to natural sand aggregates was used, together with a water-to-cement ratio (w/c) of 0,40, and 5% of shredded PET straps by weight of the paving blocks. Paving blocks were demoulded after 24 hours and cured for 28 days submerged at a controlled temperature of $20 \pm 2^\circ\text{C}$ [7]. While technical and environmental analyses were carried out, the political, legal, social, and economic evaluations were not performed.

Meanwhile, panels were manufactured under a fume hood and demoulded after 24 hours of curing to ensure complete crosslinking of the polymer network. The selected dosage was 23% of shredded PET strap relative to the total mass of the manufactured panel, with epoxy resin binder [5].

2.3 PESTEL analysis

A PESTEL (political, economic, social, technological, environmental, legal) analysis provides a comprehensive view of the factors that influence the viability of different options. It has been successfully used to evaluate recycling alternatives in various sectors, such as plastics [17], construction and demolition waste [18], municipal waste [19], and healthcare waste [20]. This approach allows the identification of opportunities, risks, and external barriers that affect the implementation and success of different recycling strategies. Each dimension was described for the recycling alternatives, including qualitative and quantitative indicators and criteria, such as:

- Political: included waste policies, incentives for recycling, and circular economy goals.
- Economic: Life Cycle Costing (LCC) and complementary analyses of the impact of each alternative's costs on the market value of the resulting product. The objective was to calculate the costs of waste valorisation alternatives. These alternatives considered both the technical valorisation processes and the associated transport, since this has a significant influence on reverse logistics. The functional unit used for the research was 1 ton of shredded PET straps.

The LCC of paving blocks alternative considered transport from the shredding plant to the paving blocks manufacturing plant. The process included materials consumption, mixing in an automated electric mixer, moulding on a moulding line, and curing the blocks, which consumes fuel to maintain a stable temperature. For the panels it was considered transport to the manufacturing plant and materials consumption. Data on panels fabrication is not available since they were handmade at laboratory. Finally, the panels were cured at room temperature. An efficiency of 95% was assumed, as some material is lost in the process.

Both primary and secondary data were used to build the inventory. Primary data came from measurements, interviews, and documents from the stakeholders involved, while secondary data was obtained from databases and other studies. The quantification of material inputs and

outputs for the processes was obtained from primary data from technical trials and from estimates based on interviews and measurements at the PET shredding plant. The market values of the products were estimated from secondary data, specifically using similar products available online. Costs were considered in Argentinian pesos calculated in 2022.

- Social: labour requirements and education levels were described for each alternative. The social dimension is descriptive, since neither alternative has been implemented in practice to date. Therefore, actual social conditions cannot be measured.

- Technological: Technology Readiness Level (TRL), technology availability, pre-treatment requirements, and specific performance indicators related to tests were considered.

- Environmental: midpoint indicators using method CML-IA baseline V3.06, were considered to assess the environmental impact in a Life Cycle Assessment (LCA) following ISO standards 14040 [21] and 14044 [22]. The functional unit of analysis was 1 ton of shredded PET straps. Indicators were abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (POCP), acidification potential (AP) and eutrophication potential (EP). These indicators are recommended for LCA of construction products [23].

- Legal: considered environmental permits or restrictions, waste laws and Sustainable Development Goals (SDG) alignment.

3 Results and discussion

3.1 Political and legal dimensions

In Argentina, the political and legal framework related to the circular economy and the management of recyclable waste is still being consolidated, with limited and fragmented progress across jurisdictions. The circular economy agenda in Argentina is mainly implemented through municipal solid waste management programs and guidelines. However, unlike other Latin American countries, there is no national strategy supported by a comprehensive framework law. Current regulations are structured around sectoral laws and are complemented by municipal initiatives focused on source separation, differentiated collection, and strengthening recycling. This still-dispersed regulatory framework reflects a process in transition toward more sustainable production and consumption models, in which extended producer responsibility and the recovery of materials are beginning to position themselves as central pillars of the country's contemporary environmental policy [24].

In Mendoza there are increasingly favourable conditions for the development of waste recycling. The province has recently implemented a new waste management law [25], which promotes waste reduction, separation at source, material recovery, and the creation of waste separation centres. The law mandates municipal participation, establishes sanctions, and aligns provincial objectives with the UN Sustainable Development Goals, particularly SDG 12 on responsible production and consumption. The executive regulation for this law is currently under development.

However, no specific extended producer responsibility schemes for plastics are available, and PET straps have not been included in specific waste policies, while there are no incentives for recycling them yet. In municipal waste separation plants, PET straps are discarded since it is not

economically feasible to transport them for mechanical recycling. This is why they are perceived as worthless waste. In conclusion, both alternatives are subject to a similar political and legal context.

3.2 Economic dimension

Regarding the national economic context of the recycling industry, recent resolutions have reduced barriers to import recyclable waste. This situation has had a significant impact on the materials market, leading to a drop in the price of cardboard and plastic of up to 60% [26].

The LCC analysis showed that the cost of producing 93,4 tons of paving blocks from 1 ton of shredded PET straps was \$700000, while 1,3 tons of panels were produced with the same amount of shredded straps, demanding \$205000. The cost of producing paving blocks was made up by materials consumption, electricity consumption and fuel consumption of associated machinery and transport. The cost of the panels considered transport and materials consumption. The materials included aggregates and cement for the paving blocks and polymer resin for the panels alternative.

Using a net cost-to-market ratio of the resulting product, since the products obtained from each alternative are different and have different market prices, shows the impact of the costs of shredded PET straps on the final product price for each alternative. The use of ratios to complement LCC analyses is very common in literature [27]. The ratio of net costs for paving blocks was 20% while for panels it was 1%. This low value can be explained because the panel price is high, they have very good mechanical properties and can be used for a wide variety of applications. On the other hand, the lack of data on the panels cost inventory excluded costs of an industrial production such as electricity consumption for mixing the resin.

3.3 Social dimension

Both alternatives require collecting, transporting, and shredding PET straps. After that, the material is transported to the production plant, where it is mixed, poured and cured for making paving blocks, and mixed with epoxy resin, pressed and cured to produce panels. All these stages require operators.

Collection, transport and shredding operations could be performed by non-qualified operators. In Mendoza, waste pickers are grouped in recycling cooperatives who collect diverse recyclable waste streams such as plastic, glass, metals. Those cooperatives work together with some big waste generators such as industries and large commercial facilities and receive support from municipalities. National encouragement to those cooperatives has recently declined, reducing the number of beneficiaries of subsidies as salary complements for members of recycling cooperatives [26].

Production of paving blocks can be largely automated, while panels do not have specific technology for their production yet. The required educational level in those activities is medium, and operators can be trained internally to perform their tasks.

3.4 Technological dimension

The present dimension combines an analysis of products properties with the study of the actual production processes available in Mendoza and their TRL.

The studied properties of paving blocks were flexural strength (6,77 MPa), dry density (2027 kg/m³) and water

absorption (3,18%) [7]. Flexural strength is an essential mechanical property for a traffic load-resistant pavement and the acceptance requirement for the modulus of rupture is 4.2 MPa according to standard IRAM 11656 [28]. Density can be used as indicator of uniformity between different paving blocks and water absorption is related to long-term durability, which must be below 5% [28]. Apart from these specific performance indicators, the production of paving blocks has available technology with a maturity level of TRL 9. Existing equipment can be used to produce paving blocks with shredded PET straps, in fact, some automated plants in Mendoza have the technology to produce these products.

Until now, the analysed panels were manufactured at a laboratory scale, using hand tools. While other existing machines could be adapted to increase production, the current TRL is 3, as only proof-of-concept testing exists. Tensile tests were performed on ten flat type I tensile specimens with rectangular section. The mechanical tests were carried out using an Amsler universal testing machine with a maximum capacity of 60 tons and a sensitivity of 10 kg. The maximum average load was 14 N, with a tensile strength of 1,35 kg/mm² [3] according to standard D-638 ASTM [29].

3.5 Environmental dimension

Recycling materials reduces the amount of waste disposed in landfills and raw materials and energy consumption. However, recycling could also have negative environmental impacts [30], so LCA is useful to analyse in more detail the environmental impacts of both studied recycling alternatives. LCA allowed to obtain the midpoint indicators of both alternatives. In panels, a larger quantity of shredded PET straps is used in comparison to paving blocks. Therefore, the functional unit of 1 ton of shredded PET straps defined before, results in 93,4 tons of paving blocks, but just 1,3 tons of panels (Figure 3).

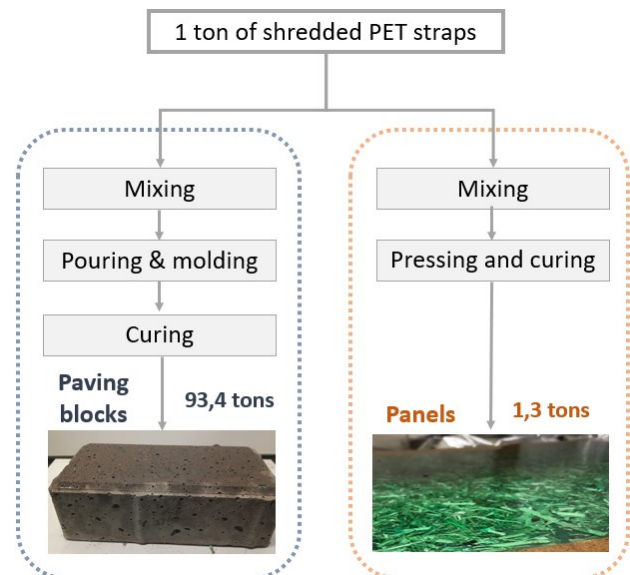


Figure 3. System boundaries for paving blocks and panels with shredded PET straps

The life cycle inventory was constructed for the functional unit using primary data, some based on laboratory studies and others from companies in the sector, and secondary data from international databases [31]. Table 1 shows the inputs required to recycle 1 ton of shredded PET straps.

The life cycle impact assessment results for the functional unit are presented in Table 2.

Results show higher impacts for recycling 1 ton of PET straps in paving blocks than in panels. However, it must be considered that they are different products with distinct functions. Additionally, as mentioned, 1 ton of shredded PET straps produces 93,4 tons of paving blocks, but just 1,3 tons of panels. Both alternatives require transporting and shredding the PET straps before starting the new production cycle.

While producing panels incorporates larger quantities of PET straps per ton of final product, from a wider environmental perspective, the results shown in Table 1 can be reinterpreted. For example, to manufacture 1 ton of paving blocks, an impact of 276 kg of CO₂ eq. is produced, while 925 kg of CO₂ eq. are emitted per ton of panels. The final product will also have a specific lifespan, approximately up to 50 years for paving blocks and up to 20-30 years for panels. End-of-life management is complex in both cases, since they are composite materials containing concrete in paving blocks and epoxy in panels. Therefore, recycling these products may be a challenge that must be further studied.

3.6 Summary

Table 3 summarizes the main findings obtained for each PESTEL dimension when comparing the two recycling alternatives. The analysis shows that both products operate under the same emerging political and regulatory framework for circular economy and waste management in Argentina. However, relevant differences arise in the economic, technological, and environmental dimensions.

4 Conclusions

This study evaluated two open-loop recycling alternatives for waste PET straps: paving blocks and epoxy panels, using the PESTEL framework. Results indicate that both options may represent potential pathways to recover this waste stream in regions lacking closed-loop mechanical recycling infrastructure.

From the political and legal perspectives, PET straps are not yet included in specific waste policies or incentive schemes, which limits their recovery potential. Economically, paving blocks show higher production costs relative to their market value, whereas panels show a more favourable ratio. However, the available data for the panel alternative remain

Table 1. System inputs for both alternatives

Input	Paving blocks	Panels
Materials	61,6 tons of fine aggregates 30,8 tons of cement	333 kg of epoxy resin
Water	15400 litres of water 110 litres of fuel	-
Energy	477 kWh of electricity	9,3 kWh of electricity

Table 2. Midpoint impacts for both alternatives

Midpoint indicator	Units	Paving blocks	Panels
ADP	kg SB eq.	0,0006235	0,0001366
GWP	kg CO ₂ eq.	25759	1230
ODP	kg CFC-11 eq.	0,0013795	0,0001309
POCP	kg C ₂ H ₄ eq.	3,2526907	0,6663755
AP	kg SO ₂ eq.	49,3	4,1
EP	kg PO ₄ ³⁻ eq.	10,8	1,6

Table 3. PESTEL summary for both alternatives

Dimension	Paving blocks	Panels
Political & Legal	Operates within an emerging regulatory framework for waste management and recycling in Argentina, without specific incentives for PET strap recycling.	
Economic	Production cost: \$700000 for 93,4 t of blocks. Net cost-to-market ratio: 20%.	Production cost: \$205000 for 1,3 t of panels. Net cost-to-market ratio: 1%.
Social	Production can be largely automated; medium qualification required for plant operators.	Production currently manual at laboratory scale; operators require internal training.
Technological	Mature technology (TRL 9) with existing industrial equipment available.	Early-stage technology (TRL 3) with proof-of-concept laboratory testing.
Environmental	Lower environmental impacts per ton of product, larger lifespan, but incorporates small quantities of PET straps.	Higher impacts per ton of product, shorter lifespan, but incorporates larger quantities of PET straps.

preliminary and correspond to laboratory-scale production. Socially, both alternatives could generate local employment with low to moderate training requirements. Technologically, paving blocks benefit from industrial-scale readiness, while panels are currently at a proof of concept stage and would require further technological development for large-scale implementation. Environmental impacts differ due to material requirements and product outputs, and end-of-life management remains a challenge for both composite materials.

Overall, both alternatives could contribute to reducing PET strap disposal in landfills and supporting regional circular economy initiatives, although further research is needed to validate the technical and economic performance of the panel alternative at industrial scale. The present work highlights the value of integrating political, economic, social, technological, environmental and legal perspectives to inform decision-making and policy discussions regarding emerging recycling pathways.

CRedit authorship contribution statement

JPO: Conceptualization; Formal analysis; Investigation; Methodology; Writing - original draft.

CA: Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Visualization; Writing - review & editing.

IM: Formal analysis; Investigation; Methodology; Funding acquisition; Project administration; Resources; Supervision; Writing - review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] Zhang, K., Hamidian, A. H., Tubić, A., Zhang, Y., Fang, J. K., Wu, C., & Lam, P. K. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. *Environmental Pollution* 274, 116554. <https://doi.org/10.1016/j.envpol.2021.116554>
- [2] Kibria, M. G., Masuk, N. I., Safayet, R., Nguyen, H. Q., & Mourshed, M. (2023). Plastic waste: challenges and opportunities to mitigate pollution and effective management. *International Journal of Environmental Research* 17(1), 20. <https://doi.org/10.1007/s41742-023-00507-z>
- [3] Chen, Y., Awasthi, A. K., Wei, F., Tan, Q., & Li, J. (2021). Single-use plastics: Production, usage, disposal, and adverse impacts. *Science of the total environment*, 752, 141772.
- [4] Raj, B., Rahul, J., Singh, P. K., Rao, V. V. K., Kumar, J., Dwivedi, N., ... & Strzałkowski, K. (2023). Advancements in PET packaging: driving sustainable solutions for today's consumer demands. *Sustainability*, 15(16), 12269. <https://doi.org/10.3390/su151612269>
- [5] Alejandrino, C., Giaroli, C., López, R., Ninago, M., Mercante, I., Llamas, S., & Ojeda, J. P. (2023). *Reciclado de flejes PET en placas compuestas con resinas poliméricas comerciales*. In *Actas del X Simposio Iberoamericano de Ingeniería de Residuos "Hacia la circularidad y el residuo cero"* (Castelló de la Plana, España, 20–22 de junio de 2023).
- [6] Ojeda, J. P., Alejandrino, C., & Mercante, I. (2024). *Análisis ambiental de alternativas de logística inversa y valorización de flejes plásticos*. In *Libro de actas XII EnIDI: Décimo Segundo Encuentro de Investigadores y Docentes de Ingeniería* (EnIDI 2023, San Rafael, Mendoza, Argentina).
- [7] Ojeda, J. P., Alejandrino, C., & Mercante, I. T. (2024). Recycling PET straps in paving blocks: experimental testing and life cycle assessment. *International Journal of Environmental Studies*, 81(6), 2725–2734. <https://doi.org/10.1080/00207233.2024.2417620>
- [8] Voskamp, W. (2000) Index and performance testing a new geogrid made of highly oriented straps. *Advances in Transportation and Geoenvironmental Systems Using Geosynthetics* 360–372. [https://doi.org/10.1061/40515\(291\)24](https://doi.org/10.1061/40515(291)24)
- [9] Miyata, Y., Bathurst, R. J., and Allen, T. M. (2018). Evaluation of tensile load model accuracy for PET strap MSE walls. *Geosynthetics International* 1–36. <https://doi.org/10.1680/jgein.18.00032>
- [10] Si, J. H., Chen, J. B., Feng, S. Y., and Qiu, S. X., 2021, Experimental research on eccentric compression of reinforced concrete columns strengthened by prestressed PET straps and angle steel. *Structures* 31, 1254–1264. <https://doi.org/10.1016/j.istruc.2021.02.052>
- [11] Ojeda, J. P., Mercante, I. T., de Borbon, F. M., Zerbino, R., Torrijos, M. C., & Giaccio, G. (2025). Pull-out performance of plastic and steel fibers recycled from waste. *Journal of Reinforced Plastics and Composites*, 44(19-20), 1955–1963.
- [12] Khatab, H. R., Mohammed, S. J., & Hameed, L. A. (2019). Mechanical properties of concrete contain waste fibers of plastic straps. In *IOP conference series: materials science and engineering* (Vol. 557, No. 1, p. 012059). IOP Publishing. <https://doi.org/10.1088/1757-899X/557/1/012059>
- [13] Norouzi, M., Châfer, M., Cabeza, L.F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering* 44, 102704. <https://doi.org/10.1016/J.JOBE.2021.102704>
- [14] European Commission. (2020). A new circular economy action plan for a cleaner and more competitive Europe. (Brussels: Publications Office of the European Union).
- [15] Kirchherr, J., Yang, N. H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): an analysis of 221 definitions. *Resources, conservation and recycling*, 194, 107001. <https://doi.org/10.1016/j.resconrec.2023.107001>
- [16] Foti, D. (2019). Recycled waste PET for sustainable fiber-reinforced concrete. In *Use of recycled plastics in eco-efficient concrete* (pp. 387–410). Woodhead Publishing. <https://doi.org/10.1016/B978-0-08-102676-2.00018-9>
- [17] Torkelis, A., Dvarionienė, J., & Denafas, G. (2024). The Factors Influencing the Recycling of Plastic and Composite Packaging

- Waste. *Sustainability*. <https://doi.org/10.3390/su16219515>.
- [18] Turkyilmaz, A., Guney, M., Karaca, F., Bagdatkyzy, Z., Sandybayeva, A., & Sirenova, G. (2019). A Comprehensive Construction and Demolition Waste Management Model using PESTEL and 3R for Construction Companies Operating in Central Asia. *Sustainability*. <https://doi.org/10.3390/su11061593>.
- [19] Loizia, P., Voukkali, I., Zorpas, A., Pedreño, J., Chatziparaskeva, G., Inglezakis, V., Vardopoulos, I., & Doula, M. (2020). Measuring the level of environmental performance in insular areas, through key performed indicators, in the framework of waste strategy development. *The Science of the total environment*, 753, 141974. <https://doi.org/10.1016/j.scitotenv.2020.141974>.
- [20] Thakur, V. (2020). Framework for PESTEL dimensions of sustainable healthcare waste management: Learnings from COVID-19 outbreak. *Journal of Cleaner Production*, 287, 125562 - 125562. <https://doi.org/10.1016/j.jclepro.2020.125562>.
- [21] International Organization for Standardization. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO.
- [22] International Organization for Standardization. (2006). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. ISO.
- [23] European Committee for Standardization. (2014). *EN 15804:2012+A1:2013 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*. CEN.
- [24] Conti, M. E., Simone, C., El Awag, N., & Tudino, M. B. (2026). An Overview of the Plastics Sector in the European Union-Italy-and Mercosur-Argentina and Brazil. *Revista Tecnologia e Sociedade*, 21(67), 361-378.
- [25] Gobierno de la Provincia de Mendoza. (2025). *Law 9659: Sistema de Gestión Integral de Residuos Sólidos Urbanos (GIRSU)*. Official Gazette de Mendoza.
- [26] Guevara Perez, A. V., Alejandrino, C., Guevara, O. J., Mercante, I. (2025). Análisis territorial de actores en la gestión integral de residuos sólidos urbanos del Área Metropolitana de Mendoza (2023-2025). *Cuyonomics* ISSN 2591-555X (In Press)
- [27] Alejandrino, C., Mercante, I., & Bovea, M. D. (2021). Life cycle sustainability assessment: Lessons learned from case studies. *Environmental Impact Assessment Review*, 87, 106517. <https://doi.org/10.1016/j.eiar.2020.106517>
- [28] IRAM. (2019). IRAM 11656: Adoquines de hormigón para pavimentos intertrabados. Requisitos y métodos de ensayo. Instituto Argentino de Normalización y Certificación. Sixth edition.
- [29] ASTM. (2005). Standard D-638 - Standard test method for tensile properties of plastics. American Society for Testing and Materials
- [30] Peña, C., Civit, B., Gallego-Schmid, A., Druckman, A., Pires, A.C.-, Weidema, B., Mieras, E., Wang, F., Fava, J., Canals, L.M. i, Cordella, M., Arbuckle, P., Valdivia, S., Fallaha, S., Motta, W. (2021). Using life cycle assessment to achieve a circular economy. *The International Journal of Life Cycle Assessment*. 1–6. <https://doi.org/10.1007/s11367-020-01856-z>
- [31] Ecoinvent. (2021). *Ecoinvent database* (Version 3.7.1). <https://www.ecoinvent.org/>



Navigating circular economy in key construction materials – Part 1: general regulations and reuse, recycling, and circular practices for steel and timber

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ABSTRACT

Construction and demolition waste represents one of the largest waste streams worldwide and plays a central role in achieving circular economy objectives in the built environment. This study aims to systematize and synthesize recent knowledge on the potential for reuse and recycling of key construction materials - steel, timber, concrete, and bricks and blocks - at the end of their service life. The research is structured in two papers: Part 1 focuses on regulatory frameworks, recycling rates, and reuse and recycling practices for steel and timber, while Part 2 addresses concrete and bricks and blocks. The objective was to identify opportunities for reuse and higher-value recycling as more effective circular solutions. The results indicate that, although the European regulatory framework for C&DW is well developed and aligned with circular economy principles, significant gaps remain, particularly the lack of harmonized end-of-waste criteria and quality standards for most material fractions. Consequently, high reported recovery rates often conceal downcycling practices and limited material circularity. Steel exhibits consistently high recycling rates, driven by strong market demand and established regulatory criteria, while direct reuse remains marginal. In contrast, timber recovery is dominated by energy recovery, with material recycling and reuse constrained by heterogeneous material quality, limited classification systems, and insufficient policy support.

1 Introduction

As the world progresses towards an urban future, the linear economic model, characterized by the "take, make, and dispose" pattern, has experienced significant growth. However, this model presents challenges, including resource supply risks and increased waste generation. The idea of developing a circular economy (CE) model was inspired by natural ecosystems that produce no waste. Therefore, the circular economy aims to close the loops in industrial ecosystems by applying the principles of "reduce", "reuse", and "recycle" (3Rs), thereby preventing the creation of waste and transforming waste into resources. The main concept of CE is to limit resource consumption, reduce waste, and decrease gas emissions, while ensuring global economic development is not disrupted. Circular Economy is described

by Geissdoerfer et al. 2017 as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" [1]. Construction and demolition waste (C&DW) is the primary source of gross waste generation in modern society. The amount of C&DW grows along with worldwide urbanization. EU-28 has good practice thanks to an advanced C&DW management system supported by policies, laws, regulations, and technologies for C&DW management. Thus, in 2018, the C&DW recovery rate in the EU-28 was about 90% [2].

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C&DW is the largest waste stream in the European Union (EU), which accounts for almost 40% of all waste generated in the EU. Expanding the construction sector leads to a corresponding increase in construction materials. In 2020, demolition and renovation were responsible for 83% and 17% of material flows, respectively. Corresponding percentages for 2050 are expected to be 87% and 13% [3]. C&DW is composed of different waste fractions and materials registered under specific codes according to two main coding systems applied within the EU: the List of Waste (LoW), which is administration-oriented, and the European Waste Code Statistics (EWC-Stat), which is substance-oriented. The average composition of C&DW is presented in Fig. 1 [4].

According to Fig. 1, concrete, bricks, metals, and wood are dominant fractions of C&DW.

The Waste Framework Directive 2008/98/EC (WFD) [5] is a milestone of modern waste management in the EU. A notable contribution of the WFD is the introduction of the waste hierarchy. Contrary to the 3Rs framework of circular economy, which focuses on reducing, reusing, and recycling, the waste hierarchy prioritizes waste management strategies through a five-stage inverted pyramid. The hierarchy ranges from the most preferred option of "prevention" to the least preferred option of "disposal" (Fig. 2).

From a life cycle perspective, both the waste hierarchy and circular economy consider the whole life cycle of a product, including the pre-use phase, use phase, and post-use phase. (1) The first stage of the waste hierarchy pyramid

is prevention, which is considered the pre-use phase. To meet the basic requirements of prevention, the smarter creation and use of products should be prioritized. (2) The second stage involves preparing for reuse during the use phase, aiming to extend component life through reuse. (3) The third stage of the hierarchy pyramid involves recycling, other recovery methods, and disposal, which are part of the post-use phase. It is important to identify useful applications for waste materials and to minimize disposal. The minor difference is that the waste hierarchy still allows disposal, while the framework of a circular economy does not [2].

Directive (EU) 2018/851 [6] introduces a new concept within the waste hierarchy, namely "material recovery." This term refers to forms of recovery other than energy recovery and excludes the reprocessing of waste into materials used as fuel or other means of generating energy. It includes preparing for re-use, recycling and backfilling and other forms of material recovery such as the reprocessing of waste into secondary raw materials for engineering purposes in construction of roads or other infrastructure. In addition, the Directive defines the term "backfilling" as any recovery operation in which suitable non-hazardous waste is used for the reclamation of excavated areas or for engineering purposes in landscaping.

Taking these newly introduced concepts within the waste hierarchy into account, we modified the original "waste hierarchy pyramid" as defined in [5]. The revised structure of waste hierarchy pyramid is presented in Fig. 3.

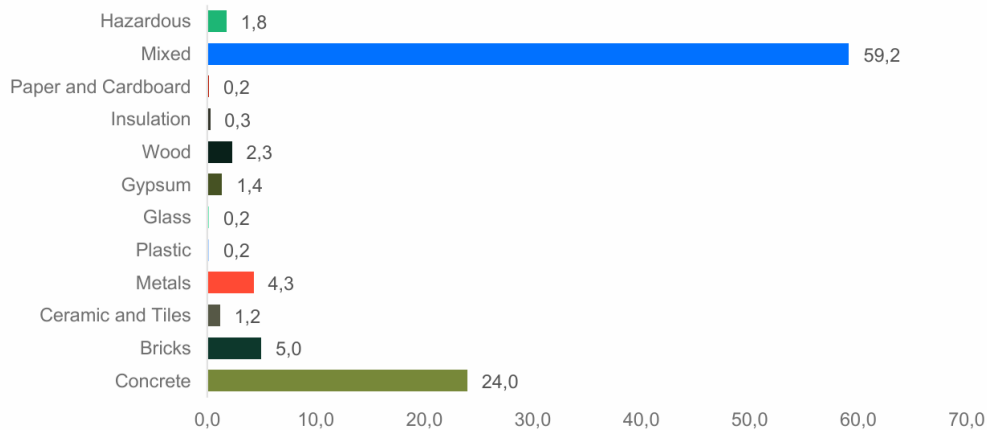


Figure 1. C&DW composition in the EU [4]



Figure 2. Waste hierarchy pyramid according to WFD 2008/98/EC [5]

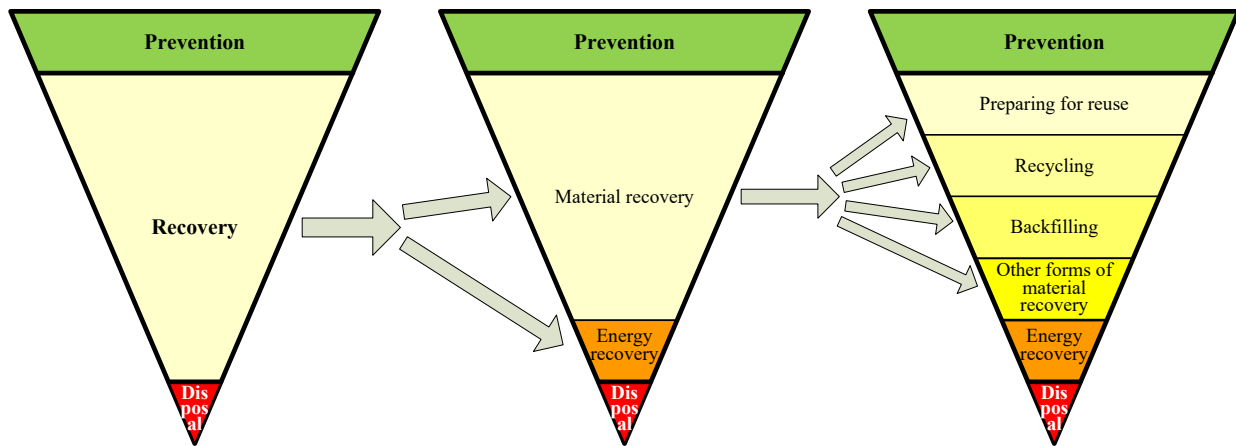


Figure 3. Adapted waste hierarchy pyramid according to Directive 2018/581/EC, [5]

Although Directive [5] proposes the selective collection of waste, Directive [6] provides additional clarifications aimed at improving the waste management system. In this context, Member States shall take the necessary measures to ensure that waste undergoes preparation for reuse, recycling, or other recovery operations in accordance with the waste hierarchy and respecting the protection of human health and the environment. These measures include, where necessary, the application of separate collection to prevent mixing with other waste or materials with different properties. When it comes to C&DW, Member States shall take measures to promote selective demolition to enable the removal and safe handling of hazardous substances and to facilitate re-use and high-quality recycling through the selective removal of materials, as well as to ensure the establishment of sorting systems, at least for wood, mineral fractions (concrete, bricks, tiles and ceramics, stones), metal, glass, plastic, and plaster.

In the case of buildings and construction materials, "prevention" is ensured by achieving "Longevity" and "Durability". This is achieved primarily by appropriate design, comprehensive quality control during construction, and proper maintenance.

Reuse is using an object or material again, either for its original or a similar purpose, without significantly altering the physical form of the object or material. In a fully circular economy, the reuse of a manufactured product is considered in the earliest design phases of its creation [7]. Reuse makes good environmental sense, saving both resources and carbon emissions [8]. It is a high priority that the natural resource extraction for construction should be slashed down by developing alternative technologies, such as direct reuse in construction, to reduce the unsustainable pressure on the environment [9].

Existing buildings can be reused in situ or dismantled and re-erected at a different location. By reusing existing buildings, not only is demolition waste minimized, but the new resources required to renovate and refurbish the building are much less than those required to construct a new building. In addition, reusing existing buildings can preserve the cultural and historic value of older buildings [10].

It is also possible, but less desirable, to reuse building structural components/products individually by sending them to warehouses and building material suppliers to be used for new purposes.

By promoting circularity in construction and fostering trust in recycled materials, the most recent Joint Research Centre report on the management of C&DW in the EU, published in 2024, aims to improve C&DW management [11]. The report emphasizes the significance of transparent waste logistics, selective demolition, and pre-demolition audits. Additionally, to encourage circularity in construction, it highlights the necessity of policy frameworks that foster cooperation between industry, government, and society.

Our two papers (Parts 1 and 2) address the reuse and recycling processes and the end-of-life potential of key construction materials—steel, timber, concrete, and bricks and blocks. The objective was to systematically compile and analyze the most recent data on reuse and recycling practices for these materials through collaborative research, in order to provide an objective assessment of the current state and future potential for implementing circular economy principles in the construction sector. Both papers are based on joint work conducted within COST Action CA21103 Circular B and aim to contribute to a clearer understanding of the current level of circularity in construction, while identifying opportunities for improvement and innovation, as well as key barriers that need to be addressed.

2 Materials and methods

2.1 Paper organization

In the scope of this work, an analytical and comprehensive literature review was conducted. The literature was gathered from multiple sources, including official documents and directives of the EU, reports of EU C&DW management projects, reports of official associations for specific construction materials, and articles in journals.

The EU WFD (2008) was taken as the basis for definitions of the waste hierarchy and other associated terms related to C&DW management. The information on the developmental trajectory of the waste hierarchy and circularity framework was collected from EU documents and directives, as well as scientific articles. Since we decided to analyze and present the current circularity level of four key construction materials, we divided our work into two related papers.

The algorithm describing the organization, structure, and content of the papers is shown in Fig. 4.

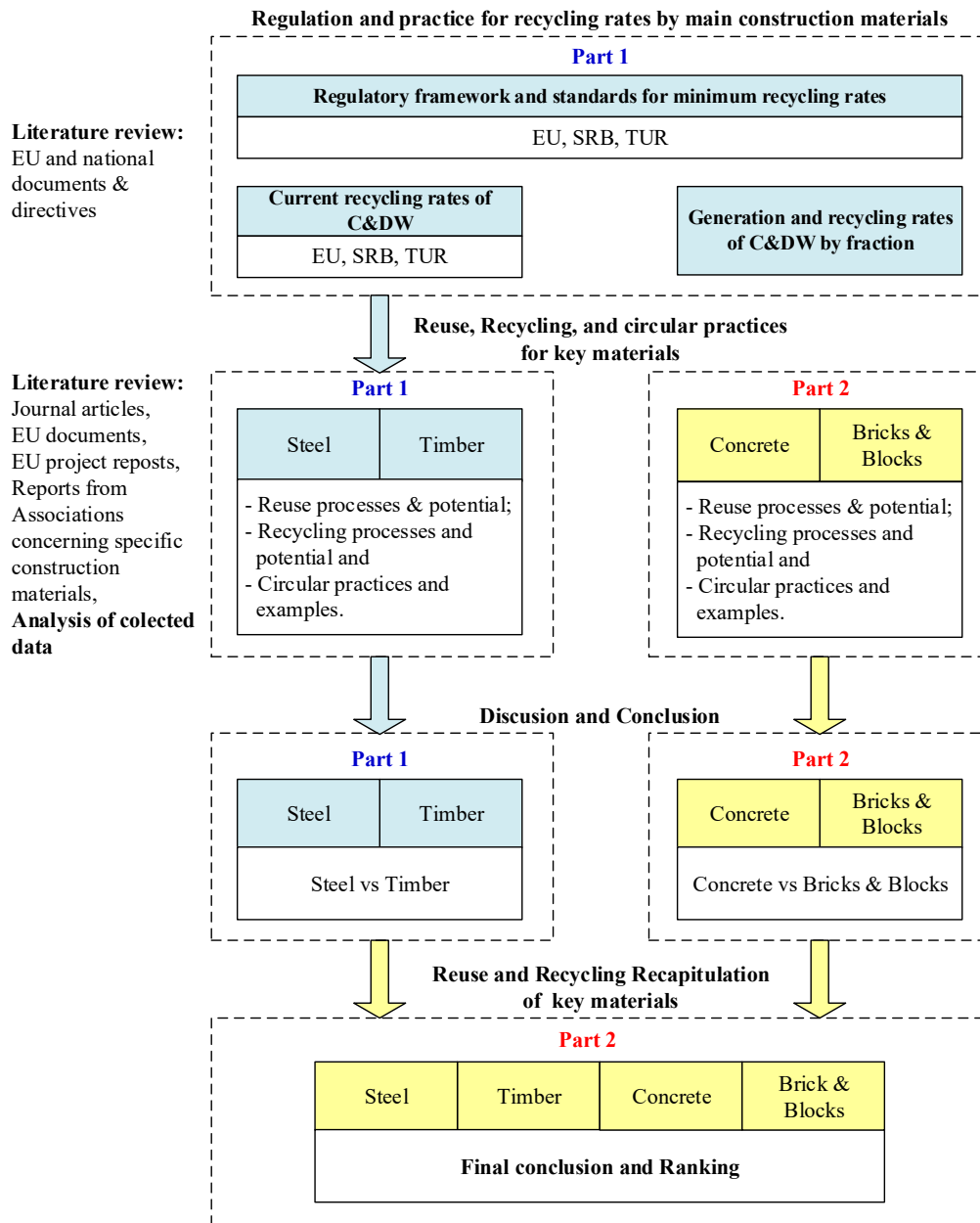


Figure 4. Organization of papers

2.2 Literature selection and review approach

To ensure transparency and reproducibility in the selection and thematic organization of the cited literature, a light PRISMA-informed approach was applied to all 174 references. The analysis was structured in three phases: (1) references were classified by source type, distinguishing between peer-reviewed journal articles, official EU and governmental reports, technical and professional websites, books and technical reports, and conference proceedings; (2) each reference was assigned to one or more of seven thematic areas - general circular economy frameworks, waste management, regulatory frameworks, steel reuse, steel recycling, timber reuse, and timber recycling; (3) the temporal distribution of references was examined by publication year to assess the recency and evolving focus of the reviewed literature. Tab. 1 presents the distribution of the references across five source types.

Peer-reviewed journal articles represent the largest single source category with 62 references (35.6%), providing the scientific backbone of the review. Technical and professional websites and portals account for 41 references (23.6%), reflecting the importance of industry-facing knowledge bases and organizational repositories in this field. Books, book chapters and technical reports contribute 34 references (19.5%), while official EU and governmental documents account for 29 references (16.7%), underpinning the regulatory and policy dimensions of the analysis. Conference proceedings represent the smallest category with 8 references (4.6%). Among all source types identified in the analysis, peer-reviewed journal articles were selected for further examination due to their scientific rigor and direct relevance to the research themes. The 62 peer-reviewed journal articles were published in 38 journals, indicating a broad and diverse scientific base. The five most frequently

cited journals, together with the number of references and primary themes covered, are presented in Tab. 2.

As shown in Tab. 2, the five most frequently cited journals together account for 25 out of 62 peer-reviewed articles (40.3%). *Journal of Cleaner Production* is the most represented journal with 8 articles (12.9%), followed by *Resources, Conservation and Recycling* with 5 articles (8.1%) and *Sustainability* with 4 articles (6.5%). The remaining 37 articles are distributed across 33 journals (one article each or two), reflecting broad coverage across the field.

Each of the 174 references was assigned to one or more thematic labels using a multi-label coding approach. Tab. 3 presents the resulting distribution across seven identified thematic areas.

The distribution of references across research themes reflects broader trends in the construction sector. The dominance of the general circular economy category (94 references) indicates that, in recent years, material use, waste management, and resource efficiency are increasingly framed within the overarching CE paradigm rather than as isolated technical topics. This reflects a fundamental shift in how the sector approaches sustainability, moving from

material-specific solutions towards integrated systemic thinking. Among the material-specific themes, timber recycling is the most represented with 54 references, which is consistent with the long-standing tradition of wood recycling in the construction sector and the continuously expanding range of products in which recycled timber can be incorporated, from particleboard and MDF to engineered wood products such as CLT and glulam. The remaining material-specific themes, steel recycling (35 references), steel reuse (34 references), and timber reuse (29 references), are comparably represented, suggesting a relatively balanced, though still emerging, body of evidence across these areas. Waste management (31 references) and regulatory frameworks (36 references) complete the thematic landscape, reflecting the growing legislative attention to construction and demolition waste streams at both EU and national levels.

Regarding the annual distribution, 146 of 174 references have an identifiable publication year. The remaining 28 are URL-only sources for which no dateable publication year could be established and are therefore excluded from the temporal analysis. The results of temporal analysis are presented in Tab. 4.

Table 1. Distribution of references by source type

Source Type	n	%
Peer-reviewed journal articles	62	35.6%
Technical/professional websites & portals	41	23.6%
Books, book chapters & technical reports	34	19.5%
Official EU/Government reports	29	16.7%
Conference proceedings	8	4.6%
TOTAL	174	100%

Table 2. Distribution of peer-reviewed journal articles in top 5 journals (multi-label thematic coding applies)

No.	Journal	Number of papers	References	Primary theme(s)
1	Journal of Cleaner Production	8	[44], [57], [82], [100], [109], [117], [143], [165]	CE, Steel recycling, Timber reuse/recycling
2	Resources, Conservation and Recycling	5	[54], [56], [60], [81], [112]	Steel reuse, Steel recycling, Timber recycling
3	Sustainability	4	[134], [140], [142], [144]	Timber recycling, CE
4	Construction and Building Materials	3	[114], [125], [156]	Timber reuse/recycling
5	Journal of Building Engineering	3	[84], [105], [166]	CE, Timber reuse/recycling

Table 3. Distribution of references by research theme (multi-label coding)

Research Theme	n	Description / scope
General circular economy	94	Overarching CE frameworks, LCA studies, broad construction sector topics
Timber recycling	54	Wood waste, panel products (MDF, OSB, CLT), cascading use, biomass
Steel recycling	35	EAF/BOF processes, scrap flows, green steel, decarbonization
Regulatory frameworks	36	EU Directives, national legislation, standards, policy documents
Steel reuse	34	Pre-demolition audit. direct structural reuse, demountable connections, material passports
Waste management	31	C&DW streams, treatment, waste hierarchy, data and statistics
Timber reuse	29	Reclaimed wood, salvage, reversible connections, design for disassembly

Note: Since thematic coding was applied using a multi-label approach, whereby a single reference could be assigned to more than one thematic category if its content spans multiple topics - the sum of references across all seven themes (n = 313) exceeds the total number of unique references analyzed (n = 174).

Table 4. Distribution of references by publication period

Publication Period	n	%	Observation
≤2014	14	10%	Foundational & methodological references
2015–2017	11	8%	Early CE framework development
2018–2019	18	12%	EU Green Deal preparation period
2020–2021	22	15%	New CE Action Plan (2020) impact
2022–2023	37	25%	Intensified EU policy & research activity
2024–2025	44	30%	Most active period; 2024 alone: 36 references
Total number of references with identified year	146	100%	28 URL-only references have no identifiable year

The temporal distribution reveals a pronounced recency profile, consistent with a review focused on the current state of circular economy practice in construction. References published between 2020 and 2025 account for 70% of all dated references (103 out of 146). The year 2024 alone contributes the largest single-year count (36 references), and 2025 already contributes 8 references despite being an incomplete publication year at the time of the literature search.

3 Regulation and practice for recycling rates by key construction materials

3.1 Regulatory framework and standards for minimum recycling rates of C&DW

Since 2008, when WFD was adopted, C&DW has been a priority stream in the EU. This directive has set a target for 2020 of having 70% by weight of a non-hazardous C&DW pre-treated for reuse, recycling, and other forms of recovery [5]. The target aimed to divert non-hazardous C&DW from landfills and increase the use of secondary resources. By 2018, the EU average for disposal was about 10%, with a recycling rate above 80% [12]. Nevertheless, there were several issues with these figures, which came from Eurostat. The statistics are usually unreliable, as most companies from less developed countries are not motivated to report the actual amounts of waste generated and treated. Apart from this, the information on the treatment lacked details regarding the particular waste streams inside the C&DW, their potential use in the future, and their eventual return to the resource loop - that is, whether they were downcycled or upcycled. The latter would facilitate the transition to a circular economy, one of the EU's ambitions since the first Circular Economy Action Plan - Closing the Loop, came into force in 2015 [13].

With the adoption of the Green Deal Strategy, this plan has become one of the EU's key objectives: "to make Europe the first climate-neutral continent by 2050." Aside from reducing gas emissions by 55% by 2030 (compared to 1990) and eliminating net emissions by 2050, this strategy also foresees the separation of economic development from the use of resources [14]. The New Action Plan for the Circular Economy "For a cleaner and more competitive Europe" is one of its 47 main actions. It emphasizes sustainable consumption, more resource-efficient production and use, waste reduction, reuse, and recycling to double the rate of circularity in the next ten years [15].

Construction is one of the key economic sectors for achieving these goals, and the New Circular Economy Action Plan calls for adopting a comprehensive strategy for a sustainable built environment to increase material efficiency

and decrease climate impact. As part of this strategy, the Construction Products Regulation should be revised to include requirements for recycled content in construction products. In this context, Directive (EU) 2018/851 [6] amends Article 11 (Preparing for re-use and recycling) by introducing a new obligation for Member States to promote selective demolition. This measure aims to ensure the safe removal and handling of hazardous substances and to facilitate re-use as well as the high-quality recycling of C&DW. In addition, Member States are required to establish sorting systems for C&DW covering at least six material fractions: wood, mineral fractions, metals, glass, plastics, and plaster. Mineral fractions include concrete, bricks, tiles, ceramics, and stones.

Aside from the forthcoming Strategy for a Sustainable Built Environment and the recent amendments of the WFD, the strategic and regulatory framework for higher C&DW hierarchy treatments has been set. However, the lack of end-of-waste (EoW) criteria and quality standards currently hinders the broader application of reused and recycled C&DW fractions. At this point, end-of-waste criteria have only been established for copper scrap (Commission Regulation (EU) No. 715/2013), glass cullet (Commission Regulation (EU) No. 1179/2012), and iron, steel, and aluminum scrap (Council Regulation (EU) No. 333/2011).

Without other EoW criteria, an EoW definition from WFD may help. The WFD states that waste no longer qualifies as waste if it has undergone a recovery operation, is widely used for specific purposes, meets market or demand, satisfies technical requirements, complies with current laws and standards, and won't harm the environment or public health [6]. While wider usage and market demand fall under the regulatory framework and fiscal instruments, the existing standards may be used for the quality assurance procedure. According to EN 206:2013+A2:2021, for example, up to 50% of coarse recycled concrete aggregate may be used in concrete for in situ structures, precast structures, and structural precast products for buildings and civil engineering structures, depending on the type of recycled aggregate and the intended use of the concrete [16].

Although having been created for 2022–2024, the Serbian Circular Economy Development Program [17] has established a course that Serbia will take in the following years. Initially planned as part of the Green Agenda for the Western Balkans [18], the program focused on the need to increase waste reuse and recycling, with a particular focus on C&DW, identified as one of the program's priority streams. This is further elaborated in the Waste Management Program for the period 2022-2031 [19], which was adopted at the beginning of 2022. According to this program, 40% of C&DW is expected to be recovered by 2029, and 70% of C&DW will be pretreated by 2034 [19]. Recovery is related to the entire C&DW stream without specifying individual

waste streams such as concrete, clay, etc. Although they have not yet been determined, the program anticipates setting recycling rate targets for particular C&DW streams.

Building on these strategic documents, Serbia has actively established the regulatory framework necessary to achieve these goals in recent years. In addition to amendments to the Waste Management Act [20], a significant step was taken with the recent adoption of the Construction and Demolition Waste Management Regulation in 2023 [21] and preparing a Rulebook on Construction and Demolition Waste Management. These documents, however, focused primarily on the pre-demolition audit and the primary separation, collecting, and storage of C&DW; they did not address the financial incentives and taxes that would have increased the motivation of waste operators to invest in treatment facilities and, consequently, increase the recovery rates.

Similar to the EU, one of the key obstacles to the broader adoption of recycled C&DW in Serbia is the absence of EoW criteria. This is a pressing issue that needs to be addressed. Like the EU, Serbia currently only has EoW criteria for iron, steel, aluminum, copper, and glass cullet [22]. Likewise, the use of recycled concrete aggregate is governed by harmonized EU standards (SRPS EN 206-1:2021).

Türkiye is actively working on the transition to a circular economy and published the Green Deal Action Plan in line with the EU Green Deal, which includes 32 targets and 81 actions under 9 main titles, and 'housing and construction' is one of the sectors focused on for the preparation of the National Action Plan for Sustainable Consumption and Production [23]. Targets related to the circular economy are also included in the Twelfth Development Plan (2024-2028) [24]. The National Waste Management and Action Plan includes required actions on C&DW, such as the establishment of a C&DW collection system, an effective vehicle tracking system for collecting vehicles, recycling at maximum levels, obligatory selective demolition of buildings, usage of soil in recreational areas, etc. [25].

In terms of legislation, C&DW in Türkiye is regulated by the By-law on Excavation Soil and Construction and Demolition Waste Control [26]. According to them, minimizing at source, recovery, and reuse of waste are essential. However, there is no stated recycling target in the mentioned document. In addition, the By-law on Zero Waste is also connected to the C&DW despite not specifically including the waste type [27],[28].

Similar to the EU, Türkiye uses a harmonized EU standard for the use of recycled aggregate (TS EN 206+A2, 2021) [29]. In the cited standard, a limit for the replacement of natural normal-weight coarse aggregates by coarse recycled concrete aggregate ($d \geq 4$ mm) is defined in the range of 0% to 50% in relation to recycled aggregate type, exposure classes for risk of corrosion induced by carbonation, and the intended use of the concrete.

3.2 Current recycling rates of C&DW

Driven by a strong commitment to the circular economy, the EU has made significant progress in managing C&DW. Many member states have already exceeded the target of 70% recycling and non-hazardous C&DW recovery by 2020, established by the WFD. The EU's average C&DW recovery rate as of 2020 was over 80% [30]. A leading example is Germany, with a high recovery rate of 94% from 2010 to 2020 [30]. All four construction materials under investigation are currently being recycled. Concrete recycling involves crushing and reusing the material for foundations, road

construction, and other uses. Since steel scrap has great economic value, its recycling is quite efficient. Bricks and blocks are often crushed and used as an aggregate in new construction projects. Denmark also boasts strong rates of recycling, especially for metals and concrete, with recovery rates around 97% [30]. Spain has achieved gains in its C&DW recycling rates, with 73%, while Italy reached 80.1% of C&DW in 2020. Strong market demand for recycled products and strict regulatory systems help to explain these high rates of recycling.

According to Eurostat [31] for the EU-27 countries, the total waste treated increased from 779 million tonnes in 2004 to over 1 billion tonnes by 2020. This shows a significant improvement in waste management infrastructure and practices, aligning with the EU's broader environmental goals to improve recycling and reduce landfill usage. Notably, the EU-28 (2013-2020 configurations) also shows substantial waste treatment achievements, with over 1 billion tonnes managed annually in the years reported. The data from 2016 provides insights into the performance of various EU member states not only in percentages but also in millions of tonnes of C&DW [32]. Germany reported a high recycling rate of 83.7%, processing over 70 million tonnes of C&DW. Despite this high recycling rate, 7.3% of the waste was still sent to landfills and other disposal methods, totaling over 6.1 million tonnes. Additionally, 1.2% was directed to energy recovery, involving more than 1 million tonnes. According to [33], Denmark reported a recycling rate of 89.2%, processing over 3 million tonnes of C&DW. The country used landfills for 4.1% of the waste, and backfilling was not practiced. Then, Spain recorded a recycling rate of 70.5%, managing around 6.5 million tonnes of C&DW. However, 21.2% of the waste was directed to landfills, and 8.3% to backfilling. In Estonia, concrete, bricks, and ceramic waste are classified as C&DW, which accounted for 14% of all waste in 2024. The Ministry of Environment manages C&DW data in databases from 2010 to 2019. In 2019, C&DW generation was 1.2 million tonnes, with a recycling rate of 84%. According to the paper [33] that analyzes the construction waste disposal practices in Romania, it highlights the current state and potential improvements in the recycling and recovery of C&DW. Romania's waste recovery level is significantly below the European Union's target of 70% set for 2020. Most of the C&DW collected in Romania is disposed of in landfills, with minimal recovery or reuse efforts. This waste includes materials such as concrete, bricks, wood, glass, metals, plastic, solvents, asbestos, and excavated soil. Among these, concrete, bricks, tiles, and ceramics constitute approximately 78% of the total C&DW. Despite the potential for recovery, Romanian practices have largely focused on landfilling. Data from the Romanian Ministry of Environment show that from 2006 to 2011, although there was an increase in the amount of C&DW collected (from around 200,000 tonnes in 2006 to over 800,000 tonnes by 2011), the recovery rates remained low. Romania declared a C&DW recovery rate of 46% in 2020, which includes reuse, recycling, and backfilling of all non-hazardous C&DW streams. In 2020, it is estimated that the UK generated 59.4 million tonnes of non-hazardous C&DW, of which 55.0 million tonnes were recovered. England generated 53.9 million tonnes of this waste, of which 50.3 million tonnes were recovered. In 2022, England generated 63.0 million tonnes of non-hazardous C&DW, of which 59.4 million tonnes were recovered [34].

Aiming to raise recycling rates and support the circular economy, Serbia has been trying to match its waste management methods with EU norms. The Waste

Management Program of the Republic of Serbia for the Period 2022-2031 presents the strategic objectives, legislative environment, and the current status of the waste management situation [35]. The initiative establishes particular targets for the recycling and recovery of C&DW and emphasizes compliance with the EU Waste Framework Directive. By 2029, Serbia wants a 40% recovery rate for C&DW and by 2034 a 70% pre-treatment rate. According to the program, Serbia's recycling rates of different materials are still developing. The current focus is on improving infrastructure and data collection to achieve higher recycling rates. Specific recycling rates for C&DW materials such as concrete, steel, bricks, and timber are not detailed in the program.

In Türkiye, the general application in the field related to building demolition is dismantling the plastic, wooden, and metal components with the aim of reuse and recovery. Most of the scrap materials and metal reinforcement are recovered after the demolition of the buildings, and the rest of the generated C&DW, which is a mix of waste concrete, brick, ceramic, and other materials and constitutes almost 80% of C&DW in weight, is collected and used as a filler or disposed of at landfills. C&DW disposal plants, which are licensed for storage, temporary storage, incineration, pre-treatment, land reclamation, and physicochemical processes, are located mostly in large cities. Also, except for six cities, there is at least one plant that is licensed for recovering C&DW in each city of Türkiye [30]. For the waste concrete, there are 428 licensed plants (346 pre-treatment plants (R12); 37 recycling/reclamation plants for other inorganic materials than metals (R5); 14 temporary storage plants (R13); 7 landfills; 6 recovery plants for pollution abatement (R7); 5 physical blending or mixing plants (D13), 3 specially engineered landfills (D5), who may accept this type of waste and dispose or recover it according to the current legislations. This information is based on the list of licensed plants, and it does not guarantee that all the licensed plants are currently accepting C&DW waste and waste concrete [36]. There is no published statistical data on the recycling rate of C&DW for Türkiye [36], [37], [38]. Preparation of this statistical data is under the responsibility of the Ministry of Environment, Urbanization, and Climate Change, and it is planned for 2026, with the requirement of a variation of related legislation [36], [37]. Similar to the EU, in Türkiye, there is no existing EoW criteria for C&DW. The studies related to the definition of EoW criteria for specific waste streams in Türkiye, in line with the Waste Framework Directive (2008/98/EC) and the Directive (2018/851) amending Directive 2008/98/EC, are still ongoing in the context of the Technical Assistance for Development of End-of-Waste Concept in Türkiye Project [39].

3.3 Generation and recycling rates of C&DW by fraction

When it comes to the generation and treatment of C&DW (other than reuse), the most comprehensive and trusted source of data is Eurostat. This European statistical office collects and aggregates C&DW-related data at the national level. Companies that generate and treat C&DW send this

data to the relevant national statistical offices. Although this is a legal requirement, companies in many countries perceive it as voluntary, as national statistical offices often mention limited reporting coverage. Furthermore, the guidelines for reporting are not explicit enough for non-experts and may result in misleading information. As a result, there is a lack of trust in this data, which is often observed in academic circles. However, with reasonable caution, these statistics may indicate the distribution and scale of specific C&DW streams and their treatment rates.

Figures regarding the generation of mineral, wood, and metal C&DW fractions in the EU for 2020 are illustrated in Fig. 5 and Fig. 6 [40]. Both figures display the generation statistics for every European country (where data were available); however, they are split into two parts for better visibility. The upper chart shows only nations whose quantities are less than 10% of the lead quantity.

The notable difference (about 30 times) in the generation between the mineral C&DW fraction (Fig. 5) and wood and metal waste stream (Fig. 6) can be observed by comparing these two figures [40]. Germany, France, Italy, the Netherlands, and Belgium are leaders in generating all three specified waste streams. Minor variations among nations can be attributed to differing national construction methods and practices. For instance, Sweden, Norway, and Finland rank in the top ten for generated wood and metal waste, primarily due to the high prevalence of timber-based construction. Conversely, Spain and Austria are among the top generators of the mineral fraction of C&DW.

It is noteworthy that when all countries from the upper chart of C&DW mineral fractions (Fig. 5) are combined, the total waste generation equals that of Italy. Similarly, for wood and metal fractions (Fig. 6), the aggregate amount is slightly higher than that of Belgium. This analysis suggests that countries leading in waste production should bear the primary responsibility for the EU's transition toward a circular economy.

On the other hand, based on the mineral fraction of the C&DW treatment rate statistics [41], it can be seen that new countries emerge as leaders in Europe's C&DW treatment, such as Slovenia, Latvia, Bulgaria, and the Czech Republic (Fig. 7). These countries reported recycling more than 75% of the mineral C&DW fraction. Slovenia, the Netherlands, and Italy are leaders in European mineral C&DW recycling. Nearly all mineral C&DW fractions (concrete, bricks, tiles, ceramics, and stones) are recycled in these countries. However, the subsequent usage of secondary material obtained with this treatment remains unknown.

Finally, as with reuse, there is currently a lack of harmonized and transparent data regarding the specific recycling rates of wood and metal fractions within the C&DW stream across Europe. While metals are largely recovered due to their high market value, wood often flows into energy recovery rather than material recycling, making it difficult to accurately track its circularity. This data is becoming increasingly important as Europe strives to separate resources from economic growth. The EU should consider revising its statistics laws to better promote and monitor construction circularity.

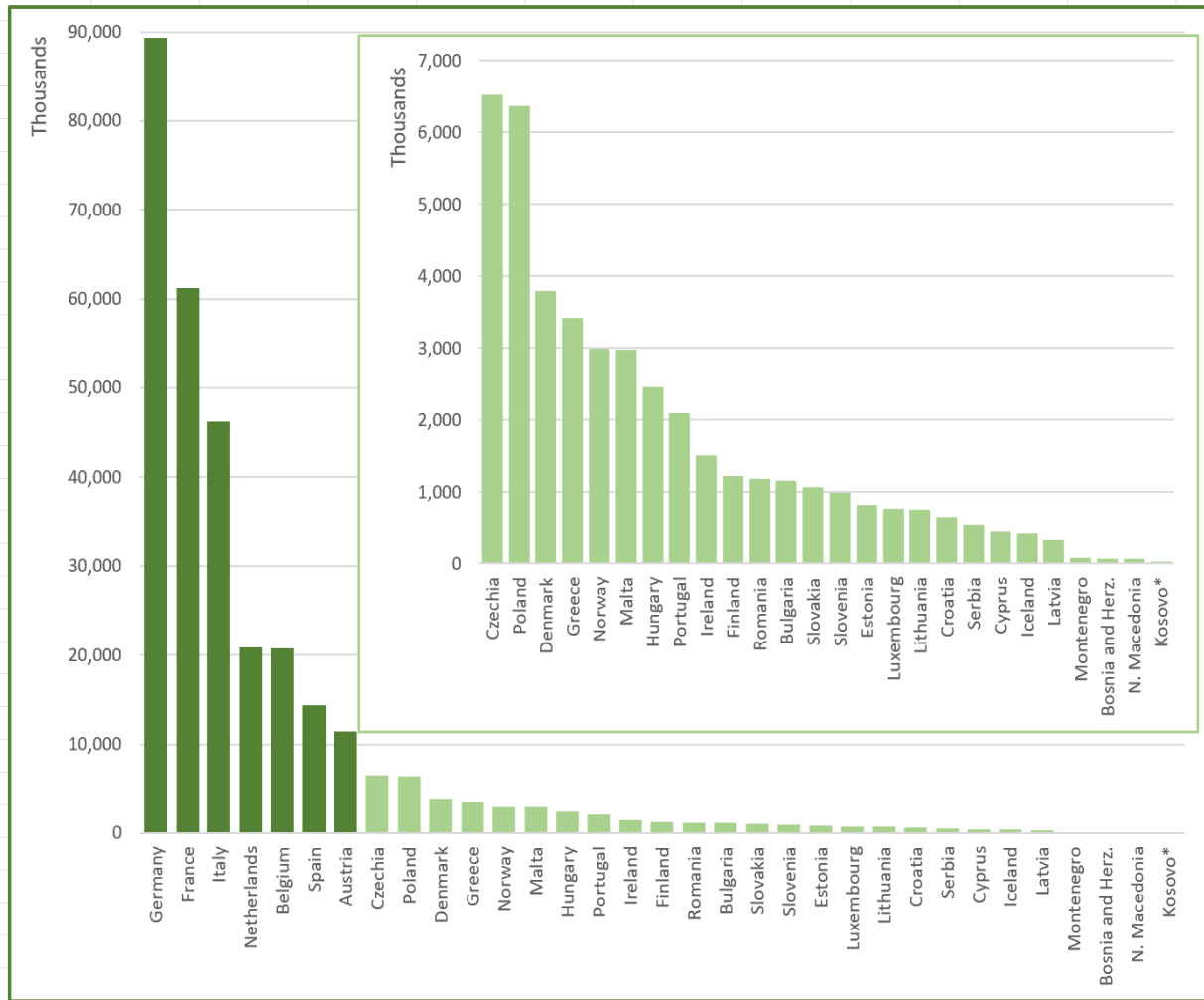


Figure 5. Generation of mineral C&DW fraction in Europe in 2020 [40]

In the absence of official EU statistics detailing the recycling rates of key construction materials derived from C&DW, we aimed to gather complementary data at the national level. Accordingly, a questionnaire was prepared and circulated among MC members representing EU and non-EU countries participating in COST CA21103 Circular B. We set 2 basic and 6 optional questions for each key construction material. The example of set questions for steel is given below. The basic questions are marked with (1) and (2).

(1) *Is there an official recycling rate for steel in your country?*

(1a) If yes, please state the official rate and the source (e.g., report name, link, institution).

(1b) If no official rate is available, please provide your estimated recycling rate for concrete based on your professional knowledge or experience.

(1c) Additional comments about steel recycling

(2) *Is there an official reuse rate for steel in your country?*

(2a) If yes, please state the official rate and the source (e.g., report name, link, institution).

(2b) If no official rate is available, please provide an estimated reuse rate based on your knowledge or experience.

(2c) Additional comments about steel reuse.

These questions were repeated for other key construction materials: timber, concrete, and bricks and blocks. Representatives of 11 EU countries (Austria (AUS), España (ESP), Hungary (HUN), Italy (ITA), Estonia (EST), Romania (ROU), Lithuania (LTU), the Czech Republic (CZE), Latvia (LVA), Portugal (PRT), and Luxembourg (LUX)) and 3 non-EU countries (Switzerland (CHE), North Macedonia (MKD), and the United Kingdom (GBR)), participated in the survey. The Excel document with all the information gathered from the survey is given as a supplementary file to this paper. This file contains many helpful statements, figures, and links. Some basic information on the survey's findings is shown in Tab. 5 and Tab. 6. The meanings of the abbreviations (1) in the table are: "Yes" - there are official data, "N/S" - I am not sure, "No" - there are no official data

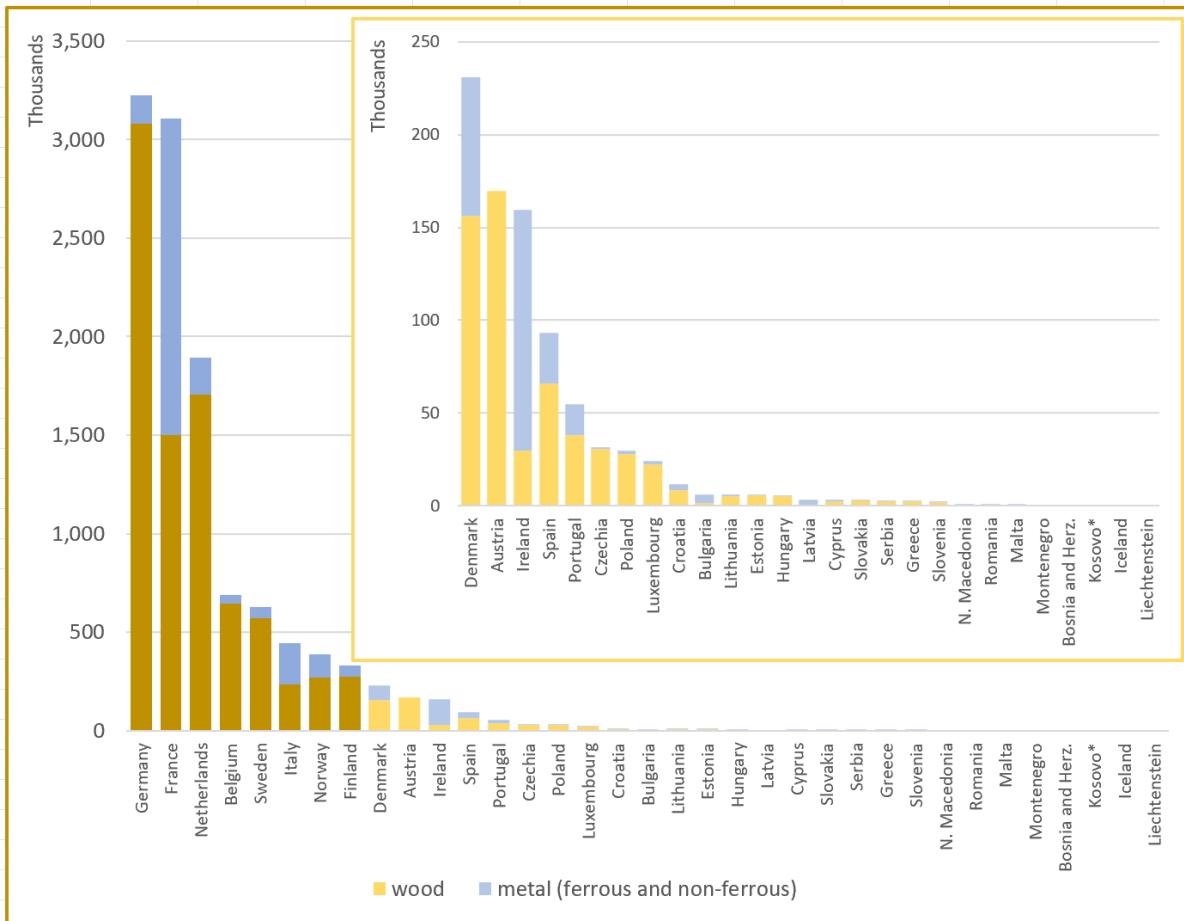


Figure 6. Generation of wood and metal fractions (from construction activity) in Europe in 2020 [40]

Table 5. Questionnaire findings on recycling rates of key construction materials

Country	Steel			Timber			Concrete			Bricks & Blocks		
	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)
AUS	Yes	30%	-	No	-	55%	N/S	-	14%	No	-	45%
ESP	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
HUN	No	-	70%	Yes	98,4%*	-	No	-	3,4%	No	-	75%
ITA	Yes	~85%	-	Yes	-	64,9%**	Yes	10%	-	Yes	80,1%*	-
EST	Yes	52%	-	Yes	50,7%	-	Yes	-	46%*	Yes	98%	-
ROU	No	-	70-76%*	No	-	5-10%	No	-	20-25%	No	-	5-10%
LTU	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
CZE	No	-	98%	No	-	80%	No	-	90%** 15% RCA	No	-	-
LVA	No	-	-	No	-	-	No	-	-	No	-	-
PRT	Yes	78%	95-100%	No	-	77%***	Yes	-	-	Yes	-	-
LUX	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
CHE	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
MKD	No	-	<1%	No	-	<1%	No	-	<1%	No	-	<1%
GBR	Yes	96%** 86%***	-	Yes	60%*	-	Yes	-	-	N/S	-	-
	* Data includes construction, industrial and consumer sources ** Recovery rate for all steel construction products *** Recycling rate of structural sections			* Related to "waste wood" ** As reported by "Rilegno" *** Combined with glass and plastic			* Mineral C&DW (concrete, bricks, and ceramic waste) ** Recovered concrete waste			* Recycling rate of C&DW		

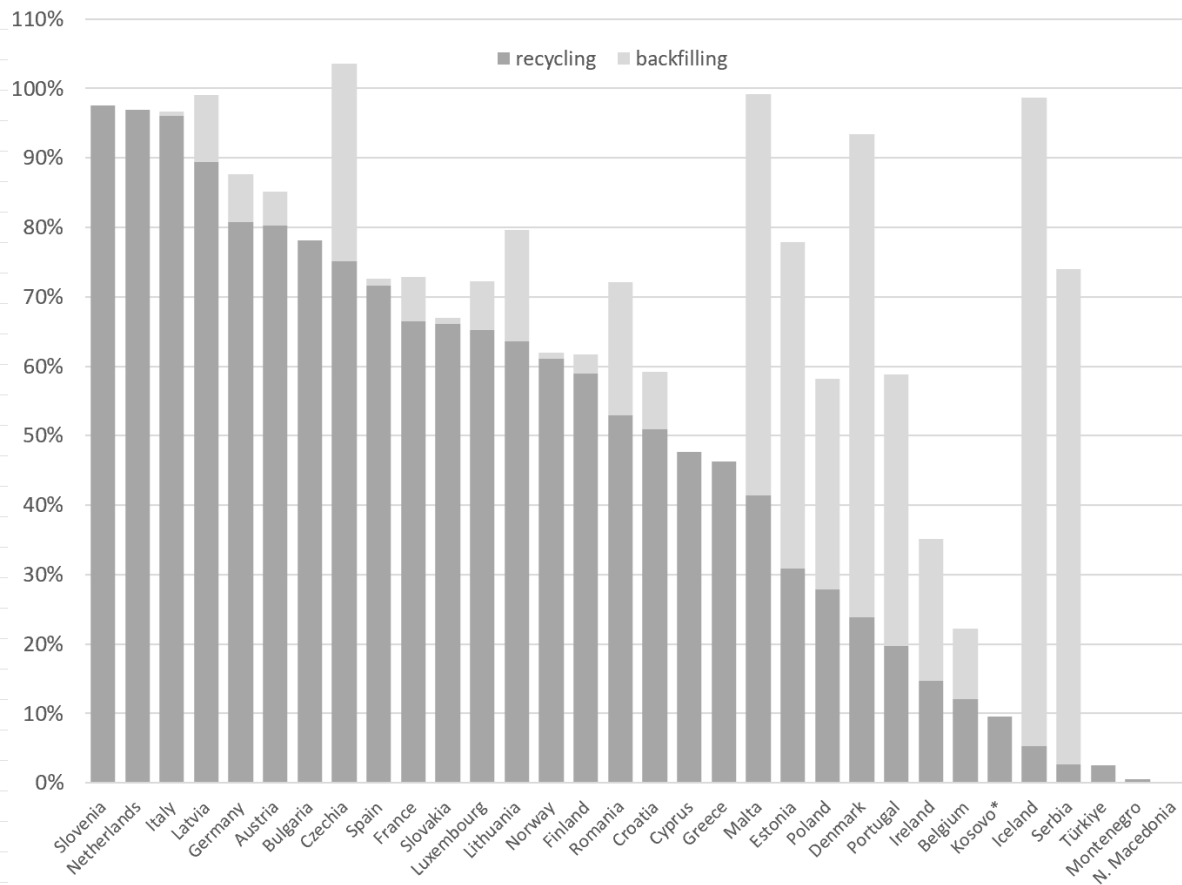


Figure 7. Share of treatment of mineral C&DW fraction in Europe in 2020 [41]

Table 6. Questionnaire findings on reuse rates of key construction materials

Country	Steel			Timber			Concrete			Bricks & Blocks		
	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)	(1)	(1a)	(1b)
AUS	N/S	-	-	N/S	-	25%	N/S	-	10%	N/S	-	8%
ESP	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
HUN	No	-	1-5%	No	-	<5%	No	-	<10%	No	-	<5%
ITA	No	-	-	Yes	-	30%*	Yes	0,4%*	-	N/S	-	-
EST	Yes	-	-	Yes	-	-	Yes	-	-	No	-	-
ROU	No	-	<1%	No	-	5-15%	No	-	<1%	No	-	1-3%
LTU	N/S	-	-	N/S	-	-	N/S	-	-	N/S	-	-
CZE	No	-	-	No	-	10%	No	-	-	No	-	<1%
LVA	No	-	-	No	-	0%	No	-	-	No	-	-
PRT	No	-	<1%	No	-	0%	Yes	0%	-	No	-	-
LUX	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
CHE	Yes	-	-	Yes	-	-	Yes	-	-	Yes	-	-
MKD	No	-	<1%	No	-	<20%	No	-	<1%	No	-	<5%
GBR	N/S	-	13%*	N/S	-	-	Yes	-	-	No	-	<5%
	* Reuse rate of structural sections			* Reuse rate related to packaging			* Reuse of components of fresh concrete (percentage of total production of fresh concrete)					

The questionnaire results were analyzed separately for the recycling rate and the reuse rate, according to key construction materials. Based on the results presented in Tab. 5, it can be concluded:

– An official recycling rate for steel exists in 7 countries, while the remaining 7 have no official data available. 5 out of 7 countries reported an official recycling rate for steel,

ranging from 30% (AUS) to 96% (GBR), whereas 4 out of 7 countries provided estimated rates ranging from 70% (HUN) to 100% (PRT). Regardless of whether the data are official or estimated, it is evident that steel recycling from C&DW is widely implemented and achieved at high rates across the EU and the United Kingdom. This result was expected because steel has an established end-of-waste criterion.

– An official recycling rate for timber exists in 6 countries, while the remaining 8 have no official data available. 3 out of 6 countries reported an official recycling rate for timber, ranging from 51% (EST) to 98% (HUN), whereas 6 out of 8 countries provided estimated rates ranging from 5% (ROU) to 80% (CZE). Regarding official data, only Estonia reported a recycling rate for timber generated from C&DW (waste code 17 02 01), while the recycling rates provided by Hungary and the UK refer to waste wood. The wide range of estimated values for the timber recycling rate can be explained based on the additional comments (question 1c), which indicate that in countries with low timber recycling rates, waste wood is predominantly used for incineration.

– Six countries reported having official concrete recycling rates, while the remaining eight stated that no official data were available. Only Italy gave an official recycling rate for concrete (10%), however, this data is not official since it was published on a commercial website ([Ingenio Web](#)). Five out of eight countries provided estimated rates ranging from 3% (HUN) to 25% (ROU). It is noted that the Estonian data include recycling of bricks and ceramic waste in addition to concrete (mineral fraction), so its estimated concrete recycling rate (46%) was excluded from the analysis. Based on available information, it can be concluded that the concrete recycling rate is relatively low, which can be explained by the high share of mixed waste in C&DW (approximately 59%, Fig. 1). Furthermore, official concrete recycling data are generally unavailable because concrete is included in the mineral fraction of C&DW together with bricks, ceramics, and tiles. We believe that the concrete recycling rate in the EU is significantly higher, regardless of the results of our survey, since countries, such as the Netherlands, Denmark, and Belgium, that are known to have high utilization of recycled concrete, did not participate in the survey.

– An official recycling rate for bricks and blocks was declared for five countries, while the remaining nine had no official data available. Only Estonia and Italy reported official figures for bricks and blocks recycling rates (98% and 80.1%, respectively). However, the Italian data had to be excluded from further analysis, as they refer to the recycling of total C&DW. Four out of the nine countries provided estimated rates, ranging from 5% (ROU) to 75% (HUN). A wide range of estimated rates might be a consequence of a personal estimation in the case of the absence of available public sources. The small number of collected data is a consequence of the fact that bricks and blocks are included in the mineral fraction of C&DW together with concrete, ceramics, and tiles.

According to the results shown in Tab. 6, the following conclusions can be drawn:

– Three countries reported having official steel reuse rates, but none of them provided an actual figure. Among the remaining eleven countries, only five provided an estimated steel reuse rate, ranging from 1% (HUN, ROU, PRT, MKD) to 13% (GBR). It is clear that the reuse of steel from C&DW is still not widely implemented across the EU, because recycling is considerably easier than reusing. Additional reasons include the high rate of steel recycling, the lack of legislation supporting steel reuse, and limited market interest.

– An official reusing rate for timber was reported by four countries, although none of them provided an actual figure. The remaining ten countries have no official data available, while eight reported estimated rates ranging from 0% (LVA, PRT) to 30% (ITA). However, since the data provided by Italy

refers to the reuse rate of packaging, the highest actual timber reuse rate is even lower-25% (AUS). Overall, the low estimated timber reuse rates can be attributed to the fact that waste wood is predominantly used for incineration.

– Six countries declared an official reuse rate for concrete, while the remaining 8 had no official data available. Only Italy and Portugal reported official figures for concrete recycling rates (0.4% and 0%, respectively). However, the Italian data had to be excluded from further analysis, as it refers to the recycling of fresh concrete instead of concrete from C&DW, which means that the official reuse of concrete in participating countries is zero. Four out of the eight countries provided estimated rates, ranging from 1% (ROU, MKD) to 10% (AUS, HUN). Given that the data reported by Austria and Hungary have no associated source, these figures should be treated with caution. We assume that the actual concrete reuse rate is lower than 10%. Possible reasons include the lack of regulations, the absence of quality assurance protocols and design standards for reusing old concrete structural elements in new buildings, as well as limited market interest.

– Two countries reported having official reuse rates for bricks and blocks, although none of them provided an actual figure. Among the remaining twelve countries, eight reported estimated reuse rates ranging from 1% (CHE) to 8% (AUS). It is evident that the reuse of bricks and blocks from C&DW is still not widely implemented. One possible reason is that preparing old bricks and blocks for reuse is a time- and labor-intensive process.

4 Steel

4.1 Reuse of steel

Steel is one of the most utilized metals in the world, especially in the construction sector. It is an iron alloy, meaning it is made up of a combination of metals and non-metals, including iron, tin, and carbon [42]. Steel's durability allows for the reuse of many products at the end of their life cycle. Existing steel buildings can be reused in situ, relocated, or deconstructed into elements such as cold-formed or hot-rolled sections, sheets, panels, frames, or truss girders. Reuse helps extend the product's lifespan and eliminates the need for long-distance transporting, re-melting the steel, and manufacturing new products. This has significant advantages for the environment by minimizing the use of natural resources.

This chapter reviews how steel can be reclaimed and reused in buildings, outlines the main reuse pathways, and summarizes practical protocols and requirements for integrating reclaimed steel into new designs.

4.1.1 Reuse processes and their efficiency

Construction steel can be reused at both the building and product level, in situ or relocated. All building structures could be specified in a range from fixed to deconstructable. Circular economy, from the point of reuse view, tends towards deconstructable structures, since they can be reused in many different ways. Reusing fixed steel buildings is also possible, but only in two situations: in situ, when service life is extended by renovating and adapting building structures, and for certain small-scale structures, if it is feasible to move the whole building or its main components over a short distance without disassembling them, using appropriate vehicles. Therefore, identifying the type of steel

building, whether fixed or demountable, is of crucial importance.

Regardless of the type of steel buildings, the following circular pathways for the reuse processes of load-bearing systems and components are possible [43]: (1) In-situ adaptive reuse and renovation of building structures; (2) System reuse at the new location for the same purpose; (3) System reuse at the new location for a different purpose; (4) Component reuse at a new location for the same purpose; (5) Component reuse at a new location for a different purpose. Option (1) reduces interventions to a minimum on existing load-bearing systems and prevents demolition. However, buildings are often not designed to accommodate new uses easily within existing load-bearing systems. The more probable options are (2) and (3), where the structure or its parts can be disassembled and reassembled at different locations for identical or new purposes, respectively. Examples of this are modular systems, such as building blocks, containers, scaffolds, etc., and hall or tent structures. Options (4) and (5) may be easier to implement and are more

commonly found in the literature [43]. Additional environmental and economic analyses, such as life cycle costing (LCC) and life cycle assessment (LCA), are required in order to determine the most favorable scenario.

Similarly, a group of authors [44], developed their own types of reuse, distinguishing between in-situ reuse and relocated reuse, for whole buildings, component systems, and individual elements (Tab. 7).

In practice, the reuse scenario depends on technical feasibility, environmental impacts, and financial costs [44]. The decision for the reuse of steel can be made early, in the project phase, for on-site reuse, or at a later stage, during tendering for steelwork, for the relocated elements. The design team is therefore critical in determining the reuse scenario [44]. Three potential options are shown in Fig. 8, which illustrates the various procurement routes for obtaining reused steel: sourcing directly from a demolition contractor, from a traditional steel stockist, or, more recently, from specialized reused steel stockists.

Table 7. Different types of reuses [44]

	In-Situ Reuse	Relocated Reuse
Building Reuse	Reuse of a sizable portion of a building, e.g., entire structural frame, façade, or envelope, in situ	Deconstruction and reassembly on a new site of a building frame/envelope
Component System Reuse	Reuse of a small part of a building in situ, e.g., foundations	Reuse of the system of components, e.g., a steel truss, on a new site
Element Reuse	Deconstruction and reuse of elements in a new configuration	Reuse of individual elements, e.g. steel section(s), on different sites

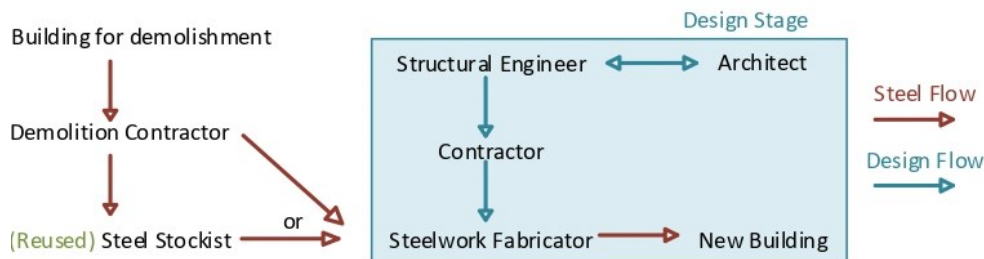


Figure 8. Steel reuse flows for relocated reuse [44]

Regardless of the scenario (type), the steel reuse process includes the following phases (adapted from [45]):

- *Pre-deconstruction audits and assessment for reuse of existing structures*: this phase involves assessing the existing structure before deconstruction to determine the potential for reuse of steel components. It includes a detailed inspection of the condition of structural elements, identification of corrosion or deformation, documentation of material properties, and evaluation of the types of connections used. The aim is to identify which elements are suitable for safe and efficient reuse.

- *Preparation for safe demounting, deconstruction, and labeling of component elements*: before dismantling, a deconstruction plan should be prepared to ensure that elements can be removed without damage. This phase covers on-site preparation, labeling and documentation of each component, selection of appropriate lifting and handling methods, and ensuring workers' safety. Proper labeling and cataloguing are essential to preserve traceability and facilitate reuse in future projects.

- *Testing and verification*: after removal, steel components must be tested to confirm their structural integrity and mechanical properties. Certainty in material properties, both mechanical and chemical, is important in the context of warranting reclaimed steel structures and the professional indemnity insurance of the designers. Destructive and non-destructive tests may be performed to check tensile strength, ductility, weldability, and possible material fatigue. Verification also includes visual inspection, geometric measurements, and assessment of compliance with current standards for reuse in new constructions. Reclaimed steel members should meet the performance requirements for mechanical, physical, dimensional, and other relevant properties to ensure their adequacy in design according to EN 1993.

- *Integration of reused steel elements in new building design*: in this phase, the verified components are integrated into the design of a new building. The design must account for the dimensions, mechanical properties, and connection types of the reused elements. Adaptation or modification of

existing components may be required to ensure compatibility with the new structural concept. The relevant standard for structural design is EN 1993.

– *Environmental and economic assessment*: finally, environmental and economic evaluations are carried out to quantify the benefits of reuse compared to recycling or producing new steel. Life Cycle Assessment (LCA) and cost-benefit analyses (LCC) help determine potential reductions in CO₂ emissions, energy use, and overall project costs. This phase supports the development of sustainable and economically viable reuse strategies.

The reuse process phases described above are further supported by CEN/TS 1090-201:2024 [174], a technical specification prepared by the Technical Committee CEN/TC 135, which provides complementary provisions to EN 1090-2 for the use of reclaimed structural components in steel structures designed in accordance with the EN 1993 series and executed in accordance with EN 1090-2. The specification applies to structures in execution classes EXC1 to EXC3, designed for quasi-static loading and not subject to fatigue loading.

In accordance with CEN/TS 1090-201 [174], the assessment of reclaimed structural steel components comprises two interconnected stages. The first is the *reusability assessment*, which involves data collection and condition evaluation to determine whether a component is admissible for reuse. The second is the *quality assessment*, which establishes the mechanical and geometrical properties required for structural design, including yield and tensile strength, elongation, tolerances on dimensions and shape, heat treatment delivery conditions, and weldability. These two stages align directly with the *pre-deconstruction audit* and *testing and verification* phases described above, providing a standardized framework for their execution.

The practical implementation of these two stages follows a structured sequence of steps. It begins with *initial data collection*, whereby available records of the source structure are gathered, including construction drawings, material specifications, age of the structure, and any evidence of prior damage or repair. This is followed by *visual inspection and admissibility screening*, in which each component is examined for signs of significant corrosion, plastic deformation, impact damage, or unverifiable weld repairs, any of which would disqualify the element from the reuse pool. Components that pass admissibility screening proceed to *non-destructive testing (NDT)* and *material characterization*, primarily through hardness testing to establish the material grade, with optional destructive testing to determine the carbon equivalent value (CEV) and impact toughness where greater precision is required. To manage the scope of testing efficiently, admissible members are organized into *groups of fundamentally identical elements*, with one or more representative members tested on behalf of the entire group. Once testing is complete, the holder of the salvaged stock is responsible for *declaring the material properties*, enabling the reclaimed steelwork to be CE marked in accordance with EN 1090-2 and CEN/TS 1090-201. Finally, *structural design verification* is carried out by the design engineer, using the declared or conservatively assumed material properties as the basis for member calculations in accordance with the EN 1993 series.

Although all EU member states have adopted and published CEN/TS 1090-201 at the national level, it remains a voluntary technical specification whose implementation relies on contractual agreements or specific regulatory references rather than automatic legal enforcement, making

it widely accessible compared to other similar guidance documents.

The assessment of the existing steelwork is essential for making a decision on reuse. The overall framework to reclaim existing structural steel elements is explained in detail in [45]. The importance and role of the pre-deconstruction audit in the case when the entire primary structure is assessed to be reused (existing steelwork) was especially emphasized. Pre-deconstruction audit summarizes the data about building systems, components, and materials that can be reused or treated as waste. Also, it offers recommendations for the reconditioning of reclaimed products and waste management. The main steps in the pre-deconstruction audit are preliminary and comprehensive assessments. Preliminary assessment is mandatory and includes analysis of available documentation and limited inspection with optional minimal testing. The limited inspection should assess the condition of the existing steelwork. The goal of this inspection is the evaluation of the feasibility of reclaiming and reusing the existing steelwork. The comprehensive assessment shall be undertaken if the existing steelwork was classified as "suitable for reuse" by the preliminary assessment. In a comprehensive assessment, a detailed evaluation of the condition of existing steelwork should be done; thus, a prescribed percentage of members and details have to be checked for geometry and dimensions in accordance with EN 1090-2. Also, all members and details must be visually inspected to detect defects, damage, or other problems in line with EN 13018. The primary goal is to determine admissibility for reuse.

After approval for reuse the basic mechanical and chemical properties of the steel should be obtained. Methods for obtaining property information include: (1) destructive testing, (2) non-destructive testing, and (3) based on the steel age. [46]. Mechanical testing includes both destructive testing, which can measure tensile strength, yield strength, and elongation, and non-destructive testing, such as hardness parameters. Non-destructive testing of steel is highly developed, with various portable testers available for use in steel production, fabrication, and scrap processing industries. The chemical composition of reclaimed steel can be quickly determined by XRF, which efficiently analyzes the steel's chemical composition. Sometimes, the basic data on steel properties may be found based on the age of the building and the steel within it, through knowledge of the history of steel section production and engineering judgment [46].

Deconstructed sections without evaluation of actual condition can be subsequently inspected to verify their dimensional characteristics and tested to confirm their basic properties [46], [47].

After verification, the sections are usually shot or sandblasted to remove any coatings, refabricated, and primed according to the requirements of the new project. This usually involves cutting the ends of the sections to the specified length. To help facilitate the reuse of existing structural steel, the Steel Construction Institute (SCI) has published a protocol (SCI P427) setting out recommendations for data collection, inspection, and testing to ensure that reclaimed structural steelwork can be reused with confidence. Also, the British Constructional Steelwork Association (BCSA) published a model specification for the purchase of reclaimed steel sections, to be used in conjunction with the National Structural Steelwork Specification for Building Construction (NSSS) Annex J – Sustainability Specification [48].

4.1.2 Possibility and potential of steel for reuse

The possibility of reusing steel structures mainly relies on the design approach, where everything must be initially suited for disassembling the structure into individual components. The main characteristics of deconstructable structures are: (1) the use of accessory joint types, (2) the application of parallel instead of sequential assembly/disassembly, (3) the use of mechanical connections in place of chemical ones, and (4) open hierarchy [49]. To enable the deconstruction and efficient reuse of steel components, the connections between steel elements need to be modified. For instance, Xianghe Dai et al. [50] examined the potential application of a novel block shear connector in demountable frame structures. Also, standardization of components and connections, and modular construction can significantly improve the steel construction capacity of the industry.

Many projects focus on steel reuse possibility, such as: REDUCE - Reuse and Demountability using Steel Structures and the Circular Economy, and PROGRESS - European recommendations for reuse of steel products in single-story buildings [8], [45]. The primary goal of the project REDUCE was to provide practical tools and steel-based technologies for designing steel and composite structures that can be deconstructed and reused. The other goal of this project was to assess methodologies for quantifying the benefits of demountable buildings and reuse, including LCA and circularity benchmarks. Additionally, the project examined how BIM can provide information for easy adaptation and deconstruction of buildings, facilitating component reuse at end-of-life [8]. Project PROGRESS cited similar possibilities for the reuse of steel in single-story buildings depending on the level of disassembly: D0: reuse of the entire steelwork or its part, in situ without disassembly; D1: reuse of the disassembled steelwork; D2: reuse of the fabricated components; D3: reuse of the constituent products; as well as from the deconstruction and transport point of view: DA: in-situ reuse without disassembly; DB: reuse on the same site in the same configuration; DC: reuse on the same site in different configuration; DD: reuse on different site in the same configuration; and DE: reuse on different site in different configuration [45].

Reusing steel offers many benefits. Fig. 9 illustrates the benefits of steel reuse, which were analyzed in [9], [44], [51], and [52] in terms of their frequency.

We indicated eight benefits of construction steel reuse; seven of them (reduced embodied carbon and energy, reduced use of virgin materials, reduced waste generation and landfill usage, economic advantage by lowering fabrication cost, expanding business opportunities for fabricators, improved sustainability, and additional salvage of other construction materials) belong to general ones, which are also applicable to other materials. The potential growth of a reused steel market is specific to construction steel. The most often mentioned advantage of reusing steel is the reduction in embodied carbon and energy.

The primary benefit of reusing structural steel elements is the reduction in embodied carbon. The carbon reduction for reused steel is greater than that of recycled steel, since no electric arc furnaces are required to re-melt and re-form the scrap steel. Reusing steel can extend the design life of buildings since structural elements are often over-designed due to material availability [53]. To estimate the amount of steel saved, two different structural models for the designed building have been carried out and compared. In the first one, the structure has been designed on the assumption of the reuse of recovered structural elements; in the second one, the same structure has been designed considering the use of new elements only. The final result of the analysis shows that steel reuse allowed for savings of up to 30% of steel [54].

Despite the cited benefits, there are also many barriers and challenges when it comes to steel reuse. To identify the main barriers to the reuse of steel structures, a literature review [44], [46], [47], [51], [52], [55], [56] - was conducted. A total of 33 barriers were identified, reflecting the diversity of perspectives and the variety of approaches used to define them. It was concluded that the large number of barriers results primarily from a lack of consistency in terminology, as many barriers share the same or similar meanings but are referred to by different names.

An analysis of the identified barriers revealed that they can be summarized into three categories: economic and market barriers, technical and logistical barriers, and others. Within these categories, we proposed unified names for barriers with the same or similar meanings. The results of our analysis are presented in Tab. 8.

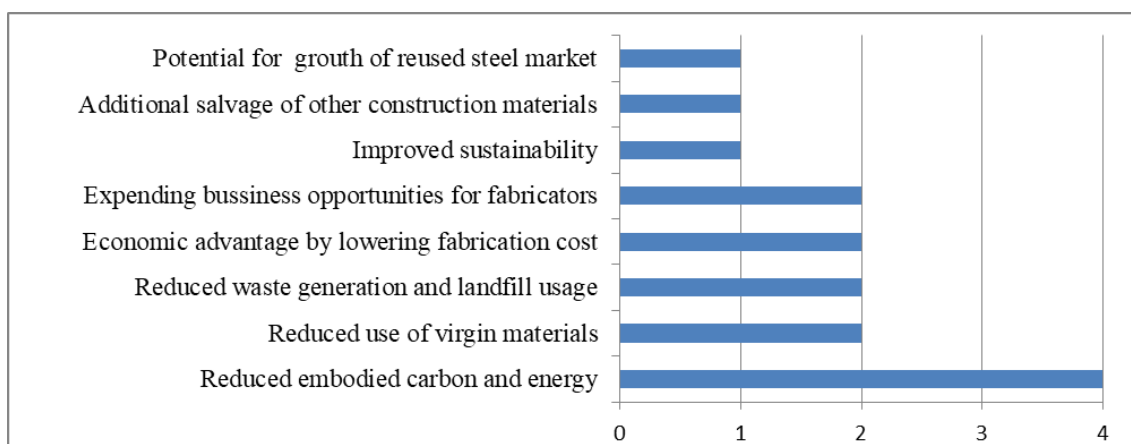


Figure 9. Frequency diagram of benefits of steel reuse, [9], [44], [51] and [52]

Table 8. Proposed categories and unified names of barriers to steel reuse

Economic and market barriers	
Identified barriers	Unified barriers
Cost/economic, Lack of incentives No clear financial incentive The complexity of the construction value chain	High cost
Availability and storage Supply chain gaps and a lack of supply chain integration Fragmentation and collaboration issues Lack of information about existing structures and materials Lack of information/communication Lack of defined benefits	Supplier and market gaps
Client perceptions No client demand	Lack of demand
Technical and logistical barriers	
Identified barriers	Unified barriers
Lack of traceability Lack of information about existing structures and materials	Traceability and performance
Quality assurance Ambiguity on the strength of the use of structural members	
Delay in deconstruction due to the complexity and irreversible nature of structural connections Potential time constraints of incorporating the deconstruction of an existing building into the project plan Overlooked the carbon impact of demolition prior to construction	Deconstruction challenges
Lack of adequate design rules, regulations, and standards for steel reuse Design for deconstruction Impact on design/design codes focus on new materials Lack of principles towards construction design sustainability Lack of designer knowledge	Design and standards
Jointing technique, i.e., welded steel work/inaccessible joints	Jointing and composite construction
Other barriers	
Identified barriers	Unified barriers
CE marking Automation and health and safety The need to engage and coordinate the complete construction ecosystem	Health and safety
Limited knowledge and experience of circular economic principles	Circularity
The lack of infrastructure for a circular economy	
Inertia in the construction sector	
Uncommon practice	

The most important demand in analyzing the possibility of steel structures reusing is design for deconstruction (DfD). It should be fulfilled in the pre-use phase. To reduce the environmental impact, the DfD of steel structures has recently received more attention. DfD considers the end-of-life scenario of buildings at the (early) design stage so that they can be fully or partially deconstructed without disproportionate effort and material loss. Steel structures have the potential to reuse components, whereby the connection between steel frame systems is a key member that allows the adaptability of construction member reuse. In the DfD the basic principles are: (1) simplicity, through a limited number of different material types and component sizes (fewer larger elements which are more durable and easier and quicker to remove); (2) standardization and regularity in design building systems, using repeating patterns consisting of the standardized construction elements; (3) simplification of building element separation by connection details that allow efficient construction and deconstruction and (4) facilitates reuse without modification after deconstruction [8]. Steel, as a construction material/product, with its performance, can fulfill all these

principles. However, DfD principle requires improvement, since some technical challenges arise from DfD; for example, welded shear studs are traditionally used to connect metal decks to beams, making it challenging to salvage these elements without causing significant damage. Thus, the other types of connections, i.e., bolted stud connections, are suggested to be used. However, in that case, it would be more labor to deconstruct the resulting quantity of bolted connections, increasing costs. Therefore, the following upgraded principles were created: Design for Manufacture and Assembly (DfMA), Design for Disassembly and Adaptability (DfD/A), Design, Build, Maintain, and Remove (DBMR), and Design for Deconstruction and Reuse (DfDR) [9]. Also, using the components from the donor structure may impact the design practice, since structural geometry and topology will be influenced by the stock element characteristics, i.e., of available components and their cross-sections and lengths. For instance, there might not be enough elements of a specific length and cross-section available, or the new structure will be oversized compared to the structures made of newly produced

elements [51]. Yet, there is a lack of adequate design rules and standards.

Reused steel is somewhat more expensive than new elements, except in certain circumstances, such as when the reused elements are available from a nearby site, or when testing elements can be avoided for the efficient use of materials [57]. Many fabricators are moving to fully automated fabrication lines where the difficulties of working with previously used sections are exacerbated. The costs include structural design, deconstructing, additional transport and storage of the reclaimed sections, and chemical and mechanical testing of the properties of the reclaimed sections. These additional activities are highly variable and project-dependent. Also, the pricing of structural steel is usually on a ‘per ton basis’, whereas some activities, e.g., testing, are generally on a piece basis [57]. Although the cost of reusing steel is currently relatively high, the reuse of steel has the potential to become more economically viable due to increased competition between product manufacturers [58].

The carbon footprint of a building constructed with reused steel depends on the required level of repair and reconditioning of the reused elements [58]. This is largely influenced by various parameters, including the condition, connection design, and material degradation, as well as the recovery method used for the components from the old construction. The paper [58] illustrates how these factors impact buildings’ life environmental aspects (LCA). The paper considered different case studies where the building is constructed from new or reused components, and in which the components will be reused or recycled in the future. LCA and global warming potential (GWP) evaluation are based on the modular building life cycle approach, which includes the product stage, construction process stage, use stage, end-of-life stage, and loads beyond the system boundary. The LCA result for the product stage shows that GHG emissions in the steel reuse case are significantly lower than in the case where the steel structure is used for the first time and for the whole building life cycle. However, due to the large variation of materials and building practices, LCA calculations are recommended to be carried out on a case-by-case basis, as the results could differ significantly from the present study [58].

To support the greater reuse of steel structures and help facilitate the reuse of structural steel sections reclaimed from existing building structures, the Steel Construction Industry has developed a protocol [59] for reclaiming and reusing individual members for new purposes. The protocol recommends data collection, inspection, and testing to ensure reclaimed structural steel sections are safe for reuse. It focuses on individual members rather than entire structures and lays out investigation and testing procedures to determine material characteristics. Responsibilities of those handling salvaged steelwork include identification, assessment, control procedures, and conformity declarations. Salvaged steel needs different handling from new steel due to potential obsolete standards and a lack of test results. This protocol suggests declaring properties of reclaimed structural steel as follows: (1) steel grade (non-destructive tests), (2) steel sub-grade (conservative assumption or optional destructive tests), (3) tolerances (inspection), and (4) maximum carbon equivalent (conservative assessment or optional test).

According to the recommendations, all structural steel recovered for reuse is subject to control and testing. Several requirements must be fulfilled: (1) Steelwork must be from 1970 or newer, (2) no built-up members, (3) no spliced members (individual lengths with bolted splice may be reclaimed), (4) no localized section loss, (5) no plasticity or corrosion protection issues, and (6) members must meet geometric tolerances. The evaluation of the reclaimed steel structure begins before the deconstruction of the existing structure, with the collection of relevant data. All information and relevant data according to [59], should be collected for reclaimed steel and divided into (1) the building information and (2) the information for individual members. They are shown in Tab. 9.

The document “Guidance on establishing European rules for the design of reclaimed steel components for reuse” represents one of the most comprehensive recent efforts to link existing steel reuse practices with the Eurocode-based structural design framework [173]. Developed in close alignment with the principles of Eurocode 3, the guidance aims to support the future formalization of reclaimed steel within European structural design standards, while maintaining consistency with established safety and reliability concepts.

Table 9. Information and relevant data necessary to be collected for the reclaimed steel [59]

Building information	Individual members
<ul style="list-style-type: none"> • Building age • Form of construction • Any related information, such as drawings, modifications, and records. 	<ul style="list-style-type: none"> • Section size • Length • Member group • Tolerance check • Comments: e.g., stiffeners or fabricated features • Coating: <ul style="list-style-type: none"> – Coating type (and thickness if determined) and – Condition of coating • Material properties: <ul style="list-style-type: none"> – Yield and ultimate strengths (non-destructive or destructive tests) – Carbon equivalent value (assumed, or by test) – Impact toughness (assumed or by test)

A key contribution of the guidance lies in its clarification that reclaimed steel components may be designed within the existing Eurocode 3 philosophy, provided that their material properties, geometric characteristics, and structural condition are adequately verified. Rather than proposing an entirely new design framework, the document builds upon familiar limit state design concepts and partial safety factor approaches, thereby facilitating the integration of reclaimed steel into conventional structural engineering practice. The guidance places particular emphasis on the verification of reclaimed steel components prior to reuse. It distinguishes between elements with available documentation (e.g., known steel grade, production standards, and service history) and those without such information, proposing different levels of material testing, inspection, and assessment accordingly. This verification process is presented as a prerequisite for reliable structural design and is directly linked to the selection of appropriate safety factors within the Eurocode framework.

From a structural reliability perspective, the document underlines that the reuse of steel components should achieve safety levels equivalent to those required for new steel structures [173]. Where uncertainties related to material properties, fatigue, or prior use cannot be fully eliminated, the guidance allows for conservative assumptions or adapted partial factors, ensuring that target reliability levels are maintained without compromising structural safety. Although the guidance does not yet constitute a binding European standard, it provides a pragmatic and technically grounded framework for designers, regulators, and standardization bodies. Its inclusion in the discussion of steel reuse highlights the ongoing transition from practice-driven reuse approaches toward formally codified, Eurocode-consistent design methodologies, thereby strengthening the regulatory and practical relevance of steel reuse within the European circular economy context.

The reuse of steel in practice has potential in the future despite numbered barriers, such as costs, availability, storage of elements, lack of adequate design rules, regulations, standards, supply chain gaps, etc. These challenges can be overcome by introducing the mandatory use of reclaimed components up to a certain percentage, then with better fiscal incentives, design for deconstruction, design of reclaimed steel components for reuse, standardization, etc.

Also, the economic conditions must be conducive, minimizing environmental impact, and frameworks to connect different stakeholders in the steel industry and illustrate their contributions to the reuse process should be well-developed [60].

4.2 Recycling of steel

From bridges and cars to paper clips, steel is the most versatile material on earth that has led to the most progress in the living standards of humanity. Even more, steel demand is forecasted to increase over the next decades. But manufacturing this shiny, ductile metal is a dirty, old-fashioned process that's changed little in the past 150 years. Traditional steel production methods have contributed significantly to carbon emissions, resource depletion, and environmental degradation. Yet, as with all other emitting economic sectors and materials production, the steel industry needs to decarbonize to meet the climate challenge. Global crude steel production is over 1.9 Gt annually and it is responsible for approximately 3 Gt of CO₂ emissions. Since steel accounts for around 8% of total global carbon

dioxide emissions, finding cleaner, commercially viable ways to make it is vital. According to the International Energy Agency, to meet global net-zero goals, steel industry emissions must fall by at least half by 2050. Steel recycling is a widely used technology in the decarbonization process of steel production. Steel can be continuously recycled without any damage to its properties, regardless of the product or form it takes. Steel recycling includes melting steel products at the end of their lifecycle (EoL) to make new steel. Today, instead of using raw materials, it is essential to bring materials into the circular economy as much as possible according to the 9R approach. This approach is provided by the use of scrap, which is a secondary resource in steel production. Unfortunately, the utilization of scrap in steel production is not enough to achieve a net-zero economy. The concept of "green steel," which embraces innovative and environmentally friendly technologies, offers a potential solution to balance industrial advancement with environmental responsibility. [61], [62], [63], [64], [65].

Scrap is a term used to describe steel that has reached the end of its life, known as 'post-consumer scrap', or has been generated during the manufacture of steel products, known as 'pre-consumer scrap'. The "scrap" is a valuable raw material used in every steelmaking process. Due to its inherent magnetism, steel is very easy to separate and recycle after demolition, making steel the most recycled material in the world. Melting steel scrap at the end of its life allows the creation of new steels, adjusting the chemistry and shape of the new product. Almost every steel plant uses scrap as part of its raw materials mix, and therefore almost every steel plant is also a recycling plant. Also, using scrap in steel production enables reduction of greenhouse gas emissions [66].

In theory, all new steel could be made from recycled steel. However, currently, this is not feasible due to the scarcity of scrap. This is because of the long service life of steel products, given steel's strength and durability [66].

Long-term sustainability and recycling in the steelmaking sector primarily depend on scrap quality. The ideal scrap for steelmaking is called black. This scrap is undesirable to contain metallic and organic coverings/coatings, attachments, and tramp elements [63].

4.2.1 Recycling processes and their efficiency

In 2023, the global raw steel production per capita was 234.8 kg [65]. The construction industry has the highest steel demand of 52% (Fig. 10) [67].

Although steel is theoretically 100% recyclable, in practice the recycling rate is around 70% due to corrosion and losses that occur over time [63]. Moreover, in some developed countries, steel stocks have reached saturation or are even declining. This situation increases the share of scrap used in steel production. Consequently, the recycling rate is expected to rise further in the coming years and may reach 80% by 2050 [64]. The recycling process of steel consists mainly of three phases: (1) dismantling, (2) shredding and sorting, and (3) melting at the furnace. The dismantling phase focuses on collecting and separating steel components from end-of-life products, such as vehicles and buildings. This can be done manually or mechanically, depending on the waste type. In construction, it involves deconstructing to recover steel beams and rebars, while in the automotive sector, it means removing reusable or hazardous parts before shredding. The main goal is to maximize steel recovery with minimal contamination from materials like concrete and plastics, enhancing recycling

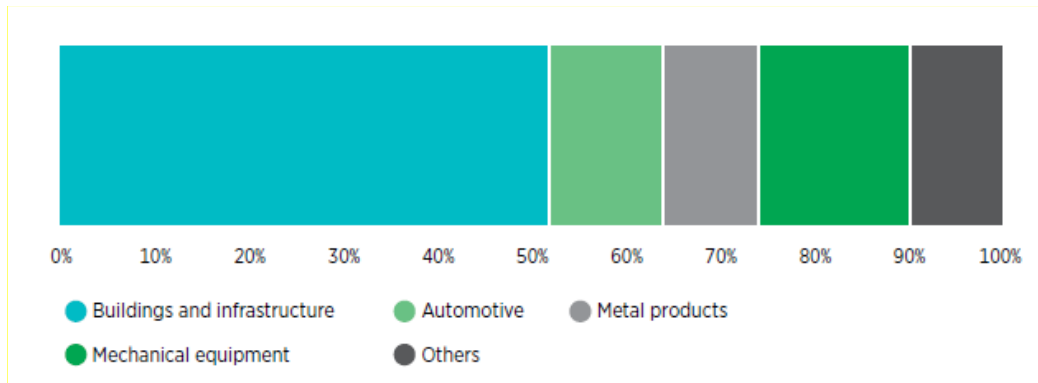


Figure 10. Breakdown of steel demand by sector, adopted from [67]

efficiency and quality. After dismantling, the recovered steel parts are transported to recycling facilities where they undergo mechanical size reduction and material separation. In the shredding stage, large steel components are broken down using powerful hammer mills or rotary shredders into smaller, more manageable fragments. This not only facilitates handling and melting but also exposes embedded non-metallic materials. The shredded mixture then enters a multi-stage sorting process designed to separate ferrous metals (containing iron) from non-ferrous metals and non-metallic residues [68]. The outcome of this phase is clean, well-classified steel scrap suitable for melting.

There are two main processes in steel production. The first is the Basic Oxygen Furnace (BOF) process, also known as ore-based steelmaking, which primarily uses iron ore but typically includes about 10–30% scrap as a coolant. The second method is the Electric Arc Furnace (EAF) process, commonly referred to as scrap-based steel production,

where recycled steel scrap serves as the main feedstock, even up to 100% [64], [66]. BOF process, which uses raw materials (iron ore, coal, and limestone) and scrap steel for steel production, is one of the most common and efficient production methods. This process converts molten pig iron into steel by blowing oxygen through a lance into the molten pig iron inside the converter. The injected oxygen reacts with dissolved impurities such as carbon, silicon, manganese, and phosphorus, oxidizing them and generating heat autothermally through exothermic reactions. These oxidation and purification reactions reduce the impurity and sulfur content of the melt, transforming it into steel. In the subsequent stage, alloying elements are added to achieve the desired composition, and the steel is then cast - typically using continuous casting - and cooled with water [69]. Steps of BOF process and the interior view of an oxygen furnace are given in the Fig. 11.

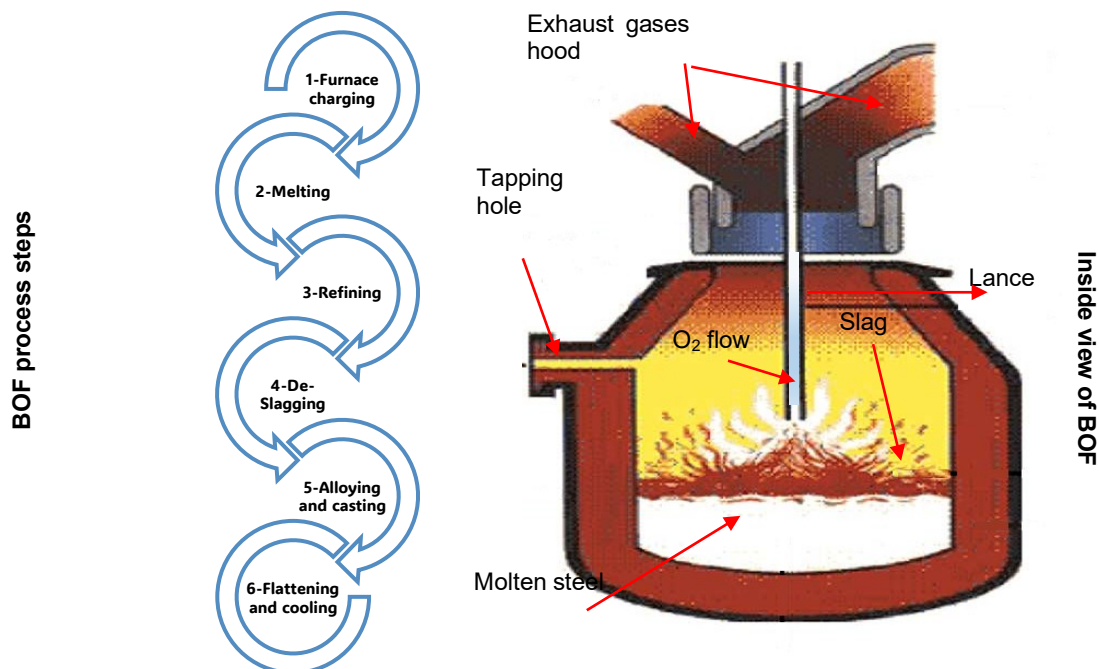


Figure 11. BOF process steps and inside view of an BOF, adopted from [69], [70]

The Electric Arc Furnace, (EAF), is an even more modern method of steel production by remelting steel scrap into new steel and is called scrap-based steel production. Steel scrap is secondary-sourced material i.e., discarded steel that becomes available from manufacturing waste generation and from recovered steel in buildings, infrastructure, equipment, vehicles and products discarded at their end of life. The EAF process lasts about 60 minutes and includes six main steps. First, scrap and slag-forming materials are charged into the furnace. An electric arc is then created to melt the scrap. Next, impurities such as phosphorus and silicon are removed, while gases like hydrogen and nitrogen are reduced. Oxygen and natural gas are injected to speed up reactions and improve steel quality. The oxidized impurities form slag, which is drained when the furnace is tilted. Finally, the steel's composition and temperature are adjusted before it is poured into a ladle for the next stage [69]. Process steps of EAF and the interior view of an electric arc furnace are given in the Fig. 12.

The amounts of key raw materials used to produce 1000 kg of crude steel, depending on the applied production method, are given in Tab. 10.

Iron ore: Steel is an alloy primarily composed of iron with less than 2% carbon. Therefore, iron ore is a crucial raw material in steel production. Approximately 98% of all mined iron ore is used for this purpose. High-quality iron ore typically contains about 60–65% iron. Mining operations take place in around 50 countries, with Australia and Brazil together accounting for one-third of global exports. In 2021,

worldwide iron ore exports reached 1.65 billion tonnes [66], [71].

Limestone: Limestone plays an essential role in steel production as a fluxing agent. During the smelting process, it is added to remove impurities such as silica, phosphorus, and sulfur from the molten iron. When heated in the furnace, limestone decomposes into lime (CaO) and carbon dioxide (CO₂). The resulting lime reacts with impurities to form slag, which floats on the molten metal and can be easily separated.

Coke and Coal: Since iron occurs in the Earth's crust mainly as iron oxides, it must be reduced to metallic iron using carbon. The primary carbon source for this process is coking coal, which is converted into coke through a heating process known as carbonization. Coke then serves as both the fuel and reducing agent in the blast furnace, where it reacts with the iron ore to produce molten iron, which contains a high carbon content. There are about 80 countries worldwide with significant coal reserves. The largest reserves are found in the United States, China, Russia, Australia, and India. Each year, approximately 1 billion tonnes of metallurgical (coking) coal are used in global steel production, accounting for about 15% of total coal consumption worldwide. In 2021, the global metallurgical coal export market amounted to 0.31 billion tonnes, of which Australia accounted for around 0.2 billion tonnes. The largest producer of coking coal, however, is China [71].

Recycled Steel (Scrap): Steel has excellent circularity properties. Whereas other materials are often downcycled at

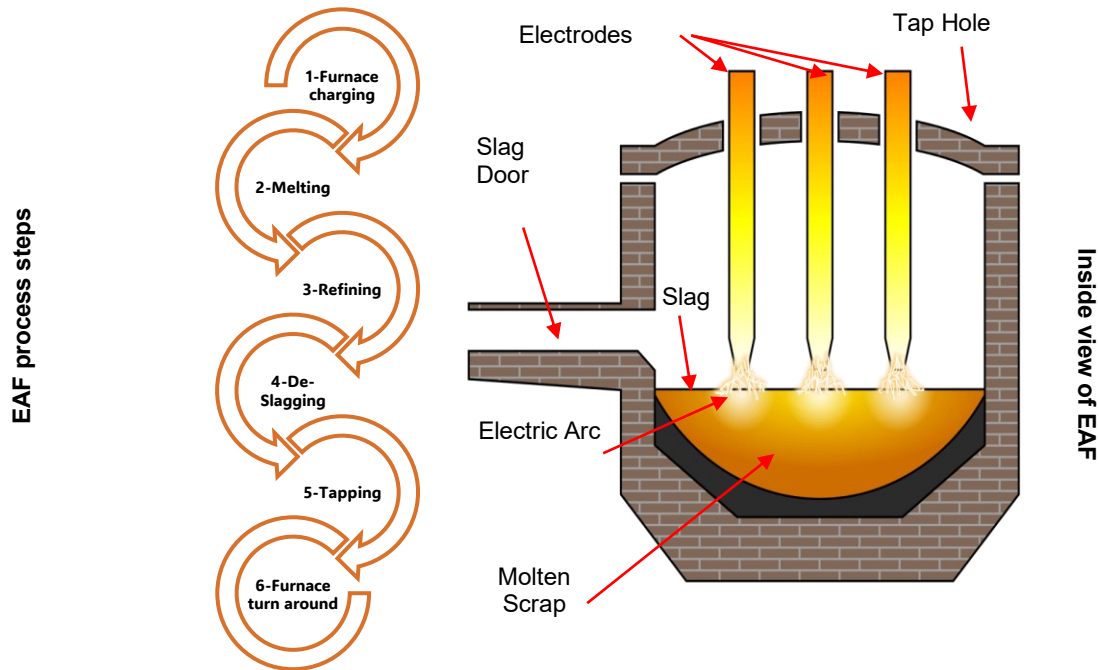


Figure 12. EAF process steps and inside view of an EAF, adopted from [69], [70]

Table 10. Consumption of key raw materials and energy sources to produce 1000kg of crude steel, depending on the technological processes used, adapted from [71]

Raw materials/energy source	BOF process	EAF process
Iron ore, kg	1370	586
Recycled steel (scrap), kg	125	710
Limestone, kg	270	88
Coal, kg	780 (metallurgical coal)	150 (coke)
Electricity	-	2.3GJ

their end of life, for many applications, steel scrap can be turned back repeatedly into new steel, retaining its original properties [72]. Scrap is an essential raw material in modern steel production, offering both economic and environmental advantages. It reduces the need for primary raw materials such as iron ore and coke, while cutting energy consumption by up to 70% and CO₂ emissions by more than half. Globally, about 30–35% of total steel output comes from recycled scrap, making it one of the most sustainable materials in the industry [73]. For example, in 2021, the global steel industry consumed around 0.65 billion tonnes of scrap steel for production, in the context of a total crude-steel output of about 1.9 billion tonnes [66]. This scrap usage contributes significantly to sustainability: it is estimated to avoid approximately 975 Mt CO₂ annually and reduces the consumption of iron ore, coal and limestone.

By sector, global steel recovery rates are estimated at approximately 85% for construction, 90% for automotive (reaching close to 100% in the US), 90% for machinery, and 50% for electrical and domestic appliances [71].

The world's crude steel production in 2021, was 1.95 billion tonnes, from which produced through the BOF process is 1.38 billion tonnes (70.8% of total production), while 0.56 billion tonnes (28.9% of total production) were produced through the EAF process. However, the involvement of these two technological processes in steel production varies greatly between continents. For instance, in the EU-28, BOF accounts for 57.3% and EAF for 42.7%; in North America, BOF is 31% and EAF 69%; while in Asia, the situation is reversed, with BOF at 81.7% and EAF at 19.3%. However, since Asia accounts for 72% of global steel production, it gives the impression that the BOF process is still dominant worldwide [74]. From these analyses, it can be concluded that scrap is used much more in steel production in the EU and North America than in Asia.

According to the World Steel Association data for 2022, the CO₂ intensity of the BF-BOF process is around 2.33 tonnes CO₂/tonne crude steel cast. In the EAF process using direct reduction iron (DRI) for production, the CO₂ intensity is 1.37, and in the EAF process using scrap, the CO₂ intensity is around 0.68 tonnes CO₂/tonne crude steel. In this context, steel production from raw materials causes approximately 2 times more greenhouse gas formation than production from scrap [75].

According to ArcelorMittal [72], producing 1 tonne of crude steel from a primary source (iron ore) emits 1–2 tonnes of CO₂, whereas using a secondary source (scrap) results in only 0.1–0.4 tonnes of CO₂ emissions per tonne of crude steel. Similarly, the energy required for steel production from primary sources is 18–22 GJ (solid fuel for iron production plus electricity for steelmaking), while production from secondary sources requires only 5–7 GJ of electricity per tonne of crude steel.

4.2.2 Possibility and potential of steel for recycling

The global steel sector is already circular to an extent. About 30% of the steel produced today comes from scrap recycling. It is also possible to rely on renewable power sources in steelmaking. However, most steel produced today still relies on fossil fuels as energy sources and reducing agents for iron ore processing.

There are numerous benefits associated with the use of steel scrap in steelmaking. However, there is no unified systematization of these benefits, as their categorization varies across authors - some explicitly name the benefits, while others describe them in a more narrative form. By

reviewing relevant scientific papers, as well as technical and industrial reports ([61], [68], [76], [77], [78], [79]), we identified and systematized the most significant benefits into four main categories: environmental, economic, social, and technological (Tab. 11).

Stell construction industry faces several barriers and challenges in spite of the environmental, economic and other benefits of using recycled steel. Some of main barriers and challenges are: (1) Limited scrap recycling potential, (2) Decarbonization of steelmaking, (3) Scrap quality and contamination, (4) Market dynamics - supply-demand mismatch, (5) Regulatory, standardization, and legal impediments.

Limited scrap recycling potential. The limited circularity of the global steel flow is not due to poor waste management. In fact, 85 % of end-of-life scrap was collected and recycled in 2019. Instead, the key limiting factor is the growing in-use steel stock – the steel embedded in products, buildings, and infrastructure [80]. According to forecasts, global demand for crude steel is expected to rise from 1.9 billion tonnes in 2021 to over 2.6 billion tonnes per year by 2050. Although the share of end-of-life steel scrap in total steel production will increase substantially by 2050, it will still represent only about 44% of global steel production [72], [81]. Scrap availability depends on the average life and the volume of steel products. The average service life of steel products varies from a few weeks for steel packaging to up to 100 years for buildings and infrastructure, with the average lifespan of a steel product being 40 years [80]. It is estimated that global end-of-life ferrous scrap availability will reach approximately 600 million tonnes in 2030 and 900 million tonnes in 2050. Increased reuse and remanufacturing may alter the amount of scrap availability in the future [72].

Decarbonization of steelmaking. The steel industry has a significant challenge ahead to decarbonize the industry [72]. The global steel sector is the second largest in GHG emissions after cement, heavily relying on fossil fuels. It accounts for 7-9% of CO₂ emissions. As steel demand grows, the decarbonization to meet the Paris Agreement's 2050 net-zero goal is a significant challenge [82]. Studies exploring emission reduction potential in the steel sector, show that the capacity to reduce emissions using traditional energy-efficiency measures is limited to collectively abating around 25–40% of average CO₂ emissions per ton of crude steel produced [82]. To achieve further reductions, advance technologies are required, such as carbon capture, utilization, and storage (CCUS), using hydrogen or biomass as reducing agents, or electrolysis (i.e., using electricity to reduce iron ore) [82]. CCUS is one of novel climate mitigation technologies; in this process CO₂ emissions are captured from sources such as fossil power generation and industrial processes, and further either reused or stored [83]. In terms of biomass research shows that the CO₂ footprint of a direct reduction plant fed with biomass-based reducing gas is more than 80% lower compared with the conventional blast furnace route and could be even more if carbon capture and utilization is applied [82]. In terms of electrolysis, high temperature electrolysis (HTE) has the potential to reduce the specific electricity consumption of liquid steel production by 21% compared to the low temperature electrolysis case [84]. Tab. 12 shows several initiatives promoting the use of breakthrough technologies in steelmaking. Steel produced using these technologies is referred to as "fossil-free", "carbon-lean", "CO₂-lean", or "CO₂-neutral" steel. Recently, the term "responsible steel" has been adopted to describe steel products that are responsibly sourced and produced [82].

Table 11. Classifications of steel recycling benefits

Basic groups	Identified benefits	Efficiency
Environmental benefits	Resource conservation	Reduction of virgin iron ore, coal and water
	Energy savings	Using steel scrap can cut energy consumption in steelmaking by up to 70%
	Lower CO ₂ emissions	The use of EAF with scrap reduces CO ₂ emissions by up to 80% compared to BOF process
	Waste reduction	Recycling steel reduces waste by repurposing end-of-life products into new raw materials
	Pollution control	Recycling steel can lead to an 86% reduction in air pollution and a 76% reduction in water pollution
Economic benefits	Cost savings	Using recycled scrap as a primary feedstock allows steel manufacturers to significantly reduce material costs compared to the expensive and energy-intensive extraction of virgin ore
	Reduced operational expenses	Scrap-based production through EAF requires less energy and has shorter production cycles, leading to lower operational costs
Social benefits	Job creation	The steel recycling industry is labor-intensive, creating numerous jobs in the collection, sorting, processing, and resale of scrap metal
	Infinite recyclability	Steel can be recycled indefinitely without losing quality
	Support for the circular economy	Steel recycling is essential to the circular economy, ensuring materials are used longer and resources are conserved for future generations
	Healthier communities	Steel recycling reduces pollution from mining and manufacturing, leading to cleaner air and water and improved public health in surrounding communities
	Stable domestic supply chains	Increasing the use of locally sourced scrap can reduce reliance on imported raw materials, stabilizing supply chains and enhancing economic resilience
Technological benefits	Automated sorting	Sensor-based sorting technologies, like X-ray fluorescence (XRF) and artificial intelligence (AI), have significantly enhanced the speed and accuracy of separating various metals from complex waste streams
	Advanced furnace techniques	Modern EAF technologies incorporate digital controls for precise temperature and composition management, resulting in improved efficiency and higher-quality recycled steel
	Digital traceability	Technologies like blockchain are being explored to create transparent supply chains that track recycled materials from source to destination, enhancing accountability and fostering trust among stakeholders

Table 12. Recent steelmaking project/technologies, adapted from [82]

Company	Project/technology	Location	Target
ArcelorMittal	Hydrogen reduction with grey hydrogen derived from natural gas; Blast furnace + electrolysis for hydrogen production; Hybrid blast furnace with direct reduced iron (DRI) gas injection; Coke oven gas with grey hydrogen; hydrogen in DRI-EAF;	Hamburg, Germany	Fossil free by 2050
		Bremen, Germany	
		Dunkirk, Germany	
		Asturias, Spain	
HYBRIT (SSAB, LKAB and Vattenfall)	Replacing coking coal with hydrogen and fossil-free electricity	Sweden	Fossil free by 2045
Voestalpine Primetals Tech.	Hydrogen as reducing agent to process iron ore concentrates	Linz, Austria	80% carbon emissions reduction by 2050
Salzgitter AG (Salcos project)	Electrolysis/hydrogen-based steelmaking	Wilhelmshaven, Germany	2 million tonnes per year of DRI, expected in 2025
Celsa, Statkraft & Mo industrial park AS	Electrolysis/hydrogen-based steelmaking	Norway	50% emissions reduction by 2030, decarbonization by 2050
H2 Green Steel Initiative	Hydrogen-based steelmaking	Northern Sweden	Planned production to start in 2024. Annual production target of 5 million tonnes of green steel by 2030

However, these technologies are still in the early research stages, and others are only at the pilot/demonstration phase [82]. Also, all of them are very expensive in terms of utilization for production [83], [85], [86].

Scrap quality and contamination. The scrap provided to the steelmaker, known as merchant scrap, is typically a mixed material that lacks adequate chemistry measurement. This deficiency limits accuracy, consistency, and compatibility with the required product chemistry. Recycled scrap accumulates residual alloying elements such as Cu, Sn, Sb, Pb, Zn and Cr. These elements will not be removed as slag or off-gas through oxidation or reduction during EAF steelmaking, leading to an increased concentration in the metallic products [80]. Changes in steel chemistry due to increased scrap use can have both negative and positive effects on processing and final properties, requiring careful consideration to determine what modifications in composition, processing parameters, and product performance may be caused. For example, copper (Cu) is generally regarded as beneficial for improving corrosion resistance and is therefore intentionally added to produce weathering steels. On the other hand, concentrations of copper exceeding 0.1 wt.% lead to hot shortness, a phenomenon that results in surface cracking during hot rolling and forming [87]. Therefore, improved scrap sorting and quality control are essential to ensure the supply of low-residual scrap suitable for producing all steel grades [80]. There are two possibilities to avoid unwanted element accumulation: diluting virgin material to reduce concentration without recovery or removing them during sorting.

Market dynamics - supply-demand mismatch. Scrap availability and location don't always match where secondary steelmaking capacity or demand exists; this causes regional shortages, price volatility, and exports/imports that complicate domestic circularity strategies. Forecasting and market coordination are weak in many regions [80], [81]. Steel scrap is often found far from regions with high steel demand. Consequently, both steel products and their inputs are traded in large quantities on an international scale. Currently, around 17% of the world's annual scrap supply, equivalent to about 110 million tonnes, is traded internationally. For example, Turkey depends on the EU, the USA, the UK, and Russia to import roughly 25 million tonnes of low, grade scrap each year. In contrast, the United States faces a shortage of prime scrap and relies on imports from Canada to bridge the gap, while Japan exports its surplus prime scrap to South Korea, Southeast Asia, and China [88]. The steel scrap market will be unstable in the future as demand for recycled steel grows faster than the amount of scrap steel available.

Regulatory, standardization, and legal impediments. Environmental regulations governing waste management and recycling are continuously evolving to promote greater sustainability. For the steel industry, which operates under some of the most stringent environmental standards, this presents ongoing challenges. Regulations often differ across countries and regions, covering aspects such as emissions control, waste disposal, and recycling practices. As a result, recyclers must constantly adapt to shifting requirements while ensuring full compliance, which can create administrative complexity, increase operational costs, and cause confusion for companies operating globally [89]. Further, unclear classification (waste vs product) and lack of standards/certification for recycled steel hinder high-value recycling. There are only several available steel scrap specifications, including the UK Ferrous Metals Specifications, EU-27 Steel Scrap Specification, Japanese

standards for ferrous scrap, and ISRI Scrap Specifications; however, these specifications do not include complete chemistry requirements [80].

Overcoming these barriers is essential for advancing circularity in steel production [90].

4.3 Circular practices and examples for steel

The primary aim for the circular economy in the built environment is to reduce material and resource consumption, to optimize the lifespan of materials, to design for disassembly, reuse, and recycling, and to ensure positive contribution to the natural ecosystem [91].

A key aspect of circular economy in built in environment is to extend the life of building materials, components, and systems beyond the end-of-life of the building through disassembly, reutilization, and recycling. This requires a holistic approach in which specific design strategies can be developed for reversibility, adaptability, and flexibility. Design in the circular economy consists of designing buildings for easy disassembly and materials reuse and recycling, hence reducing demolition costs and consumption of resources. The major strategies are reducing material inputs, standardizing connections for easy disassembly, and keeping information about materials [92].

Designing buildings for disassembly aims to create structures that adapt to future changes and ultimately disassembles. The process involves maximizing economic value and minimizing environmental impact through reuse, repair, re-manufacture, and recycling by planning construction methods and management systems [93].

Closed-loop material cycles are another tool supporting circular economy in built environment. The target of the closed-loop material cycles is to achieve zero waste and resource efficient construction by using byproducts from one process for another. Steel is a closed-loop cycle material because it can be recycled back into its original forms. This outstanding characteristic results in strong circular economic credentials [94].

Options for improve the circularity in steel sector are: (1) Material efficiency in steel use, (2) Steel scrap recycling, (3) Process efficiency and (4) Renewables-based steel production. Material efficiency measures can contribute to advancing the circularity of the iron and steel sector by optimizing the use of steel products, like producing lighter steel products and structures, refurbishing and reusing steel products, and redesigning products with alternative materials when justified based on life cycle analysis. Recycling steel improves circularity by reducing the need for primary steel production. Process efficiency enhances circularity by minimizing the need for resources, especially for energy, in steel production, which would contribute to reducing the environmental impact. A shift to renewable-based steel production replaces fossil fuels with renewable energy and green hydrogen, improving environmental performance, reducing fossil fuel dependence, and supporting circularity [67].

Circularity in the built environment can be achieved through various strategies, such as repurposing entire buildings, reusing building structures, or reusing individual structural components [95]. In the following section, one example is provided for each of the three main strategies of circularity in the built environment. Below, one example is provided for each of the three main strategies of circularity in the built environment.

One well-known example of repurposing an entire building is the Musée d'Orsay in Paris, France. The museum,

which opened in 1986, originally functioned as the Gare d'Orsay railway station, inaugurated in 1900 for the Exposition Universelle. When long-distance trains began terminating at Gare d'Austerlitz in 1939, Gare d'Orsay was used primarily for suburban services. In the following decades, the building served several other purposes, including housing a theatre company and hosting film productions. Recognizing its architectural and historical significance, the station was classified as a historical monument in 1973, and later transformed into the Musée d'Orsay [96]. Fig. 13 shows images of the former station and the present museum [97].

Argentinian Warehouse is an example of reusing the building structure. It was built in 1915 in Amsterdam for storage and transshipment site for coffee and cocoa beans. After 80 years of service storing cocoa and coffee beans, the 200 m long steel structure was dismantled to its original components. The components were recoated and reused for reconstruction in the same configuration into a new shopping center - Brazilian Shopping Center [98], [99]. The appearance of the steel structure and façade of the old and new building is shown in Fig. 14 and Fig. 15.

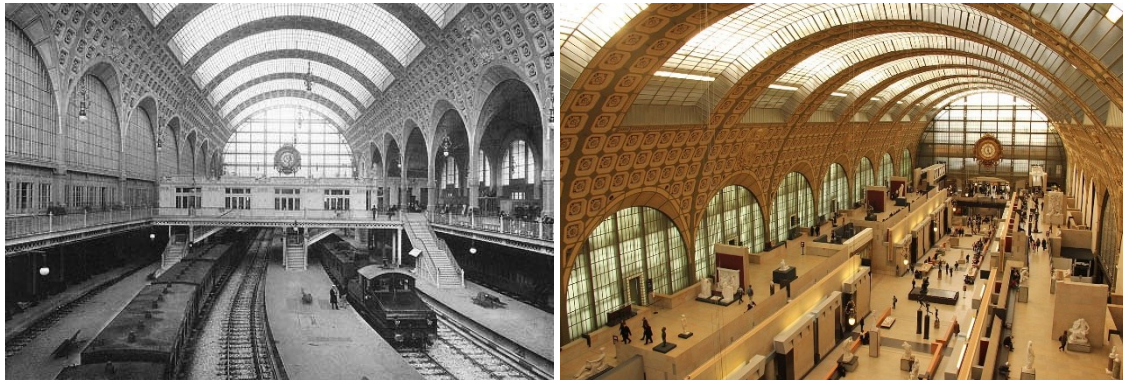


Figure 13. The Gare d'Orsay (on the left) and Musée d'Orsay (on the right) [97]

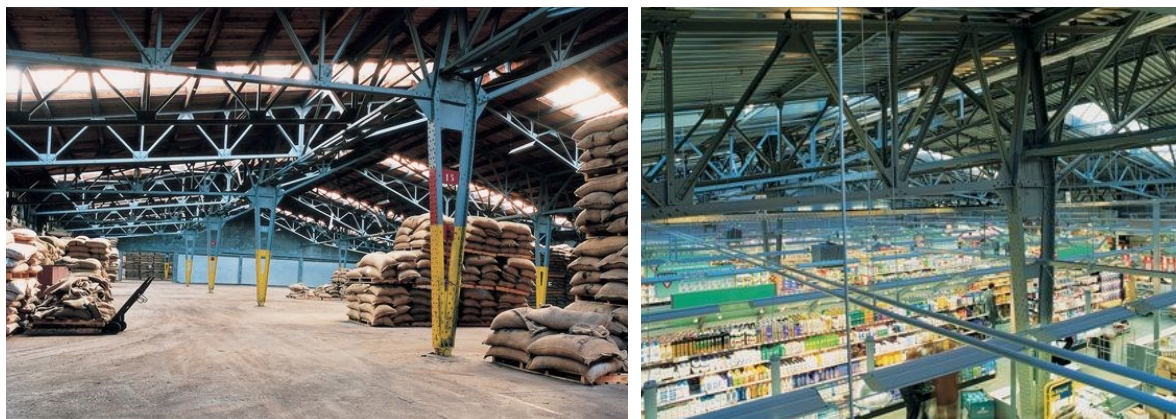


Figure 14. Original steel structure of Argentinian Warehouse (left) and reused steel structure in Brazilian Shopping Center (right), Amsterdam [99]



Figure 15. Argentinian Warehouse on the left and Brazilian Shopping Center on the right [98]

A new floor extension was made on the top of an existing “Grosvenor Estate” building. This office building was built in 1980. By extending for one floor additional 25% of available floor space was obtained. The aim of net zero was primarily achieved by relying on reclaimed steelwork and Cross Laminated Timber (CLT). In the building, 34% of the steel elements were reused from demolition on 2 existing Grosvenor projects and from reused stock from Cleveland Steel. The test results allowed the structural properties of the sections to be proven, and hence, the structure can be CE marked according to legislative requirements. This project involved approximately 67 tonnes of steelwork involving reused elements. 25 tonnes were reused material interconnected with new ones and not designated to specific areas. This allowed a carbon saving of approximately 60 tonnes. The reconstruction and extension of the Holbein Gardens building were completed in 2023 as part of Grosvenor’s net-zero carbon development program [77]. Reclaimed steel elements, a detail of upgrading and final appearance of the extended building are shown in Fig. 16.

5 Timber

5.1 Reuse of timber

One of the most promising eco-friendly sustainable building materials is wood. When sustainably sourced from managed forests, this renewable material not only acts as a carbon sink but also permits a decrease in embodied energy when compared to traditional materials like steel and concrete. This presents a significant opportunity to lessen the effects of the built environment on our climate and natural habitats, especially when combined with the effective use of wood in design. Furthermore, the carbon stored in timber during sequestration usually outweighs the carbon emissions related to timber production. However, the potential to fully utilize the sequestered carbon in timber is limited because structural timber is typically only used for a single service life in construction [100]. Thus, imposing the demand for responsible wood waste management to achieve low carbon emissions and environmental benefits, such as the conservation of natural resources through forest preservation and the reduction of landfill waste by decreasing methane emissions from decomposing wood.

Improving the industrial economics through cost savings and job creation represents the additional but essential aspect of timber waste reuse and recycling as a key step in the circular economy (CE) of timber use.

To reduce the impact of the built environment on CO₂ emissions and consumption of non-renewable materials, it is essential to apply bio-based materials, i.e., increase the amount of sustainable timber in construction. To achieve a total CO₂ reduction of 18% (37 Mt) in 2030, 50% of new residential buildings should be bio-based. This requires 566 million m³ of round wood by 2030. Since only 3.6% (18.5 million m³) of roundwood is used for the production of Engineered Wood Products (EWPs), such as cross-laminated timber (CLT), glue-laminated timber (GLT), and laminated veneer lumber (LVL), therefore the production capacity of EWPs has to be increased significantly in the coming years [101]. For comparison, data on wood production and processing taken from Eurostat are given: roundwood production in the EU in 2022 reached an estimated 510 million m³. This is 26% more than at the beginning of the millennium. Wood has been increasingly used as a source of renewable energy. Almost a quarter (24 %) of the EU’s roundwood production in 2022 was used as fuelwood, while the remainder was industrial roundwood mostly used for sawnwood and veneers or for pulp and paper production. Sawnwood production in EU was approx. 105 million m³ in 2022 [102]. By comparing the demands with the actual timber availability, it is clear that roundwood and EWP production should be significantly increased. However, there is a limit to how much sustainable wood can be harvested without jeopardizing the crucial functions the forests provide. One of the viable solutions to compensate for the increased need for timber lies in reusing “old” timber elements for structural purposes.

Commonly, wood waste could be generated from main structural elements from old buildings, construction and demolishing processes, engineered wood products industry, and municipal-wide spectra use (furniture, packaging material, pallets, etc). EWPs, like GLT, CLT, or LVL, as well as mass solid timber elements, have a great potential to be reused as structural elements in new assemblies or, depending on their state condition, into non-structural but new useful function, such as urban or home “do it yourself” (DIY) furniture, etc.

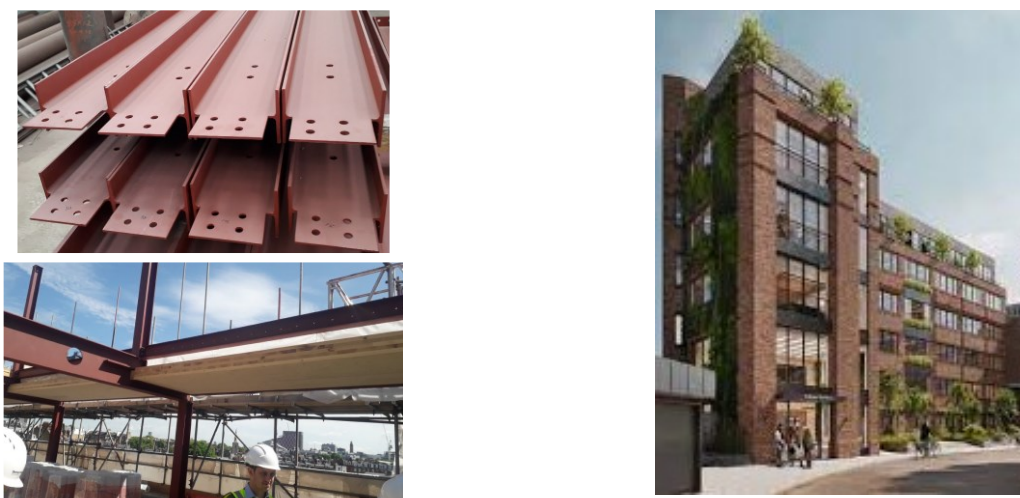


Figure 16. “Grosvenor Estate” building reclaimed steel (upper/left); new structure made of reclaimed steel (bottom/left); appearance of extended building in London (right) [77]

The data for the EU28 indicates an annual production of 52.9 million tonnes of wood waste. Of this waste, 48% is found in municipal solid waste, 38% in C&DW, and the rest as wood industry waste [103]. According to the same source, in 2016, 87% of wood waste was treated, from which 49% was recycled, 48% was combusted for energy recovery, and 3% was landfilled or incinerated. The fate of the untreated waste wood is unclear. In EU27, in 2020, 99.38 % of waste wood was recovered from which 46.02 % was recycled, 53.36 % was used for energy recovery, while only 0.59 % of waste wood was disposed [107]. The amount of wood treated has reached its maximum over four years, but a slight drop in the participation of waste wood in recycling processes is noted. Currently, no information is available regarding the reuse of waste wood for both structural and non-structural uses.

It was estimated that 2.3 million tonnes of timber were reclaimed across the UK in 2018 from construction and demolition activities. However, most reclaimed timber is recycled or used for energy recovery, and only around 2.5% is kept in its original form for reuse or remanufacturing. On the other hand, reclaimed timber can be easily worked and transformed, allowing it to serve various functions. However, as a biogenic material that releases carbon dioxide and methane at its end of life, it is critical to prolong the retention of sequestered carbon [104]. For comparison's sake, in 2023, the total amount of waste wood generated was 4.5 million tonnes. More than 97% of this wood waste was processed, meaning that less than 3% was sent to landfill. Of the processed waste wood, 65% was reprocessed for biomass, 22% was used as feedstock for the panel board industry, and 5% was exported, while animal bedding, equine surfaces, and other recycling and reuse processes accounted for the remaining 8% [100]. Although these figures are not directly comparable, it can be concluded that from 2018 to 2023, there was no significant shift toward reusing wood.

Ahn et al. [105] prepared a state-of-the-art review on the circular economy in mass timber construction, noting that the environmental benefits and CE potential of EoL and post-EoL timber structures are still underemphasized. The report indicates a lack of knowledge and the need for urgent research in creating holistic approaches to circularity in mass timber buildings.

There are two classification systems at the EU level which are particularly relevant to waste wood – the European List of Waste (LoW) and the European Waste Classification for Statistics (EWC-Stat). The LoW provides a harmonized catalogue of wastes for administrative purposes, such as statistical reporting of waste quantities. This list is organized by waste codes based on the origin and composition of waste and whether the waste is considered hazardous. The EWC-Stat is a substance-based catalogue of waste used for reporting waste statistics to Eurostat, with categories which can be transposed to LoW codes via an annexed table of equivalence. Beyond classifications, there are also several environmental regulations and directives which are relevant to waste wood classification and management, including the Waste Framework Directive (WFD), the Landfill Directive, and the POPs Regulation. National waste wood approaches vary from one EU Member State to the next. However, several common features emerge across the various national waste wood schemes. These common features include the use of quality criteria related to mechanical processing and chemical treatment, as well as presence of hazardous substances and preservatives to classify waste wood. Individual waste wood approaches are given for five EU Member States - Germany, the Netherlands, Finland,

France, and Slovenia, as examples [107]. In the listed countries, wood classification, the criteria for each class, and the use prescriptions by class are defined. Germany, the Netherlands, Finland, and Slovenia classify wood waste into four classes, while France uses three classes (Tab. 13). These classifications are predominantly designed for wood waste from the perspective of its potential use as fuel and for energy production, although some countries also allow alternative applications. For example, the German waste wood classification scheme includes use prescriptions by class, distinguishing between “*material recycling procedures*”, “*energy recovery*” according to the conditions set out in the Federal Immission Control Act (BImSchG – Bundes-Immissionsschutzgesetz), and “*disposal*”. Wood waste classified as Classes AI, AII, or AIII can be used in “*material recycling procedures*”. Under the Waste Wood Ordinance, material recycling procedures include three different processes: processing of waste wood into wood chips, production of synthesis gas for further chemical use, and production of activated carbon/industrial charcoal. Wood from C&DW is mostly allocated to AII-AIV. The waste wood classification scheme in the Netherlands is a part of the National Waste Management Plan 3 (LAP3). Although the sectoral plan recognizes that classes A and B of wood waste can be “*materially recycled*”, it also includes “*other useful applications*”, such as “*energy recovery*”. The Finnish classification scheme focuses primarily on the fuel and energy use of waste wood, setting use prescriptions that specify whether wood in each class can be recovered for energy and in which types of energy plants. It does not include material-use prescriptions. However, the Finnish Waste Act mandates adherence to a waste management hierarchy that prioritizes preparation for reuse, followed by recycling. This hierarchy is explicitly applied to C&DW under the Government Decree on Waste. In France, for material recovery, waste wood must not be hazardous, which limits material recovery to wood belonging to Class A and Class B. In Slovenia, the wood waste classification has been developed solely to assess the potential for processing wood into solid fuel. The Slovenian Waste Regulation also sets reuse and recycling targets for household waste; however, wood is not included in this target, although it is included in the overall preparation for reuse and recycling of C&DW.

This small analysis revealed that although the EU Waste Framework Directive (WFD) introduced the waste management hierarchy and promotes its application through the limited use of economic instruments and incentives such as Extended Producer Responsibility (EPR) schemes, separate collection obligations, and sectoral reuse, recycling, and recovery targets, [107] the actual situation in waste wood management is different. Unfortunately, cited national Waste wood classifications consider wood waste predominantly as an energy source. Drawing from the abovementioned waste wood classifications and favoring the highest priority uses, in line with the EU waste hierarchy, Project CEPS wood2wood proposed a possible harmonized classification scheme in terms on quality criteria and priority uses (Tab. 14), [107]. The proposed new classification comprises five classes: Clean, Non-Hazardous I, Non-Hazardous II, Hazardous I, and Hazardous II. This classification is primarily based on content and type of chemical substances, which can help prevent downgrading and upgrading of wood waste classes. As can be seen, priority use is not strictly prescribed. Priority uses aim to maximize the value of each waste wood class, adopting a flexible approach that permits waste wood to be used in various ways (i.e., reuse, repurposing, recycle etc.), including the priority uses.

Table 13. Waste wood classification in Germany, The Netherlands, Finland, France, and Slovenia, adapted from [107]

Germany			
A I	A II	A III	A IV
Untreated, non-hazardous	(Surface) Treated, non-hazardous	Contaminated, non-hazardous	Hazardous
The Netherlands			
A	B	C (non-wolmanized)	C (wolmanized)
Untreated, non-hazardous	Treated, non-hazardous	Hazardous	Hazardous
Finland			
A	B	C	D
Untreated, non-hazardous	Chemically treated, non-hazardous	Chemically treated, non-hazardous (HOCs or heavy metals above thresholds)	Preservative treated, hazardous
France			
A1	A2	B	C
Natural, untreated, and uncoated, non-hazardous wooden packaging waste	Natural, untreated, and uncoated, non-hazardous wood from processing industry	Surface treated, non-hazardous	Heavy metal or HOC treated, hazardous
Slovenia			
Unpolluted biomass waste	Contaminated biomass waste	Other waste	Hazardous biomass waste
Non-hazardous	Non-hazardous	Non-hazardous	Hazardous

Table 14. Proposed classification scheme in terms of quality criteria and priority uses, adopted [107]

	Clean	Non-hazardous I	Non-hazardous II	Hazardous I	Hazardous II
Quality criteria	Mechanically processed	Chemically treated. HOCs in coating. HOC, heavy metals below thresholds.	Chemically treated. HOCs in coating. HOC, heavy metals below thresholds.	Chemically treated. HOC, heavy metals above thresholds. PAH-treated.	PCB, CC/CCA treated.
Priority uses	Material recovery	Material recovery	Material recovery (coating removed).	Material recovery (limited). Energy recovery	Disposal

5.1.1 Reuse processes and their efficiency

Timber, as a natural material, is one of the most promising sustainable construction materials that can help mitigate climate change. However, there is currently no guidance or framework within existing business models to facilitate its circularity, meaning the reuse and repurpose of the material, and to assess its suitability for various purposes. Reusing timber helps maintain the material's highest value while also eliminating the need to source new materials. To promote and encourage reuse of structural timber in building redevelopment projects a various recommendations and guides have been proposed ([100], [106], and [108]). By combining them, we prepared a general, simplified proposal, which includes following stages: (1) a pre-demolition visual inspection and audit, (2) a feasibility assessment and a reuse/repurposing plan, (3) careful deconstruction/disassembly and reconditioning, (4) testing and structural characteristic assessment, and (5) sorting, grading, and proper storage.

Pre-demolition visual inspection and audit: A visual inspection should be performed to make an inventory of the timber elements to be salvaged such as beams, columns, rafters, etc. Pre-demolition audits estimate the amount of wooden materials likely to be generated from demolition

projects and offer recommendations on those waste management routes. They also provide a list of hazardous wooden materials and those with potential for reuse or recycling. The LoW and EWC-Stat systems can help identify hazardous waste wood.

Feasibility assessment and reuse/repurposing plan: Timber that is about to be sourced directly from demolition sites needs to be evaluated for careful deconstruction and preparation for reusing or repurposing. Since the additional time and cost are associated with the reuse/repurposing of structural timber, a feasibility plan serves to provide detailed information on suitable demolition methods to recover the identified materials, as well as to estimate the time needed to enable reusing/repurposing.

Careful deconstruction/disassembly and reconditioning: According to a thoughtfully prepared plan of deconstruction of the old timber building, the disassembly of timber members will be done. This operation includes dismantling, handling, separation, and stockpiling on-site, and transporting and storing the timber members. A specific skill set is required during the deconstruction to ensure the timber is salvaged without further damage. Further, cleaning and preparation processes have to be done, such as removing fasteners (nails, staples, screws, etc.), cutting out splits and notches, repairing and cleaning wood by washing to remove

dirt, grime, and mildew. Also, a metal detector can be used to ensure that all metal is removed before re-milling.

Testing and structural characteristic assessment: This operation can be performed before or after deconstruction, depending on the availability of elements for testing, their condition (they should be without paint or coat) investigation company's ability to conduct testing in situ, and other factors. Since, there are no standards available for the assessment of reclaimed timber, the structural characteristics should be verified according to current EU standards (EN 338:2016, EN 14081- 1:2020, EN 1309-3:2018, EN 1912:2024) [108]. Therefore, it is crucial to prepare carefully the testing program to best assess the reclaimed wood for the intended purpose. Different non-destructive test methods are available; however, their accuracy depends on consistency in the shape and size of the reclaimed timber members, thus a certain prior processing is requested. Furthermore, any fixings, splits, notches, etc. could hamper this process, so it is important to remove them before testing. Also, visual grading plays very important role in assessing timber residual performances. If the timber element is planning to be reused for structural purposes, the visual grading according to the parameters set by current regulations/standards should be performed.

Sorting, grading, and proper storage: After the deconstruction and testing, the salvaged timber elements are to be sorted based on their quality and condition. They can additionally be reconditioned if a possible future application requires it. Then, the wood is grouped according to its potential end-use, such as for structural, non-structural, or decorative applications. Any small sections or fragments from the resizing (i.e. waste) can be sorted, developed into by-products or sent out for recycling. The whole timber pieces can then be sorted and grouped into the materials that are going to be reused and upcycled. High-quality timber can be re-milled to its original size and used for the same or similar structural purposes - *reuse*; if direct reuse isn't viable, the timber can be used for other products, such as flooring, decking, or furniture - *repurposing*; In some cases, the timber can be manufactured into new structural products with enhanced properties (CLT, GLT or LVL) - *upcycling*. When the timber can no longer be reused, it can be recycled into products like particleboard, insulation, or animal bedding or recovered as biomass energy.

To optimize reuse in the new life cycle, it is essential to note down the information from the first life cycle of the used timber element at the time of demolition regarding the structural position (column, beam, rafters, etc.), the endured loads, as well as the environmental conditions to which the used timber element was subjected [108]. Moreover, this data could be very helpful during visual grading, since this operation must be carried out considering the area of maximum stress according to the structural scheme detected in the first life cycle.

To reuse the wood the visual characterization is critical, and it needs strict selection due to its nature of weakness in bio-attack, insects and moisture. For instance, Markues et al. [110] investigated mechanical properties of the removed utility poles for structural application. Based on the visual characterization results, 41% of specimen was damaged by biological attack, while 20% of the specimens had woodpecker holes and minor mechanical damage. They concluded that 47.2 % of specimens could be reused for structural applications.

Stefania De Gregorio [108], suggested visual grading as a method for determining residual structural performances of used timber. This method is internationally regulated by

specific standards (in the EU, this is EN 1912:2024). Also, visual grading is not affected by boundary conditions, and it is immediately applicable at the construction site after disassembly. The visual grading classes have been defined through the standard as a function of the species, the strength classes, and the characteristic values.

There are numerous nondestructive methods for assessing timber mechanical properties for structural use (ultrasound grading, near infrared reflectance spectroscopy, resistograph, sclerometer test, etc.) but their correlations are mainly established for new timber elements and cannot be directly use for "old" timber. Accordingly, new correlations should be established for timbers to be reused [108].

To ensure the viability of reusing structural timber, it is essential to incorporate reclaimed timber in the early phase of design. In such cases, the design should be based on the actual structural properties (characteristic strength, stiffness, density) of the reused timber. Besides, a comparison of this reuse-based design with other construction options to determine if the project is still feasible with reuse has to be done [106]. Also, UNECE [103] states that reuse timber constructions should be prioritized with holistic-circular approaches from the early stages of design.

However, none of those processes are currently in place, thus it is impossible to assess reuse efficiency.

5.1.2 Possibility and potential of timber for reuse

The potential for reusing wooden elements largely depends on the methods used for building demolition. Currently, many buildings are demolished using heavy machinery that crushes the structure. As a result, wooden components often cannot be salvaged for reuse. However, intact wooden beams and columns with larger cross-sections can be reused effectively, provided they have suitable fixings in place. Glued connections are typically instable, as they cannot be separated without damaging the components. Carpenter joints can be appropriate, but notches may lead to stress concentrations when the elements are configured differently. Nails and staples might also be suitable; however, they tend to fail under bending forces and can be difficult to remove without causing damage. Screws are generally a good option; thus, the same connector does not remain effective in the same hole after removal. The best choices are bolts and dowels, but it is important to inspect both the holes and any cracks carefully [111].

Höglmeier et al. [112] investigated the potential for reuse wood after deconstruction in South-East Germany and noted that 26% of recovered wood was suitable for reuse, with 38% of this having potential for residential buildings and other part was suitable for non-residential buildings. Another state-of-the-art discussion (InFuUReWood project) on timber structure reuse in Sweden, UK, Ireland, Spain, Slovenia, Finland, and Germany also addresses the technological underpinnings of possible circular use of timber in building construction. It particularly emphasizes Design for Deconstruction and Reuse (DfDR) in low-rise timber structures up to three stories [1]. DfDR covers how to dismantle the components readily and separate them from each other for reuse or recycling in building construction. This report indicates that digital tools as log books, material passport, BIM etc. would be highly effective way to ensure detailed documentation about the use and performance of recycled and reused building components [1].

Finch and Marriage [113] investigate reuse of recovered buildings materials using computer-aided design and manufacturing (CAD/CAM) technology. They found that

using CAD/CAM to produce advanced assemblies could lead to a 67% reduction in the time required to reuse of the recovered building materials.

Desk-based research revealed that there is no single list of wood reuse benefits, so we compiled what we found in papers: ([100], [103], [113], [114], [115], [116], [117], and [153]). The results are summarized in Tab. 15. As shown, they are classified into four main groups of benefits: environmental, economic, social, and technical. In a similar vein, we addressed the barriers associated with wood reuse. In addition, a proposal was added on how to mitigate specific barriers. The analyzed literatures are [100], [117], [119], [120], [121], [122], [123] and [153]. The results are summarized in Tab. 16.

As can be seen, the lack of specific regulations for the reuse of timber elements for structural purposes belongs to the group of major barriers to timber reuse, since applicable

standards are limiting factors. Even if the timber element has performed its structural function for a certain number of years and has proved to be suitable because it has not failed structurally and no degradation has occurred, when it is disassembled for reuse, it should be verified according to current EU standards and would probably be discarded due to safety margins. It is clear that information from the first life cycle is an added value to understanding the component but is currently not taken into consideration [108].

Reconditioning stands as a vital technology in waste wood processing, as it necessitates careful manual operations like segregation, de-nailing, and de-screwing of timber waste to prevent further damage to the reclaimed timber components. Afterwards, reconditioned timber elements need to be moved and stored again. All listed operations are labor-intensive and increase costs; therefore, this logistics process should be carefully planned [124].

Table 15. Benefits of timber reuse

Environmental Benefits	Conservation of natural resources	Lower demand for virgin wood that needs to be harvested from forests, and consequently, reduction of deforestation.
	Long-term carbon storage	By reusing timber elements, the carbon absorbed during tree sequestration remains locked in the built environment for longer.
	Reduction of CO ₂ emissions	Lower demand for virgin timber -lower CO ₂ emissions. By preventing CO ₂ emissions associated with felling, processing, and transportation of new wood.
	Waste minimization	By redirecting usable wood from landfills for reuse purposes, construction waste will be reduced.
	Reduced energy consumption	Timber reuse requires less processing compared to the production of new timber.
Economic	New market value	Cost benefits through the prolonged life of wood waste.
	Economic resilience and value chain development	Coherent financial structure and viability of the case companies. Employment and value creation for partners in the value chain network.
	Local availability	Timber prepared for reuse is often available locally and, thus, faster.
Social Benefits	Job creation & skills development	Deconstruction for reuse purposes is labor-intensive and can create more jobs than traditional demolition. Wood reuse initiatives offer valuable training and job opportunities, particularly for individuals excluded from the traditional job market.
	Community empowerment & inclusion	Reuse projects often involve local social enterprises, giving communities ownership over material reuse and enabling participation in sustainable practices. Community-driven wood-waste reuse enhances skills and fosters knowledge exchange, empowering residents to participate in sustainable waste management.
	Stronger community ties & social cohesion	Deconstruction and reuse processes can foster cooperation across engineers, architects, local governments, and social enterprises, strengthening community networks.
	Cultural heritage preservation and valorization	Timber craftsmanship (carpentry, joinery) has deep cultural roots; reusing wood supports these traditions and connects modern construction to local heritage. Timber reuse helps maintain local identity and craftsmanship possibility to preserve the heritage value of the components and valorize the technical know-how embedded in the reclaimed components.
Technical Benefits	Dimensional stability	Mature timber usually has balanced humidity with the environment in which the wood is used; consequently, it is dimensionally more stable making it less prone to warping, splitting, or shrinking.
	Potential aesthetic value	Weathered or aged timber can offer a unique visual appeal.

Table 16. Identified barriers for reuse of timber and possible mitigation solutions

Barrier category	Specific barrier	Barrier description	Proposed mitigation measures
Technical and logistical barriers	Insufficiently developed processing technologies	Unprofessional dismantling causes additional damage of timber components.	Enforcement of the requirement that only licensed professional demolition companies are permitted to dismantle buildings.
		Lack of knowledge on sorting technologies.	Improve sorting technologies.
		Lack of efficient waste wood reconditioning processes.	Develop step-by-step reconditioning protocol.
	Complex design	Iterative design process due to adaptation to currently available timber elements on stock.	Consecutive and parametric design. An integrated design process and the use of digital tools.
Lack of appropriate regulation and standards	Salvaged timber elements must fulfill current design regulations and quality standards.	Revision of regulations and standards.	
Economic and market barriers	Underdeveloped supply-demand chain market	The market currently lacks any available reused wood.	Create a market for reused timber. It is necessary to develop circular distribution centers. Better cooperation between all stakeholders.
		No demand for reuse timber.	
		Lack of cooperation of all parties.	
	Extra costs	Pre-demolition audit and careful dismantling of obsolete structure. Sorting, grading and reconditioning of salvaged timber elements. Customized design and adjustment of joints.	Introducing automatic classification, sorting, and storing. Implementation of new digital technologies in a framework for the supply chain. Implementation of a business model that combines deconstruction/demolition with the sale of salvaged timber elements within the same company.
		Different stakeholders require different data and information.	Unique digital information platform.
Higher investment	Increased expenses at all stages for the reuse of timber in new construction.	Provide the economic incentive for all stakeholders.	
Other barriers	Knowledge and awareness gap	Lack of awareness of waste conservation practices.	Require building rating systems certification. The development of plans for dismantling.
		Lack of knowledge and education.	Persuade all stakeholders to design for deconstruction based on CE strategies. Encourage the reuse of materials from demolished buildings.
	Renewable energy source	Biomass is a major part of the EU's renewable energy sources, accounting for its largest single source.	Significant shifting towards solar and wind sources according to EU Renewable Energy Directive III (2023).

Piccardo and Hughes [117] explored the possibility of reusing wood in buildings by employing two circular strategies referred to as “upstream” and “downstream” methods. The terms upstream and downstream are generally used to describe the early and late stages of a process, supply chain, etc., respectively. In this study, upstream strategies were those developed during the design phase to facilitate the future reuse of wood elements throughout the building life cycle, especially during maintenance and end-of-life phases. These strategies pertain to the Design for Disassembly and Adaptation (DfD/A) concept. Downstream strategies concern the salvage of wood materials from buildings in the process of

being renovated, deconstructed, or demolished, and their subsequent use in new buildings through their design phase. This case-study research revealed that upstream strategies are effective in increasing the potential cascading of wood for reuse, regardless of the construction system of the building. The downstream strategies can also be implemented regardless of the construction system of the building, in both load-bearing and non-load-bearing elements. Upstream strategies can facilitate the future reuse of wood elements if a few challenges, such as extra costs due to customized design and manufacturing of fastenings, as well as the need to adapt to new building standards, are overcome. Similarly, downstream strategies can enhance

the reuse of wood by addressing challenges such as lower quality of salvaged wood, the difficulties in grading salvaged wood to be reused as load-bearing elements and increased construction time due to re-manufacturing operations. Additionally, the implementation of upstream and downstream strategies in wood buildings might be more complex compared to a conventional use of wood, as they entail the use of specific expertise in DfD/A as well as in the procurement of salvaged wood.

Ottenhaus et al. [125] stated that design for adaptability is crucial to extend the service life of buildings during the construction sector's transition to CE. Possible process of circular timber buildings based on DfA principles, where entire buildings can be reused, repurposed, relocated, reconfigured, etc., is presented in Fig. 17. They recommended that multiple reuse scenarios for timber building components at the end of their service life should be considered during the initial design and planning stage.

The main challenge of reusing timber and primary construction materials in urban areas is optimizing the waste-to-resource loops [126]. Digital technologies can help identify material stock existing in obsolete buildings that will no longer serve society, enabling their relocation to new purposes. In the scope of the project "SirLåve" [153], the possibility of implementation of new digital technologies in a framework for the supply chain, encompassing five essential steps: Data, Detection, Disassembly, Distribution, and Design, was investigated. This innovative framework, known as the 5 "D"s, was developed by Catherine De Wolf. The brief descriptions of these five steps are: (1) *Data* stands for the collection of macro-level data to track which material stocks are or will be available soon, helping planners to prioritize which stocks to reclaim. (2) *Detection* refers to the collection of micro-level data that are necessary for material and building passports or building information models. (3) *Disassembly* refers to a careful process of deconstructing structures with the goal of retrieving valuable components or materials for future design applications. (4) *Distribution* includes logistics: transport and storage. As materials are often not reused directly after dismantling, the workflow

requires a physical circular hub, material banks, and other spaces where the salvaged material can be collected and pretreated. (5) *Design*: Salvaged timber materials can be returned to the supply chain and marketed to those who build new buildings or refurbish current ones. When these materials are intended for use as load-bearing elements, it is advisable to employ a consecutive design or parametric design approach. Wuyts et al investigated the implementation of high-technologies in step "Detection", like scan-to-BIM (laser scanning, photogrammetry, GIS, etc.), automation detection and artificial intelligence (i.e. deep learning methods). Regarding the quality of built-in materials, they used conventional destructive and nondestructive testing methods. Their final observation was that this model is not competitive on its own. However, insights can aid in shaping future research designs, focusing on balancing the costs of data collection and storage against the benefits for various actors in different regulatory and economic contexts.

The timber structures, especially single-story buildings, are common in Middle and North European countries (e.g., Austria, Germany, Denmark, Finland, Norway and Sweden) and in South America. In other European countries timber is mainly used in roof structures. In developed countries, such as Australia or the United States, numerous government programs were created to support and encourage the processing and use of construction wastes as well as taking into consideration the idea of reuse the whole structures or structural elements [127]. For example, to support reuse of timber, the directory of companies in the United States involved in wood-framed building deconstruction, dismantling, and reused building materials, as well as those specializing in value-added wood products, including reclaimed and antique lumber is published [128]. It serves as a resource for individuals and businesses looking for suppliers of reclaimed and antique lumber, as well as value-added wood products. Additionally, it aims to promote environmental sustainability and support the market for salvaged and value-added wood products.

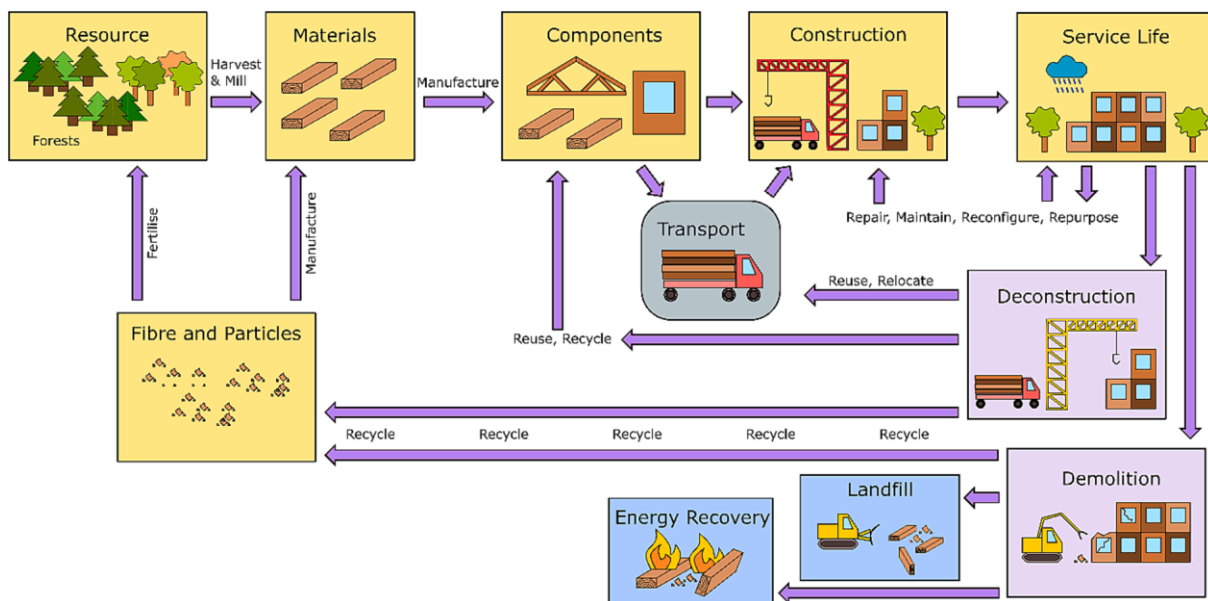


Figure 17. Circular solutions for timber buildings in the technosphere adopted from [125]

Norway utilizes most of its wood waste in biofuel production. Besides, the main obstacles for the direct reuse of wood are demands for altered dimensions and better thermal properties in new construction [120]. Junginger et al. [129] stated that the increasing demand for wood waste-based energy production is the biggest obstacle to reuse of wood in many European countries.

Passarelli [130] reported the building industry in Japan is based on the constant renewal of the building stock, leading to a short average lifespan and an unsustainable system from both environmental and economic perspectives. As an alternative to this situation, a modular mass timber system using CLT is designed for consecutive reuse. This system fulfills the criteria for reusability, portability, and adaptability.

The possibilities for reusing structural timber would be mainly for private builders working in the residential sector (e.g., homes, extensions, or sheds), temporary works, and historical buildings with timber structures. This is because the retail market for constructing these types of structures is not overly concerned with recertification, which is assumed to be expensive due to the additional testing required. The possibility of using reclaimed timber as the structural material for building types other than residential, such as commercial and industrial, is very improbable. Some of the repurposing opportunities identified include floorboards, feature timber, cladding, and temporary elements used in construction (e.g., shutters) [124].

Additionally, the reuse of old wooden products can be increased by encouraging their use in new constructions thanks to their architectural aesthetic value [121]. Architects are important actors in the construction industry. They are the key drivers of the first life-cycle phase of buildings, that is, the design, i.e., the critical decision-makers whose decisions impact all later phases of the life cycle of buildings and determine the environmental impact through those phases. The reuse of wood elements in architectural projects has gained popularity in recent years due to potential benefits in terms of sustainability and cost-effectiveness. Architects who incorporate reused wood elements into their designs may experience a range of advantages and challenges. Besides, reuse can be more cost-effective than buying new wood and can add value to a building by creating a rustic or vintage look that appeals to clients [111]. Also, research on possibilities of application of upstream and downstream strategies [117] emphasized the importance of the role of architects in enhancing the reuse of wood.

5.2 Recycling of timber

Wood is generally considered to be a recyclable material. Logging and wood-processing residues have posed a utilization challenge for those involved in harvesting and manufacturing wood products due to their large volume. For example, in a sawmill or plywood plant, residual materials account for up to 60% of the log volumes delivered. Thus, early commercial efforts have sought to maximize the use of these residues for charcoal, poultry bedding, and heating fuels. The modern history of timber recycling processes began with the use of wood residues to produce hardboards (made from pulp mats) in the 1920s. It continued in the United States in the 1940s with the production of nonstructural particleboard (a composite panel product). The first industrial production of particleboards in Europe occurred in 1941 in Germany, using phenolic binders and spruce particles. Medium-density fiberboard (MDF) was first manufactured commercially in 1965. Until the 1970s, the USA was generally oriented towards the production of

plywood (made from veneers), which was widely used for wood-framed houses. However, the lack of suitable timber for plywood production encouraged the development of technologies for producing structural types of particleboards. The invention of oriented strand boards (OSB) made them a leading commercial competitor to plywood in structural sheathing markets in the 1980s. Further inventions and production of MDF/HDF boards with particles the size of dust and with wax/resin binders, dating back to the 1980s, led to their widespread production in the 1990s [131].

Recyclable wood waste is dominantly generated from logging and wood-processing residues, but nowadays there are numerous other materials that have the potential to be treated in the same way, such as waste wood coming from different businesses, home renovation, or construction and demolition activities. However, not all waste wood is recyclable. It depends on its classification and grade, since additional features, like paint, varnish, nails, plastics, and contaminants, can all lead to additional processing before the wood can be recycled or sent to landfills [132]. Therefore, waste wood other than logging and wood-processing residues should be graded before recycling can proceed. However, the European member states are lacking a common legislation scheme about the recycling of wood regarding classification and thresholds [133].

The European List of Waste (LoW) can help in the classification of waste wood. Also, the national classifications, which are predominantly designed for waste wood from the perspective of its potential use as fuel and for energy production (see chapter 5.1) or [107], can also be used in making a decision whether waste wood is recyclable, since they allow for certain classes alternative applications of waste wood. To support waste hierarchy and circular economy in waste wood management a new categorization was adopted in the UK [146]. This classification prioritizes recycling to biomass fuel. According to the Wood Recycling Association's guide [146], there are four grades of waste wood:

- **Grade A: clean, untreated wood.** Grade A waste wood is free from contaminants, including paint, preservatives, or coatings. It typically consists of materials like solid, soft, and hardwood, pallets, crates, and various packaging waste. This waste wood has the highest recycling potential.

- **Grade B: Treated and non-hazardous wood.** (Industrial feedstock). This category includes wood with minor contamination, such as painted or varnished surfaces and binders or glue. Mainly consist of grade A materials mixed with construction and demolition waste wood (C&DWW) and domestic furniture made of solid wood. Before recycling, Grade B waste wood requires processing to remove impurities. It is commonly used for production of board panel materials, mulch, compost, or as biomass fuel.

- **Grade C: Treated and non-hazardous wood.** (Fuel grade) Comprising contaminated or treated wood, mostly board products. Grade C waste wood requires specialized treatment to remove (potentially) hazardous substances before recycling. It is often repurposed for biomass energy generation or converted into engineered fuels-

- **Grade D: Hazardous.** Comprising heavily contaminated wood with hazardous substances - such as railway sleepers, telegraph poles, trailer beds, agricultural fences, etc. Requires special disposal.

Based on the waste code (LoW) or, if needed, chemical analysis, waste wood items arising from household, commercial, industrial, construction/demolition, and agricultural sources should be classified into wood waste grades. Categorized waste wood can be more easily directed

into the appropriate processing funnel. This also helps to match the waste wood with its most suitable application in the recycling process.

A typical appearance of certain types of wood waste [153] is given in Fig. 18, Fig. 19. and Fig. 20.

5.2.1 Recycling processes and their efficiency

The process of recycling waste wood considers several key steps. We identified the most frequently used terms and descriptions by comparing the key steps of the recycling process from the cited literature ([132], [134], [136]). By gathering them, the recycling procedure would consist of:

- **Collection and transportation:** Waste wood is collected from various sources, including construction sites, manufacturing facilities, and waste management centers, and transported to recycling plants.

- **Sorting according to grading:** Waste wood is graded by quality and contamination level and sorted. This step helps identify the most suitable recycling route for each type of wood.

- **Cleaning and pre-treatment:** Depending on the grade, this step may include removal of contaminants and impurities, such as metals, coatings, paints, or adhesives. Different mechanical treatments are commonly used, but chemical cleaning treatments may be required in some cases.

- **Processing - size reduction:** Depending on the grade of waste wood and the selected repurpose, various processes may be used, such as cutting, planing, chipping, sanding, shredding, or grinding, to make suitable recycled wood raw material (chips, fibers, or lamellae) for new purposes.

- **Repurposing:** In this step, the processed waste wood is repurposed into a new wood-based product, which dominantly depends on grade.

The described key steps of the recycling process are typical for processing waste wood into chips or fibers, which are usually repurposed into different types of wood-based boards. However, lamellae must undergo additional strength grading, visual inspections, and moisture level adjustments when repurposed into structural engineering wood products like CLT and GLT.

Faraca et al [138] analyzed the resource quality of 8 tonnes of post-consumer waste wood from three Danish recycling centers. The authors subdivided collected waste into 34 individual material fractions, distinguished by source, type, and a quality grade (Grade I - Clean waste wood; Grade II - Clean waste wood with some contamination; Grade III - Waste wood with considerable contamination;

Grade IV - Hazardous waste wood). Then, they analyzed each fraction regarding physical impurities and chemical contamination. The findings showed that contaminant levels (both physical and chemical) vary significantly depending on the type and source of waste wood. Regarding the implementation of a circular economy in waste wood management, the authors concluded that waste wood should be sorted more carefully—not as a monolithic “waste wood” category, but as a heterogeneous resource requiring sorting according to quality grading and chemical screening.

First step in proper segregation of waste wood is to separate clean, solid wood from wood-based panel products (particleboard, chipboard, OSB, plywood, and MDF), i.e., from products that contain glue, varnishes, and other coatings [132]. This operation is labor-consuming; thus, utilization of advanced solutions for waste wood sorting, such as systems based on X-rays and deep-learning sorting technologies, can save time and money, as well as improve the quality of segregated fractions. Also, physical and mechanical contaminants in waste wood can be removed using appropriate sorting techniques. Therefore, focusing on improving sorting methods will bring benefits in cleaning the waste wood mix [133].

Waste wood from construction and demolition activities, as well as other sources, is typically sent to wood recycling companies for processing. To increase the recycling potential of waste wood, it is necessary to create many small market enterprises for salvaged timber, boards, or other components, which, after screening the size of the required particular pieces of elements or fiber requirement, could send the product to processing facilities for repurposing into new products.

Depending on the source and classifications after pre-treatments, different recycling processes could be done:

- For clean wood, the processes are relatively easy to achieve; clean, untreated wood has the broadest range of applications in a second life. In the sense of new wood-based building materials, the sawn timber from construction and demolition processes could be used for the production of GLT [139] or CLT elements [114], [140], as well as for LVL production.

- Industrial wood may be repurposed into products such as panel board products, insulation, animal bedding, mulch, compost, or biomass fuel. Pre-treatments involve mechanical and chemical decontamination processes, after which the selected repurposing method requires similar operations, like using new wood raw materials. This type of waste wood should be favored in the production of wood-based boards.



Figure 18. Clean, untreated wood



Figure 19. Treated and non-hazardous wood, mostly solid wood



Figure 20. Treated and non-hazardous wood, mostly board products

- For heavily but non-hazardous contaminated or treated waste wood, such as plywood, MDF, chipboard, and blockboard plywood, the recycling processes are challenging. [133]. Wood-based boards are made by gluing timber pieces together. The gluing process makes it quite difficult to recycle, so the prevailing view is that they cannot be recycled; thus, they often end up for biomass energy generation or, rarely, for panel board in controlled volumes. However, certain companies [141] made progress that enables the MDF boards to be recycled, enabling them a "second life". The innovative recycling process for MDF/HDF boards includes moistening of the boards, then heating and subjecting them to high pressure, and releasing the pressure to free the fibers.

The aforementioned recommendation concerning suitable recycling processes gives a wide spectrum of waste wood potential utilization. However, waste wood is not a homogeneous material even after grading, since it originates from various resources. Therefore, there are still some limitations that need to be overcome before waste wood can be used as a raw material for wood composite production. Thus, Nguyen et al. [133] investigated the quality of wood-based panels produced from recycled wood resources. They drew several conclusions: (1) Particleboard is nowadays the most favorable product to be made from waste wood materials. It is simpler and cost-efficient to process all types of old wood-based panels into particles by mechanical treatment (e.g., chipping) than into fibers by chemical methods. Also, converting old fiberboard into fiber or old OSB and plywood into strands is quite demanding. Furthermore, waste wood streams are typically a mixture of wood-based panel products, so producing the proper strand size would require additional segregation of already graded waste. (2) Waste wood materials are not used for plywood production because it is impossible to process them into veneers. (3) Using waste wood for production of wood-based panels increases the risk of formaldehyde emissions in particleboard and OSB products. However, this risk can be addressed by applying pretreatment steps to reduce formaldehyde emission (e.g., hydrothermal process) or using formaldehyde-free adhesives (e.g., PMDI).

The effectiveness and expenses associated with the recycling process are significantly influenced by the source and type of waste wood, along with the categorized grades

of waste. Therefore, further improvements of all processes are needed to optimize and reduce the variability of wood properties, enabling more efficient processing and production of more reliable products. Emphasis should be placed on establishing a unique EU classification of waste wood for recycling and setting thresholds, as well as on the improvement of waste sorting techniques.

5.2.2 Possibility and potential of timber for recycling

Although wood is a renewable resource, its growth and processing require time, effort, and energy. Thus, recirculating waste wood, which is already on the market, eliminates a significant portion of this, making it more sustainable and easier to acquire [132]. Waste wood in the form of engineered/industrial wood products is widely present in our society and can be found in construction and demolition, packaging, and municipal waste streams [142]. In the European Union, common management methods for dealing with waste wood include converting it into energy or recycling it, because the EU Waste Framework Directive 2008/98/EC prohibits landfilling waste unless it is the only option available for disposal. The priority for each country is a stable and independent energy market, so 60-95% of collected waste wood in European countries is used for energy, often for district heating. However, the EU is committed to increasing the recycling of materials as part of its drive to a fully circular economy and suggested using the cascade principle in waste wood management.

The concept of "cascading" was developed in the Netherlands to improve resource efficiency by Sirkin and ten Houten (1994). The term "cascading" applies the same principle to all materials, simply put, prioritizing material use first and energy use last. The concept was later adapted to wood by Fraanje (1998) and is visually represented in Fig. 21 [1]. This cascade approach illustrates the true long-term potential of wood circularity.

Bais-Moleman et al. [143] using a life-cycle approach found that cascading use of wood could increase wood-use efficiency in the European wood sector by 23 to 31%, with the added benefit of reductions in global warming potential of 42 to 52%.

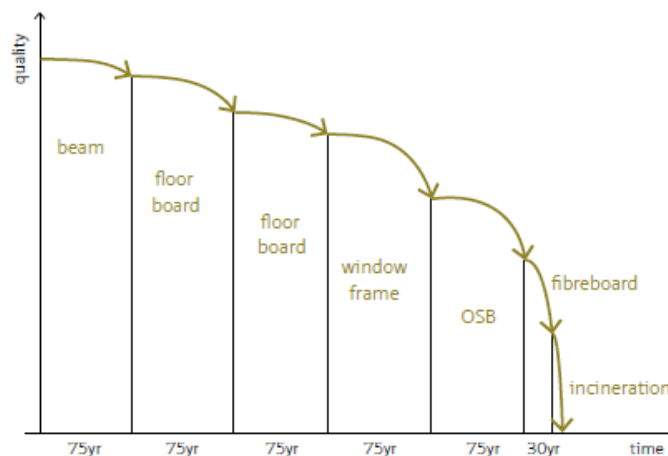


Figure 21. Potential cascading of pine wood; Fraanje (1998), adapted by Icbaci (2019); [1]

The recent world review given by Jahan et al. [144] indicates that the world leaders in wood production and export are Canada, the USA, Sweden, Finland, Germany, Russia, and Brazil. They produce 31, 19.5, 18.5, 16, 14.5, 14, and 11 million tonnes of wood annually, supplying the industries with raw wood material for producing industrial round wood, sawn timber, wood-based products, engineering wood products, pallets, paper, pulp, furniture, and other products for global economic growth. A green economy that favors wood as a sustainable material contributes to the increased use of wood and wood-based products in the building and construction sector. This extensive use of wood as a material generates significant and heterogeneous waste wood streams. Fig. 22 shows trends in the total waste wood generation by sectors in the EU27 from 2004 to 2020 based on Eurostat data. Between 2004 and 2020, waste wood generation decreased by 22.25 %, but it seems to be at almost same level from 2016 to 2020 [107].

As of 2020, waste wood in the EU-27 mainly comes from three sources: the construction and demolition sector, the commercial and industrial sector, and the waste collection sector (municipal waste). The total estimated potential of waste wood in the EU is about 50 million tonnes, with a share of about 11.5% from the commercial and industrial sector, 48.7% from municipal waste, and 38.8% from C&DW. The leaders in the production of waste wood are Germany, France, the UK, Italy, and Spain. Considering the way of final waste wood use, three strategies were distinguished: energy recovery, recycling, and mixed. Sweden, Finland, Portugal, Slovenia, and Hungary are dominantly determined to energy recovery; Poland, the Netherlands, Belgium, Romania, Austria, Croatia, Ireland, Estonia, Latvia, Bulgaria, and Greece are practicing mixed solutions. Germany and Slovakia are also practicing mixed solutions, but towards energy-oriented solutions, while the UK, France, Denmark, Lithuania, and the Czech Republic are oriented to mixed solutions as well, but oriented to recycling. Finally, Spain, Italy, and Malta are dominantly oriented to recycling [145].

Pazzaglia and Castellani [137] reported that in 2020, the EU27 generated 48.28 million tonnes of waste wood, of which 40.20 million tonnes (~83%) were treated. Among the treated waste wood, only 0.24 million tonnes were disposed of (0.60%), with the remaining 39.96 million tonnes (96.40%) being recovered. Of the recovered waste wood, 21.45 million tonnes were used for energy recovery, while 18.51 million tonnes were utilized for recycling and backfilling,

representing 9.88 million tonnes (53.36%) and 8.63 million tonnes (46.04%), respectively. According to new data released by Wood Recyclers' Association [146], the UK's waste wood sector generated 4.5 million tonnes of waste wood in 2024, with more than 96% (4.33 million tonnes) processed for reuse, recycling, or recovery. The primary destination of processed waste wood is the energy production sector, with 2.8 million tonnes (68%). The panel board manufacturing sector is the second largest user, processing over 920,000 tonnes (21%). Other recycling and reuse outlets, including applications such as animal bedding, equine surfacing, and landscaping, account for 310,000 tonnes. At the same time, Donaldson [119] reported that the waste wood recycling rate in Canada is still less than 8% due to cheap virgin wood material, its availability, and the ease of obtaining incineration permits.

Recently, the EU policy has shifted to prioritize waste wood recycling (as a part of material recovery) over energy recovery, aiming to transform waste wood into a secure industrial resource within the framework of a circular economy. This means future rates of material recycling are expected to increase.

Pazzaglia et al. [137] proposed the necessary joint measures for the treatment of waste wood in EU member states: waste wood management policy should establish a common European law for waste wood, encompassing pollutant limit values for material recovery (recycling) and energy recovery, mandatory extended producer responsibility (EPR) for waste wood, EoW criteria for waste wood, and compulsory separate post-consumed wood collection to enhance waste wood quality. Each of these measures should be carefully studied to make the system dynamic and suitable for the diverse environmental, economic, and social contexts of the European Union.

Austria is the only the EU state with EoW criteria related to waste wood [137]. EoW criteria have the potential to prevent the unnecessary continuation of waste status, facilitating the trade and utilization of wood from waste wood in products. The EoW status for recycled wood is tied to designated use and can be declared. Waste wood intended for recycling may be used only in installations serving to produce wood-based materials. The waste owner must adhere to the Austrian standard for solid recovered fuels, ÖNORM EN 15358, which outlines the necessary quality management systems and external quality assurance requirements for declaring the EoW status of recycled wood.

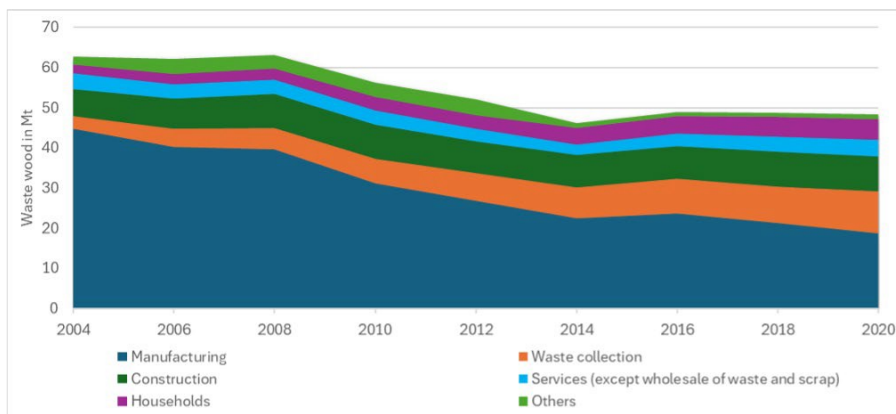


Figure 22. Total waste wood generated in the EU-27 (million tonnes) from 2004 to 2020 based on Eurostat data (2024a) [107]

After reviewing relevant scientific papers and various technical and industrial reports ([132], [142], [147], [154], [155]), we reached the same conclusion we initially assumed: there are no significant differences between the benefits of reusing and recycling waste wood. The benefits of recycling can be organized into three main categories: environmental, economic, and social. Key *environmental benefits* include (1) conserving natural resources by reducing logging, which helps preserve forests, biodiversity, and habitats; (2) mitigating climate change through long-term carbon storage and lowering CO₂ emissions; and (3) decreasing landfill burden by diverting organic waste and reducing the space required for landfills. *Economic advantages* are summarized as (1) new market value instead of being treated as waste; (2) cost savings since recycled materials are cheaper to buy and process than new timber; (3) economic resilience and value chain development; (4) local availability; and (5) a broad range of uses such as engineered wood, panels, bio-composites, insulation, and animal bedding. Since the waste wood recycling in a wider definition comprises "renewable energy source", the additional benefits can be energy production to reduce fossil fuels. *Social benefits* include (1) supporting the circular economy by maximizing material use; (2) job creation and skill development by fostering new industries and jobs in collection, processing, and manufacturing; and (3) community empowerment and inclusion by promoting sustainable practices and material awareness. Green practices are an integral part of modern business, demonstrating that participating in and respecting recycling practices will improve public perception, resulting in higher returns in the future.

Cakaj et al. [147], through a systematic literature review, identified, then sorted and classified the barriers that hinder the implementation of a circular economy in general waste wood management. Respecting their proposal, we created a comprehensive systematization of barriers to wider waste wood recycling. The proposed systematization is more than just a "copy-paste" from selected literature ([107], [137], [138], [147], [148], [150], [152], and [154]) it also includes our interpretation and barrier perception. The results are summarized in Tab. 17.

The main barrier to reusing/recycling waste wood is the widely held belief that wood, in any form, is a natural and biodegradable material that can be returned to nature without restriction or used as solid fuel. The importance of a specific barrier varies across EU regions, as forest resources, timber construction traditions, and economic and legislative developments all play important roles. Also, the barriers listed above complement and intertwine, resulting in the final cost of recycled waste wood, which varies by region and may be unacceptably high for some countries.

The use of waste wood as a renewable energy source represents a strategic barrier to expanding material recycling because energy security remains a high national priority for many countries. Governments increasingly rely on biomass to reduce dependence on fossil fuels, stabilize energy supply, and meet renewable energy targets, which makes the redirection of waste wood away from combustion politically and economically difficult. As a result, large volumes of potentially recyclable timber are consistently channeled into energy recovery, limiting the availability of suitable material for higher-value recycling processes. Although current energy-from-waste policies limit the

material availability of waste wood suitable for recycling, this situation may gradually improve in the future. The EU aims to significantly increase the share of solar and wind energy in its power mix, which is expected to reduce the reliance on biomass for energy generation. In such a scenario, a certain portion of waste wood that is currently diverted to energy recovery may become available for higher-value recycling and material reuse. Besserer et al. [151] concluded that current waste wood recycling processes require improvement to prioritize material recovery over energy recovery. A comprehensive study about the Swedish experience in waste wood recycling [142] revealed that energy recovery and true recycling of waste wood shouldn't be competing methods. They have to be complementary, even in countries with advanced incineration facilities, like Sweden.

The lack of new production lines for utilizing waste wood generated from construction and demolition sites and the municipal/commercial sectors in new products also presents an important barrier. For instance, only one of particleboard manufacturers in Norway can use waste wood. Thus, it would be important to plan new production lines for increased recycling. However, the economic viability of the project could be an additional barrier if recycling stations can sell wood chips for energy recovery at the same or higher price as for particleboard production [150].

The sorting and classification of waste wood must be more accurate, as certain repurposing processes restrict the use of specific original wood products, such as fiberwood boards, which are limited to a 3% share in the panel board industry [150]. Utilizing established advanced technologies like near-infrared (NIR), fluorescence spectroscopy (XRF), and GC-Drift Tube Ion mobility spectrometry enables the detection of chromatid copper arsenate (CCA) and pentachlorophenol (PCP), while also allowing for the separation of undesirable fiberboard and wood-plastic composite materials. Besserer et al. [151] stated that a better understanding of the composition and quality of waste wood, as well as improvements to current sorting techniques, are required. They suggested improving recycling routes by purifying wood particles or fibers. This purification can be accomplished by physicochemical methods and biological approaches based on using fungi.

Waste wood is usually derived from a variety of resources, demonstrating a lack of homogeneity as a material. Furthermore, it is characterized by a variety of physical and chemical contaminants, which pose significant challenges during recycling processes and affect the properties of the resulting recycled products [152]. According to the UK Waste and Resources Action Program [156], 74% of waste wood, which comes from construction and building sites, is treated with toxic preservatives, such as CCA, PCP, and creosote, to prevent or delay decay caused by fungi or termites. Since the beginning of the 21st century, the EU has established stringent regulations on CCA and waste wood recycling due to the leaching of heavy metals and arsenate poisoning. A large amount of CCA-treated wood remains out of service, and there is concern about disposal and recycling applications.

Overcoming these barriers requires a holistic approach that combines policy refinement, technological innovation, and a significant shift in industry culture and economic incentives.

Table 17. Identified barriers for recycling of waste wood and possible mitigation solutions

Barrier category	Specific barrier	Barrier description	Proposed mitigation measures
Technical and logistical barriers	Insufficiently developed processing technologies	Unprofessional demolition/dismantling is causing mixing and additional contamination of waste wood.	Better control of demolition companies' qualifications to selectively dismantle buildings.
		Lack of adequate sorting infrastructures and technologies. Lack of new/adapted production lines.	Implementation of advanced sorting technologies for efficient sorting, better cleaning, and non-destructive quality assessment of mixed waste wood. Proper planning and investment in new/adapted production lines for increased recycling.
	Unstable composition	Physical impurities and hazardous substances complicate sorting and cleaning processes, limiting the potential for high-value recycling. High levels of inhomogeneity caused by variations in the source, size, and moisture content make it difficult to ensure the consistent quality required for high-quality products.	Introducing a unique classification system and grading method, as well as thresholding for waste wood to be recycled.
Economic and market barriers	Underdeveloped supply chain market	Low demand for recycled waste wood.	Create a stable market for recycled waste wood, especially in supplying manufacturers. Better cooperation between all stakeholders. Unique digital information platform.
		Market instability.	
		Lack of cooperation among all parties.	
	Extra costs	Selective demolition/ dismantling is often more expensive and labor-intensive than traditional mechanical demolition and disposal. Collection, segregation, classification, and pre-treatment of waste wood require quite costly modern technical equipment to be properly recycled. Logistics and transport to specialized facilities.	Introducing automatic classification, sorting, and storing. Improvements to current sorting techniques to be more accurate. Implementation of new digital technologies in a framework for the supply chain.
Higher investment	Increased expenses to adapt manufacturing for the implementation of recycled waste wood into new products.	Provide the economic incentive for all stakeholders.	
Renewable energy source	Biomass is a major part of the EU's renewable energy sources, accounting for its largest single source. Incineration to produce energy is a more profitable and convenient option for waste wood.	Significant shifting towards solar and wind sources according to the EU Renewable Energy Directive III (2023). Government incentives for recycling to support circularity in waste wood management.	
Regulatory and institutional barriers	Inconsistent regulation and standards	A fragmented landscape of policies and standards across different regions creates confusion and complicates the wood recycling process. The lack of a harmonized EU classification system for waste wood limits cross-border trade and market expansion.	Revision of regulations and standards. Prioritize material recovery over energy recovery.
	Weak enforcement and policy gaps	Insufficient policy support, a lack of law enforcement for proper waste management, encouragement of biomass for energy production, and low penalties for illegal dumping all work against sustainable practices.	Strengthening legislation, improving supervision, increasing penalties, investing in infrastructure, and raising public awareness.
Social barriers	Knowledge and awareness gap	Lack of awareness of waste recycling practices.	Raising awareness about the importance and the potential of waste wood to be recycled, efficient collection techniques, and the environmental benefits. Encourage the recycling of materials from demolished/renovated buildings.
		Lack of knowledge and education among stakeholders.	
	Perceived risk	The industry views using recovered materials as risky due to quality and liability uncertainties.	Significant shift in industry culture and economic incentives.

The rates of waste wood recycling vary significantly among the EU member states. For instance, due to the high availability of virgin wood, some highly developed countries, such as Norway, recycle a negligible percentage of waste wood [150]. Waste wood management in Norway is oriented toward energy recovery (90% of waste wood) [157]. Finland has also reported significant use of waste wood for energy purposes and has a well-developed system for categorizing waste wood as fuel, established even before 2015. Therefore, the country still faces challenges in promoting the reuse and recycling of waste wood [158]. On the other hand, some EU countries strive to improve their relatively high percentage of waste wood recycling, like Italy [137].

Shifting towards renewable energy sources, such as solar and wind energy will raise volumes of wood waste from forestry, industry, and construction activities, offering opportunities for recycling lignocellulosic residuals into sustainable building materials. There are many types of waste wood that are suitable for recycling. An overview of the waste wood fractions commonly found in waste collections, along with their potential for recycling is given in Tab. 18.

Contemporary wood composites are engineered wood-based products manufactured from a wide range of raw materials, including virgin wood, waste wood, and other non-wood lignocellulosic materials. These materials are bonded using either synthetic or natural bio-based adhesive systems, increasingly replacing conventional formaldehyde-based resins. Traditional wood-based composites produced with formaldehyde-based adhesives are associated with the emission of hazardous volatile organic compounds (VOCs),

many of which are carcinogenic and harmful to both human health and the environment. In addition, the presence of such adhesives poses significant challenges for the recycling of these materials. The adoption of bio-based adhesive systems in wood composite production can substantially reduce harmful emissions and improve the recyclability and environmental performance of wood-based composites [118].

Buschalasky and Mai [160] investigated the recyclability of MDF bonded with modern urea–formaldehyde (UF) resins. The study examined the properties of recovered fibers and newly produced MDF panels. They produced three generations of panels: Generation I with virgin fibers (VF), Generation II with fibers recovered from first-generation MDF (RF1), and Generation III with fibers recovered from second-generation MDF (RF2). For the disintegration of MDF panels and the release of fibers, a thermo-hydrolytic method was used. The results showed that MDF could be disintegrated under milder conditions than previously investigated, and that using up to 100% recovered fibers did not significantly reduce panel strength or increase formaldehyde emissions. The disintegration process altered the chemical properties of the fibers, increased their pH, and led to formaldehyde release from remaining UF resin, while repeated recycling could enhance internal bond strength and reduce emissions. The authors conclude that recovered fibers from MDF represent a feasible and environmentally friendly raw material for new MDF production.

The possibilities for implementing recycled waste wood in material production are presented in Tab. 19.

Table 18. Recyclability of waste wood (post-industrial and post-consumer solid woods and wood-based products), adapted from [159]

Type of waste wood	Description	Recyclability
Post-industrial wood	Clean, untreated wood scrap and untreated board products such as chipboard, MDF and plywood.	High recyclable potential.
Post-consumer solid woods		
Commercial	Untreated wood-based packaging (pallets, crates, transport bases) and cable drums.	High recyclable potential.
	Treated and non-hazardous wood materials from joinery activity and manufacturing processes.	Possible recycling, but with pre-treatment processes.
Construction and demolition	Treated and non-hazardous wood from renovation and demolition activities (softwood fence panels/posts, timber components).	Possible recycling. Material must be sorted and pre-treated.
Household/Municipal	Untreated softwood or hardwood beams and natural wood furniture (kitchens, tables, shelves, wardrobes) that have not been coated or veneered.	High recyclable potential, but with pre-treatment processes.
	Treated and non-hazardous wood items (doors, plywood frames, staircases) that have not been exposed to excessive moisture.	Possible recycling, but with pre-treatment processes.
Wood-based products*		
Particleboard	An engineered wood product made of compressed wood particles and a synthetic resin or binder.	Possible recycling, but with pre-treatment processes.
Oriented Strand Board (OSB)	An engineered wood product made of compressed rectangular-shaped wood strands arranged in a specific pattern and cured with a waterproof resin.	Possible recycling, but with pre-treatment processes.
Plywood	An engineered wood product manufactured by gluing thin layers of wood veneers.	High recyclable potential, but with pre-treatment processes.
Medium-Density Fiberboards (MDF)	An engineered wood product made from lignocellulosic fibers.	Generally, MDF is not recycled. However, a few companies have developed innovative technologies for recovering fibers from MDF on an industrial scale.

* A vital step in improving the recyclability of engineered wood is to sort waste wood by type (e.g., MDF, plywood, OSB) to create clean, mono-material fractions.

Table 19. Recycled waste wood in material production

Type of recycling	Product category	Product
Upcycling	Wood composites: Structural engineered wood products	CLT and GLT (both products are developed and used in R&D and specialized projects).
Recycling	Wood composites: Engineered Wood-Based Panels	Chipboard, particleboard, Medium-Density Fiberboard (MDF), High-Density Fiberboard (HDF), Oriented Strand Board (OSB), Hardboard.
	Wood composites: Wood–Cement (Wood–Concrete) Composites	Wood particle-cement boards. Wood fiber cement panels. Wood wool cement boards. Lightweight aggregate. Lightweight wood-concrete blocks.
	Wood composites: Wood-Polymer (Wood-Plastic) composites	Molded or extruded hollow core or solid products with any shapes even of complex forms.
Downcycling	Thermal and acoustic insulation materials	Loose-fill wood fiber insulation.
	Landscaping, horticulture, and secondary products	Mulch and horticultural substrate. Compost additives. Equestrian surfaces. Playground and sports surfaces. Animal bedding. Pallets and pallet blocks.
	Adsorbent in industrial and environmental remediation processes	Coal and biochar from low-cost waste wood have adsorption capacity for heavy metals, dyes, pharmaceuticals, and other priority pollutants in water treatment.

The primary use of recycled wood is currently in the particleboard industry. Since engineered wood-based panels are made from processed wood, these products do not need to use fresh timber, making them the perfect target for wood recycling efforts [132]. The proportion of recycled wood in particleboard varies widely by country. For instance, in Italy, the percentage is 100%, while in Belgium, the United Kingdom, and Denmark, it is 50%. In Germany, France, and Spain, the percentage ranges from 15% to 30%. Switzerland has a percentage of 0% [151]. However, there appears to be room for improvement in many European countries. Manufacturing particleboards from waste wood can reduce greenhouse gas emissions from 34 to 77% across impact categories [171].

The second group of products based on recycled waste wood is lightweight cement and polymer/plastic composites. Wood processing residuals such as sawdust and powders can be added to lightweight cement mortars, ranging from 2.5 to 10% by mass, without a significant reduction in compressive strength, while improving thermal resistivity by 25%. Wood aggregate concrete is a lightweight, mineral-organic composite material made by replacing some or all of the traditional stone coarse and fine aggregate with organic materials like wood chips, fibers, or sawdust. It combines the properties of concrete (durability, fire resistance) with those of wood (thermal and acoustic insulation). Consequently, wood aggregate concrete has better thermal insulation, sound absorption, reduced weight, lower carbon footprint, and satisfactory strength. This is not a new material, as it has been utilized for almost 100 years; however, steel remains challenging due to its high potential for improvement in terms of properties and sustainability. For instance, pre-processing via drying techniques helps address these limitations, such as high moisture absorption and dimensional stability. Also,

chemical or thermal modification can tailor the hydrophobicity, adhesion, and degradation resistance of recycled wood particles [171]. Adding a certain percentage of processed waste wood, such as chips, fibers, and sawdust, contributes to the sustainability of wood - cement composites. It is also ideal for prefabricated building elements, such as blocks, slabs, panels, and boards; therefore, there are various commercial products available in the construction and do-it-yourself markets. Recycling waste wood into lightweight aggregate is one of the sustainable solutions available. The method of obtaining lightweight aggregate, so-called roasted free or cold hardening, is based on the granulation of the mix in a disc granulator. The mix includes 40 to 60 % of waste wood sawdust, 40 to 60 % of cement, and 25 to 32 % of water (relative to the mass of cement). With this composition, the bulk density of the resulting aggregate corresponds to 750 - 850 kg/m³. The composition of the mix can be improved by using two binders, cement and polymer, i.e., combining two matrices from cement hydration and polymerization [161].

Wood-plastic composites (WPCs) are non-structural materials manufactured from industrial wood residues, waste wood from other sources, and recycled or virgin plastics. WPCs can be produced in a wide variety of shapes and sizes and may have either solid or hollow-core cross-sections, including curved or geometrically complex forms. In North America, WPCs are predominantly used for outdoor applications such as residential decking and railings, whereas in Europe they are more commonly applied in the automotive industry. Wood typically accounts for approximately 30–65% of the total mass of finished WPC products. The lignocellulosic raw material, recovered from sawdust, pulp fibers, or other sources such as bamboo and straw, must be dried to a moisture content of around 0.5%

and processed promptly to prevent moisture reabsorption. It is then ground into very fine particles to ensure uniform mixing with the plastic matrix. During processing, various chemical additives may be incorporated to tailor the material properties to specific end-use requirements. Finally, the composite material is molded or extruded to produce solid or hollow-core profiles for the intended applications [162].

Additionally, waste wood can be upcycled into engineered wood products (EWPs), such as CLT and GLT [104]. Compared to the direct reuse of reclaimed timber, EWPs produced from secondary wood are not limited to residential applications and can be employed in a wider range of structural uses. Furthermore, upcycled timber is well-suited for modern construction approaches, including modular and prefabricated systems, as well as designs for demountable timber products. Reclaimed timber intended for upcycling into EWPs should meet strength classes C16 or C24 and have a minimum cross-section of approximately 20 × 70 mm [124]. However, legislative, commercial, and technical barriers currently limit the structural use of secondary timber. Study [104] evaluated a comprehensive process for reusing demolition timber in new structural applications, encompassing sourcing, processing, characterization, manufacturing, and testing of glulam beams produced from reclaimed timber. The results highlight several critical requirements: appropriate on-site storage and pre-demolition surveys to prevent unnecessary scraping; retention of the longest possible timber elements to improve commercial viability by minimizing finger joints; and suitability criteria for material characterization, including adequate aspect ratios and trimming of damaged ends. The study further emphasizes the need for process automation, particularly for the safe removal of metallic fasteners. Additionally, a hierarchical reuse strategy is proposed, in which high-quality timber is directly reused, while shorter or defective elements are upcycled into EWPs. Despite these opportunities, the limited availability of large-scale manufacturing facilities remains a significant barrier to wider adoption of EWPs made from reclaimed timber.

While waste wood represents a versatile renewable resource, its large-scale and responsible utilization requires further technological development, robust quality control, and supportive policy frameworks. Continued research focused on technical performance, economic feasibility, and environmental impacts is essential to unlock its full potential. Equally important is the integration of the entire supply chain through effective communication and cooperation among waste generators, processors, and end users. With coordinated efforts from both public and private stakeholders, wood waste can play a meaningful role in circular economies and sustainable material systems [171].

In light of these considerations and following the strategic decision to design efficient supply chains that maximize overall process profitability while minimizing environmental impacts, EU countries have initiated several large-scale projects focused on waste wood. For example, in Germany, the *H2Wood - BlackForest* project (2021–) aims to convert regional waste wood into a local hydrogen resource. In addition, *Recycling for Future* and *Recycling for Reuse* are nationally funded projects addressing resource-efficient management of construction and demolition waste wood (2024–2026). In Norway, the Norwegian Institute of Bioeconomy Research has initiated the R&D project *CircWOOD's* (2022–), which seeks to enhance the reuse and recycling of wood. This project investigates the quantity and quality of reclaimed wood resources, material flows, digitalization approaches, environmental and climate

impacts, economic implications, and relevant policy and regulatory frameworks [157].

5.3 Circular practices and examples for timber

This chapter presents one representative example for each category of material recovery: reuse, upcycling, and recycling of waste wood. The selected examples illustrate current trends in innovative repurposing and end-use applications of reused and recycled wood products.

Examples of reuse are quite rare in practice and are mostly implemented within research and development projects. The Durley Chine Environmental Hub is an example of sustainable design and the reuse of timber in construction. The hub is a seafront visitor center in Bournemouth, which was built using low-carbon and repurposed materials [135]. It is located at Durley Chine beach, and serves as an educational, welfare, and exhibition space for the public. It comprises a 2-storey welfare and education building, an exhibition space covered with a green roof canopy, a café kiosk, and public toilets. Its key features include the use of reclaimed groyne timbers from the local beachfront, decking from a decommissioned submarine base, and recycled newspaper insulation. The welfare and education building was built and certified to Passivhaus standards, using a structural insulated panel frame, supplied and installed by Eden Insulation Ltd, triple-glazed windows, and solar paneling on the roof. The façade was built from ungraded groyne timber, resized and milled by a local Salisbury-based mill. Low-carbon ground granulated blast-furnace slag concrete was used to form the walls of the kiosk and toilet block, and ring beams, while reclaimed ekki (Azobe) beams were used for the roof structure. The decking primary structure was constructed using graded, unmilled groynes. The reclaimed basralocus, previously in place in a German naval dockyard, was used for the decking boards. 45 tons of reclaimed groyne timber were used to create the secondary structure of the canopy roof, the decking primary structure, fence, parapets, and the (non-structural) cladding on the education building. Since the groynes had already completed one use-life in the water, their remaining durability did not need to be determined. The structural isometric view, the detail of canopy roof isometric view, and the ground floor plan of the Durley Chine Environmental Hub are illustrated in Fig. 23, while its overall appearance is shown in Fig. 24.

The basic data regarding the project includes *Date of completion*: 2022; *Gross (internal & external) floor area*: 887 m²; *Architect*: Footprint Architects; *Client*: BCP Council; *Structural engineer*: WSP; *MEP engineer*: WSP Products; *Main contractor*: Seascape South. The basic data regarding the building properties are: upfront embodied carbon (A1-A5): 210 kgCO₂ e/m²; operational energy (B6): 75.862 kWh/m²/yr; design life: 40+ years.

Bergsagel et al [139] conducted a feasibility study to demonstrate whether reclaimed (secondary) timber from demolition sites can be successfully reused as feedstock for new structural glued laminated timber (GLT). The research forms part of the CIRCuiT (Circular Construction in Regenerative Cities) project and aims to support circular economy principles in construction. The study began with an analysis of existing timber waste flows and reuse practices in London, identifying that although large quantities of timber are reclaimed annually, only a very small percentage is reused in structural applications. Secondary timber was sourced from multiple demolition sites in London, primarily from internal structures such as raised floors and suspended ceilings. These sources were selected because they provide

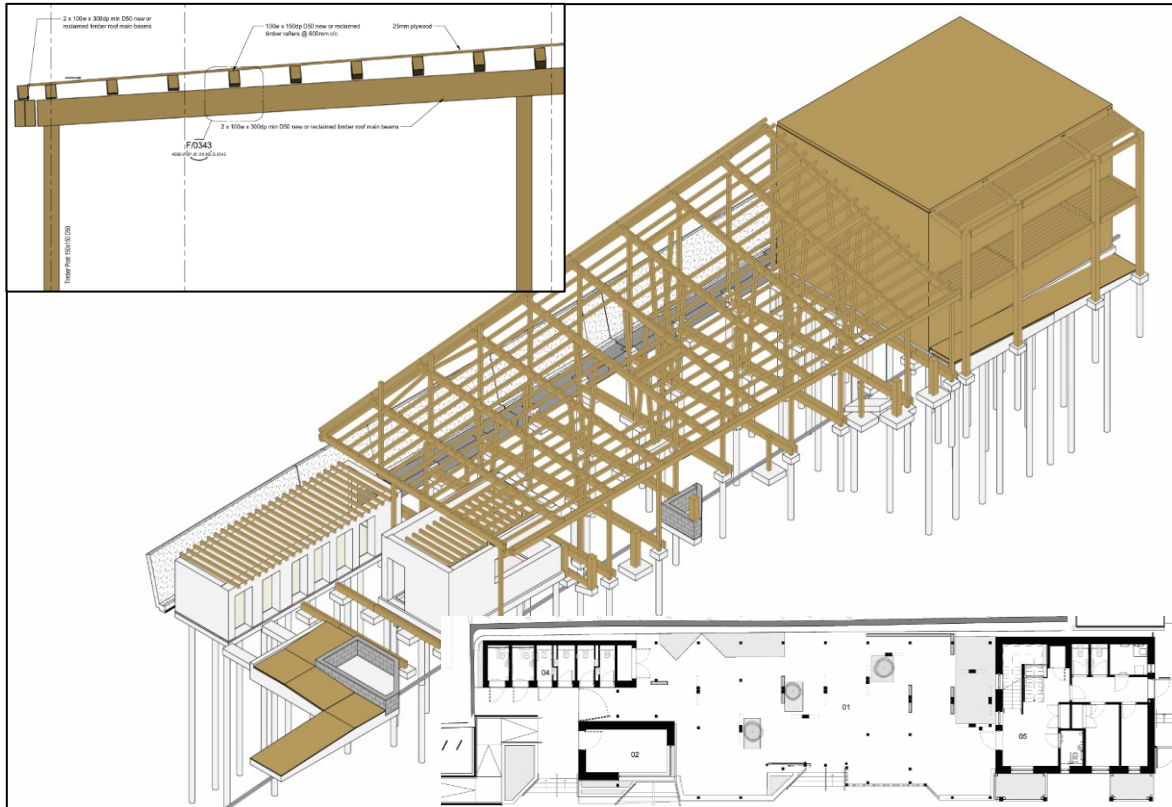


Figure 23. Structural isometric view and Detail of canopy roof isometric view, drawing by WSP. Ground floor plan showing exhibition space, kiosk, WCs, and education space, drawing by Footprint Architects [135]



Figure 24. The Durley Chine Environmental Hub in Bournemouth [135]

relatively dry, homogeneous timber with minimal degradation and limited exposure to weather. A key part of the work involved systematic non-destructive characterization of the reclaimed timber population. Each timber element was individually recorded and tested for dimensions, moisture content, density, visual characteristics (slope of grain, ring width, knots, fasteners, damage), and mechanical properties. Mechanical stiffness was estimated using longitudinal acoustic resonance testing, allowing an approximate assessment of dynamic modulus of elasticity. Based on visual and mechanical data, the authors assessed whether the reclaimed timber met the minimum grading requirements for glulam feedstock. Despite variability and damage typical of demolition timber, a filtered subset of the population achieved stiffness values equivalent to C14 strength class, which is sufficient for lamella used in GLT production according to BS EN 14080. The reclaimed timber was then processed and manufactured into GLT beams by a certified UK glulam manufacturer. This included additional

metal detection and removal, planning, finger-jointing short lengths into lamella, gluing, and pressing. Fig. 25 outlines sourced secondary timber, measuring of moisture, removing of fasteners, and the produced GLT beams.

The study highlighted challenges specific to secondary timber, particularly undetected embedded metal, higher defect rates, and increased processing time compared to primary timber. Finally, six full-scale GLT beams (width 100mm, height 214-215mm, length 4612-4613mm) made from reclaimed timber, were structurally tested in bending and glue-line shear. The four-point bending tests showed that all specimens reached failure stresses exceeding the characteristic bending strength specified for GL24h (BS EN 14080). In addition, the measured global moduli of elasticity (MOE) were consistently higher than the corresponding characteristic MOE values for GL24h. However, the average value obtained for the glue line shear strength fell below the minimum required by BS EN 386 (3.5 N/mm² average compared with 6 N/mm² required). In recognition of these



Timber sourced from multiple demolition sites in London



Measuring of moisture



Removing fasteners



Completed GLT beams

Figure 25. Process of upcycling the structural timber from construction sites into glulam products [139]

limitations, the authors conducted additional shear testing using an alternative test setup. These supplementary tests yielded substantially higher average shear strength values (approximately 8.37 N/mm²) and wood failure percentages that satisfied the requirements of the relevant standards. The results showed that the beams achieved satisfactory strength, stiffness, and bonding performance, confirming the technical feasibility of manufacturing structural GLT from secondary timber. Overall, the authors demonstrated that upcycling of demolition timber in GLT is technically viable, provided that appropriate sourcing, testing, grading, and processing protocols are followed. The work identifies key barriers, such as logistics, grading uncertainty, and metal contamination, while establishing a strong proof of concept for circular use of timber in engineered wood products.

Besides the recycling of all kinds of particleboards and fiberboards, the most challenging innovations striving toward a circular economy were made in recycling of MDF/HDF boards. UNILIN Company [141] invented in 2021 the recycling process of MDF based on pressure cooker operation. Thanks to advanced sorting and cleaning facilities, wood waste is cleared of all impurities using magnets, wind sifters, centrifuges, infrared scanning, and AI to separate a clean MDF fraction. MDF recycling, based on innovative processes, enables the retention of CO₂ at least twice. Recovered wood fibers (Fig. 26) can be used in the same way as virgin ones. UNILIN plan to replace 25% of all fibers in the MDF wood mix with recycled fibers.



Figure 26. Recycled wood fibers from MDF [141]

Another company, “MDF Recovery”, patented its own MDF recycling technology that can be easily integrated into every existing production line. Main phases of MDF recovery process are sorting, ohmic disaggregation, and multi-stage cleaning. Sorting process is based on AI-powered optical scanner that ensures MDF waste purity of over 95%. Using “ohmic disaggregation process” the fibers are gently released from MDF without compromising their integrity and length. Advanced multi-stage cleaning processes are used to remove contaminants, leaving clean, reusable fibers. Fig. 27 outlines the MDF recovery process [163].

Both examples of recycling the MDF boards are an important step in worldwide CE practice because of massive commercial production (not pilot project).

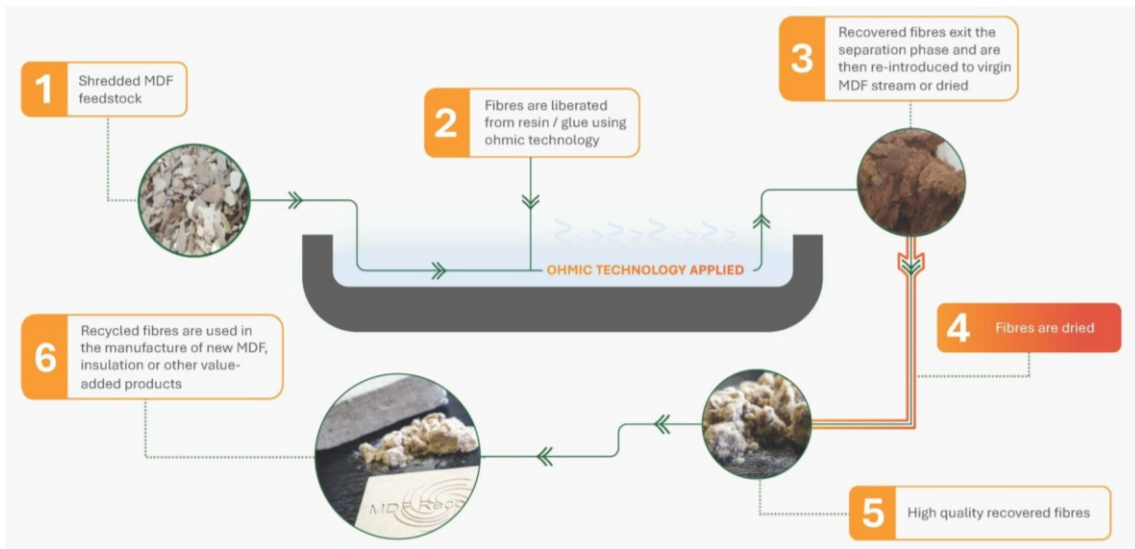


Figure 27. MDF recycling technology, adopted from [163]

6 Discussion and Conclusion

6.1 Key findings on regulation and recycling rates for construction materials

At the European level, the regulatory framework for C&DW is well established and increasingly aligned with circular economy principles. The Waste Framework Directive, with its amendments, provides clear policy direction by prioritizing material recovery (preparing for reuse, recycling, backfilling, and other forms of material recovery) to energy recovery. Also, selective demolition and separate collections of C&DW in at least six fractions are required to facilitate reuse and high-quality recycling. However, despite ambitious targets and strategic coherence, significant regulatory gaps exist, particularly the absence of end-of-waste criteria and harmonized quality standards for most C&DW fractions. This shortfall continues to hinder the effective uptake of reused and recycled materials. At this point, end-of-waste criteria have only been established for glass cullet and for copper, iron, steel, and aluminum scrap. Globally, regulatory approaches remain fragmented, with significant disparities between regions in terms of targets, enforcement, and market integration.

In Serbia, the regulatory framework for C&DW management is under active development and increasingly aligned with EU policies. Strategic documents adopted in recent years have recognized C&DW as a priority waste stream and established medium- and long-term recovery targets. According to the new Waste Management Program, 40% of C&DW is expected to be recovered by 2029. It is evident that this is far lower than the current C&DW recovery target in the EU; however, a significant increase is expected in a relatively short period, as 70% of C&DW is planned to be pretreated by 2034. The introduction of regulations addressing pre-demolition audits and source separation represents a significant step forward. Nevertheless, the regulatory focus remains primarily on waste management rather than on enabling higher-value reuse and recycling. The absence of end-of-waste criteria limited economic incentives, and insufficient market-support mechanisms continue to hinder broader implementation of circular practices.

Türkiye has made notable progress at the strategic level through the adoption of the Green Deal Action Plan and national development plans that emphasize circular economy objectives. C&DW is addressed through sectoral regulations, such as the By-law on Excavation Soil and Construction and Demolition Waste Control, which prioritize waste minimization and recovery. Furthermore, EU-harmonized standards are applied to recycled aggregates. However, the regulatory framework does not yet define explicit recycling or reuse targets for C&DW, nor does it include end-of-waste criteria for construction materials. As a result, implementation remains uneven, and regulatory support for high-quality reuse and recycling is still limited.

European statistics (Eurostat) on C&DW are essential for understanding waste scale and treatment trends; however, their reliability is significantly undermined by inconsistent reporting, vague guidelines, and a lack of expert trust. Nevertheless, these statistics remain valuable, provided they are used with 'reasonable caution' as high-level indicators rather than absolute facts. Recycling rates for C&DW in the EU are generally high, with many Member States exceeding the 70% recovery target set by 2020, established by the WFD. The EU's average C&DW recovery rate as of 2020 was over 80%. However, the management of C&DW varies widely across European countries, reflecting differences in regulatory frameworks, infrastructure, and recycling practices. For instance, countries like Germany, Denmark, and the UK show high C&DW recovery rates of 94%, 97%, and 92%, respectively. Romania presents a contrasting situation, with waste recovery levels significantly below the EU target. Most collected C&DW in Romania is landfilled, with minimal reuse or recycling efforts. In 2020, Romania declared a C&DW recovery rate of 46%. In contrast, reliable data on reuse rates remain scarce. Globally, reuse rates are consistently low, reflecting persistent technical, regulatory, and market barriers that favor recycling over direct reuse.

In Serbia, recycling and recovery rates for C&DW are still developing, with official targets set for future years rather than achieved outcomes. Current practices focus primarily on collection and basic treatment, while material-specific recycling and reuse rates are largely undocumented.

In Türkiye, demolition practices generally involve the dismantling of plastic, wooden, and metal components for

reuse and recovery. Scrap materials and metal reinforcement are largely recovered, while the remaining mixed C&DW (concrete, brick, ceramics, and other materials), which accounts for almost 80% of total C&DW by weight, is either used as filler or sent to landfills. Licensed C&DW disposal and recovery plants are present in most cities, dedicated to various activities, including pre-treatment, recycling/reclamation, temporary storage, landfills, and specialized recovery processes. However, no official statistical data on the recycling rates of C&DW are currently published.

Since C&DW must be sorted, figures on the generation of mineral, wood, and metal fractions indicate that the quantity of collected mineral fractions is notably higher (about 30 times) compared to the wood and metal waste streams. Germany, France, Italy, the Netherlands, and Belgium are the leaders in generating all three specified waste fractions. With 80% of the C&DW mineral fraction recovered and approximately 71% recycled, the 2020 WFD target has ostensibly been fulfilled at the EU27 level. However, while this high recovery rate might suggest that secondary raw materials are widely used for new construction products (such as concrete), challenges related to material quality and technical standards mean that only a small fraction is truly returning to the economy in high-value applications. Furthermore, another factor impeding the construction industry's efforts to close the resource loop is the substantial share of backfilling in many countries, which remains classified as recovery despite being a downcycling activity. Finally, there is a prevalent lack of harmonized and transparent data regarding the specific recycling rates of wood and metal fractions within the C&DW stream across Europe. While metals are largely recovered due to their high market value and defined end-of-waste criteria, waste wood often flows into energy recovery rather than material recycling, making it difficult to accurately track its circularity.

Reuse of construction materials remains marginal, constrained by limited infrastructure, insufficient data, and the absence of regulatory and economic incentives that would support higher-value circular solutions.

Due to the lack of official EU statistics providing detailed information on the recycling and reuse rates of key construction materials derived from C&DW, such as steel, timber, concrete, and bricks and blocks, complementary data were collected from Management Committee (MC) members representing EU and non-EU countries participating in COST Action CA21103 Circular B. Representatives from 11 EU countries, 3 non-EU countries, and the UK took part in the survey. Both national official and estimated rates indicate that steel recycling from C&DW is widely practiced, achieving consistently high rates across the EU and the UK. This outcome was expected, given that steel has an established end-of-waste criterion. Although a wide range of estimated values for the timber recycling rate is noticed, the disparity can be explained by the fact that countries with low timber recycling rates prefer to use waste wood for energy recovery. Official recycling figures for concrete and for bricks and blocks are generally unavailable, as these materials are typically reported within the aggregated C&DW mineral fraction. Although the estimated concrete recycling rates reported in the survey are predominantly low, it is likely that the actual concrete recycling rate in the EU is significantly higher. This assumption is based on the absence of participation from countries such as Germany, France, the Netherlands, Denmark, and Belgium, which are known for their high levels of recycled concrete utilization. For bricks and blocks, the limited amount of data and the large variation in estimated recycling rates prevented the formulation of a

reliable conclusion. National official reuse rates for all analyzed construction materials are currently unavailable, as none of the participating countries provided reliable figures. This indicates that such data are not systematically collected or reported officially. The reuse of steel from C&DW remains limited across the EU, primarily because recycling is considerably easier to implement. In addition, several participating countries identified the lack of supportive legislation and limited market demand as the main barriers to steel reuse. Regarding timber, the relatively low estimated reuse rates can be attributed to the prevailing practice of utilizing waste wood primarily for energy recovery and, to a lesser extent, for recycling. Romania reported that the reuse of timber from construction and demolition activities remains limited due to the absence of certification schemes, insufficient industrial demand, and a lack of consistent deconstruction practices. Selective demolition or deconstruction and reuse of concrete structural components is rarely implemented in practice. This is due to multiple barriers, including the absence of regulatory frameworks, national guidelines, and quality assurance protocols. Furthermore, precast concrete components are typically heavy, difficult to extract intact, and often structurally tailored to their original designs, which significantly limits their reuse potential. These challenges were confirmed by several participating countries, including Romania, the UK, and Latvia. Approximately half of the participating countries reported estimated reuse rates for bricks and blocks ranging between 1% and 8%, indicating that reuse of these materials from C&DW is not yet widely implemented. When practiced, it is generally limited to specific applications, such as historic building renovation, architectural reuse, low-grade construction, and self-build projects.

6.2 State of steel reuse and recycling

Reuse represents a fundamental principle of the circular economy, prompting extensive research and engineering efforts aimed at enhancing the practical reuse of key construction materials. Nevertheless, despite its clear benefits, the implementation in practice remains limited due to numerous unresolved barriers. Even in the case of steel that is considered as the material with the greatest reuse potential, only a few successful examples have been documented in construction practice. Main barriers to implementing steel reuse include additional costs, uncertainty of structural properties, the availability and storage of dismantled elements, supply chain gaps, and a lack of adequate design rules, regulations, standards, and frameworks to connect stakeholders in the steel reuse market and the construction industry.

The main obstacle to using reused steel is the uncertainty of structural properties since steelmaking processes, standards, and testing were different before 1970. Namely, before 1970, most structural steels were produced using open-hearth furnaces or Bessemer converters, which characterized with less precise control over temperature and chemical composition. Thus, pre-1970 steel had different chemical composition and content of impurities, microstructure, mechanical and fabricating and manufacturing properties [167]. The construction period of steel buildings is important because it can help identify the type of iron or steel used. For instance, if the buildings were constructed up until the middle of the 19th century, they likely employed wrought iron or cast iron. Between 1850 and 1950, mild (carbon) steel was predominantly used. From 1950 to 1970, medium and high-strength steel became the standard

materials for construction [168]. To identify the required properties, reused steel can be categorized based on the size and function of the original building components. Samples from each category should be tested using both non-destructive and destructive methods. However, the results may vary significantly between groups due to the aforementioned factors. Another challenge is the availability of reused components. New buildings need to be designed based on the available stock, which can change frequently [53].

The reuse of steel elements is often more expensive than the use of new ones under current market conditions, due to additional direct costs related to the dismantling of obsolete structures, inspection, testing and certification of dismantled elements, as well as the need to adapt new designs to the dimensions and properties of existing components. These challenges can be mitigated by introducing mandatory quotas for the use of reclaimed components, providing stronger fiscal incentives, promoting design for deconstruction, and establishing harmonized standards for steel reuse. Despite the higher upfront costs, steel reuse can result in overall savings when considering its environmental benefits, such as the conservation of raw materials and energy, the reduction of CO₂ emissions, and lower costs for waste transport and disposal.

Today, reuse is complicated because most obsolete buildings lack relevant information to assist the demolition contractor in deconstructing the building or the designers in creating new designs using the reclaimed steel sections. Collecting the necessary information about the obsolete building during the pre-demolition phase is time-consuming, costly, and difficult, especially if the structure is inaccessible and/or occupied. The future reuse of contemporary buildings, however, may be different, because those structures are progressively designed as systems and their design information can be easily maintained, for instance, as a building information model (BIM) [164]. The traceability of new steel used today to provide an audit trail of the structural steel in buildings could be fairly robust and straightforward with existing manufacturing and BIM software. This could lead to the inspection document related to the steel's manufacture, which will include all relevant chemical and mechanical properties [164]. If other aspects, such as carbon savings, social benefits, and reputational advantage, could be rigorously quantified (economically), the case for reuse would be stronger.

There is growing pressure on the construction industry to be more resource efficient, reduce waste and lower embodied carbon impacts [169].

What is the future of steel reuse?

Widespread steel reuse in the construction industry is still unpredictable for the future. The main reason is the long life of steel structures, during which the changes in steel quality standards, design codes, and construction details are inevitable. This is supported by the fact that major revisions of regulations occur approximately every 15 years and that pre-1970 steel differ significantly from modern steel as well as the obsolescence of connection details. It is certain that the steel structures we design today will face similar challenges in 50-100 years. Furthermore, there is no guarantee that steel reuse will occur, even if the obsolete structures can be dismantled and meet current steel quality standards, due to a potential mismatch between supply and demand. Additionally, there are limitations in the application of reused steel. For example, because the load history of reused elements is often unknown, reclaimed steel is not recommended in structures exposed to seismic actions,

since these structures demand reliable ductile behavior [169].

Although numerous technical and economic barriers hinder the implementation of steel reuse, environmental protection and the transition toward a circular economy represent higher societal goals that demand its faster and broader adoption in construction practice. To make this transition both scalable and safe, clear regulatory frameworks, technical guidelines, and standardized procedures are required. Today, the first steps have been taken towards these goals, as protocols, technical specifications, and recommendations have been developed and introduced. The documents already introduced include:

- Steel Construction Institute SCI: Protocol for reusing structural steel P427
- Steel Construction Institute SCI: A Supplementary Guide to Reusing Pre-1970 Steelwork (1932-1970) P440
- CEN/TS 1090-201: Execution of steel structures and aluminium structures - Reuse of structural steel
- CEN/TC 250/SC 3/WG 24: Design of reclaimed steel components for re-use
- European Recommendations for Reuse of Steel Products in Single-Storey Buildings, Provisions for greater reuse of steel structures (Project "PROGRESS")

These documents establish a harmonized approach for testing, certification, traceability, and accountability, thereby reducing legal uncertainty, supporting engineering reliability, and fostering market confidence in reused steel as a competitive alternative to new steel production. Establishing a real-time digital platform for reused steel components will also be of crucial importance.

In contrast, recycling has not only been extensively studied but also successfully implemented in practice in the previous period, serving as one of the fundamental principles of sustainable construction. Steel is one of the most widely recycled materials in the world, with an estimated recycling rate of even higher than 90% in developed countries. Since the end-of-waste criteria for steel were established in 2011, the utilization of scrap in steel production reached its maximum. Thus, in developed economies steel is very close fulfilling circularity criterion - no waste disposal.

Nowadays, steel obtained from C&DW is predominantly recycled rather than reused, even in highly developed economies. For instance, in the United States, approximately 74% of all steel waste generated in the construction sector including structural sections, reinforcement, and other components, is recycled. Moreover, up to 97% of steel structural sections are processed into scrap [170]. These figures indicate that the direct reuse of steel remains limited, occurring mainly as isolated examples of good practice rather than as a widespread practice. Our survey results (see Chapter 3.3) indicate that none of the EU countries have an official steel reuse rate. The estimated rate ranges from 1 % to 5 %, which aligns with the figures reported in [60].

The challenge for society is that steel demand far exceeds the supply of steel scrap, with only an estimated 25 % of steel demand currently met from recycled steel. Achieving full circularity, where sufficient steel scrap is generated to meet demand, will only be possible once the world possesses enough buildings, infrastructure, equipment, vehicles, and products to satisfy the needs of a fully developed global economy. This transition will take time. While steel consumption in many mature economies has plateaued, demand in developing countries continues to grow strongly as they converge with developed-world standards. At the same time, the global shift toward a carbon-neutral economy is accelerating the replacement of

energy and manufacturing assets, infrastructure, and buildings, which will temporarily increase demand for materials, including steel [72]. Moreover, the use of scrap negatively affects steel quality due to the accumulation of residual elements (particularly copper), so a certain amount of raw materials will still be required in steelmaking to mitigate the negative effects of contaminated scrap. Additionally, recycling is not enough to reduce CO₂ emissions by 50% according to Sustainable Development Scenario (International Energy Agency), so this goal must be achieved by implementing the reuse of structural steel in construction practice.

The future decision-making regarding the reuse or recycling of steel components could be more effective if digital twin models of the buildings were established. These comprehensive models will obtain essential information such as the original design model, construction data, operation and maintenance history, real-time building condition, and decommissioning data. By integrating a material passport into the digital twin model, full traceability of materials and components could be achieved. An economic and environmental analysis of future buildings, including different scenarios, are also important. These analyses are essential for optimizing design, selecting materials/components, and ensuring sustainability by balancing financial goals with environmental protection.

6.3 State of timber reuse and recycling

Timber has the highest positive environmental impact among other construction materials [103]. Waste wood represents a strategically important secondary resource within the transition toward a circular bioeconomy, but its full material recovery potential is only partially exploited. Since forest regeneration is slow and resource-intensive, the recirculation of post-industrial and post-consumer wood products offers substantial environmental, economic, and societal benefits. Waste wood should be considered a heterogeneous material resource whose value depends strongly on origin, contamination level, and degree of prior processing. Increasing the amount of wood planned for reuse or recycling requires an understanding of the composition of waste wood [137]. To recover as much clean wood as possible, it is important to begin with efficient sorting of waste wood at sites during careful dismantling or selective demolition. This process then continues at recycling centers or facilities. The challenges of reusing and recycling waste wood stem from its unique properties, which set it apart from other building materials, a renewable natural material of organic origin. These properties also explain why its use as an energy source is still dominant.

The total estimated potential of waste wood in the EU is approximately 50 million tonnes, of which nearly 40 million tonnes are currently recovered. Of this recovered amount, approximately 18.5 million tonnes are used for material recovery, i.e., recycling and backfilling, while about 21.5 million tonnes are used for energy recovery. The data regarding the waste wood reuse in structural purposes is still unavailable. The actual distribution of recovery pathways is highly uneven, as forest-rich countries, such as Norway, Finland, and Germany prioritize the use of waste wood for energy recovery. In many EU member states, waste wood is mainly used as biomass fuel due to priorities related to energy security, existing incineration infrastructure, and favorable economic conditions. While energy recovery is an important part of renewable energy systems, its prevalence creates a systemic barrier to the circular use of waste wood,

as it irreversibly removes potentially recyclable wood from the material loop. However, the new EU Renewable Energy Directive III is shifting the focus from energy recovery to material recovery, particularly to recycling. This change, along with the goal of achieving climate neutrality by 2050, will lead to significant modifications in waste wood management policies.

The cascade approach of utilizing salvaged wood yields beneficial environmental effects, linked to the manufacture of new products, and aids in climate change mitigation by extending the duration of carbon storage and delaying carbon emissions [1]. From the first life cycle to the ultimate end of life, numerous opportunities exist to use salvaged wood by gradually diminishing the level of waste hierarchy, aiming to maximize the number of life cycles through methods such as reuse, repurposing/upcycling, recycling, downcycling, and energy recovery/incineration. Nowadays, the cascade approach exists, but not in full range. For example, the reuse of mass structural timber is limited to individual cases, such as residential low-rise or historical buildings, since modern timber construction is not currently aligned with circular economy principles and is seldomly taking buildings end-of-life-into account. In contrast, recycling, downcycling, and especially energy recovery are widely incorporated into everyday practice. Upcycling into engineered wood products, such as CLT or GLT, is a very promising possibility for wood waste utilization. For the successful implementation of the full cascade approach in wood waste management, it will be essential to incorporate it into the current EU legislation and secure supportive policy.

Waste wood recycling holds considerable untapped potential to contribute to climate mitigation, resource conservation, and sustainable construction. Unfortunately, the term "recycling" of wood waste is often used in the case of energy recovery. According to the WFD 2008/98/EC definition, recycling refers to materials being transformed into new products but does not include energy recovery and the reprocessing into materials that are to be used as fuels. Thus, the published data concerning the percentage of waste wood recycling must be taken with some suspicion.

Recyclable wood waste mainly originates from logging and the wood processing industries. However, other sources, such as commercial, municipal, and construction and demolition waste, also represent a significant potential resource. Since not all waste wood can be recycled, its suitability depends on its classification and grade, as surface treatments, fasteners, plastics, and more often require extra processing or even block recycling. Therefore, waste wood must be properly graded before recycling. Quality-driven classification and sorting constitute the critical enablers of high-value recycling. There is no harmonized European classification system for waste wood recycling since energy production policy in the EU favors the use of renewable resources. Thus, EU Member States have introduced national waste wood classification schemes primarily designed for energy recovery. This situation significantly limits the potential for material recovery. Without standardized grading for recycling, waste wood is frequently diverted to energy recovery, even when material recycling would be technically feasible. The UK is the only country that has introduced grading for wood waste recycling through national regulations. Although the EU Waste Framework Directive introduced the waste management hierarchy, extended producer responsibility (EPR) schemes, separate collection obligations, and sectoral reuse, recycling, and recovery targets, the actual situation in waste wood management is different, since national waste wood

classifications consider wood waste predominantly as an energy source. These classifications have several common features, such as the use of quality criteria related to mechanical processing, chemical treatments, and the presence of hazardous substances and preservatives. National waste wood classifications grade waste wood most often into four basic classes: Untreated, clear solid wood, Treated, non-hazardous solid wood, Treated, non-hazardous mostly board products, and Hazardous wood. Illustrated classification can help in sorting waste wood to be recycled. Further improving the recyclability of waste wood requires the implementation of effective, high-quality sorting and segregation processes into well-defined fractions. Advanced sorting technologies, such as NIR, XRF, and AI-assisted systems, emerge as essential tools for improving material purity, reducing contamination risks, and enabling reliable downstream applications in composite manufacturing. For instance, a vital step in improving the recyclability of board products is to sort waste wood by type (e.g., MDF, plywood, OSB) to create clean, mono-material fractions for higher value recycling.

Although the benefits of recycling waste wood are obvious, economic and market-related barriers remain significant. Recycling waste wood often entails higher short-term costs due to selective demolition, logistics, sorting, and pre-treatment requirements. At the same time, low prices and the availability of virgin timber undermine the competitiveness of recycled alternatives. These challenges underscore the need for system-level interventions, including extended producer responsibility schemes, End-of-Waste criteria, targeted subsidies, and the creation of stable demand for recycled wood products. Without such measures, technological progress alone is unlikely to shift prevailing practices. Social and institutional dimensions are equally influential. Persistent perceptions of waste wood as a low-quality and high-risk material and a lack of law enforcement for proper waste management continue to limit its acceptance in the construction and manufacturing sectors. Addressing these concerns requires not only strengthening legislation, improving supervision, increasing penalties and level of responsibilities, and investing in infrastructure, but also raising public awareness through education and knowledge transfer.

Also, the growing number of national and EU-funded research initiatives represents a positive trend toward evidence-based policy and industrial transformation.

Regardless of the obstacles, there is a wide spectrum of possibilities for the implementation of recycled waste wood into material production. They vary from high-value to low-grade recycling products. Such diversity in the products

indicates the high potential of wood waste to be recycled and to obtain unique EoW criteria, as well as that of steel waste. Austria is the only the EU state with EoW criteria related to waste wood. Realizing this potential requires a holistic and coordinated approach that integrates regulatory harmonization, technological innovation, market development, and cultural change across the entire value chain. Under such conditions, waste wood can evolve from a marginal by-product into a reliable and valuable secondary raw material within circular material systems. From a technological perspective, the findings indicate that particleboard production currently represents the most robust and economically viable outlet for recycled waste wood, particularly in mixed and heterogeneous waste streams. The core layer of OSB panels can be made from waste wood particles. The percentage of substitution is limited by the low slenderness ratios of particles and the presence of contaminants. Recycling MDF into fibers or waste timber into higher-value products, such as structural engineered wood products (i.e. CLT, GLT), remain theoretically possible but are constrained by additional sorting into more clean fractions, very demanding pre-treatments, and limited industrial infrastructure. Nevertheless, recent advances, especially in the recycling of MDF through thermo-hydrolytic fiber recovery and the adoption of bio-based adhesives, demonstrate that these barriers are not fundamental but transitional. Continued innovation in pre-treatment, purification, and bonding technologies is therefore likely to expand the feasible application range of recycled wood. The use of waste wood in wood–cement and wood–plastic composites also requires sorting, cleaning, and, in many cases, specific pre-treatment. Although these composite systems are generally more tolerant to lower-grade and more heterogeneous wood waste than fiberboards or structural engineered wood products, contaminants such as coatings, metals, plastics, and mineral impurities must still be removed. Proper pre-treatment is particularly important for wood–cement composites to avoid inhibition of cement hydration, while wood–plastic composites mainly require control of particle size, moisture content, and material homogeneity to ensure stable performance.

6.4 Final findings on steel vs. timber

Tab. 20 synthesizes the available treatment options for ferrous metals (iron and steel) and wood as construction and demolition waste (C&DW), highlighting key differences in regulatory classification and practical implementation across the EU.

Table 20. Available treatment options for ferrous metals and wood as C&DW (adapted from [11])

C&DW	Available treatment options	Classification according to WFD
Ferrous metals (iron and steel)	Ferrous metals (iron and steel) can be remelted and used for production of new metal. This is largely common practice across Europe, as ferrous metals are easy to identify and sort, and recycling is typically economically sustainable.	Recycling EoW directive (Regulation 333/2011) Preparation for reuse (CEN/TS 1090-201)
Wood	Depending on the quality and the content of hazardous substances, wood from construction activities can be recycled or used for energy recovery. If waste wood is clean, it can be used in the production of particleboards (<i>recycling</i>). If contaminated, incineration with energy recovery is often the preferred solution. In rare cases, wood is prepared for <i>reuse</i> , e.g. for structural purposes	Energy recovery. Recycling (if used for particleboard production, or in wood cement and wood plastic composites). EoW criteria only in Austria. Preparation for reuse, in rare cases.

CRedit authorship contribution statement

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Declaration of Competing Interest

The authors declare no conflict of interest.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors partially used generative AI tools (Grammarly and ChatGPT) in order to do language editing and proofreading. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. The authors confirm that the content, methodology, and conclusions presented are entirely their original contributions, and the use of AI does not conflict with ethical guidelines or scientific publishing standards.

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References

- [1] Cristescu, C., Honfi, D., Sandberg, K., Shotton, E., & Walsh, S. J., et al (2020): Design for deconstruction and reuse of timber structures-state of the art review, In *FutUReWood Report:1.*, doi: 10.23699/bh1w-zn97
- [2] C. Zhang, M. Hua, F. Di Maio, B. Sprecher, X. Yang, A. Tukker (2022): An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe, *Journal „Science of the Total Environment“* 803, 149892. <https://doi.org/10.1016/j.scitotenv.2021.149892>
- [3] García, C. et al. (2024): Techno-economic and environmental assessment of construction and demolition waste management in the European Union Status quo and prospective potential. Luxembourg. doi: 10.2760/721895.
- [4] Damgaard, A. and Lodato, C. (2022): Background data collection and life cycle assessment for construction and demolition waste (CDW) management, doi: 10.2760/772724.
- [5] The European Parliament and the Council of the European Union (2008): Directive 2008/98/EC on waste and repealing certain directives. *Official Journal of the European Union* L312/3
- [6] The European Parliament and the Council of the European Union (2018): Directive 2018/851 amending Directive 2008/98/EC on waste Framework. *Official Journal of the European Union* L150/109
- [7] <https://worldsteel.org/circular-economy/> (accessed June 16, 2024).
- [8] <https://steel-sci.com/reduce-and-progress.html> (accessed June 7, 2024).
- [9] Sivaganesh, S., Chan, T., M. (2024): Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures; *Journal of Constructional Steel Research* 214 (2024) 108439. <https://doi.org/10.1016/j.jcsr.2023.108439>
- [10] https://www.steelconstruction.info/Recycling_and_reuse (accessed August 21, 2025)
- [11] EU Construction & Demolition Waste Management Protocol including guidelines for pre-demolition and pre-renovation audits of construction works, Updated edition 2024, European commission B-1049 Brussels.
- [12] Eurostat (2024): Treatment of waste-by-waste category, hazardousness and waste management operations. (accessed September 10, 2024).
- [13] European Commission (2015): Closing the loop - An EU action plan for the circular economy. COM (2015) 614 final.
- [14] European Commission (2019): The European Green Deal. COM (2019) 640 final
- [15] European Commission (2020): A new Circular Economy Action Plan. For a cleaner and more competitive Europe. COM (2020) 98 final
- [16] European Committee for Standardization (CEN). CEN/TC 104 (2022): EN 206:2013+A2:2021. Concrete - Specification, performance, production and conformity.
- [17] Government of the Republic of Serbia (GOV RS) (2022): Circular Economy Development Program for the Republic of Serbia for 2022-2024 (In Serbian). The Official Gazette of the Republic of Serbia No.137/2022.
- [18] Regional Cooperation Council (RCC). (2020): Sofia Declaration on the Green Agenda for the Western Balkans (Issue November 2020).
- [19] Government of the Republic of Serbia (GOV RS). (2022): Waste Management Program in the Republic of Serbia for 2022-2031 (In Serbian). The Official Gazette of the Republic of Serbia No.12/2022
- [20] National Assembly of the Republic of Serbia (NARS). (2023): Waste Management Act (In Serbian). The Official Gazette of the Republic of Serbia No.35/2023

- [21] Government of the Republic of Serbia (GOV RS). (2023): Construction and Demolition Waste Management Regulation (In Serbian). The Official Gazette of the Republic of Serbia No.94/2023
- [22] Ministry of Environmental Protection of the Republic of Serbia (2019): Rulebook on End-of-Waste Criteria (In Serbian). The Official Gazette of the Republic of Serbia No.78/2019
- [23] Republic of Türkiye Ministry of Trade (MT) (2021): Green Deal Action Plan. : (accessed July 12. 2024 - in Turkish)
- [24] Presidency of Strategy and Budget (2023): Twelfth Development Plan (2024-2028). Retrieved from: (accessed July 12. 2024)
- [25] Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (MEUCC) (2023): National Waste Management and Action Plan. Retrieved from: (accessed July 12, 2024 - in Turkish)
- [26] Official Gazette of the Republic of Türkiye (2004). By-law on Excavation Soil, Construction and Demolition Waste Control (accessed March 18, 2004 - in Turkish)
- [27] Official Gazette of the Republic of Türkiye (2019): By-law on Zero Waste (Date: 12 July 2019, No 29314) (In Turkish). (accessed July 12, 2024)
- [28] Official Gazette of the Republic of Türkiye (2021): Change in By-law on Zero Waste (Date: 09 October 2021, No 31623) (In Turkish). (accessed July 12, 2024)
- [29] TS EN 206+A2 (2021): Concrete - Specification, performance, production and conformity (Standard No: TS EN 206+A2:2021). Turkish Standards Institute, Ankara, Turkey.
- [30] https://db.nomics.world/Eurostat/cej_wm040?tab=list
- [31] https://ec.europa.eu/eurostat/databrowser/view/env_wastrt_custom_12356695/default/table?lang=en
- [32] https://www.eea.europa.eu/data-and-maps/daviz/mineral-waste-from-construction-and#tab-googlechartid_chart_13_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%7D%3B%22sortFilter%22%3A%5B%22obsValue_recycling%22%5D%7D
- [33] Puskás, A., Corbu, O., Szilágyi, H., & Moga, L. M. (2014): Construction waste disposal practices: The recycling and recovery of waste. *WIT Transactions on Ecology and the Environment*, 191, 1313-1321.
- [34] [UK statistics on waste - GOV.UK](https://www.gov.uk/government/statistics/uk-statistics-on-waste) (accessed August 21, 2025)
- [35] https://www.ekologija.gov.rs/sites/default/files/2022-03/program_upravljanja_otpadom_eng_-_adopted_version.pdf
- [36] SKD Türkiye (The Business and Sustainable Development Council, Türkiye) (2024): Guide for the Management of Demolition Waste Resulting from Urban Transformation, Earthquake and Possible Disasters (In Turkish) (accessed July 11, 2024)
- [37] Türkiye Official Statistics Portal (2024). (Under Waste Statistics Tab). Date of Access: 11th July 2024.
- [38] Eurostat (2024): Data on Recycling rate of all waste excluding major mineral waste, (accessed September 2, 2024)
- [39] Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (MEUCC) (2024): Technical Assistance for Development of End-of-Waste Concept in Türkiye. (accessed September 2, 2024)
- [40] Eurostat (2024): Generation of waste-by-waste category, hazardousness and NACE Rev. 2 activity. (accessed September 10, 2024)
- [41] Eurostat (2024): Treatment of waste-by-waste category, hazardousness and waste management operations. (accessed September 10, 2024)
- [42] <https://www.rubicon.com/blog/steel-recycling/> (accessed June 14, 2024)
- [43] Brutting, J., Wolf, C., D., Fivet, C. (2019): The reuse of load-bearing components; SBE19 Brussels BAMB-CIRCPATH, IOP Conf. Series: Earth and Environmental Science 225 (2019) 012025, doi:10.1088/1755-1315/225/1/012025
- [44] Tingley, D., D., Cooper, S., Cullen, J. (2017): Understanding and overcoming the barriers to structural steel reuse, a UK perspective, *Journal of Cleaner Production*, 148 (2017) 642-652, <https://doi.org/10.1016/j.jclepro.2017.02.006>
- [45] Girao Coelho, A., M., Pimentel, R., Ungureanu, V., Hradil, P., Kesti, J. (2020): European Recommendations for Reuse of Steel Products in Single-Storey Buildings, Provisions for greater reuse of steel structures (Project "PROGRESS"). chrome-extension://efaidnbnmnibpcjpcglclefindmkaj/https://www.steelconstruct.com/wp-content/uploads/PROGRESS_Design_guide_final-version.pdf
- [46] <https://asbp.org.uk/wp-content/uploads/2016/08/Barriers-to-structural-steel-reuse-and-means-of-overcoming-them-SCI-Report-1.pdf>. (accessed 9 November 2024).
- [47] Smeets, A., Wang, K., Drewniok, M., P. (2019): Can Material Passports lower financial barriers for structural steel re-use? SBE19 Brussels BAMB-CIRCPATH, IOP Conf. Series: Earth and Environmental Science 225 (2019) 012006, doi:10.1088/1755-1315/225/1/012006.
- [48] https://www.steelconstruction.info/Recycling_and_reuse
- [49] Durmisevic, E., Noort, N.: Re-use potential of steel in building construction, Netherlands, <http://www.irbnet.de/daten/iconda/CIB890.pdf> (accessed June 23, 2024)
- [50] Dai, X., Yang, J., Lam, D., Sheehan, T., Zhou, K. (2022): Experiment and numerical modeling of a demountable steel connection system for reuse; *Journal of Constructional Steel Research* 198 (2022) 107534. <https://doi.org/10.1016/j.jcsr.2022.107534>
- [51] Tingley, D., D., Allwood, J. (2014): Reuse of structural steel: the opportunities and challenges, Conference paper for European Steel Environment & Energy Congress 2014, 15-17 September, Teeside University UK
- [52] Cervantes Puma, G., C., Salles, A., Turk, J., Ungureanu, V., Braganca, L. (2024): Utilization of Reused Steel and Slag: Analyzing the Circular Economy Benefits through Three Case Studies, *Buildings* 2024, 14 979. 3390/buildings14040979
- [53] <https://architecturetoday.co.uk/ask-the-expert-steel-reuse/>, (accessed June 22, 2024)
- [54] Pongiglione, M., Calderini, C. (2014): Material savings through structural steel reuse: A case study in Genoa, *Resources, Conservation and Recycling* 86 (2014) 87-92
- [55] Kanyilmaz, A., Birhane, M., Fishwick, R., Castillo, C. (2023): Reuse of Steel in the Construction Industry:

- Challenges and Opportunities; International Journal of Steel Structures (2023) 23(5):1399-1416.
- [56] Dunant, C., F., Drewniok, M., P., Sansom, M., Corbey, S., Allwood, J., M., Cullen, J., M. (2017): Real and perceived barriers to steel reuse across the UK construction value chain, Resources, Conservation & Recycling, 126 (2017) 118-131
- [57] Dunant, C., F., Drewniok, M., P., Sansom, M., Corbey, S., (2018): Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain, Journal of Cleaner Production 183 (2018) 102-111,
- [58] Vares, S., Hradil, P., Sansom, M., Ungureanu, V.: Economic potential and environmental impacts of reused steel structures, Structure and Infrastructure Engineering, Maintenance, Management, Life-Cycle Design and Performance, ISSN: 1573-2479 (Print), 1744-8980 (Online) Journal homepage://www.tandfonline.com/loi/nsie20
- [59] [https://www.istructe.org/journal/volumes/volume-101-\(2023\)/issue-3/reusing-structural-steel-new-istructe-guide/](https://www.istructe.org/journal/volumes/volume-101-(2023)/issue-3/reusing-structural-steel-new-istructe-guide/) (accessed November 12, 2024)
- [60] Yeung, J., Walbridge, S., Hass, C. (2015): The role of geometric characterization in supporting structural steel reuse decisions; Resources, Conservation and Recycling, 104 (2015) 120–130. DOI: 10.1016/j.resconrec.2015.08.017
- [61] Harvey, L., D., D. (2021): Iron and steel recycling: Review, conceptual model, irreducible mining requirements, and energy implications, Elsevier, Renewable and Sustainable Energy Reviews, Volume 138.
- [62] Griffin, P., W., Hammond, G., P. (2021): The prospects for 'green steel' making in a net-zero economy: A UK Perspective, Global Transitions 3, 72-86.
- [63] Kreschel, T., Volkova, O. (2024): Chapter 19 – Steel, Handbook of Recycling (Second Edition) State-Of-the-art for Practitioners, Analysts, and Scientists, 301-318
- [64] Björkman, B., Samuelsson, C. (2024): Chapter 6 - Recycling of Steel, Handbook of Recycling (Second Edition) State-Of-the-art for Practitioners, Analysts, and Scientists, 65-83
- [65] Ghosh, D. (2023): Evaluating Green Steel Production Viability DOI:10.13140/RG.2.2.24406.22088.
- [66] <https://worldsteel.org/steel-topics/raw-materials/>, (accessed, October 15, 2024)
- [67] IRENA 2023: Towards a circular steel industry, International Renewable Energy Agency, Abu Dhabi, ISBN: 978-92-9260-538-4
- [68] Horno, B., P., Feldmann, A., Samuelsson, P. (2025): Mapping the dynamics shaping the future of steel recycling, Discover Sustainability vol 6, art 808, 2025. DOI: 10.1007/s43621-025-01750-4
- [69] Singh, R. (2012): Production of Steel. Applied Welding Engineering, 33–50.
- [70] Kubat, C., Taşkin, H., Artir, R., Yilmaz, A. (2004): Bofy-fuzzy logic control for the basic oxygen furnace (BOF), Robotics and Autonomous Systems 49, 193–205.
- [71] World steel association, Steel and raw materials, <https://worldsteel.org/wp-content/uploads/Factsheet-raw-materials-2023-1.pdf>, (accessed, October 15, 2024)
- [72] Bonapata, J. (2023): What is steel scrap and how can it help us reach net zero? <https://www.weforum.org/agenda/2023/01/davos23-steel-scrap-decarbonization/> (accessed October 13, 2024)
- [73] Metal Recycling Factsheet, EuRIC AISBL – Recycling: Bridging Circular Economy & Climate Policy (www.euric-aisbl.eu) (accessed, October 19, 2025)
- [74] World Steel Recycling in Figures 2017-2022, Steel Scrap -Row Material for Green Steel Making, Bureau of International Recycling, Ferrous Division, 13th edition.
- [75] <https://worldsteel.org/data/world-steel-in-figures-2024/>, (accessed October 15, 2024)
- [76] James, S. (2022): From Waste to Resource: The Importance and Benefits of Steel Recycling, J Steel Struct Constr 8 (2022): 163.
- [77] Katta, B., Sambandam, M., Premalatha, M. (2025): Life cycle and economic assessment of recycled steel sing waste heat in industry, Journal of Environmental Engineering and Science (2025), <https://doi.org/10.1680/jenes.25.00067>
- [78] Broadbent, C. (2016): Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy, Int J Life Cycle Assess (2016) 21:1658–1665, doi 10.1007/s11367-016-1081-1
- [79] World steel association (2025): Steel – the permanent material in the circular economy, worldsteel-circular-economy, PDF (decarbonization.unido.org), (accessed, October 28, 2025)
- [80] Davis, C., Hall, R., Hazra, S., Debattista, K., Zhuang, S., Duan, J., Li, Z., Shenton, J., Panni, A. Halfpenny, D. (2024): Reuse, remanufacturing and recycling in the steel sector, Philos Trans A Math Phys Eng Sci, 2024 Nov 4;382(2284):20230244. doi: 10.1098/rsta.2023.0244
- [81] Watari, T., Fishman, T., Wieland, H., Wiedenhofer, D. (2025): Global stagnation and regional variations in steel recycling, Resources, Conservation and Recycling, Volume 220, 2025, 108363, ISSN 0921-3449, <https://doi.org/10.1016/j.resconrec.2025.108363>
- [82] Muslemani, H., Liang, X., Kaesehage, K., Ascui, F., Wilson, J. (2021): Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products, Journal of Cleaner Production,
- [83] Yan, J., Zhang, Z. (2019): Carbon Capture, Utilization and Storage (CCUS), Applied Energy 235 (2019) 1289–1299, <https://doi.org/10.1016/j.apenergy.2018.11.019>
- [84] Illankoon, C., Vithanage, C., C. (2023): Closing the loop in the construction industry: A systematic literature review on the development of circular economy, Journal of Building Engineering, Volume 76, 2023, 107362,
- [85] Hammerschmid, M., Müller, S., Fuchs, J., Hofbauer, H. (2021): Evaluation of biomass-based production of below zero emission reducing gas for the iron and steel industry, Biomass Conversion and Biorefinery 11:169–187, <https://doi.org/10.1007/s13399-020-00939-z>
- [86] Krueger, A., Andersson, J., Gronkvist, S., Cornell, A. (2020): Integration of water electrolysis for fossil-free steel production, International Journal of Hydrogen Energy, doi:10.1016/j.ijhydene.2020.08.116

- [87] Daehn, K., E., Serrenho, A., C., Allwood, J. M. (2017): How Will Copper Contamination Constrain Future Global Steel Recycling?, *Environmental Science & Technology*, Vol 51/Issue 11, April 26, 2017, doi: 10.1021/acs.est.7b00997
- [88] Boston Consulting Group (2024): Shortfalls in Scrap Will Challenge the Steel Industry, by Janice Lee, Nicole Voigt, Martin Feth & Gaurav Chhibbar. Published March 12, 2024.
- [89] Fischer, L. (2024): Recycling in the steel industry - the environmentally friendly process from scrap to new steel, *Swiss Steel Group Journal*, 29/08/2024, <https://swisssteel-group.com/en/journal/recycling-in-the-steel-industry>
- [90] Bukowski, H, Fabrycka, W. (2023): *Circular construction in practice*, INNOWO, Warsaw, 2019.
- [91] Jackson, A., Brady, C., Owen, C., M. (2023): *The Circular Built Environment Playbook*, World Green Building Council, 2023.
- [92] Rahla, K., Mateus, R., Bragança, L. (2021): Implementing Circular Economy Strategies in Buildings—From Theory to Practice, *Applied System Innovation*, vol. 4, no. 2, p. 26, 2021.
- [93] Guy, B., Ciarimboli, N., Hendrickson, K. (2013): *Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building*, Hamer Center for Community Design, The Pennsylvania State University, Seattle, 2013.
- [94] Little, J., M., K. (2019): *Zero-waste buildings and the circular economy in practice*, 2019.
- [95] Sustainable in Steel (2024): Examples of reuse, https://www.sustainableinsteel.eu/p/539/examples_of_reuse.html
- [96] Schneider, A., K. (1998): *Creating the Musees d'Orsay the Politics of Culture in France*, Pennsylvania: The Pennsylvania State University Press.
- [97] Wikipedia (2024): Gare d'Orsay, https://en.wikipedia.org/wiki/Gare_d%27Orsay. (Accessed October 28, 2024).
- [98] Winkelcentrum, B. (2024): De Historie Van Winkelcentrum Brazillie, <https://www.winkelcentrumbrazillie.nl/de-historie-van-winkelcentrum-brazillie/> (accessed October 28, 2024).
- [99] https://www.sustainableinsteel.eu/p/539/examples_of_reuse.html (accessed, October 19, 2025)
- [100] Godina, M., Gowler, P., Rose, C., M., Wiegand, E., Mills, H., F., Koronaki, A., Ramageb, M., H., Shah, D. U. (2025): Strategies for salvaging and repurposing timber elements from existing buildings in the UK, *Journal of Cleaner Production* 489 (2025) 144629; <https://doi.org/10.1016/j.jclepro.2024.144629>
- [101] Metabolic (2023): Impact scan for timber construction in Europe. <https://globalabc.org/resources/publications/impact-scan-timber-construction-europe>
- [102] Eurostat (2024): Wood products - production and trade - Statistics Explained, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_products_production_and_trade#Roundwood_production.
- [103] United Nations Economic Commission for Europe (2023): *Circularity Concepts in Wood Construction*, Geneva Timber and Forest Study Papers, July 2023, ISBN: 9789210024174
- [104] Bergsagel, D., Isaac, P., Koeck, A. (2022): *Reusing Timber in Construction Feasibility Study Exploring Turning Reclaimed Timber into Structural Glulam*. Grimshaw, Simple Works.
- [105] Ahn, N., Dodoo, A., Riggio, M., Muszynski, L., Schimleck, L., & Puettmann, M. (2022): Circular economy in mass timber construction: State-of-the-art, gaps and pressing research needs. *Journal of Building Engineering*, 53, 104562.
- [106] Ridley-Ellis, D., Porter, S. (2025): Planning the reuse or recycling of structural timber in redevelopment projects, a practical guide, ECOS - Environmental Coalition on Standards, Brussels.
- [107] Ikenze, N., Rizos, V., Nipius L. (2024): Improving Waste Wood Circularity in the EU: Classification Frameworks and Policy Options, *Wood2Wood* project, 69p.
- [108] Gregorio, S. (2022): Reuse process for timber elements to optimize residual performances in subsequent life cycles. *VITRUVIO-International Journal of Architectural Technology and Sustainability*, 7(2), 88-99.
- [109] Li, Y., Zhang, X. (2024): Intelligent X-ray waste detection and classification via X-ray characteristic enhancement and deep learning, *Journal of Cleaner Production*, Volume 435, 2024, 140573, ISSN 0959-6526, <https://doi.org/10.1016/j.jclepro.2024.140573>.
- [110] Marques, A., F., S., Martins, C., E., J., Dias, A., M., P., G., Costa, R., J., T., Morgado, T., F., M. (2016): Assessment of Reuse Potential of Maritime Pine Utility Poles for Structural Applications after Removal from Service, *BioResources* 11(4), 9340-9349.
- [111] Kuzman, K., Zbašnik-Senegačnik, M., Kosanović, M., Miloshevska Janakieska, S., Novaković, M., Rajković, N., Grošelj, P. (2024): Architectural Perspectives on Wood Reuse within Circular Construction: A South-Central European Study. *Buildings*, 14(3), 560.
- [112] Höglmeier, K., Weber-Blaschke, G., Richter, K. (2017): Potentials for Cascading of Recovered Wood from Building Deconstruction - A Case Study for South-East Germany. *Resource Conservation and Recycling* 117 (2017): 304-314
- [113] Finch, G., Marriage, G. (2019): Eliminating building and construction waste with computer-aided manufacturing and prefabrication. In *Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management*, pp. 805-814, Springer International Publishing.
- [114] Llana, D., F., González-Alegre, V., Portela, M., & Íñiguez-González, G. (2022). Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: Structural properties and non-destructive evaluation. *Construction and Building Materials*, 339, 127635. <https://doi.org/10.1016/j.conbuildmat.2022.127635>.
- [115] Kaltimber (2024): How Reclaimed Wood Helps Reduce CO₂ Emissions, October 7, 2024, (accessed November 27, 2025)
- [116] Agyemang, E., Ofori-Dua, K., Dwumah, P., Forkuor, J., B. (2024): Towards responsible resource utilization: A review of sustainable vs. unsustainable reuse of wood waste. *PLoS ONE* 19(12): e0312527. <https://doi.org/10.1371/journal.pone.0312527>






- [117] Piccardo, C., Hughes, M. (2022): Design strategies to increase the reuse of wood materials in buildings: Lessons from architectural practice. *Journal of Cleaner Production*, 368, 133083. <https://doi.org/10.1016/j.jclepro.2022.133083>
- [118] Reh, R., Kristak, L., Antov, P. (2022): Advanced Eco-Friendly Wood-Based Composites, *Materials* 2022, 15, 8651. <https://doi.org/10.3390/ma15238651>
- [119] Donaldson, J. (2022): The Growth of the Canadian Wood Recycling Industry, 2022. Canadian Wood Waste Recycling Business Group.
- [120] Bohne, R. A., Waerner, E. R. (2014): Barriers for deconstruction and reuse/recycling of construction materials in Norway. *Barriers for deconstruction and reuse/recycling of construction materials* 89-107, cib publication 397, ISBN 978-90-6363-085-0.
- [121] Earle, J., Ergun, D., Gorgolewski, M. (2014): Barriers for deconstruction and reuse /recycling of construction materials, in Canada, *Barriers for deconstruction and reuse/recycling of construction materials* 20-37, CIB publication 397, ISBN 978-90-6363-085-0.
- [122] Nakajima S., Russel, M. (2014): Barriers for deconstruction and reuse/recycling of construction materials, CIB Publication, Working Commission W115 Construction Materials Stewardship 397 ISBN 978-90-6363-085-0.
- [123] Falk, R. H., Guy, G. B. (2004): *Directory of Wood-framed Building Deconstruction and Reused Building Materials Companies*, 2004 (No. 150). US Department of Agriculture, Forest Service, Forest Products Laboratory.
- [124] Godina, M. (2022): Strategies for salvaging and repurposing timber elements from existing buildings. Elliott Wood Partnership Ltd Strategies, CIOB, UCEM.
- [125] Ottenhaus, L. M., Yan, Z., Brandner, R., Leardini, P., Fink, G., Jockwer, R. (2023): Design for adaptability, disassembly and reuse—A review of reversible timber connection systems. *Construction and Building Materials*, 400, 132823.
- [126] Tsui, T., Venverloo, T., Benson, T., Duarte, F. (2024): Spatial optimization of circular timber hubs. *npj Urban Sustainability*, 4(1), 13.
- [127] Brol, J., Dawczy, S., Adamczyk, K. (2015): Possibilities of timber structural members' reuse. In *Proceedings of the 3rd International Conference on Structural Health Assessment of Timber Structures*, Wroclaw, Poland (pp. 9-11).
- [128] Falk, B. (2002): Wood frame building deconstruction: A source of lumber for construction? <http://www.fpl.fs.fed.us/documnts/pdf2002/falk02a.pdf>
- [129] Junginger, M., Järvinen, M., Olsson, O., Hennig, C., Dadhich, P. (2019): Transboundary Flows of Woody Biomass Waste Streams in Europe. *IEA Bioenergy: Task 40*: 2018: 12.
- [130] Passarelli, R., N. (2019): Environmental benefits of reusable modular mass timber construction for residential use in Japan: an LCA approach. *Modular and Offsite Construction (MOC) Summit Proceedings*, 157-164.
- [131] Zerbe, J., I., Zhiyong, C., Harpole, G., B. (2015): An evolutionary history of oriented strandboard (OSB). *General Technical Report FPL-GTR-236*. Madison, WI: U. S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.
- [132] ETM Recycling (2024): The ultimate guide to wood recycling: <https://www.recyclingbristol.com/the-ultimate-guide-to-wood-recycling/>; (accessed September 17, 2024)
- [133] Nguyen, D., L., Luedtke, J., Nopens, M., Krause, A. (2023): Production of wood-based panel from recycled wood resource: a literature review. *European Journal of Wood and Wood Products* (2023) 81:557–570
- [134] Jimenez, L., F., et al. (2020): A Review on Recycling Waste Wood for Sustainable Construction Materials, *Sustainability*, 2020
- [135] Case Study 0018 (2023): Timber Development UK, Durley Chine Environmental Hub - Commercial & Leisure, Nov. 2023. www.timberdevelopment.uk
- [136] Pickering, S., J. (2019): Recycling Technologies for Wood Waste and Fibreboards, *Journal of Material Cycles and Waste Management*, 2019.
- [137] Pazzaglia, A., Castellani, B. (2023): Wood Waste Valorization in Europe: Policy Framework, Challenges, and Decisional Tools, *SNSIM, Procedia Environmental Science, Engineering and Management* 10 (2023) (2) p.345-352
- [138] Faraca, G., Boldrin, A., Astrup, T. (2019): Resource quality of wood waste: The importance of physical and chemical impurities in wood waste for recycling. *Waste Management*, 87, 135-147.
- [139] Bergsagel, D., Isaac, P., Koeck, A. (2022): Reusing Timber in Construction - Feasibility Study Exploring Turning Reclaimed Timber into Structural Glulam, *Circuit Research Paper MS8*: 109p.
- [140] Rose, C., M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T., Duffour, P., Stegeman, J., A. (2018): Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties. *Sustainability* 2018, 10, 4118. <https://doi.org/10.3390/su10114118>
- [141] UNILIN (2021): <https://www.unilinpanels.com/en/sustainability/wood-revolutions>
- [142] Elginöz, N., Blokland, J., Safarian, S. Movahedisaveji, Z., Yadeta Wedajo, D., Adamopoulos, S. (2024): Wood Waste Recycling in Sweden—Industrial, Environmental, Social, and Economic Challenges and Benefits. *Sustainability* 2024, 16, 5933. <https://doi.org/10.3390/su16145933>
- [143] Bais-Moleman, A., Sikkema, R., Vis, M., Reumerman, P., Theurl, M., Erb, K. (2018): Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. *Journal of Cleaner Production*. 2018; 172:3942-54. doi:<https://doi.org/10.1016/j.jclepro.2017.04.153>
- [144] Jahan, I., Zhang, G., Bhuiyan, M., Navaratnam, S. (2022): Circular Economy of Construction and Demolition Wood Waste—A Theoretical Framework Approach. *Sustainability*, 14, 10478. <https://doi.org/10.3390/su141710478>
- [145] Borzecka, M., Fernando, A., L., Costa, J., Boulday, D., Antoine, P., Cocchi, I., Bern, I., Forsgren, H., Detterfelt, L., Supancic, K. (2020): The European wood waste platform: Wood waste recycling for circular bioeconomy; <http://bioreg.eu/platform/>
- [146] *Waste Wood Assessment Guidance for the UK Waste Wood Industry*, Version 3, February 2024, Wood Recyclers' Association, pp. 54, <https://woodrecyclers.org/wp->

- content/uploads/WRA-Waste-Wood-Assessment-Guidance-V3-Feb-2024.pdf
- [147] Cakaj, A., Hesse, L., Krause, A., Speth, H., Ludtke, J. (2025): Barriers and Potentials for Circular Use of Waste Wood in Construction and Demolition Sector with Special Focus on Germany. *Urban Sci.* 2025, 9, 367. <https://doi.org/10.3390/urbansci9090367>
- [148] Knauf, M. (2015): Waste hierarchy revisited - an evaluation of waste wood recycling in the context of EU energy policy and the European market, *Forest Policy and Economics* 54 (2015) 58–60, <http://dx.doi.org/10.1016/j.forpol.2014.12.003>
- [149] Korba, A., Lekawska-Andrinopoulou, L., Chatziioannou, K., Tsimiklis, G., Amditis, A. (2025): Wood Waste Valorization and Classification Approaches: a Systematic Review, *Open Research Europe* 2025, <https://doi.org/10.12688/openreseurope.18862.2>
- [150] Gedde, K., B., Lamøy, E., Stenstad, A., Müller, D., Ross, L. (2025): Post-consumer wood in Norway: composition analysis and potential for reuse and recycling, *Journal of Material Cycles and Waste Management* (2025) 27:3905–3918, <https://doi.org/10.1007/s10163-025-02306-4>
- [151] Besserer, A., Troilo, S., Girods, P., Rogaume, Y., Brosse, N. (2021): Cascading Recycling of Wood Waste: A Review. *Polymers* 2021, 13, 1752. <https://doi.org/10.3390/polym13111752>
- [152] Rimkiene, A., Vejelis, S., Vaitkus, S. (2025): Analysis and Use of Wood Waste in Lithuania for the Development of Engineered Wood Composite. *Forests* 2025, 16, 577. <https://doi.org/10.3390/f16040577>
- [153] <https://www.sylvagen.co.uk/materials-we-supply-for-recovery-and-recycling/waste-wood-for-processing/> (accessed January 9, 2026)
- [154] Bioenergy insight, <https://www.bioenergy-news.com/news/uk-waste-wood-market-thrives-in-2024/> (accessed December 10, 2025)
- [155] Maier, D.: A Review of the Environmental Benefits of Using Wood Waste and Magnesium Oxide Cement as a Composite Building Material, *Materials* 2023, 16, 1944. <https://doi.org/10.3390/ma16051944>
- [156] Berger, F., Gauvin, F., Brouwers, H., J., H. (2020): The recycling potential of wood waste into wood-wool/cement composite, *Construction and Building Materials* 260 (2020) 119786, <https://doi.org/10.1016/j.conbuildmat.2020.119786>
- [157] <https://www.nibio.no/en/news/educating-professionals-on-the-reuse-of-woodNorway>, (accessed January 9, 2026)
- [158] PUUWOOD (2024): Towards an economically viable use of recycled wood, <https://puuinfo.fi/2024/06/18/towards-an-economically-viable-use-of-recycled-wood/?lang=en>, (accessed April 17, 2025)
- [159] <https://www.tomra.com/waste-metal-recycling/media-center/news/2022/extending-the-lifecycle-of-wood-from-forest-to-products>, (accessed December 30, 2025)
- [160] Buschalsky, F., Y., B., Mai, C. (2021): Repeated thermo-hydrolytic disintegration of medium density fibreboards (MDF) for the production of new MDF, *European Journal of Wood and Wood Products* (2021) 79:1451–1459. <https://doi.org/10.1007/s00107-021-01739-6>
- [161] Yespayeva, A., S., Altayeva, Z., N., Sarsenbayev, B., K., Karshyga, G., O., Sauganova, G., R. (2020): Lightweight materials based on wood waste, *IOP Conference Series: Materials Science and Engineering* 945 (2020) 012030, doi:10.1088/1757-899X/945/1/012030
- [162] <https://natural-resources.canada.ca/forest-forestry/forest-industry-trade/wood-plastic-composites>, (accessed January 2, 2026)
- [163] MDF recovery London, UK, <https://www.mdfrecovery.co.uk/> (accessed January 2, 2026)
- [164] <https://www.steelconstruct.com/eu-projects/advance/> (accessed June 27, 2024).
- [165] Yu, Y., Yazan, D., M., Junjan, V. Iacob, M., E. (2022): Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies, *Volume 349, 2022, Journal of Cleaner Production*, vol. 349, p. 13133, 2022.
- [166] Illankoon, C., Vithanage, S., C. (2023): Closing the loop in the construction industry: A systematic literature review on the development of circular economy, *Journal of Building Engineering*, vol. 76, p. 107362, 2023.
- [167] Historical Changes to Steel Bridge Design (2021): Composition, and Properties, Publication No. FHWA-HRT-21-020. 2021, Federal Highway Administration (FHWA), Research, Development, and Technology Turner-Fairbank Highway Research Center
- [168] Villalobos, J., C., Del-Pozo, A., Campillo, B., Mayen, J., Serna, S. (2018): Microalloyed Steels through History until 2018: Review of Chemical Composition, Processing and Hydrogen Service, *Metals* 2018, 8(5), 351; <https://doi.org/10.3390/met8050351>
- [169] Structural steel reuse (2019): Assessment, testing and design principles, Publication Number: SCI P427, Steel Construction Institute, 2019. ISBN 13: 978-1-85942-243-4
- [170] American Iron and Steel Institute and Steel Manufacturers Association (2021): Technical Report “Determination of Steel Recycling Rates in the United States”, July 27, 2021, (accessed October 31, 2025)
- [171] Agyemang, E., Ofori-Dua, K., Dwumah, P., Forkuor, J., B. (2024): Towards responsible resource utilization: A review of sustainable vs. unsustainable reuse of wood waste, *PLoS ONE* 19(12): e0312527. <https://doi.org/10.1371/journal.pone.0312527>
- [172] EN 1090-2:2024, Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures.
- [173] Bartsch, H., Eyben, F., Voelkel, J., Knobloch, M., Feldmann, M. et al., Guidance on establishing European rules for the design of reclaimed steel components for reuse, DENTON, S. (editor), Publications Office of the European Union, Luxembourg, 2025, <https://data.europa.eu/doi/10.2760/9138843>, JRC144410.
- [174] CEN/TC 135 (2024): CEN/TS 1090-201:2024 - Execution of steel structures and aluminium structures - Reuse of structural steel. European Committee for Standardization, Brussels.



Original scientific paper

The role of aerogel-based insulation in sustainable renovation of cultural heritage within a circular economy framework

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ABSTRACT

Improving the energy performance of existing buildings while preserving their architectural value represents a major challenge in achieving European Union climate targets and advancing circular economy (CE) principles in the construction sector. This challenge is particularly pronounced in culturally protected buildings, where conventional insulation systems may compromise authenticity and material integrity. This study investigates the potential of aerogel-based thermal insulation materials, with a focus on silica aerogel plaster, as a non-invasive solution for sustainable renovation of heritage buildings.

A comparative evaluation of commercially available nanomaterial-based insulation systems was conducted based on thermal conductivity, environmental impact, required thickness, and compatibility with conservation criteria. Silica aerogel thermal plaster was identified as the most suitable solution for façade applications in protected structures. Its performance was assessed through dynamic energy simulation of the Macedonian Academy of Sciences and Arts building in Skopje, a representative example of post-earthquake modernist heritage architecture. Two scenarios were analyzed: the existing condition and an improved model incorporating aerogel façade insulation and upgraded envelope elements.

Simulation results indicate a 48.3% reduction in annual heating energy demand, a 10% reduction in cooling energy consumption, and a 15% decrease in overall electricity use. Total annual CO₂ emissions were reduced by 35%, accompanied by significant operational cost savings. The findings demonstrate that aerogel-based plaster enables substantial energy and environmental improvements while maintaining architectural authenticity and reversibility, thereby supporting both energy efficiency goals and circular economy principles in heritage renovation.

1 Introduction

In recent years, scientific and technological interest in the application of nanomaterials and biomaterials in energy-efficient construction has grown substantially, largely driven by the introduction of the “Nearly Zero-Energy Buildings” (NZEB) concept under the Energy Performance of Buildings Directive 2010/31/EU [1]. This directive requires that all new buildings achieve near-zero energy consumption by 2030, thereby significantly tightening energy efficiency (EE) standards. This shift has led to an increase in the required thickness of thermal insulation materials, introducing both economic and technical challenges, particularly the rising costs of high-performance insulation systems [2]. On the other hand, sustainability in construction extends beyond thermal performance. Reducing embodied energy in material

production and transportation, minimizing environmental toxicity and waste, and promoting material longevity have become key priorities. These objectives align with circular economy (CE) principles, which emphasize resource efficiency, material durability, and extended building lifespans.

Considering that new buildings account for only about 1% of Europe’s annual building stock, existing structures offer the greatest opportunity for implementing CE strategies [3]. It has been shown that renovation, compared to new construction, is significantly more resource-efficient, consuming four to eight times fewer resources [4]. Nevertheless, a review of the literature indicates that one of the main challenges in retrofitting heritage buildings is preserving their architectural authenticity while enhancing EE and sustainability.

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This paper presents the use of advanced nanomaterials in construction, with a focus on their energy-saving performance in alignment with CE objectives and sustainability in culturally significant buildings. Particular emphasis is placed on nano-ceramic coatings and silica aerogel-based materials, which have demonstrated promising results. Among these, silica aerogel thermal plaster stands out as the most effective solution, offering high thermal performance, low embodied energy, and compatibility with heritage conservation requirements. To validate these findings, an energy simulation was conducted on a culturally protected building. The analysis considered two scenarios: the building's original condition and its condition after the application of aerogel-based thermal plaster to the façade. The comparison of results confirmed notable improvements in energy efficiency and sustainability, achieved without compromising the building's architectural integrity.

2 State of the art review of nanomaterials and aerogel-based thermal insulation plasters

Nanomaterials, particularly silica aerogels, vacuum insulation panels (VIPs), phase-change material composites, and nano-ceramic coatings, have emerged as cutting-edge solutions for enhancing energy efficiency in buildings due to their ultra-low thermal conductivity, multifunctionality, and adaptability to historic structures [5,6]. Their ability to deliver high thermal performance in thin layers makes them especially suitable for renovation projects where spatial constraints and conservation requirements limit the use of conventional insulation systems.

Aerogel-based plasters are particularly promising for façade applications, as they significantly reduce heat losses while preserving the architectural integrity and material authenticity of cultural heritage buildings. Early studies reported thermal conductivities of $\lambda = 0.025\text{--}0.027\text{ W/mK}$ for mineral and organic binder plasters [7–9], while lime-based aerogel plasters achieved $\lambda = 0.014\text{--}0.016\text{ W/mK}$ at high aerogel content and $\lambda \approx 0.05\text{ W/mK}$ for mechanically optimized formulations [8,9]. More recent research confirms their long-term compatibility with historic façades, improved mechanical performance through fiber additives, and reliable in situ thermal behavior [10–14].

Beyond energy efficiency, current developments increasingly emphasize sustainable renovation within a circular economy framework, focusing on bio-based or recycled aerogel precursors, low-energy manufacturing processes, and composite systems that minimize environmental impact while maintaining high performance [15–19]. Consequently, aerogel-based materials represent a state-of-the-art solution for energy-efficient, environmentally responsible, and culturally sensitive building renovation, supporting the preservation of architectural heritage while meeting contemporary sustainability goals.

3 Methodology

3.1 Criteria for selecting nanomaterials

In recent years, a variety of commercially available nanomaterials have been developed and deployed to improve energy efficiency in buildings, such as:

- **Graphite-enhanced expanded polystyrene:** a material with incorporated graphite nanoparticles or carbon particles within a polystyrene matrix, which significantly enhances its thermal insulation properties [20].

- **Nano-ceramic thermal coatings:** advanced thin-film coating materials applicable to a range of surfaces, providing both reflective and insulating properties and contributing to overall thermal performance [21].

- **Vacuum Insulation Panels (VIPs):** materials that provide outstanding thermal insulation in ultra-thin configurations, making them ideal for applications where spatial constraints are critical.

- **Phase Change Materials (PCMs):** materials comprising paraffin nanoparticles and salt hydrates encapsulated in polymer shells, which regulate indoor temperatures by undergoing phase transitions in response to thermal fluctuations. These materials enable precise and passive thermal regulation, achieving high capsule densities—up to three million per square centimeter—due to particle diameters ranging from 2 to 20 nm [22].

- **Aerogel-based insulation systems:** materials suitable for both transparent and opaque building elements, offering exceptional thermal performance at minimal thicknesses [23].

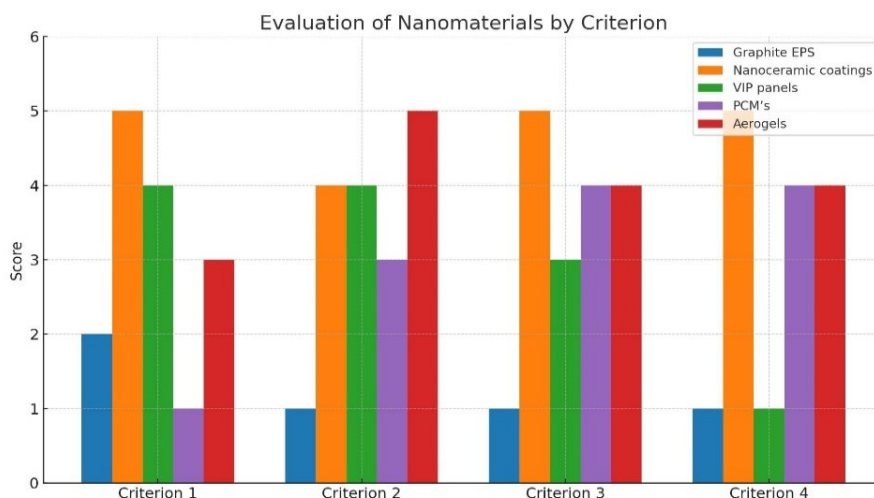


Figure 1. Evaluation of nanomaterials according to different criteria

For the purposes of this study, the performance of the five listed nanomaterial categories for façade applications was evaluated according to four criteria:

1. Thermal conductivity
2. Environmental impact (toxicity, pollution, and embodied energy)
3. Material thickness
4. Compatibility with cultural heritage conservation

The results obtained from the analysis, shown in Figure 1, reveal that aerogel-based products and nano-ceramic coatings consistently outperform other materials across all assessment parameters. These solutions demonstrate low environmental toxicity, reduced embodied energy, and minimal pollution during production. Moreover, they provide superior thermal insulation with minimal thickness. Crucially, their integration has a negligible impact on the architectural authenticity of façades, making them particularly suitable for the sustainable renovation of historically and culturally protected structures.

3.2 Criteria for selecting aerogel products

Due to their exceptional thermal performance, even at minimal thicknesses, and significantly lower embodied energy compared to conventional insulation systems and other nanomaterial-based solutions, silica aerogel-based products have emerged as some of the most advanced and promising insulation materials currently available in the building industry [23].

Silica aerogels exhibit remarkable physical and thermal characteristics, including an extremely low density of approximately 1.9 kg/m³, porosity of up to 99.8%, and a specific surface area ranging from 400 to 1000 m²/g. Pure silica aerogels demonstrate exceptionally low thermal conductivity ($\lambda \approx 0.014$ W/mK), while commercial variants typically range between 0.01 and 0.02 W/mK [24]. Their high porosity also makes them highly effective for acoustic insulation, with typical pore sizes ranging from 1 to 100

nanometers. Furthermore, the presence of silanol groups in their structure can be modified to induce hydrophobic behavior, enhancing durability in humid environments.

Silica aerogel insulation materials are commercially available in various configurations, including panels, blankets, plasters, lightweight concrete, granules, and transparent films, offering diverse solutions tailored to different architectural requirements.

On the other hand, aerogel-based products are considered sustainable and environmentally friendly due to their mineral nature, as well as their recyclability and reusability as insulation materials, aligning with circular economy (CE) principles. These materials offer versatile applications and can be tailored to meet specific CE requirements, owing to their relatively low embodied energy compared to conventional insulation materials [25,26]. Moreover, aerogels can be integrated into green building composites, providing unique properties and significant potential for sustainable construction [26,27].

Nevertheless, certain CE-related criteria—such as the applicability of aerogels on façades of cultural heritage buildings—are not universally satisfied by all aerogel types, which may limit their use in building renovation and adaptive reuse, key objectives of the CE framework.

To provide a comprehensive overview of current applications in the construction sector, as well as their potential to enhance energy efficiency (EE), support circular economy (CE) practices, and contribute to the preservation of architectural heritage through non-invasive renovation techniques, various types of silica aerogel-based nanomaterials were examined. Several commercially available aerogel-based products were analyzed in terms of their application methods in cultural heritage buildings. Their technical properties, along with their roles and impacts in the restoration and renovation of cultural heritage, were evaluated according to four key criteria: authenticity, integrity, reversibility, and compatibility (Table 1).

Table 1. Evaluation of aerogel-based products according to their Impact on cultural heritage

Type of aerogel product	Authenticity	Integrity	Reversibility	Compatibility
Aerogel blanket	Adaptable to uneven surfaces and suitable for applications where space and proportions must remain fixed, such as around windows and doors	Removal and replacement of original materials, as well as the use of anchoring points, should be minimized	Reversibility is essential; it can be added to existing façades, and visual distinction from original materials is beneficial	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required
Panel / board	The authentic appearance must be preserved and not obscured; interior application is permissible only if no protected elements are present	Boards may be installed using adhesive fixation without mechanical anchors	Application must be reversible; it may be added to existing façades, and visual distinction from original materials is desirable	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required
Plaster / render	Suitable as a mouldable material for uneven surfaces and detailed architectural features, allowing replication of the original appearance	Can be applied as an additional layer over existing plaster without compromising structural integrity	Reversible; it can be removed to expose original layers using a trowel, with a stiff brush for residue removal; its softness is an advantage	Must be compatible with historic materials and techniques; note that exterior rendering may reduce vapour permeability, therefore scientific validation of compatibility is required

Granular form	Filling of unexposed cavities with granules does not affect authenticity	Addition of granules does not affect the structural integrity of the building	Reversible; material can be removed to restore the previous state	May reduce adhesion of adjacent materials; increased hydrophobicity should be considered
Translucent panel	Provides diffused daylight while remaining visually distinguishable from original glazing; also improves acoustic performance	Existing translucent panels can be replaced without compromising integrity, although additional framing may be required	Reversible; panels can be removed and replaced to restore the original condition	Generally compatible with existing glazing systems; panels may fit within existing frames; glass and polycarbonate outer layers are considered compatible

Based on the analysis presented in Table 1, it can be concluded that aerogel-based thermal insulation plasters emerge as the most suitable materials for the renovation and preservation of historic buildings. Aerogel-based thermal plasters or renders demonstrate significant potential for application in existing buildings, particularly in cultural heritage contexts, due to their soft texture and adaptability to varied surfaces [26,27].

In accordance with preservation criteria for historic structures, aerogel plasters exert minimal impact on authenticity, provided that they are chemically compatible with the original materials and can be removed without causing damage or requiring invasive fixings [28].

The application of aerogel plasters not only enhances a building's energy efficiency and sustainability but also provides protection against climatic effects, thereby extending its lifespan. Owing to their composition and application methods, these plasters are available in various textures and colors, enabling them to closely replicate existing materials. This makes differentiation challenging while preserving the original fabric (Figure 2).

3.3 Case Study: Energy Performance Simulation

3.3.1 Description of the selected case study building

Buildings constructed after the 1963 Skopje earthquake represent more than 60% of today's building stock in Skopje and, at the same time, constitute an important part of the city's modernist cultural heritage. Most of these buildings have significant architectural, cultural, and historical value, not only for Skopje but also within the broader context of the global heritage of the Modern Movement.

However, these buildings were constructed without adequate thermal insulation, in accordance with the standards of their time, when energy efficiency and circularity were not considered key factors in building design. As a result, they are now major energy consumers, characterized by poor thermal comfort, high energy demand for heating and cooling, and substantial CO₂ emissions. In addition, they experience accelerated material degradation and increased maintenance costs, making them far from sustainable [29].



Figure 2. Visual comparison of façades in case of original materials and aerogel plaster application: (a) Renaissance building façade; (b) natural concrete façade

Furthermore, these buildings are equipped with outdated heating systems connected to the municipal district heating network, which relies heavily on fossil fuels and contributes significantly to air pollution in Skopje—one of the city's most pressing environmental challenges.

It can be concluded that these types of buildings are highly exposed to climate-related degradation, and that circular economy (CE) practices are difficult to implement under their current conditions. Therefore, there is an urgent need for their modernization and proper renovation, incorporating contemporary systems and equipment, as well as effective thermal insulation and sustainable, circular materials. At the same time, their architectural authenticity must not be compromised during the renovation process.

For this study, the building of the Macedonian Academy of Sciences and Arts was selected as a representative example of the post-earthquake period and its characteristic typology (Figure 3). The building serves as a multifunctional public facility with administrative and educational functions and represents significant architectural heritage. It has a total net area of 8,298 m² and a heated volume of 29,770 m³, supplied by the city's central district heating system. Constructed entirely from exposed concrete, the structure lacks thermal insulation and includes a large glazed façade, with a total window area of 2,236 m² (Figure 3a).

To evaluate the building's energy performance, a 3D model was developed based on the original project documentation (Figure 3b). Condition assessments were carried out through on-site inspections, complemented by interviews with building occupants.

The key challenge in terms of sustainability, energy efficiency, and maintenance of the building of the Macedonian Academy of Sciences and Arts, as a protected example of Skopje's modernist architectural heritage, is the preservation of its original appearance during renovation. Therefore, an energy performance simulation was conducted for two building conditions: the existing state and an improved scenario incorporating thermal insulation materials applied to the building envelope.

3.3.2 Energy Performance Simulation Methods

An energy performance analysis of the building was conducted using the EnergyPlus simulation engine. A detailed model of the building, internally divided into 257 thermal zones, was developed using DesignBuilder. In addition to the thermal zoning, the baseline model incorporated all relevant information obtained from the

project documentation and on-site assessments, including detailed geometry, HVAC systems, and material specifications.

The second building model was derived from the baseline model by adding insulation to the walls, roof, and windows. To preserve the building's original appearance, 10 cm of extruded polystyrene (XPS) was applied only to non-visible elements, such as the basement slab and roof. The windows and glass doors were upgraded to energy-efficient, aluminum-framed triple glazing. The selection of aerogel-based thermal plaster (FIXIT 222) as the primary insulation material was based on its advantages over conventional insulation materials, particularly for cultural heritage applications, including low thickness, environmental sustainability, and the ability to replicate the texture and visual characteristics of exposed concrete.

Due to its compatibility with historic materials and minimal visual impact, 6 cm of aerogel plaster was applied to façade walls where the preservation of authenticity is critical. The analyses were performed with respect to energy efficiency, environmental impact, and heritage conservation for both models, the baseline and the improved one. The results obtained were compared and discussed in terms of key performance indicators, including heating and electricity consumption, operational costs, and CO₂ emissions.

4 Results

The simulations demonstrated significant reductions in the U-values of all envelope assemblies (walls, ground floor, roof, windows, and doors). Notably, substantial improvement was observed in the façade walls where aerogel plaster was applied across all façade wall assembly types. Optimizing the U-values of the façade walls was critical, as they represent the largest fraction of the building envelope, while the aerogel insulation is limited to a 6 cm layer and the walls must maintain their original architectural appearance. Table 2 presents a comparison between the baseline condition, with U-values prior to renovation, and the improved scenario, with U-values after renovation, clearly illustrating the reductions achieved across all assemblies.

The results obtained for average monthly heating energy consumption in kWh of the baseline and improved model are compared in Figure 4. The simulation results indicate that required thermal energy for heating of the building in the current state during the winter months established it as huge energy consumer.

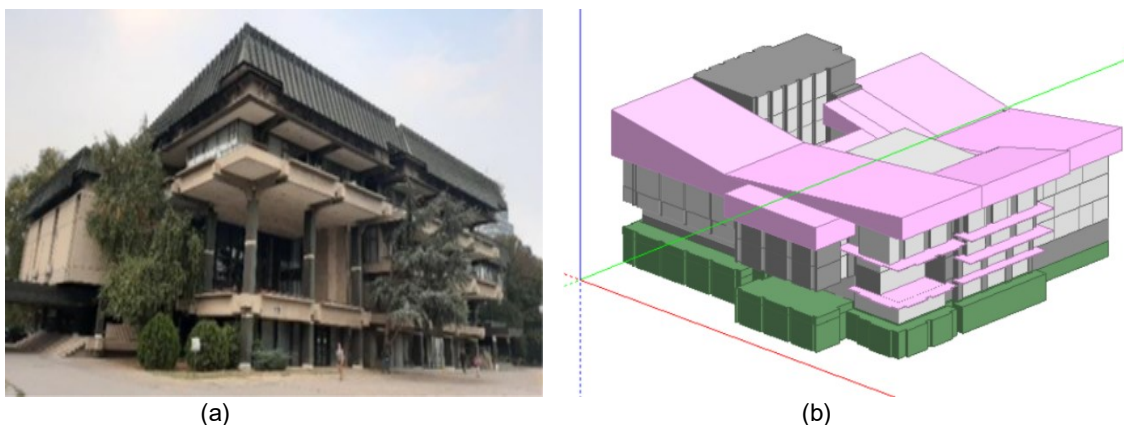


Figure 3. Building of the Macedonian Academy of Sciences and Arts: (a) current condition; (b) 3D model

Table 2. Comparison of U-values of building envelope assemblies before and after renovation

Envelope assemblies	Baseline – U-values before renovation [W/m ² K]	Scenario 1 – U-values after renovation [W/m ² K]
Facade wall assembly type 1	4.632	0.284
Facade wall assembly type 2	3.966	0.393
Facade wall assembly type 3	4.679	0.424
Facade wall assembly type 4	0.542	0.251
Ground floor assembly type 1	1.188	0.244
Ground floor assembly type 2	0.995	0.235
First floor assembly type 1	1.982	0.378
Roof assembly type 1	0.420	0.127
Roof assembly type 2	0.280	0.153
Windows and doors (type 1)	5.61	0.60
Windows and doors (type 2)	2.00	0.60

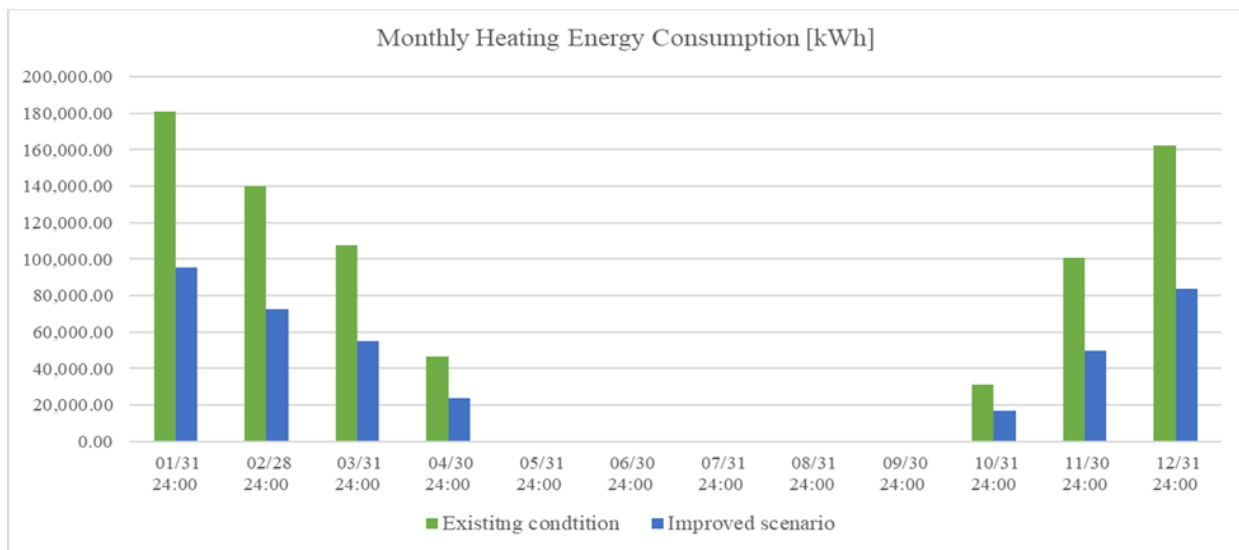


Figure 4. Monthly heating energy consumption of the baseline and improved building

From the results shown in Figure 4, it can be observed that the baseline model requires an average monthly heating energy of 64,107 kWh, corresponding to an annual heating energy consumption of 769,284 kWh, or 96.5 kWh/m². On the other hand, the improved building requires an average monthly heating energy of 33,112.6 kWh, corresponding to an annual heating energy consumption of 397,351.2 kWh, or 51.6 kWh/m².

It can be concluded that the application of aerogel plaster to the façade walls, along with conventional thermal insulation applied to non-visible building elements, leads to a significant reduction of 48.3% in heating energy consumption compared to the current state of the building.

The average monthly cooling energy consumption (kWh) of the baseline and improved models during the summer months is compared in Figure 5.

From the results shown in Figure 5, it can be observed that the baseline model requires an average monthly electricity consumption for cooling of 6,550 kWh, corresponding to an annual electricity consumption for

cooling of 78,600 kWh, or 9 kWh/m². The improved building requires an average monthly electricity consumption for cooling of 6,020 kWh, corresponding to an annual electricity consumption of 72,240 kWh, resulting in a reduction of approximately 10% in cooling electricity demand.

The relatively low percentage reduction in cooling energy consumption can be attributed to several factors. During the summer period, when the building typically experiences the highest cooling demand, a collective vacation period for building users results in reduced occupancy and overall building utilization.

Another contributing factor is that the cooling demand occurs only during the months of July and August, in contrast to the heating season, which extends over a significantly longer period of several months. A further reason is the high thermal mass of concrete, the primary construction material of the building. Due to this property, the building heats up more slowly and dissipates heat more effectively, thereby reducing the demand for cooling energy.

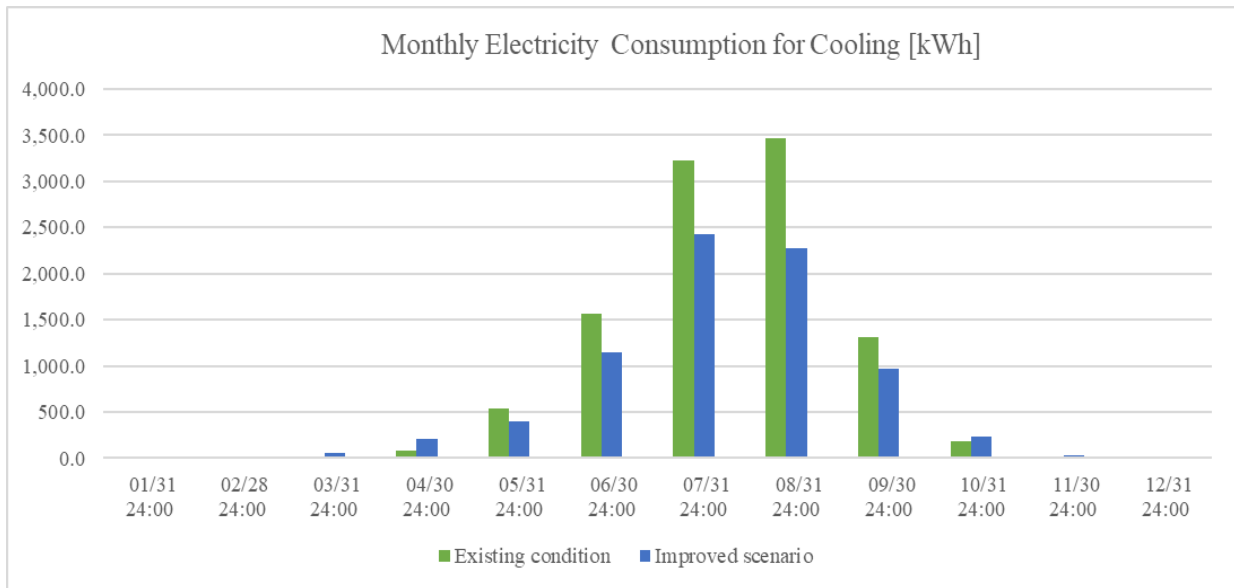


Figure 5. Monthly energy consumption for cooling of the baseline and improved building

Furthermore, the average monthly electricity consumption for lighting, operation of electrical equipment and appliances, as well as cooling and ventilation provided through a heat recovery system during the summer and supplementary air conditioning and electric heating during the winter months, is compared for the baseline and improved models in Figure 6.

From the results shown in Figure 6, it can be observed that the baseline model requires an average monthly electricity consumption of 41,335.5 kWh, corresponding to an annual electricity consumption of 496,026 kWh, or 62.2 kWh/m². The improved building requires an average monthly

electricity consumption of 36,053 kWh, corresponding to an annual electricity consumption of 432,636 kWh, or 54 kWh/m², resulting in a reduction of approximately 15% in overall electricity consumption.

These results indicate that the installed systems for maintaining indoor conditions operate inefficiently due to inadequate thermal insulation, resulting in poor thermal performance of the building envelope.

The evaluation of total energy costs for consumed thermal and electrical energy during building operation, for both the baseline and improved models, is presented in Figure 7.

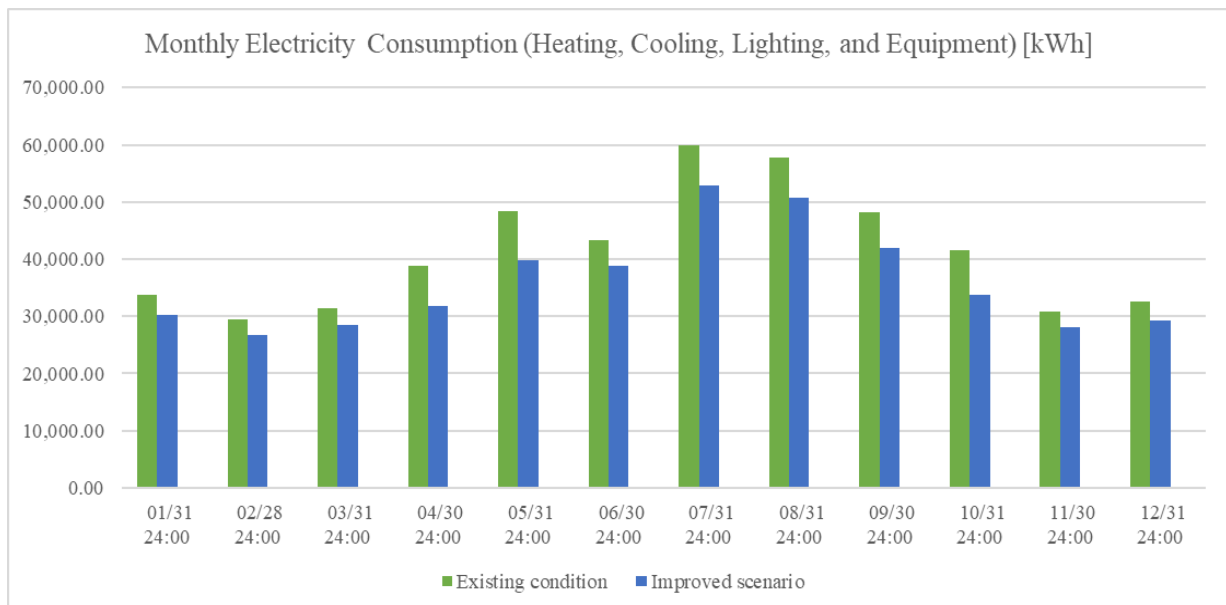


Figure 6. Overall monthly electricity consumption of the baseline and improved building

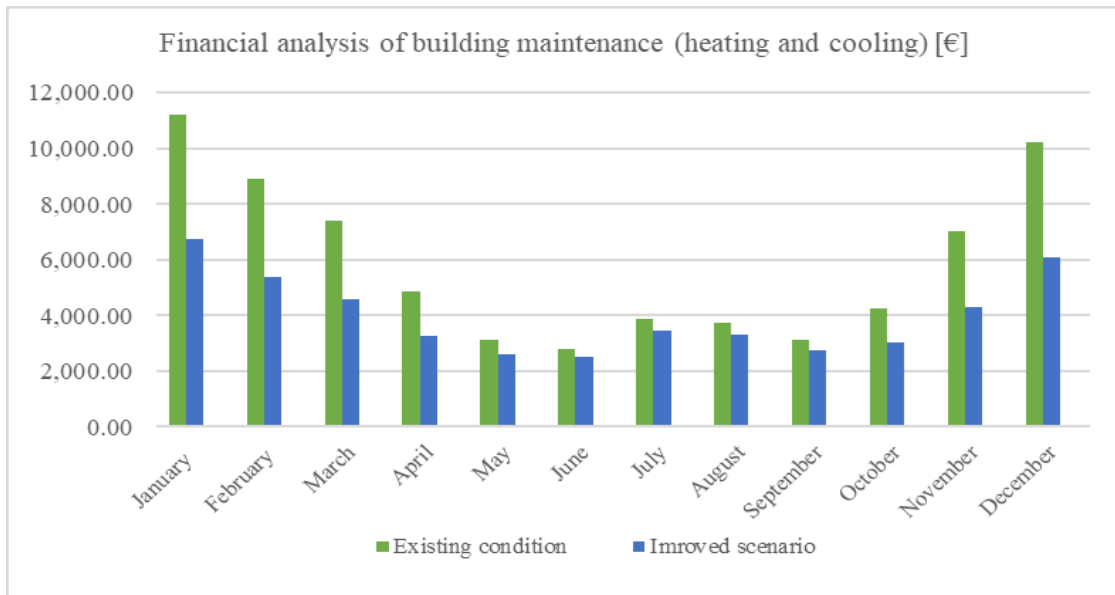


Figure 7. Overall monthly financial cost for maintenance of the baseline and improved building

From the results shown in Figure 7, it can be observed that maintaining thermal comfort in the building's current state leads to high financial costs throughout the year, particularly during the winter months. A reduction of approximately 40% in annual electricity costs for heating and cooling can be observed in the improved building compared to its current state.

The overall monthly CO₂ emissions generated during the operation of the building for both the baseline and improved models are compared in Figure 8. From the results presented in Figure 8, it can be concluded that the building of the Macedonian Academy of Sciences and Arts can be

classified as a highly polluting building, considering its size and function.

From the results shown in Figure 8, it can be observed that the baseline model produces an average monthly CO₂ emissions of 61,727.7 kg, corresponding to annual CO₂ emissions of 740,732 kg, or 92.9 kg/m². The improved building produces an average monthly CO₂ emissions of 40,078.4 kg, corresponding to annual CO₂ emissions of 480,940.8 kg, or 60.3 kg/m², resulting in an overall reduction of approximately 35% in CO₂ emissions.

From the presented results, it can be concluded that CO₂ emissions are highest during the winter months, when the building's energy demand for heating reaches its peak.

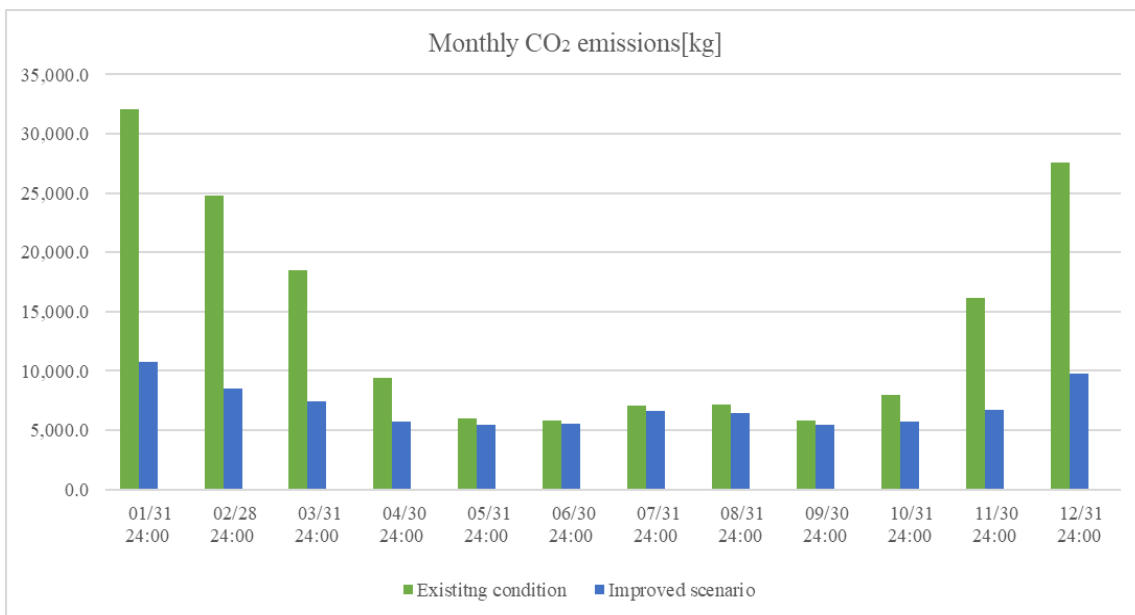


Figure 8. Overall monthly CO₂ emissions of the baseline and improved building

5 Conclusions

In order to achieve EU climate targets, improving the energy efficiency and sustainability of the building stock through the integration of circular economy (CE) practices is essential. The circular economy, particularly within the building sector, aims to reduce environmental pollution, extend building lifespans, minimize material waste, and promote the use of durable construction materials. Integrating CE principles into the renovation of existing buildings can significantly reduce material consumption, enhance energy performance and sustainability, and lower embodied emissions associated with building materials.

This paper presents the potential of various aerogel-based materials, emphasizing their superior thermal properties, low embodied energy, and versatility in application within the built environment. Aerogel-based materials are most often incorporated into new hollow walls or combined with concrete and other materials during product fabrication. However, such applications are typically limited to smaller architectural elements rather than being widely adopted as innovative solutions for improving the energy efficiency of existing structures, particularly where the preservation of authenticity and integrity is required.

The presented comparative analysis of aerogel-based materials for enhancing the sustainability of existing buildings indicates that aerogel thermal plaster is the most suitable solution for the renovation of buildings classified as cultural heritage, considering the conservation criteria of authenticity, integrity, reversibility, and compatibility. The results of the analysis show that the application of aerogel plaster to the building envelope leads to significant reductions in heating and electricity consumption, as well as lower CO₂ emissions and reduced operational costs compared to the current state.

Furthermore, the application of aerogel plaster contributes to building durability and environmental protection, in alignment with circular economy principles. Externally applied aerogel plaster can mitigate thermal bridges, protect the façade from climatic influences, and reduce material degradation and carbonation.

Therefore, it can be concluded that aerogel plaster represents an innovative and promising solution that integrates energy efficiency, circular economy principles, and the preservation of cultural heritage.

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CRedit authorship contribution statement

Liljana Dimevska Sofronievska: Data collection, Data analysis, Research, Methodology, Computer simulations, Validation, Writing - preparation of original text. Meri Cvetkovska: Methodology, Supervision, Validation, Writing-Review and Editing. Ana Trombeva Gavriloska: Methodology, Supervision, Writing-Review and Editing. Teodora Mihajlovska: Data collection, Data analysis, Writing - preparation of original text. Marija Grujic: Supervision, Validation, Writing-Review and Editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

This manuscript uses the following abbreviations:

CE – Circular Economy
 EE – Energy Efficiency
 NZEB - Nearly Zero-Energy Buildings
 VIP - Vacuum Insulation Panel
 PCM - Phase Change Material
 XPS - Extruded Polystyrene

References

- [1] Pacheco, F.T., Buratti, C., Kalaiselvam, S., Granqvist, C., Ivanov, V. (2016). *Nano and Biotech Based Materials for Energy Building Efficiency*. Springer International Publishing, Switzerland. <https://doi.org/10.1007/978-3-319-27505-5>
- [2] Attia, S., Kurnitski, J., Kosiński, P., Borodinecs, A., Belafi, D.Z., István, K., Krstić, H., Moldovan, M., Visa, I., Mihailov, N., Evstatiev, B., Banionis, K., Čekon, M., Vilčeková, S., Struhala, K., Brzož, R., Laurent, O. (2022). Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe. *Energy and Buildings*, 267, 112165. <https://doi.org/10.1016/j.enbuild.2022.112165>
- [3] Xing, Y., Hewitt, N., Griffiths, P. (2011). Zero carbon buildings refurbishment—a hierarchical pathway. *Renewable and Sustainable Energy Reviews*, 15, 3229–3236.
- [4] Power, A. (2008). Does demolition or refurbishment of old and inefficient homes improve environmental, social and economic viability? *Energy Policy*, 36, 4487–4501.
- [5] Soares, N., Zhang, Y. (2021). Nanomaterials for building energy efficiency: A comprehensive review. *Renewable Energy*, 162, 1234–1250.
- [6] Del Curto, B., Cinieri, G. (2020). Advanced thermal insulation materials for historic and existing buildings. *Building and Environment*, 175, 106816.
- [7] Koebel, M.M., Rigacci, A., Achard, P. (2011). Aerogel-based thermal insulation plasters for building applications. *Journal of Sol-Gel Science and Technology*, 63(3), 315–322.
- [8] Stahl, T., Wakili, K.G. (2012). Development of cement-free aerogel-based insulation plasters. *Energy and Buildings*, 49, 234–241.
- [9] Stahl, T., Wakili, K.G. (2013). Mechanical and thermal optimization of aerogel insulation plasters. *Building and Environment*, 60, 105–112.
- [10] Buratti, C., Moretti, E. (2015). Lime-based aerogel plasters for energy-efficient building refurbishment. *Applied Energy*, 148, 202–212.
- [11] Buratti, C., Moretti, E. (2016). High-performance aerogel composites for building insulation. *Energy and Buildings*, 128, 47–56.
- [12] Soares, N., et al. (2021). Performance assessment of aerogel-based insulation materials in building envelopes. *Journal of Building Physics*, 44(4), 301–318.
- [13] Soares, N., et al. (2021). Monitoring energy performance of aerogel-insulated heritage buildings. *Energy and Buildings*, 235, 110754.
- [14] Dicka, R., et al. (2024). In-situ thermal performance of aerogel plasters in historic façades. *Building Research & Information*, 52(1), 45–60.
- [15] Dicka, R., et al. (2024). Aerogel glazing systems for energy-efficient and heritage-sensitive buildings. *Building and Environment*, 230, 110108.

- [16] Ganobjak, S., Koebel, M.M., Malfait, W.J. (2023). Fiber-reinforced aerogels for improved mechanical performance. *Composites Part B: Engineering*, 254, 109327.
- [17] Ganobjak, M., Brunner, S., Wernery, J. (2019). Aerogel materials for heritage buildings: Materials, properties and case studies. *Journal of Cultural Heritage*, 42, 81–98.
- [18] Ganobjak, S., et al. (2023). Bio-based and recycled aerogel materials for circular economy applications. *Sustainability*, 15(7), 5432.
- [19] Del Curto, B., Cinieri, G. (2020). Aerogel-based solutions for sustainable retrofit of cultural heritage buildings. *Journal of Cultural Heritage*, 44, 89–99.
- [20] Del Curto, D., Cinieri, V. (2020). Aerogel-based plasters and energy efficiency of historic buildings. *Sustainability*, 12, 9457.
- [21] Berardi, U. (2018). Aerogel-enhanced systems for building energy retrofits: Insights from a case study. *Energy and Buildings*, 159, 370–381.
- [22] Handojo, D.U., Xiaodong, L., Eng, T.J.N. (2022). Sustainable production in circular economy: Aerogel upscaling production. *Environmental Science and Pollution Research*, 29, 20078–20084.
- [23] Castro-Díaz, M., et al. (2022). Impact of circular silica aerogel on plasterboard recycling. Loughborough University.
- [24] Carty, L. (2017). Analysis of the effects of aerogel insulation on the thermal performance of existing building envelopes. Edinburgh Napier University.
- [25] Bozsaky, D. (2017). Thermodynamic tests with nano-ceramic thermal insulation coatings. *Pollack Periodica*, 12, 135–145. <https://doi.org/10.1556/606.2017.12.1.11>
- [26] Bozsaky, D. (2016). Special thermal insulation methods of building constructions with nanomaterials. *Acta Technica Jaurinensis*, 9(1), 29–41.
- [27] Lakatos, A., Deák, I., Berardi, U. (2018). Thermal characterization of graphite polystyrene. *International Review of Applied Sciences and Engineering*, 9(2), 163–168. <https://doi.org/10.1556/1848.2018.9.2.12>
- [28] Baetens, R., Jelle, B.P., Gustavsen, A. (2010). Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings*, 42(9), 1361–1368.
- [29] Sofronievska, L.D., Mihajlovska, T., Gavriloska, A.T., Cvetkovska, M., Marina, O. (2023). Assessment of modernist architecture in Skopje in terms of energy efficiency and authentic architectural appearance. *IOP Conference Series: Earth and Environmental Science*, 1196(1), 012019. <https://doi.org/10.1088/1755-1315/1196/1/012019>



BIM uses in design for adaptability and deconstruction (DfAD): a review of strategies for circular buildings

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ABSTRACT

The construction sector accounts for 37% of global greenhouse gas emissions and consumes about 50% of all materials extracted worldwide. In the European Union, construction and demolition waste reach 40% of the total annual waste generated. Buildings often have an actual service life significantly shorter than their intended design life, intensifying environmental and economic impacts. Conventional design models that disregard building adaptability and the possibility of disassembly result in inflexible, short-lived constructions with high environmental impact. Given this context, the present study aims to investigate the uses of Building Information Modeling (BIM) in projects oriented towards Design for Adaptability and Deconstruction (DfAD), through a systematic literature review. The research is based on the principles of the Circular Economy, which proposes strategies to eliminate waste, keeping materials in continuous use, and regenerating natural systems. DfAD emerges in this context as a design approach that promotes flexibility of use, disassemblability, and the reuse of building components, integrating circularity into construction industry practices. BIM, in turn, is examined as a fundamental support strategy for enabling these principles. The systematic review included 65 selected articles, which were analyzed and organized into six main thematic axes: (a) Design; (b) Fabrication, construction, and assembly; (c) Deconstruction, disassembly, and end of life (EOL); (d) Tools and Technologies; (e) Building life cycle analysis; and (f) Materials Passport. To synthesize the analysis, a conceptual scheme of 30 key customized BIMfAD model uses was developed, providing a structured overview of their application across the building life cycle..

1 Introduction

It is estimated that population growth will add 2.5 billion inhabitants to cities by 2050, when 68% of the world's population will be urban [1]. This expansion increases the demand for buildings, infrastructure systems, utilities, transportation, and housing, intensifying both the economic commitment of the AECO sector (architecture, engineering, construction, and operation) and its responsibility for the environmental and social impacts generated. From an environmental perspective, construction is currently one of the most resource-intensive sectors on the planet. It accounts for 37% of global greenhouse gas emissions associated with energy use and consumes about 50% of all materials extracted worldwide [2]. Regarding waste, the European Union alone produces annually an amount in which construction and demolition waste represent up to 40% of all waste generated [3]. Studies also reveal that the actual service life of buildings is often shorter than the intended design life. In the United Kingdom, nearly half of

demolitions occur between 11 and 32 years, far below the normative design life expectancy [4].

The association between population growth, urban pressures, short building lifespans, underutilization of spaces, and high environmental impacts highlights the urgency of a paradigmatic transformation in the construction industry. In this context, approaches such as Design for Adaptability and Deconstruction (DfAD) emerge, introducing design practices oriented toward flexibility, disaggregation, and the reuse of construction components [5]. Buildings designed under such principles align with the logic of circularity, functioning as true material banks [6], capable of responding to functional and technological changes over time. This perspective values not only environmental sustainability, but also economic efficiency and urban resilience.

According to Contreras [7], the first aspect to be considered in the process of this transition is the evolution of computational tools that support building design. For Sacks *et al.* [8], Building Information Modeling (BIM) is one of the

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main drivers of this revolution in the AECO sector, introducing coordinated digital models rich in information [9]. These models enable virtual prototyping, predictive analysis, and simulation of a building's life cycle still in the design phase—when decisions of greatest environmental and economic impact are made [8].

The use of BIM models to support deconstruction began to gain prominence in literature over the past decade [10], with deconstruction strategies based on data extracted from the digital model, demonstrating BIM's potential to optimize component reuse and reduce environmental impacts at the end of a building's life. The conceptual consolidation of this topic occurs with the publication of ISO 20887:2020, which establishes principles and guidelines for DfD/DfA (Design for Disassembly and Adaptability) and recognizes BIM as the main digital platform supporting disassembly and adaptability [11].

Given the above, the present study aims to observe and investigate current BIM uses oriented towards Design for Adaptability and Deconstruction (DfAD) through a systematic literature review, reporting the thematic axes of analysis, highlighting their main contributions, and identifying existing research gaps. While previous review studies have predominantly focused on conceptual frameworks, adaptability strategies, and circularity assessment models, such as those presented by Askar *et al.* [12], Aziminezhad and Taherkhani [13], and Xue *et al.* [14], this study differentiates itself by specifically mapping how BIM is operationally used to support DfAD across different stages of the building life cycle. Rather than concentrating on adaptability concepts or digital tools in isolation, this review analyzes practical BIM uses reported in the literature, including design support, construction processes, deconstruction planning, digital traceability, and material information management. This approach provides a structured thematic synthesis that clarifies the current state of implementation and reveals gaps in the integration of BIM and circular construction practices.

To guide the development of this study and ensure alignment between the objectives, methodology, and analysis, the following research questions were defined: RQ1: How are BIM uses currently applied to support Design for Adaptability and Deconstruction (DfAD) across different phases of the building life cycle?

RQ2: What are the main thematic areas and technological approaches explored in the literature regarding BIM for DfAD?

RQ3: What are the main research gaps and limitations that hinder the effective integration of BIM and DfAD in circular construction practices?

2 Adaptability and building deconstruction

The term DfD (Design for Disassembly/Deconstruction) emerged in the product development industry in the 1990s, with initial studies on disassembly as a strategy for building design [15]. Although its use has intensified in recent years, DfD characteristics were already present in nomadic solutions that allowed repeated assembly and disassembly. Jaén [16] highlights that the balance between elements, form, and function has existed since classical architecture, in systems with dry joints and simple vertical loads.

Thus, the term DfAD (Design for Adaptability and Deconstruction) has advanced in the last decade as a more inclusive and sustainable ecodesign method for building adaptation and deconstruction. According to Fernandes *et al.* [17], the advantages of DfAD are divided into design,

structural, and material logic, enabling customization, resource saving, and extended durability.

Conventional construction design ignores building adaptability and disassembly, limiting environmental flexibility and generating negative impacts on resource consumption and waste generation. Crowther [18] points out that older buildings do not meet current demands, leading to excessive demolition, which results in large volumes of waste. To overcome this problem, cultural and technological changes are necessary, as waste reduction depends primarily on cultural approaches to construction and material use [19].

For EMF and ARUP [20], deconstruction through adaptable designs and low-impact construction techniques is considered a sustainable strategy within the principles of the Circular Economy. DfAD is adopted as a concept of repair, reuse, and material recovery, promoting reuse and recycling before the end of service life, keeping components at their highest level of utility and value [21], aligned with the restorative economic model. In this sense, Durmisevic [22] proposes two topics for transformable building design: the development of integrated design for dynamic multifunctional structures that interact with climate change and promote material circularity; and a dynamic balance between a stable architectural form and parts that are easily customizable, adaptable, and upgradable, creating flexible structures for additions, replacements, and updates.

2.1 BIM uses in DfAD

Building Information Modeling (BIM) is essential for integrating Design for Adaptability and Deconstruction (DfAD) practices within the Circular Economy. DfAD aims at flexible and demountable buildings, facilitating material reuse and reducing waste in the construction industry. Standards such as ISO 59004: 2024 [23], 59010:2024 [24], and 59020:2024 [25] establish principles for implementing Circular Economy in construction and metrics to evaluate circularity performance in projects, with BIM as a central tool in this process.

According to ISO 19650-1, BIM enables parametric modeling of components, storing metadata that ensures material traceability throughout the building's life cycle. The use of the Common Data Environment (CDE) facilitates the cataloging of information regarding materials, assembly, disassembly, and component tracking for future reuse [26]. For BIM interactions, Succar [27] proposes a three-node structure: policy (standards), process (information models), and technology (software, hardware, and networks). BIM digital assets, or information uses [28], can be represented as document use, model use, or data use. Succar, Salleb, and Sher [29] identified 128 BIM uses in a framework linking domain (design, construction, operation), function (policy, processes, technology), and scales (micro, meso, macro), generating a matrix of possibilities.

Messner *et al.* [30] analyzes 25 BIM uses from planning to operation, highlighting five essential ones: existing conditions capture, authoring, coordination, model review, and model compilation. Sacks *et al.* [8] expand the concept of BIM by incorporating information for strategic planning of disassembly and component reuse. They list the main BIM uses in DfAD as follows: recording information on materials and components (creating materials passports); disassembly and reuse simulation; integration with life-cycle assessments (LCA); facilitation of modularity and flexibility; creation of reusable material banks; and automation of

processes to optimize disassembly, using technologies such as digital twins and RFID tracking.

3 Research method

The present research is characterized as an integrative literature review with a qualitative approach and bibliometric support, aimed at identifying, categorizing, and analyzing the uses of Building Information Modeling (BIM) within the context of Design for Adaptability and Deconstruction (DfAD). To ensure transparency, traceability, and reproducibility of the search and study selection process, the Systematic Search Flow (SSF) method, proposed by Ferenhof and Fernandes [31], was adopted.

Although widely recognized protocols such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [32] are frequently employed in systematic reviews, especially in health-related studies and research involving quantitative meta-analysis, the present study has an exploratory and integrative character, focusing on conceptual consolidation, thematic categorization, and bibliometric analysis of multiple interdisciplinary constructs. In this context, the SSF method proved more suitable because it structures not only the search and selection process but also the stages of consolidation and synthesis through the Knowledge Matrix, enabling the systematic integration of quantitative and qualitative analyses. Thus, the choice of SSF was deliberate, considering its alignment with studies in the fields of engineering and construction management that require thematic organization and

expanded conceptual analysis. The SSF method consists of four phases and eight activities [31], described as follows:

- Phase 1 – Definition of the research protocol, composed of five activities: 1) Define the search strategy; 2) Consult databases; 3) Organize the bibliographic portfolio; 4) Standardize paper selection; 5) Compose the paper portfolio.
- Phase 2 – Analysis, composed of activity 6) Data consolidation.
- Phase 3 – Synthesis, composed of activity 7) Report preparation, which uses the Knowledge Matrix as a basis for combining and analyzing the data.
- Phase 4 – Writing, composed of activity 8) Writing, intended for consolidating the results through scientific writing.

Before initiating the first activity of the SSF method, it was necessary to identify the research problem, which relates the uses of Building Information Modeling (BIM) with decision-making in Design for Adaptability and Deconstruction (DfAD). Thus, the definition of the research protocol began with a set of procedures for the search strategy, including logical operators, relational operators, special characters, and several delimitations or filters such as document type, language, area, and publication period.

For the development of the second activity of Phase 1, the academic databases Scopus, Web of Science, and EBSCO were selected. Table 1 presents the search strategies with the definition of the procedures and delimitations for articles, reviews, and conference proceedings, with no time restrictions, filtering research in the fields of civil engineering and architecture, restricted to the English language.

Table 1. Systematic literature review

Research problem: Which uses of Building Information Modeling (BIM) can support decision-making in Design for Adaptability and Deconstruction (DfAD)?				
Research protocol				
Search strategies		Database (number of papers)		
		Scopus	Web of Science	EBSCO
1	("circul* buil*" AND "circula* econom*") OR ("circul* construct*" AND "circula* econom*") AND (bim)	24	105	87
2	(("DECONST*" OR ("design for disasseb*")) AND ("circula* econom*") AND (bim)	33	38	11
3	("DfAD") OR ("design for disasseb*") OR ("design for deconst*") AND (bim)	17	23	76
4	((build* OR construct*) AND (disassemb*)) OR ("design* deconst*") AND (bim)	57	19	209
5	((build* OR construct*) AND (reversible)) OR ("deconst*") AND (bim)	110	35	32
Total papers per database		241	220	415
Total publication				876
Exclusion of duplicate papers				-344
Exclusion based on title and keyword analysis				-194
Exclusion based on abstract analysis				-247
Exclusion of unavailable full-text papers				-11
Exclusion based on full-text analysis				-20
Additional relevant papers				+5
Final total of publications for content analysis				65

Source: the authors

For the third activity, organization of the bibliographic portfolio, the software Mendeley® was used to automate the processes of searching, counting, filtering, citing, and generating bibliographic references. In the fourth activity, standardization and selection of articles, filters were created through the reading of titles, abstracts, and keywords to exclude sources not aligned with the research theme. The identified sources were reduced from 876 to 80, which were then included in the fifth activity, the composition of the article portfolio. In this activity, the 80 articles were read in full, allowing for an additional filtering step to remove those that did not demonstrate assent to the topic, resulting in 60 articles. Five articles considered relevant to the theme, but not retrieved from the database searches, were added to the list, resulting in a total of 65 articles (Table 1).

With activity number 06, the second phase of the SSF method begins, aimed at consolidating the data and combining information such as the year with the highest number of publications on the research topic, definitions of the studied constructs, and the most frequently cited authors [31]. Sequentially, the data are interpreted, resulting in the analysis and value of the “bibliometric” data.

Additionally, in activity seven of the third phase, reports are presented in the data synthesis, using the knowledge matrix to extract and organize information from the article analyses in the section “Bibliometric Analysis.” Finally, in activity eight of Phase 4, the consolidation of results is presented, including the analysis of BIM use strategies in DfAD, possible existing knowledge gaps on the topic, and suggestions for future related studies.

4 Results and analysis

The analysis of the results is divided into the following sections: Bibliometric Analysis and Thematic Analysis of the concepts of BIM and DfAD.

4.1 Bibliometric analysis

When exploring the concepts of DfAD, it is common to find correlated or complementary terms such as Design for Assembly and Disassembly (DfAD), Design for Deconstruction (DfD), Design for Adaptability (DfA), disassembly and reuse, reversible construction design, zero-waste design, reproducible construction, configurable modular buildings, deconstructible buildings, transformable structures, generative design, adaptive reuse design, and circular building adaptability (CBA). It was also found that there is a significant difference between BIM methodology for construction projects and BIM methodology for deconstruction projects, particularly in information flows, modeling, and management. Likewise, there is strong influence on project decision-making regarding the use of new materials versus the use of reused components in adaptive projects.

Table 2 presents the bibliometric analysis with the main information from the 65 selected articles. The analyzed period (2016–2024) revealed a growing trend in research related to the topic, with 2023 being the year with the highest number of publications, totaling 13 articles. The average citation rate per article was 15.6, highlighting the influence of these studies within the scientific community. The reviewed articles came from different types of publications: 60 peer-reviewed journal articles and 5 conference papers. In total, the publications were distributed across 44 scientific journals and 21 international conferences. The three main journals that concentrated the largest number of publications were: 1) *Automation in Construction*, 2) *Journal of Cleaner Production*, and 3) *Sustainability*.

The analysis identified a total of 331 keywords, with the most recurrent being “BIM,” cited 51 times. Other relevant keywords included “Design for Disassembly (DfD),” “Circular Economy,” “Sustainable Construction,” and “Modularity.” The

Table 2. Bibliometric analysis

INFORMATION	ASNWER
TOTAL NUMBER OF PUBLICATIONS	65
TOTAL NUMBER OF SCIENTIFIC ARTICLES	60
TOTAL NUMBER OF CONFERENCE PROCEEDINGS	5
TOTAL NUMBER OF JOURNALS	44
TOTAL NUMBER OF CONFERENCE VENUES	21
TOTAL NUMBER OF KEYWORDS	331
MOST CITED KEYWORD	BIM
TOTAL NUMBER OF OCCURRENCES OF THE MOST CITED KEYWORD	51
PUBLICATION PERIOD	2016 to 2024
YEAR WITH THE HIGHEST NUMBER OF PUBLICATIONS	2023
TOTAL PUBLICATIONS IN THE YEAR WITH THE HIGHEST NUMBER OF PUBLICATIONS	13
AVERAGE CITATIONS PER ARTICLE	15.6
TOTAL NUMBER OF AUTHORS	217
TOTAL NUMBER OF SINGLE-AUTHOR ARTICLES	2
AVERAGE NUMBER OF AUTHORS PER ARTICLE	2,6
NUMBER OF DOCUMENTS PER AUTHOR	0,37
COUNTRY WITH THE HIGHEST NUMBER OF ARTICLES	United Kingdom
TOTAL NUMBER OF ARTICLES FROM THE COUNTRY WITH THE HIGHEST NUMBER	20
AUTHOR WITH THE HIGHEST NUMBER OF ARTICLES	Lukumon O. Oyedele
TOTAL DOCUMENTS BY THE AUTHOR WITH THE HIGHEST NUMBER OF ARTICLES	6
MOST USED METHODOLOGY	Case study
TOTAL NUMBER OF PUBLICATIONS USING THE MOST USED METHODOLOGY	24

Source: the authors

most frequent expression across the articles was “Building Information Modeling for Circular Construction,” highlighting the central focus of current research.

The articles were produced by a total of 217 authors, with an average of 2.6 authors per publication. Only two articles were written by a single author. The authors with the highest number of publications were Lukumon O. Oyedele, with 6 articles, followed by Lukman A. Akanbi and Elma Durmisevic, with 4 articles each. The research showed that the United Kingdom was the country with the highest number of published articles (20 articles), followed by the Netherlands (11 articles).

The bibliometric analysis revealed that the most used methodology in the articles was the case study, present in 24 of the 65 publications. This predominance, representing 36% of the articles, indicates the need to empirically validate BIM strategies for DfAD, ensuring their practical feasibility. Other methodological approaches identified include systematic and bibliometric reviews (33%), computational modeling or BIM simulations (15%), experimental studies in prototyping (12%), highlighting the concentration of research on practical implementation and model validation.

In publications from the last two years, significant growth was observed in the use of digital tools for disassembly analysis and material traceability. The themes addressed during this period included: digital materials passports, end-of-life processes, integration of BIM with Artificial Intelligence and IoT to optimize disassembly, circularity data, Digital Twins, lean construction, and carbon emission assessment during building deconstruction.

4.2 Thematic analysis

To improve understanding of the selected group, the studies were categorized into six thematic axes in the qualitative analysis of the systematic review, according to incidence and content affinity: 1) Design (17%, 11 papers); 2) Fabrication, construction, and assembly (6.15%, 4 papers); 3) Deconstruction, disassembly, and end of life (EOL) (26.15%, 17 papers); 4) Technology (40.00%, 26 papers); 5) LCA – Life Cycle Assessment (4.61%, 3 papers); 6) MP – Materials Passport (6.15%, 4 papers).

Axes 1, 2, and 3 correspond to the main stages of the building life cycle, encompassing planning, workflows, simulations of new constructions, construction methods, analysis of existing buildings, and waste management. Axes 4, 5, and 6 concentrate studies whose central contribution is associated with technologies, analytical methods, or informational instruments that enable the application of BIM in the context of circularity.

In order to reduce subjectivity in the classification and ensure methodological consistency, a decision criterion was

adopted based on the primary focus of the scientific contribution of each article, identified from the declared objectives, research questions, and presented results. Thus, when the research problem was structured around a specific life cycle phase, regardless of the tool employed, the study was classified under Axes 1, 2, or 3. When the main contribution consisted of the development, application, or operational evaluation of a digital technology or BIM solution, the study was allocated to Axis 4 – Technologies.

Axes 5 (LCA) and 6 (MP) were defined as autonomous categories because they present their own methodological structure and specific analytical objectives. Studies were classified under Axis 5 when their central contribution involved modeling, integration, or methodological application of Life Cycle Assessment within the BIM environment, even if digital tools were used. Similarly, articles were classified under Axis 6 when the primary contribution was related to the structuring, implementation, or operationalization of Materials Passports as an informational instrument, even when integrated with BIM platforms.

In cases of thematic overlap, the criterion of conceptual predominance was applied, considering the central problem investigated and the nature of the scientific contribution, rather than merely the technological instruments employed. For example, the study by Akinade et al. [33], although involving BIM-based tools, was classified under Axis 2 – Manufacturing, Construction, and Assembly, as its primary contribution focuses on construction waste management processes during the construction phase. Conversely, studies such as those by Kim and Kim [34], which emphasize the development of digital tools for evaluating disassembly performance, were allocated to Axis 4 – Technologies, as their main contribution lies in the operationalization of BIM-based technological solutions. This procedure establishes a replicable logical decision threshold, allowing greater transparency and reproducibility in the thematic organization of the review.

The selected literature did not present studies specifically applied to the use and operation phase with a focus on BIM or DfAD, concentrating predominantly on design, construction, disassembly stages, and associated technologies. Therefore, the use and operation phase was not considered as a thematic axis in this analysis.

In Table 3 – Classification of thematic axes, topics addressed, and authors of the studies included in the systematic review, nomenclatures were added for each article, referring to the relation between the study and its methodological approach, such as Case Study (CS), Literature Review (LR), Qualitative Study (QUA), or Design Science Research (DSR) when the study proposes an artifact such as a Digital Prototype (DP) or Framework (FRA).

Table 3. Classification of thematic axes, topics addressed, and authors of the studies included in the systematic review

Ranking	Thematic Axis	Topic Addressed	Authors
17,00% 11 papers	Design	Visualization of project simulations, design planning, and process flows	[35] MACHADO, R., SOUZA, H., VERÍSSIMO, G., 2018 (FRA) [36] ABRISHAMI, S., MARTÍN-DURÁN, R., 2021 (FRA, DP) [37] SANCHEZ, B., HALDER, S., SOMAN, R., YU, O.Y., 2024 (CS, DP) [38] VAN DEN BERG, M., DURMISEVIC, E., 2017 (CS, FRA) [39] GELDERMANS, R.J., 2016 (QUA) [40] OSTAPSKA, K., RÜTHER, P., LOLI, A., GRADECI, K., 2024 (LR) [41] ROXAS, C., BAUTISTA, C., DELA CRUZ, O., DELA CRUZ, R., DE PEDRO, J.P., DUNGCA, J., LEJANO, B., ONGPENG, J., 2023 (LR)

			[42] DURMISEVIC, E., BERG, M., ATTEYA, U., 2017 (DP) [43] ATTIA, S., AL-OBAIDY, M., MORI, M., CAMPAIN, C., GIANNASI, E., VAN VLIET, M., GASPARRI, E., 2024 (LR) [44] CHAREF, R., 2022 (FRA) [45] BRANCART, S., PADUART, A., VERGAUWEN, A., VANDERVAEREN, C., DE LAET, L., DE TEMMERMAN, N., 2017 (CS)
6,15% 4 papers	Fabrication, Construction, and Assembly	Fabrication processes, construction systems, construction waste management, real prototyping	[46] ZADEH, P., CALDERON, F., STAUB-FRENCH, S., CHIKHI, I., 2018 (LR, DP) [33] AKINADE, O., OYEDELE, L., AJAYI, S., BILAL, M., ALAKA, H., OWOLABI, H., ARAWOMO, O., 2018 (LR, QUA) [47] WANG, X., LI, Y., ZHOU, Z., LV, X., YUAN, P., CHEN, L., 2023 (DP, CS) [48] FINCH, G., MARRIAGE, G., GJERDE, M., PELOSI, A., PATEL, Y., 2020 (PR)
26,15% 17 papers	Deconstruction, Disassembly, and End of Life (EOL)	Construction methods for disassembly, analysis of existing buildings for disassembly, deconstruction methods, deconstruction assessment, disassembly classification frameworks, factors influencing deconstruction	[49] BASTA, A., SERROR, M., MARZOUK, M., 2020 (CS, DP) [50] CHAREF, R., ALAKA, H., GANJIAN, E., 2019 (LR, FRA) [51] ELMARAGHY, A., VOORDIJK, H., MARZOUK, M., 2018 (CS) [13] AZIMINEZHAD, M., TAHERKHANI, R., 2023 (LR) [52] OBI, L., AWUZIE, B., OBI, C., OMOTAYO, T., OKE, A., OSOBAJO, O., 2021 (QUA, FRA) [53] VAN DEN BERG, M., VOORDIJK, H., ADRIAANSE, A., 2021 (CS, DP) [54] AKBARIEH, A., JAYASINGHE, L., WALDMANN, D., TEFERLE, F., 2020 (LR) [55] JANET GE, X., LIVESEY, P., WANG, J., HUANG, S., HE, X., ZHANG, C., 2017 (CS, DP) [56] IACOVIDOU, E., PURNELL, P., TSAVDARIDIS, K., POOLOGANATHAN, K., 2021 (CS, FRA) [57] SANCHEZ, B., HERTHOGS, P., STOUFFS, R., 2023 (CS, FRA) [58] HEI, S., ZHANG, H., LUO, S., ZHANG, R., ZHOU, C., CONG, M., YE, H., 2024 (LR, CS) [59] HUANG, B., ZHANG, H., YANG, W., YE, H., JIANG, B., 2024 (DP, CS) [60] WU, B., MAALEK, R., 2023 (DP) [61] ZHAO, Z., 2023 (DP, CS) [62] AKANBI, L., OYEDELE, L., DELGADO, J., BILAL, M., AKINADE, O., AJAYI, A., MOHAMMED-YAKUB, N., 2018 (LR) [63] MATTARAIA, L., FABRICIO, M., CODINHOTO, R., 2023 (FRA, DP) [64] BALOGUN, H., ALAKA, H., EGWIM, C., AJAYI, S., 2022 (LR, FRA)
40,00% 26 papers	Technologies	Waste management technologies for deconstruction, data management, circularity, proposed prototype, artifact or digital model, digital deconstruction platforms and software, EOL analysis, performance estimator, use of technology to assess reuse potential, performance indicators, BIM-based evaluation model	[65] BERTIN, I., MESNIL, R., JAEGER, J.M., FERAILLE, A., LE ROY, R., 2020 (DE, CS, DP) [34] KIM, S., KIM, S.A., 2023 (DE, LR, DP) [66] AKINADE, O., OYEDELE, L., OMOTESO, K., AJAYI, S., BILAL, M., OWOLABI, H., ALAKA, H., AYRIS, L., LOONEY, J., 2017 (DE, FRA, QUA) [67] GHERMAN, I.E., LAKATOS, E.S., CLINCI, S., LUNGU, F., CONSTANDOIU, V., CIOCA, L., RADA, E.C., 2023 (LR) [68] BERTIN, I., LEBRUN, F., BRAHAM, N., LE ROY, R., 2019 (DE, LR, CS) [69] SANCHEZ, B., RAUSCH, C., HAAS, C., 2019 (DE, CS, DP) [12] ASKAR, R., BRAGANÇA, L., GERVÁSIO, H., 2022 (DE, LR, FRA) [70] BILAL, M., OYEDELE, L., AKINADE, O., DELGADO, J., AKANBI, L., AJAYI, A., YOUNIS, M., 2019 (D, DP) [71] DURMISEVIC, E., GUERRIERO, A., BOJE, C., DOMANGE, B., BOSCH, G., 2021 (DE, DP) [72] AKANBI, L., OYEDELE, L., OMOTESO, K., BILAL, M., AKINADE, O., AJAYI, A., DELGADO, J., OWOLABI, H., 2019 (DE, DP, FRA) [73] DERVISHAJ, A., VARGAS, J., GUDMUNDSSON, K., 2023 (DE, DP, EC)

			<p>[74] WANG, X., LIU, Z., CUI, J., OSMANI, M., DEMIAN, P., 2023 (LR, QUA)</p> <p>[75] BENJAMIN, S., CHRISTOPHER, R., CARL, H., 2022 (D, DP)</p> <p>[76] CALDAS, L., SILVA, M., SILVA, V., CARVALHO, M., TOLEDO FILHO, R., 2022 (LR, QUA)</p> <p>[77] LEBOSSÉ, M., HALIN, G., BESANÇON, F., FUCHS, A., 2022 (DE, DP)</p> <p>[78] LIMA, P., RODRIGUES, C., POST, J., 2023 (DP, CS)</p> <p>[79] MARINO, E., PAOLUZZI, A., SPINI, F., SALVATI, D., 2027 (DE, DP)</p> <p>[80] JANANI, S.E., RENUKA, S.M., UMARANI, C., 2022 (DE, DP, CS)</p> <p>[81] AKANBI, L., OYEDELE, L., AKINADE, O., AJAYI, A., DELGADO, M., BILAL, M., BELLO, S., 2018 (LR, DP)</p> <p>[82] HU, X., ZHOU, Y., VANHULLEBUSCH, S., MESTDAGH, R., CUI, Z., LI, J., 2022 (DE, DP)</p> <p>[83] AKBARI, S., SHEIKHKHOSHOKAR, M., RAHIMIAN, F., HAOUZI, H., NAJAFI, M., TALEBI, S., 2024 (LR)</p> <p>[84] SCHWEDE, D., STÖRL, E., 2016 (DP)</p> <p>[85] DURMISEVIC, E., BEURSKENS, P., ADROSEVIC, R., WESTERDIJK, R., 2017 (DE, CS, FRA)</p> <p>[86] BEHÚNOVÁ, A., MANDIČÁK, T., BEHÚN, M., MÉSÁROŠ, P., 2023 (LR, QUA)</p> <p>[87] ASKAR, R., KARACA, F., BRAGANÇA, L., GERVÁSIO, H., 2024 (LR, FRA)</p> <p>[88] DENIS, F., VANDERVAEREN, C., DE TEMMERMAN, N., 2018 (LR, DP)</p>
4,61% 3 papers	(LCA) Building Life Cycle Assessment	Key aspects, methods, indicators, drivers, BIM–LCA integration	<p>[14] XUE, K., HOSSAIN, M.D., LIU, M., MA, M., ZHANG, Y., HU, M., CHEN, X., CAO, G., 2021 (LR, FRA)</p> <p>[89] SOUST-VERDAGUER, B., LLATAS, C., GARCÍA-MARTÍNEZ, A., 2017 (LR)</p> <p>[90] TOMCZAK, A., BENGHI, C., VAN BERLO, L., HJELSETH, E., 2024 (DP)</p>
6,15% 4 papers	(MP) Materials Passport	Materials passports (MP), and inventory data	<p>[91] SANCHEZ, B., HONIC, M., LEITE, F., HERTHOOGS, P., STOUFFS, R., 2024 (CS, DP)</p> <p>[92] MARAQA, M., SPATARI, S., 2022 (CS)</p> <p>[93] SCHAUBROECK, S., DEWIL, R., ALLACKER, K., 2022 (LR)</p> <p>[94] ATTA, I., BAKHOUM, E., MARZOUK, M., 2021 (FRA, DP)</p>

CS – Case Study; DP – Digital Prototype; LR – Literature Review; FRA – Framework; QUA – Qualitative D – Design; DE – Deconstruction

Source: the authors

4.3 Thematic analysis review

Thematic Axis 1 – Design

The principles of Design for Disassembly (DfD) and Design for Manufacturing and Assembly (DfMA) aim to facilitate the reus of components at the end of a building's service life. Machado *et al.* [35] highlight design and construction characteristics that support deconstruction, such as material selection and connections. Ostapska *et al.* [40] identify DfD practices in 151 built structures, predominantly employing timber as the primary material and with an area smaller than 300 m², reinforcing the diversity of applications and the predominance of research focused on concrete and steel connections.

Roxas *et al.* [41] point out gaps in the literature, such as the lack of guidelines applicable to conventional buildings, limited integration with digital technologies, and a scarcity of comparative assessments. In response, Abrishami and Martín-Durán [36] propose a BIM framework for DfMA,

covering stages from planning to disassembly, validated through an off-site manufacturing (OSM) prototype.

The usage of BIM is also explored by Sanchez *et al.* [37], who propose a workflow for disassembly planning, and by Van den Berg and Durmisevic [38], who identify effective uses and limitations of BIM in reversible buildings. Charef [44] contributes by proposing the eighth dimension (8D) of BIM and the Deconstruction Information Model (DIM) for end-of-life asset management.

Other studies contribute with evaluations and circularity parameters. Attia *et al.* [43] compile five methods for assessing disassembly in design and present practical examples. Brancart *et al.* [45] analyze transformable structures and suggest a BIM tool for material tracking. Geldermans [39] defines circular prerequisites through interdisciplinary workshops, while Durmisevic *et al.* [42] propose algorithms to assess building transformability from preliminary design stages.

Thematic Axis 2 – Fabrication, Construction, and Assembly

The integration between BIM, DfMA, and prefabricated materials such as engineered timber has been a growing subject of interest. Zadeh *et al.* [46] explore how BIM tools and collaborative platforms can optimize solutions in solid timber projects, minimizing waste and strengthening the work of manufacturers and assemblers. They highlight benefits such as higher precision, reduced schedules, clear visualization of scope, and potential for off-site manufacturing. In addition, they emphasize the need for specific linkage between BIM and DfMA and the importance of standardized data throughout the production chain.

Complementing this perspective, Akinade *et al.* [33] analyze BIM's contribution to construction waste management (C&DW) during the construction phase, identifying five main domains: collaboration, design-oriented solutions, life cycle analysis, use of smart technologies, and documentation improvement.

Wang *et al.* [47] present a BIM–IoT system for real-time monitoring of prefabricated structures with a focus on disassembly. Using sensors such as RFID and QR-codes, the system enables annual assembly and disassembly control of a steel structure, reinforcing BIM's role in adaptable and traceable construction.

Along similar lines, Finch *et al.* [48] develop a modular and lightweight prototype with reversible connections, validating a circular construction process. The use of BIM allowed the identification of system limitations and the formulation of specific requirements for deconstruction, reinforcing its practical applicability as a decision-support tool throughout the construction cycle.

Thematic Axis 3 – Deconstruction, Disassembly, and End of Life (EOL)

The application of BIM in the end-of-life phase of buildings has advanced to support sustainable decisions, reduce waste, and improve disassembly efficiency. Basta, Serror, and Marzouk [49] propose an automated system to assess the “deconstructability” of steel structures, with a focus on reversible connections and fire protection. Van den Berg *et al.* [53] identify new BIM uses in deconstruction, such as 3D condition analysis, element tagging, and 4D simulation.

The integration of BIM with Lean Construction and digital technologies was explored by Hei *et al.* [58] and Wu and Maalek [60], who demonstrate gains in productivity, emission reduction, and improved energy performance when comparing demolition and refurbishment scenarios. Huang *et al.* [59] reinforce the importance of DfD in reducing mechanical carbon emissions through the optimization of the disassembly process.

Research by Azimenezhad and Taherkhani [13] and Obi *et al.* [52] highlights the growth of the literature on BIM and deconstruction, proposing critical factors for its implementation, identifying gaps such as performance evaluation and integration with reusable material banks. Akanbi *et al.* [62] and Mattaraia *et al.* [63] contribute predictive models and classifications to support decision-making regarding reuse at the end of service life.

Additionally, reviews by Balogun *et al.* [64] and Iacovidou *et al.* [56] emphasize factors such as cost, schedule, and design technologies as determinants of deconstruction feasibility, suggesting digitized modular construction as an effective strategy to promote circularity in the sector.

Thematic Axis 4 – Technologies

Several technologies have been developed to support DfD and the Circular Economy in the construction sector, especially those integrated with BIM. Bertin *et al.* [65] propose a toolchain that enables simulations for the reuse of structural components, focusing on “design with stock” and “design for stock” scenarios, both applied to buildings reconstructed from reused elements. Similarly, Kim and Kim [34] present a DfD performance assessment tool that integrates CO₂ emissions, cost, and disassembly feasibility, achieving reductions of up to 40.1% in emissions for steel structures.

The contribution of BIM to visualization and simulation of deconstruction is reinforced by Akinade *et al.* [66], who identify its effectiveness in stakeholder collaboration, planning, and life-cycle management. Sanchez, Rausch, and Haas [69] advance semi-automated methods for selective disassembly and adaptive reuse to schedule deconstruction works based on disassembly sequences.

Askar *et al.* [12, 87] discusses models for assessing adaptability and circularity, proposing a conceptual framework to integrate these criteria at all building levels. Bilal *et al.* [70] develop an optimization algorithm for floor layouts aimed at dimensional coordination, implemented in the BIMWaste tool, while Akanbi *et al.* [72, 81] introduce BIM-based systems for evaluating material recovery and performance throughout a building's service life.

Durmisevic *et al.* [85, 71] explore platforms for reversibility and reuse assessment, integrating BIM, databases, blockchain, and functional, technical, and material indicators. Additionally, Janani *et al.* [80] propose quantitative models such as DAS (Deconstructability Assessment Score), and Denis *et al.* [88] develop a new method to quantify DfD impact, called DNA (Disassembly Network Analysis), applicable to different types of structures. Component traceability also stands out. Dervishaj *et al.* [73] investigate the combination of technologies such as QR codes, NFC, and Bluetooth with BIM for tracking prefabricated elements, while Hu *et al.* [82] propose an Image-to-BIM framework using drones and cameras to capture data and plan demolitions, optimizing C&DW management.

In the field of BIM–IoT integration, Wang *et al.* [74] identify trends and challenges, highlighting the need to consider human and social aspects and the use of emerging technologies such as big data and cloud computing. Marino *et al.* [79] propose the use of virtual and augmented reality to support “zero-waste” design through rapid semantic modeling.

Thus, Caldas *et al.* [76] provide an integrated analysis of technologies such as environmental certifications, AR (augmented reality), and VR (virtual reality), proposing new models for reducing GHG (greenhouse gas) emissions, and Behúnová *et al.* [86] quantify how BIM affects circular performance indicators in construction projects.

Thematic Axis 5 – (LCA) Building Life Cycle Assessment

The integration between BIM and LCA has been identified as essential for advancing sustainability in the construction sector, especially within the context of the Circular Economy (CE). Xue *et al.* [14] propose an integrated framework for CE adoption in buildings based on BIM, highlighting both challenges and contributions of LCA to sustainable projects. Among the main drivers are the ability

to predict environmental impacts and guide decisions from the design stage.

Complementing this approach, Soust-Verdaguer *et al.* [89] analyze how BIM can optimize LCA application through automation of data input and output, using specific models and plug-ins for estimating impacts and energy consumption. The methodological integration between BIM data and LCA tools enables significant gains in efficiency and reliability of environmental assessments.

Advancing toward standardization and interoperability, Tomczak *et al.* [90] evaluate the use of the Information Delivery Specification (IDS) standard to ensure the quality and readability of circularity data in BIM. The proposal enables semi-automated compliance verification and facilitates the future use of such information in disassembly, reuse, and reconfiguration processes, strengthening environmental indicators in digital models.

Thematic Axis 6 – (MP) Materials Passport

The incorporation of Materials Passports (MP) into the BIM environment has gained prominence as a strategy to enhance traceability, reuse, and sustainability of construction components throughout the life cycle. Sanchez *et al.* [91] develop the SEEDP mechanism, a semantic enrichment system for BIM-based disassembly planning. The proposal automates the stages of data preprocessing, passport generation, and disassembly model evaluation, validated through two case studies.

Also focusing on BIM integration, Maraqa and Spatari [92] propose the combination of Material Flow Analysis (MFA) with life cycle inventory data to define the MP of a LEED-certified building. The study shows that components such as concrete and glass façades can be recovered or reused, providing a basis for guiding sustainable disassembly practices.

Atta, Bakhom, and Marzouk [94] introduce a BIM-integrated MP tool that calculates sustainability indicators, deconstructability scores, recovery scores, and environmental performance. The tool automates analyses and supports sustainable decision-making from the design stage, validated through a case study comparing conventional and modular construction methods, revealing the influence of materials and connections on the indicators.

Complementarily, Schaubroeck, Dewil, and Allacker [93] propose a workflow to model construction joints and disassembly sequences using 3D GIS models to store geometric and connection data. The approach aims to expand the application of MP in urban stocks at different scales, linking the information to BIM platforms to support component recovery in future interventions.

5 Main contributions and research gaps

The main contributions of BIM uses in DfAD were identified and highlighted alongside the primary research gaps observed in each thematic axis in Table 4, serving as guidance for future studies.

Table 4. Main contributions of the studies and identified gaps

Thematic Axes	Main Contributions	Main Gaps Identified
Design	<ol style="list-style-type: none"> 1. Definition of guidelines and criteria in DfD, including circular performance characteristics of materials; 2. Proposals of models and frameworks for adaptability and deconstruction; 3. Simulations of spatial and functional adaptability throughout the building life cycle; 4. Analyses of information flows to manage circularity within the model; 5. Compilation of case studies with technical solutions and strategies for transformable construction systems; 6. Definition of quantitative metrics for circularity; 	<ol style="list-style-type: none"> 1. Absence of a hierarchy of design characteristics according to their impact on disassemblability and circularity; 2. Limited integration between material properties and adaptable design parameters, hindering effective circular decision-making; 3. Limited number of real-world applications of BIM models focused on building disassembly; 4. Absence of standardized protocols for selective deconstruction or demountable components; 5. Predominance of studies focused on small scales and temporary building typologies; 6. Lack of standardized methods and indicators to evaluate disassemblability in a comparable manner.
Fabrication, Construction, and Assembly	<ol style="list-style-type: none"> 7. Integration of parametric modeling with DfMA to optimize fabrication, assembly, and on-site efficiency; 8. Incorporation of traceability tools and equipment for assembly control; 9. Validation of circular solutions through full-scale prototyping; 10. Control and management of waste through information flows and construction processes 	<ol style="list-style-type: none"> 7. Limitations in automation and full-scale fabrication of components, especially in reversible systems; 8. Lack of guidelines for integrating assembly and disassembly into BIM; 9. Low replicability of monitoring and traceability technologies across different scales and construction typologies; 10. Absence of standardized protocols for integrating BIM and IoT devices during assembly.
Deconstruction, Disassembly, and End of Life (EOL)	<ol style="list-style-type: none"> 11. Definition of guidelines for selective disassembly; 12. Planning and simulations of disassembly; 	<ol style="list-style-type: none"> 11. Lack of practical evidence of BIM and EOL in operational decisions and real disassembly; 12. Limited interoperability between BIM and EOL management tools, and challenges in large-scale application;

	<p>13. Control and management of waste during building deconstruction stages;</p> <p>14. Component traceability through selective deconstruction;</p> <p>15. Use of information in pre-demolition audits and decisions regarding refurbishment and reuse;</p> <p>16. Integration of BIM with multi-objective optimization, considering CO₂ calculations, time, and effort;</p> <p>17. Strategic reuse of façade components;</p> <p>18. Mapping of barriers to BIM adoption, including technical and organizational aspects.</p>	<p>13. Reliability issues in models of older buildings due to scarce data and technical records;</p> <p>14. Technical challenges in selective disassembly of complex structures, with low maturity in BIM–sensor integration;</p> <p>15. Lack of reliable data on materials in old/existing buildings for environmental and structural assessments;</p> <p>16. Performance of reused components.</p>
Technologies	<p>19. Proposals for the use of technologies with simulations of structural element reuse;</p> <p>20. Component traceability with integration into databases, indicators, and sorting systems;</p> <p>21. Graphic and parametric modeling for deconstructability assessment, applying algorithms and network analysis;</p> <p>22. Testing of digital technologies (IoT, sensors, AI) for tracking and building disassembly;</p> <p>23. Simulations of digital workflows with graphical interfaces (Dynamo), applied to the reuse of modular materials;</p> <p>24. Layout programming and selective deconstruction focused on waste optimization using tools such as BIMWaste;</p> <p>25. Automation of circular decision-making, with analysis and reusability indicators.</p>	<p>17. BIM tools that integrate disassembly, tracking, reuse, and waste analysis throughout the entire building life cycle;</p> <p>18. Practical application of BIM–DfAD tools in real projects, including non-repetitive or non-modular systems;</p> <p>19. Empirical studies on the real impact of digital technologies (IoT, AI) in circular construction works;</p> <p>20. Systems that support designers in the automated selection of demountable components based on technical criteria;</p> <p>21. Technical and computational limitations of digital tools, including accuracy in image capture, disassembly simulation, and scalability for large projects;</p> <p>22. Standardized indicators and metrics that enable economic, social, and environmental analyses within the BIM environment;</p>
(LCA) Building Life Cycle Assessment	<p>26. Integration between BIM and LCA to reduce data collection effort and enable real-time environmental analyses;</p> <p>27. Application of BIM–LCA tools for simulations of sustainable material and system choices;</p> <p>28. Integration of environmental databases into BIM for automated analyses of embodied impacts;</p> <p>29. Proposal of BIM as a repository for EPDs (Environmental Product Declarations) and LCA indicators to improve assessment accuracy.</p>	<p>23. Standardization in the level of detail of BIM models and in integrations with LCA tools;</p> <p>24. Environmental databases with low compatibility with local contexts, hindering realistic analyses;</p> <p>25. Need for manual inputs for detailed simulations, reducing the effectiveness of automated tools;</p> <p>26. Limited interoperability between BIM and environmental databases, compromising support for LCA and circularity;</p>
(MP) Materials Passport	<p>30. Integration between BIM and Materials Passports to quantify environmental impacts throughout the life cycle;</p> <p>31. Proposal of MP models with quantitative sustainability indicators;</p> <p>32. Efficient management of technical, environmental, and social data through MP digitization;</p> <p>33. Simulations of reuse and storage scenarios for components through modeling and urban-scale material banks.</p>	<p>27. Lack of local databases and access to accurate data for the customization and practical application of Materials Passports;</p> <p>28. Lack of clear criteria for selecting and interpreting indicators, to facilitate use by non-specialist professionals;</p> <p>29. Absence of standardized guidelines for interoperability and consistency in modeling aimed at adaptability and disassembly;</p> <p>30. Data extraction challenges in 3D urban models;</p> <p>31. Integration of Materials Passports with public policies for circular management at the urban scale.</p>

Source: the authors

The main contributions identified in Table 4 highlight important advancements in research on guidelines, models, and tools oriented toward circularity, including the development of frameworks, transformable construction systems, quantitative metrics, and improvements in the integration of BIM, LCA, and Materials Passports. These studies contribute by establishing conceptual and technical foundations that enhance the understanding of disassemblability, reuse, traceability, and simulations throughout the building life cycle. By integrating digital technologies such as IoT, parametric algorithms, environmental databases, and component sorting systems, such research expands the repertoire of solutions capable of supporting more efficient and circular decision-making in the built environment.

However, the identified gaps reveal a still fragmented scenario on the topic, a lack of consolidated standardization of selective deconstruction protocols, and difficulties in achieving robust integration among BIM, LCA, MP, and other technologies. There is also a shortage of environmental databases for materials and components, a scarcity of empirical studies on existing buildings, and limited interoperability among tools. Additionally, a significant gap remains regarding studies on the use and maintenance phase. This is compounded by the absence of a hierarchy of design criteria, the low maturity of models applied to different contexts, and technical challenges in automating, monitoring, and simulating adaptability and deconstruction processes. A critical, cross-cutting issue across all axes is the lack of specialized training, which limits the dissemination of both design practices and technical execution practices, affecting the entire AECO sector.

6 Main BIM uses in DFAD

The analysis of the reviewed studies revealed the absence of a clearly defined and structured set of customized BIM uses for Design for Adaptability and Deconstruction (DfAD). Considering the Common Model Uses distributed across the four project phases: Planning, Design, Construction, and Operation [30], Figure 1 presents 30 customized BIM uses for DfAD, identified from the reviewed literature and organized according to the different life-cycle phases. The phases of "Pre-construction", "Adaptability", "Deconstruction", and "Mapping" were added, expanding the original framework and enabling a more comprehensive approach aligned with the building life cycle.

The purpose of Figure 1 is to provide a structured systematization of BIMfAD uses (BIM for Adaptability and Deconstruction), highlighting how each use is distributed, overlaps, and interacts across the different phases. The conceptual structure makes explicit the transversal nature of several uses, demonstrating that decisions related to adaptability, circularity, and deconstruction are not confined

to a single phase. Such decisions can be anticipated, iteratively informed, and continuously updated through the BIMfAD model, supporting component traceability, impact assessment, transformation cycle planning, and integration with material banks and secondary markets.

The colors in Figure 1 represent the various possibilities for functional categorization of BIMfAD uses, indicating different natures of action, such as analytical and evaluative uses, operational and management uses, and strategic and decision-making uses. Some uses originate in the final stages of deconstruction and mapping, especially those related to integration requirements with material banks, mapping of component supply and demand connected to CIM (City Information Modeling), georeferencing of components and urban stock, and support for decision-making regarding recommissioning; and extend into the initial planning and design phases of other buildings, informing interconnected future design decisions.

There is no hierarchy among the uses, but rather a logic of interdependence, in which uses may occur in parallel and feed back into one another as each stage progresses. The vertical connections indicate possible integrations between uses, showing that data and decisions from one phase directly influence the others. The length of the arrows across the stages represents the temporal duration and persistence of each use, indicating whether it is punctual or continuous throughout multiple phases of the building life cycle.

As BIMfAD model uses begin to be systematized, the importance of a broader transformation in the way buildings are conceived, constructed, operated, and decommissioned becomes evident. The proposal of customized BIMfAD uses makes it possible to create strategies, support simulations, and enable the integrated management of process flows throughout the building life cycle.

In this sense, a building conceived under the BIMfAD methodology should be understood as an integrated informational and material system, in which each building component ceases to be merely a physical element and becomes a traceable, measurable, and reconfigurable asset over time. The consolidation of materials passports, as-built models enriched with circularity attributes, digital traceability systems, and in-use monitoring mechanisms, for example, establishes the foundation for decision-making across multiple life cycle phases.

The integration of these data with urban resource management platforms and material banks expands the scale of BIMfAD, connecting the building to networks of supply and demand for reusable components. In this way, BIMfAD ceases to be merely a modeling methodology and assumes the role of an informational infrastructure for the circular economy in the built environment, enabling the recomposition of technical cycles, the reduction of waste, and the maximization of the value of built assets.

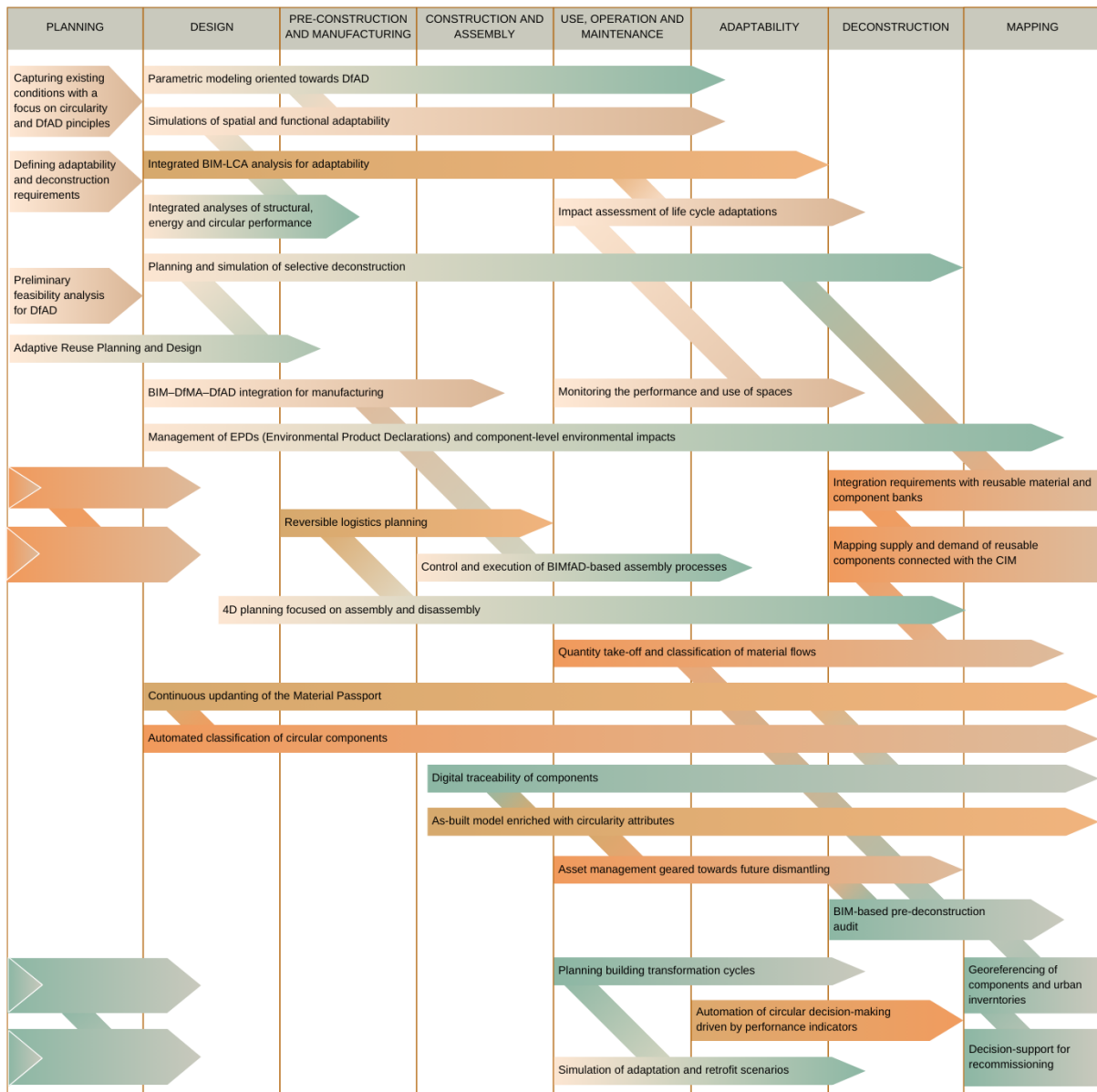


Figure 1. 30 Main Customized BIMfAD Uses Based on the Literature Review and Messner et al. [30]

Source: the authors

7 Final considerations

Despite the advancement of the research presented on DfAD and its relationship with BIM, there is still no standardized set of guidelines to guide the application of BIM in the planning and execution of disassemblable and adaptable buildings. The literature review demonstrates the fragmentation of knowledge on the subject, with studies addressing isolated aspects. The tools presented in the studies are fundamental to encouraging more ecological practices and reducing dependence on finite natural resources. However, for these strategies to be widely implemented, regulatory incentives and public policies that promote the use of BIM within the context of the Circular Economy are necessary.

Unlike previous review studies that focused primarily on conceptual adaptability frameworks and circularity assessment approaches, such as those presented by Askar

et al. [12], this study contributes by systematically identifying and organizing BIM uses that support Design for Adaptability and Deconstruction across different stages of the building life cycle. By structuring these uses into thematic axes, the study provides a clearer understanding of how BIM is operationally applied to enable adaptability, disassembly, and material traceability, highlighting both opportunities and research gaps in the integration of BIM with circular construction strategies.

The research presented four limitations to be considered in interpreting the results. The first limitation is related to the heterogeneity of the information identified in the literature. The analyzed studies employ different levels of BIM maturity, data structures, and terminologies associated with DfAD, which makes direct comparison between the identified uses difficult and hinders the consolidation of standardized protocols for applying BIMfAD throughout the building life cycle.

The second limitation refers to the uneven distribution of studies across the phases of the building life cycle. A greater concentration of research is observed in the Design and Deconstruction stages, with less in-depth investigation in the Use, operation, and maintenance phases. As a consequence, some BIMfAD uses related to in-operation monitoring and real-data feedback still lack empirical validation in real-world contexts.

The third limitation concerns the dependence on specific technological tools and solutions, often associated with prototypes or experimental environments. Many of the identified uses are linked to platforms, parametric routines, or customized systems, whose replicability and scalability across different contexts remain limited, especially in existing buildings with low levels of documentation.

Finally, the fourth limitation is associated with the predominantly qualitative and exploratory nature of the analyzed literature. Most studies are based on conceptual reviews, digital prototypes, or isolated case studies, indicating that BIMfAD uses should be understood as an initial framework for organizing knowledge, subject to refinement and future validation through large-scale empirical research.

Future research may further detail BIMfAD processes and advance the consolidation and validation of uses through applications in real contexts, involving different building typologies, project scales, and maturity levels. Case studies that follow buildings throughout life cycle phases may contribute to evaluating the effectiveness of the proposed uses, especially in the stages of use, operation, maintenance, and adaptability, which remain underexplored in the literature. In addition, there is potential for the development of standardized protocols, ontologies, and interoperability models aligned with regulatory frameworks. Finally, the incorporation of BIMfAD requirements and processes into environmental certifications, technical standards, public policies, procurement models, and urban planning strategies may also constitute a relevant strategy to raise sector awareness and stimulate the adoption of adaptability- and deconstruction-oriented processes in the built environment.

Author contributions

Conceptualization, A.K.G.; methodology, A.K.G.; validation, A.K.G.; formal analysis, A.K.G; writing—original draft preparation, A.K.G; writing—review and editing, A.K.G., S.F.T., S.S.; translation – ChatGPT AI; supervision, S.F.T. and S.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflicts of interest.

References

- [1] ONU. United Nation, Department of Economic and Social Affairs. World Urbanization Prospects 2018: Highlights. <https://population.un.org/wup/assets/WUP2018-Highlights.pdf>, 2019 (accessed 10 May 2025).
- [2] UNEP - United Nations Environment Programme; GlobalABC - Global Alliance for Buildings And Construction. *Global Status Report for Buildings and Construction 2022*. <https://globalabc.org>, 2022 (accessed 20 June 2025).
- [3] European Commission. Construction and Demolition Waste (CDW). https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en, 2023 (accessed 20 June 2025).
- [4] ARUP; EMF- Ellen Macarthur Foundation. From principles to practices: realising the value of circular economy in real estate. <https://www.ellenmacarthurfoundation.org/>, 2020 (accessed 05 March 2024).
- [5] M. Munaro; S. Tavares. Design para adaptabilidade e desmontagem (DfAD): critérios para tornar as edificações banco de materiais. V.19 (2022): XIX Encontro Nacional de Tecnologia do Ambiente Construído - ANTAC. <https://doi.org/10.46421/entac.v19i1.1958>.
- [6] E. Durmisevic. Reversible Building design guidelines. BAMB- Buildings as Material banks. <https://www.bamb2020.eu/wp-content/uploads/2018/12/Reversible-Building-Design-guidelines-and-protocol.pdf>, 2018. (accessed 02 April 2025).
- [7] JGV Contreras. Historic Building Information Modelling (HBIM) na Preservação do Patrimônio Arquitetônico Moderno. Dissertação, USP. São Paulo. https://www.teses.usp.br/teses/disponiveis/16/16132/tde-19082024-105226/publico/ME_JOSEGONZALOVIL_CHEZCONTRERAS_rev.pdf, 2024 (accessed 02 May 2025).
- [8] R. Sacks, C. Eastman, G. Lee, P. Teicholz. Manual de BIM: Um Guia de Modelagem da Informação da Construção para Arquitetos, Engenheiros, Gerentes, Construtores e Incorporadores. Terceira edição, Bookman, Porto Alegre, 2021.
- [9] CBIC- Câmara Brasileira da Indústria da Construção. Transformação Digital na Construção: O Papel do BIM e do Portal de Normas Técnicas. <https://cbic.org.br/transformacao-digital-na-construcao-o-papel-do-bim-e-do-portal-de-normas-tecnicas/>, 2024 (accessed 10 May 2025).
- [10] A. Akbarnezhad, KCG Ong, LR Chandra. Economic and environmental assessment of deconstruction strategies using building information modeling, Automation in Construction, v. 34 (january 2014) 131-144. <https://doi.org/10.1016/j.autcon.2013.10.017>.
- [11] ISO- International Organization for Standardization. ISO 20887: Sustainability in buildings and civil engineering works — Design for disassembly and adaptability. https://www.steelconstruct.com/wp-content/uploads/ISO-20887_2020_01.pdf, 2020 (accessed 05 April 2025).

- [12] R. Askar, R., L. Bragança, H. Gervásio. Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings. MDPI, Applied System Innovation, 2022, 5(1), 24. <https://doi.org/10.3390/asi5010024>.
- [13] M. Aziminezhad, R. Taherkhani. BIM for deconstruction: A review and bibliometric analysis. Journal of Buildings Engineering, v. 73 (2023) 106683. <https://doi.org/10.1016/j.jobbe.2023.106683>.
- [14] K. Xue, MD Hossain, M. Liu, M. Ma, Y. Zhang, M. Hu, X. Chen, G. Cao. BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review. Sustainability 2021, 13 (3), 1310. <https://doi.org/10.3390/su13031310>.
- [15] C. Michael. Design for disassembly for facade componentes in the circular economy. <https://www.shareyourgreendesign.com/research/design-for-disassembly-for-facade-components-in-the-circular-economy/>, 2016 (accessed 26 January 2024).
- [16] P. Jaén. Reversible Architecture for a Sustainable Future. Finding out Key Design Guidelines in Early Disassembled Systems. Journal of Sustainable Architecture and Civil Engineering, (2015), v. 12(3). <https://doi.org/10.5755/j01.sace.12.3.12886>
- [17] P. Fernandes, J. Henriques, A. Arruda. Aspectos entre o Design para Adaptabilidade (DfAD) e a Natureza: a bioinspiração em artefatos efêmeros. <https://repositorio.ufsc.br/bitstream/handle/123456789/247006/artigo%204%2060-71.pdf?sequence=1>, 2023 (accessed 19 March 2024).
- [18] P. Crowther. Design for disassembly – Themes and principle. https://www.researchgate.net/publication/27464915_Design_for_Disassembly_-_Themes_and_Principles, 2005 (accessed 26 January 2024).
- [19] B. Costa, J. Diz, M. Oliveira. Cultura de consumismo e geração de resíduos. Revista Brasileira de Estudos Políticos, Belo Horizonte, n. 116, pp. 159-183 (2018). <https://DOI: 10.9732/P.0034-7191.2018V116P159>
- [20] EMF; ARUP. First steps towards a circular built environment. <https://content.ellenmacarthurfoundation.org/m/796c0a8771496309/original/First-steps-towards-a-circular-built-environment.pdf>, 2017 (accessed 02 April 2025).
- [21] EMF. Towards a circular economy: Business rationale for an accelerated transition. <https://content.ellenmacarthurfoundation.org/m/4384c08da576329c/original/Towards-a-circular-economy-Business-rationale-for-an-accelerated-transition.pdf>, 2015 (accessed 20 June 2025).
- [22] E. Durmisevic. Circular economy in construction design strategies for reversible buildings. BAMB. <https://www.bamb2020.eu/wp-content/uploads/2019/05/Reversible-Building-Design-Strategies.pdf>, 2019 (accessed 04 May 2025).
- [23] ISO 59004:2024. Economia Circular – Vocabulário, princípios e orientações para implementação. <https://www.normas.com.br/visualizar/abnt-nbr-nm/13985/abnt-nbriso59004-economia-circular-vocabulario-principios-e-orientacoes-para-implementacao>, 2024 (accessed 12 October 2025).
- [24] ISO 59010:2024 Economia Circular – Orientações sobre a transição de modelos de negócios e redes de valor. <https://www.normas.com.br/visualizar/abnt-nbr-nm/13986/abnt-nbriso59010-economia-circular-orientacoes-sobre-a-transicao-de-modelos-de-negocios-e-redes-de-valor>, 2024 (accessed 12 October 2025).
- [25] ISO 59020:2024. Economia Circular – Mensuração e avaliação do desempenho de circularidade. <https://www.normas.com.br/visualizar/abnt-nbr-nm/13987/abnt-nbriso59020-economia-circular-mensuracao-e-avaliacao-do-desempenho-de-circularidade>, 2024 (accessed 12 October 2025).
- [26] ABNT NBR ISO 19650-1:2022. Organização da informação acerca de trabalhos da construção - Gestão da informação usando a modelagem da informação da construção Parte 1: Conceitos e princípios. <https://pt.scribd.com/document/747681731/ABNT-ISO-19650-1-2022-o>, 2022 2024 (accessed 04 May 2025).
- [27] B. Succar. Building Information Modeling: conceptual constructs and performance improvement tools. Doctor of Philosophy thesis. Faculty of Architecture and the Built Environment Faculty of Engineering and the Built Environment, University of Newcastle, Callaghan, Australia, 2013.
- [28] BIME Initiative (2025), '40. Information Taxonomy'. <https://bimexcellence.org/frameworks/project-information-taxonomy/>, First published 20 June 2016. (accessed 17 November 2025).
- [29] B. Succar, N. Saleeb, W. Sher. Model Uses: Foundations for a Modular Requirements Clarification Language. Australasian Universities Building Education Association Conference (AUBEA 2016), Cairns, Australia, July 6–8. <http://bit.ly/BIMPaperA10>, 2016 (accessed 05 April 2025).
- [30] J. Messner, C. Anumba, C. Dubler, S. Goodman, C. Kasprzak, R. Kreider, R. Leicht, C. Saluja, N. Zikic, S. Bhawani. BIM Project Execution Planning Guide, Version 3.0. Computer Integrated Construction Program, Penn State. University Park, PA, USA. 2021.
- [31] H. Ferenhof, R. Fernandes. Desmistificando a revisão de literatura como base para redação científica: Método SSF (Systematic Search Flow). Revista ACB: Biblioteconomia em Santa Catarina, Florianópolis, SC: v. 21, n. 3, p. 550-563, ago./nov., 2016.
- [32] MJ Page, JE McKenzie, PM Bossuyt, I. Boutron, TC Hoffmann, CD Mulrow, L. Shamseer, JM Tetzlaff, EA Akl, SE Brennan, R. Chou, J. Glanville, JM Grimshaw, A. Hróbjartsson, MM Lalu, T. Li, EW Loder, E. Mayo-Wilson, S. McDonald, LA Mcguinness, LA Stewart, J. Thomas, AC Tricco, VA Welch, P. Whiting, D. Moher. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. 2021. <https://doi.org/10.1136/bmj.n71>.
- [33] O. Akinade, L. Oyedele, S. Ajayi, M. Bilal, H. Alaka, H. Owolabi, O. Arawomo. Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. Journal of Cleaner Production, v. 180 (2018), pp. 375-385. <https://doi.org/10.1016/j.jclepro.2018.01.022>.
- [34] S. Kim, SA Kim. A design support tool based on building information modeling for design for deconstruction: A graph-based deconstructability assessment approach. Journal of Cleaner



- Production, v. 383 (2023), 135343. <https://doi.org/10.1016/j.jclepro.2022.135343>.
- [35] R. Machado, H. Souza, G. Veríssimo. Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings. *Sustainability* (2018), 10(8) 2604. <https://doi.org/10.3390/su10082604>.
- [36] S. Abrishami, R. Martín-Durán. BIM and DfMA: A Paradigm of New Opportunities. *Sustainability*, (2021), 13(17), 9591. <https://doi.org/10.3390/su13179591>.
- [37] B. Sanchez, S. Halder, R. Soman, OY Yu. 2024. BIM Model View Definition (MVD) for disassembly planning of buildings. <https://doi.org/10.22260/ISARC2024/0155>
- [38] M. Van Den Berg, E. Durmisevic. BIM uses for reversible building design: Identification, classification & elaboration. 2017. In E. Durmisevic (Ed.), *Vital cities and reversible buildings: conference proceedings Sarajevo Green Design Foundation*. https://www.researchgate.net/publication/320299682_BIM_uses_for_reversible_building_design_Identification_classification_elaboration (accessed 05 May 2025).
- [39] RJ Geldermans. Design for change and circularity – accommodating circular material & product flows in construction. *Energy Procedia*, v. 96 (2016), pp. 301-311. <https://doi.org/10.1016/j.egypro.2016.09.153>.
- [40] K. Ostapska, P. Rüter, A. Loli, K. Gradeci. Design for Disassembly: A systematic scoping review and analysis of built structures Designed for Disassembly. *Sustainable Production and Consumption*, v. 48, (2024), pp. 377-395. <https://doi.org/10.1016/j.spc.2024.05.014>.
- [41] C. Roxas, C. Bautista, O. Dela Cruz, R. Dela Cruz, JP De Pedro, J. Dungca, B. Lejano, J. Ongpeng. Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. *Buildings* (2023), 13(5) 1164. <https://doi.org/10.3390/buildings13051164>.
- [42] E. Durmisevic, M. Berg, U. Atteya. Design Support for revisable buildings with focus on visualizing and simulating transformation capacity during initial design phase. 2017. *International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste*. <https://www.bamb2020.eu/wp-content/uploads/2017/07/Design-Support-for-revisable-buildings-with-focus-on-visualizing-and-simulating-transformation-capacity-during-initial-design-phase.pdf>, (accessed 03 May 2025).
- [43] S. Attia, M. Al-obaidy, M. Mori, C. Campain, E. Giannasi, M. Van Vliet, E. Gasparri. Disassembly calculation criteria and methods for circular construction. 2024. <https://doi.org/10.1016/j.autcon.2024.105521>.
- [44] R. Charef. The use of Building Information Modelling in the circular economy context: Several models and a new dimension of BIM (8D). *Cleaner Engineering and Technology*, v. 7 (2022), 100414. <https://doi.org/10.1016/j.clet.2022.100414>
- [45] S. Brancart, A. Paduart, A. Vergauwen, C. Vandervaeren, L. de Laet, N. de Temmerman. Transformable structures: materialising design for change. *International Journal of Design & Nature and Ecodynamics* 12(3):357-366 (2017). DOI:10.2495/DNE-V12-N3-357-366
- [46] P. Zadeh, F. Calderon, S. Staub-French, I. Chikhi. Building Information Modeling (BIM) and Design for Manufacturing and Assembly (DfMA) for Mass Timber Construction. 2018. https://www.researchgate.net/publication/329337062_Building_Information_Modeling_BIM_and_Design_for_Manufacturing_and_Assembly_DfMA_for_Mass_Timber_Construction, (accessed 04 May 2025).
- [47] X. Wang, Y. Li, Z. Zhou, X. Lv, P. Yuan, L. Chen. Levelling Calibration and Intelligent Real-Time Monitoring of the Assembly Process of a DfD-Based Prefabricated Structure Using a Motion Capture System. 2023. DOI:10.1007/978-981-19-8637-6_45.
- [48] G. Finch, G. Marriage, M. Gjerde, A. Pelosi, Y. Patel. Understanding the challenges of circular economy construction through full-scale prototyping. 2020. https://www.researchgate.net/publication/349620529_Understanding_the_challenges_of_circular_economy_construction_through_full-scale_prototyping, (accessed 04 May 2025).
- [49] A. Basta, M. Serror, M. Marzouk. A BIM-based framework for quantitative assessment of steel structure deconstructability. 2020. <https://doi.org/10.1016/j.autcon.2019.103064>.
- [50] R. Charef, H. Alaka, E. Ganjian. A BIM-based theoretical framework for the integration of the asset End-of-Life phase. *IOP Conf. Ser.: Earth Environ. Sci.* 225 012067. 2019. DOI 10.1088/1755-1315/225/1/012067.
- [51] A. Elmaraghy, H. Voordijk, M. Marzouk. An exploration of BIM and Lean interaction in optimizing demolition projects. Conference: 26th Annual Conference of the International Group for Lean Construction, 2018. DOI:10.24928/2018/0474.
- [52] LObi, B. Awuzie, C. Obi, T. Omotayo, A. Oke, O. Osobajo. BIM for Deconstruction: An Interpretive Structural Model of Factors Influencing Implementation. 2021. <https://doi.org/10.3390/buildings11060227>.
- [53] M. Van Den Berg, H. Voordijk, A. Adriaanse. BIM uses for deconstruction: an activitytheoretical perspective on reorganising end-of-life practices. *Buildings* (2021), 11(6), 227. <https://www.tandfonline.com/doi/full/10.1080/01446193.2021.1876894>, (accessed 06 February 2025).
- [54] A. Akbarieh, L. Jayasinghe, D. Waldmann, F. Teferle. BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. *Sustainability* (2020), 12(7), 2670. <https://doi.org/10.3390/su12072670>.
- [55] X. Janet Ge, P. Livesey, J. Wang, S. Huang, X. He, C. Zhang. Deconstruction waste management through 3d reconstruction and bim: a case study. *Visualization in Engineering* 5(1) (2017). DOI:10.1186/s40327-017-0050-5.
- [56] E. Iacovidou, P. Purnell, K. Tsavdaridis, K. Poologanathan. Digitally Enabled Modular Construction for Promoting Modular Components Reuse: A UK View. *Journal of Building Engineering*, v. 42, (2021) 102820. <https://doi.org/10.1016/j.jobe.2021.102820>.
- [57] B. Sanchez, P. Herthogs, R. Stouffs. Identifying key parameters for BIM-based disassembly planning. 2023. Conference: 40th International Symposium on

- Automation and Robotics in Construction. DOI:10.22260/ISARC2023/0007.
- [58] S. Hei, H. Zhang, S. Luo, R. Zhang, C. Zhou, M. Cong, H. Ye. Implementing BIM and Lean Construction Methods for the Improved Performance of a Construction Project at the Disassembly and Reuse Stage: A Case Study in Dezhou, China. *Sustainability* 2024, 16(2), 656. <https://doi.org/10.3390/su16020656>.
- [59] B. Huang, H. Zhang, W. Yang, H. Ye, B. Jiang. Mechanical carbon emission assessment during prefabricated building deconstruction based on BIM and multi-objective optimization. *Scientific Reports*. 2024. DOI:10.1038/s41598-024-78305-6.
- [60] B. Wu, R. Maalek. Renovation or Redevelopment: The Case of Smart Decision-Support in Aging Buildings. *Smart Cities* (2023), 6(4), 1922-1936. <https://doi.org/10.3390/smartcities6040089>.
- [61] Z. Zhao. Research on building deconstruction based on BIM Technology. *Theoretical and Natural Science* 14(1):18-26 (2023). DOI:10.54254/2753-8818/14/20240869.
- [62] L. Akanbi, L. Oyedele, J. Delgado, M. Bilal, O. Akinade, A. Ajayi, N. Mohammed-Yakub. Reusability analytics tool for end-of-life assessment of building materials in a circular economy. *World Journal of Science Technology and Sustainable Development* 16(2) 2018. DOI:10.1108/WJSTSD-05-2018-0041.
- [63] L. Mattaraia, M. Fabricio, R. Codinhoto. Structure for the classification of disassembly applied to BIM models. *Architectural Engineering and Design Management*, v. 19 (2021) pp. 56-73. <https://doi.org/10.1080/17452007.2021.1956420>.
- [64] H. Balogun, H. Alaka, C. Egwim, S. Ajayi. Systematic review of drivers influencing building deconstructability: Towards a construct-based conceptual framework. *Waste Management & Research* 41(3) (2022). DOI:10.1177/0734242X221124078.
- [65] I. Bertin, R. Mesnil, JM Jaeger, A. Feraille, R. Le Roy. A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements. *Sustainability* (2020), 12(8), 3147. <https://doi.org/10.3390/su12083147>.
- [66] O. Akinade, L. Oyedele, K. Omoteso, S. Ajayi, M. Bilal, H. Owolabi, H. Alaka, L. Ayris, J. Looney. BIM-based deconstruction tool: Towards essential functionalities. *International Journal of Sustainable Built Environment*, v. 6, issue 1 (2017) pp. 260-271. <https://doi.org/10.1016/j.ijbsbe.2017.01.002>.
- [67] IE Gherman, ES Lakatos, S. Clinci, F. Lungu, V. Constandoiu, L. Cioca, EC Rada. Circularity Outlines in the Construction and Demolition Waste Management: A Literature Review. *Recycling* (2023), 8(5), 69. <https://doi.org/10.3390/recycling8050069>.
- [68] I. Bertin, F. Lebrun, N. Braham, R. Le Roy. Construction, deconstruction, reuse of the structural elements: the circular economy to reach zero carbon. *IOP Conference Series Earth and Environmental Science* 323(1):012020 (2019). DOI:10.1088/1755-1315/323/1/012020.
- [69] B. Sanchez, C. Rausch, C. Haas. Deconstruction programming for adaptive reuse of buildings. *Automation in Construction*, v. 107 (2019) 102921. <https://doi.org/10.1016/j.autcon.2019.102921>.
- [70] M. Bilal, L. Oyedele, O. Akinade, J. Delgado, L. Akanbi, A. Ajayi, M. Younis. Design optimisation using convex programming: Towards waste-efficient building designs. *Journal of Building Engineering* 23 (2019) 231-240. <https://doi.org/10.1016/j.jobbe.2019.01.022>.
- [71] E. Durmisevic, A. Guerriero, C. Boje, B. Domange, G. Bosch. Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision making and facilitate a circular economy. 2021. https://www.researchgate.net/publication/357914417_Development_of_a_conceptual_digital_deconstruction_platform_with_integrated_Reversible_BIM_to_aid_decision_making_and_facilitate_a_circular_economy, (accessed 03 May 2025).
- [72] L. Akanbi, L. Oyedele, K. Omoteso, M. Bilal, O. Akinade, A. Ajayi, J. Delgado, H. Owolabi. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, v. 223 (2019) pp. 386-396. <https://doi.org/10.1016/j.jclepro.2019.03.172>.
- [73] A. Dervishaj, J. Vargas, K. Gudmundsson. Enabling reuse of prefabricated concrete components through multiple tracking technologies and digital twins. 2023 European Conference on Computing in Construction 40th International CIB W78 Conference Heraklion, Crete, Greece (2023). DOI: 10.35490/EC3.2023.220.
- [74] X.Wang, Z. Liu, J. Cui, M. Osmani, P. Demian. Exploring Building Information Modeling (BIM) and Internet of Things (IoT) Integration for Sustainable Building. *Buildings* 2023, 13(2), 2882023. <https://doi.org/10.3390/buildings13020288>.
- [75] S. Benjamin, R. Christopher, H. Carl. Feature modeling for configurable and adaptable modular buildings. *Advanced Engineering Informatics*, v. 51 (2022), 101514. <https://doi.org/10.1016/j.aei.2021.101514>.
- [76] L. Caldas, M. Silva, V. Silva, M. Carvalho, R. Toledo Filho. How Different Tools Contribute to Climate Change Mitigation in a Circular Building Environment?— A Systematic Literature Review. *Sustainability* (2022), 14(7), 3759. <https://doi.org/10.3390/su14073759>.
- [77] M. Lebossé, G. Halin, F. Besançon, A. Fuchs. Incorporating BIM Practices into Reuse Process of Timber. Propositions of a digital workflow and tool for reclaiming structural pieces of wood. 2022. DOI: 10.52842/conf.ecaade.2022.1.205.
- [78] P. Lima, C. Rodrigues, J. Post. Integration of BIM and design for deconstruction to improve circular economy of buildings. *Journal of Building Engineering*, v. 80 (2023) 108015. <https://doi.org/10.1016/j.jobbe.2023.108015>.
- [79] E. Marino, A. Paoluzzi, F. Spini, D. Salvati. Modeling Semantics for Building Deconstruction. 12th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (2017), pp. 274-281. DOI: 10.5220/0006227902740281.
- [80] SE Janani, SM Renuka, C. Umarani. Quantification of the deconstruction potential of buildings with innovative connections using BIM based DAS (Deconstructability Assessment Score) tool. *Materialstoday: proceedings*, v. 65, part 2 (2022) pp. 1964-1975. <https://doi.org/10.1016/j.matpr.2022.05.209>.

- [81] L. Akanbi, L. Oyedele, O. Akinade, A. Ajayi, M. Delgado, M. Bilal, S. Bello. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, v. 129 (2018) pp. 175-186. <https://doi.org/10.1016/j.resconrec.2017.10.026>.
- [82] X. Hu, Y. Zhou, S. Vanhullebusch, R. Mestdagh, Z. Cui, J. Li. Smart building demolition and waste management frame with image-to-BIM. *Journal of Building Engineering* 49:104058 (2022). DOI:10.1016/j.jobe.2022.104058.
- [83] S. Akbari, M. Sheikhhoshkar, F. Rahimian, H. Haouzi, M. Najafi, S. Talebi. Sustainability and building information modelling: Integration, research gaps, and future directions. *Automation in Construction*, v. 163 (2024) 105420. <https://doi.org/10.1016/j.autcon.2024.105420>.
- [84] D. Schwede, E. Störl. System for the analysis and design for disassembly and recycling in the construction industry. 2016. https://www.researchgate.net/publication/305626924_System_for_the_analysis_and_design_for_disassembly_and_recycling_in_the_construction_industry, (accessed 04 May 2025).
- [85] E. Durmisevic, P. Beurskens, R. Adrosevic, R. Westerdijk. Systemic view on reuse potential of building elements, components and systems - comprehensive framework for assessing reuse potential of building elements. 2017. International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste. <https://www.bamb2020.eu/wp-content/uploads/2017/07/Systemic-view-on-Reuse-Potential-of-building-elements-components-and-systems-Comprehensive-Framework-for-assessing-Reuse-Potential-of-Building-Elements.pdf>, (accessed 03 May 2025).
- [86] A. Behúnová, T. Mandičák, M. Behún, P. Mésároš. The Building Information Modelling Through Information Technology and Impacts on Selected Circular Economy Performance Indicators of Construction Projects. *Mobile Networks and Applications* 29(2):506-515 (2023). DOI:10.1007/s11036-023-02268-7.
- [87] R. Askar, F. Karaca, L. Bragança, H. Gervásio. The Role of BIM in Supporting Circularity: A Conceptual Framework for Developing BIM-Based Circularity Assessment Models in Buildings. 4th International Conference "Coordinating Engineering for Sustainability and Resilience" & Midterm Conference of CircularB "Implementation of Circular Economy in the Built Environment" (2024) pp.649-658. DOI:10.1007/978-3-031-57800-7_60.
- [88] DENIS, F., VANDERVAEREN, C., DE TEMMERMAN, N. Using Network Analysis and BIM to Quantify the Impact of Design for Disassembly. *Buildings* (2018), 8(8), 113. <https://doi.org/10.3390/buildings8080113>.
- [89] B. Soust-Verdaguer, C. Llatas, A. García-Martínez. Critical review of bim-based LCA method to buildings. *Energy and Buildings*, v. 136 (2017) pp. 110-120. <https://doi.org/10.1016/j.enbuild.2016.12.009>.
- [90] A. Tomczak, C. Benghi, L. Van Berlo, E. Hjelseth. Requiring Circularity Data in BIM With Information Delivery Specification. *Journal of Circular Economy*, Vol. 1 No. 2 (2024): Special Issue - Digital Pathways to Circular Construction: Data, Design, and Reuse Across the Building Life Cycle (2024). DOI: <https://doi.org/10.55845/REJY5239>.
- [91] B. Sanchez, M. Honic, F. Leite, P. Herthogs, R. Stouffs. Augmenting materials passports to support disassembly planning based on building information modelling standards. *Journal of Building Engineering*, v. 90 (2024) 109083. <https://doi.org/10.1016/j.jobe.2024.109083>.
- [92] M. Maraqa, S. Spatari. BIM material passport to support building deconstruction and a circular economy. 2022. The Twelfth International Conference on Construction in the 21st Century (CITC-12). https://www.researchgate.net/publication/362567065_BIM_material_passport_to_support_building_deconstruction_and_a_circular_economy, (accessed 06 February 2025).
- [93] S. Schaubroeck, R. Dewil, K. Allacker. Circularity of building stocks Modelling building joints and their disassembly in a 3D city model. *Procedia CIRP*, v. 105 (2022) pp. 712-720. <https://doi.org/10.1016/j.procir.2022.02.119>.
- [94] I. Atta, E. Bakhoun, M. Marzouk. Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, v. 43 (2021) 103233. <https://doi.org/10.1016/j.jobe.2021.103233>.



Integrating virtual reality, augmented reality, and artificial intelligence for circular and sustainable construction practices

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ABSTRACT

The increasing demand for sustainable and efficient construction practices has accelerated the adoption of advanced digital technologies across the sector. This paper presents a conceptual framework based on a systematic theoretical review of the combined potential of Artificial Intelligence (AI), Virtual Reality (VR), and Augmented Reality (AR) to transform construction workflows and support the transition to circular, resource-efficient building practices. VR enhances design comprehension and stakeholder communication through immersive visualization, while AR enables real-time onsite guidance and augmented inspections, improving accuracy and reducing execution errors. Complementing these capabilities, AI introduces predictive analytics, automated defect detection, and data-driven optimisation of materials, labour, and lifecycle performance. By integrating these technologies into a unified digital ecosystem, construction projects can significantly reduce waste, improve quality, and strengthen decision-making throughout the project lifecycle. The proposed conceptual framework illustrates how immersive environments and intelligent analysis can operate in synergy to support sustainability objectives, including lifecycle extension, improved resource efficiency, and alignment with circular economy principles. No empirical component is included; empirical validation of the framework in real construction projects is identified as a primary direction for future research. This study contributes to the ongoing digital transformation of the construction industry by articulating a holistic, lifecycle-spanning perspective on integrating VR, AR, and AI, providing a replicable foundation for future research and practical implementation.

1 Introduction

The construction industry is undergoing a crucial period of transformation driven by the global demand for sustainable development, increased efficiency, and the integration of advanced digital technologies. Historically characterized by high material consumption, fragmented communication, and limited real-time control, the construction sector continues to face challenges, including cost overruns, delays, rework, and significant environmental impacts [1]. The growing complexity of infrastructure projects, stricter regulatory requirements, and global commitments to carbon reduction and resilient urban development further intensify these issues. As a result, the traditional workflows and methodologies used in construction are no longer sufficient to meet modern performance expectations [2].

Digital transformation has emerged as a strategic pathway to address these persistent challenges. Over the

past decade, the adoption of Building Information Modeling (BIM) [3] Sensors, simulation tools, and data-driven management systems have laid the foundation for more intelligent, connected project environments. However, the recent rise of immersive technologies, such as Virtual Reality (VR) and Augmented Reality (AR), and advances in computational intelligence through Artificial Intelligence (AI) have accelerated this evolution [4]. These technologies collectively offer the potential to redefine how construction projects are planned, monitored, and executed.

VR provides fully immersive, computer-generated environments that allow stakeholders to explore and interact with virtual models before construction begins. This capability improves design understanding, supports design validation, and enables early detection of conflict areas that might otherwise go unnoticed. AR, on the other hand, enriches real-world jobsite conditions with digital content, projecting BIM elements onto physical environments to facilitate real-time inspections, quality control, and more

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accurate assembly and installation processes [5]. These immersive tools significantly enhance communication and collaboration among architects, engineers, contractors, and clients by making complex information more accessible and understandable.

AI complements VR and AR by enabling automation, prediction, and real-time decision-making. Machine learning and computer vision techniques can analyze large volumes of visual and numerical data to detect defects, evaluate construction progress, optimize resource allocation, and forecast potential risks [6]. Through predictive analytics, AI helps minimize construction waste, reduce the likelihood of costly errors, and promote more efficient use of materials, key principles aligned with the circular economy. The integration of these digital technologies introduces a new level of intelligence across construction workflows, merging immersive interaction with data-driven insights.

Despite the clear potential of VR, AR, and AI, current research remains fragmented. Many studies focus on isolated applications, such as AI for defect detection, VR for training, or AR for site visualisation, without exploring how these technologies can work together to create a holistic digital ecosystem that improves sustainability and operational performance [7]. Moreover, the practical implementation of such integrated systems presents conceptual, technical, and organisational barriers that require deeper theoretical examination.

This paper aims to provide a thorough theoretical analysis of how integrating AI, VR, and AR can enhance construction processes. The study examines their combined potential to improve visualisation, automate quality control, strengthen decision-making, and support more efficient and sustainable resource use, in line with the principles of the circular economy. This article also outlines future research directions and proposes a conceptual framework for integrating these technologies into construction environments, providing a foundation for academics and practitioners seeking to adopt advanced digital solutions.

This study is guided by the following research question: how can the integrated application of VR, AR, and AI transform construction workflows to support resource efficiency, quality control, and the transition to circular economy principles across the building lifecycle? To address this question, the paper conducts a systematic theoretical analysis of the technical capabilities and synergies of each technology, framing their combined potential within a conceptual integration model that spans design, construction, quality assurance, and post-construction maintenance. Within this scope, "resource prediction" refers specifically to the anticipation of material quantities, labour needs, and equipment utilisation based on three primary input streams: BIM-derived geometric and semantic data; historical project records encompassing productivity rates and waste generation logs; and real-time site data captured through IoT sensors, drones, and photogrammetric systems. The prediction time horizon ranges from short-term operational decisions (daily to weekly scheduling) to medium-term project planning (monthly milestones), with accuracy evaluated through standard regression metrics such as Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE), or classification metrics such as F1-score for defect detection applications.

Compared with prior reviews that address VR [1], AR [19,20], or AI [12] in isolation, the specific scientific contribution of this paper lies in its unified theoretical framing of these three technologies as an interdependent ecosystem. Unlike earlier integration studies that tend to focus on

specific project phases or individual application domains, this work articulates a lifecycle-spanning conceptual framework that connects design, construction execution, quality assurance, and post-construction maintenance, and explicitly links the technological integration to circular economy performance indicators. This positions the present study as a synthesis contribution that bridges the gap between technology-specific literature and systems-level sustainability objectives in the construction sector.

2 Background: digital transformation in construction

Over the past three decades, the digital transformation of the construction industry has gradually unfolded, fundamentally altering how projects are conceptualized, designed, coordinated, and executed. Traditionally, the construction sector has been marked by fragmented workflows, low levels of automation, and a heavy reliance on manual documentation systems, all of which have contributed to inefficiencies, rework, and communication breakdowns [6]. As global challenges such as climate change, urbanization, workforce shortages, and resource scarcity become increasingly pressing, the limitations of conventional practices have come to the forefront. This has generated significant momentum toward the adoption of digital technologies that foster more innovative, safer, and more sustainable project environments [8].

2.1 From manual workflows to digital foundations

Initially, construction practices relied heavily on manual drafting, physical models, and paper-based documentation. This dependency led to frequent communication gaps, inconsistencies in project documentation, and a heightened risk of error propagation. The introduction of computer-aided design (CAD) in the late 20th century marked a significant shift towards digital workflows, facilitating faster drafting and enhancing accuracy [9]. However, CAD models largely remained geometric representations that lacked embedded information and coordination capabilities.

The emergence of BIM marked a second, more transformative wave of digitalization. BIM integrates geometrical, structural, and operational data into a cohesive model, serving as a shared knowledge resource accessible throughout the project's lifecycle [2]. This advancement improved interdisciplinary coordination, clash detection, cost estimation, and scheduling. Nevertheless, BIM models tend to be static, offering limited real-time interaction and predictive capabilities.

2.2 Rise of immersive technologies

To overcome the limitations of static digital modeling, immersive technologies, especially VR and AR, have emerged as powerful tools for enhancing on-site design comprehension and accuracy. VR allows stakeholders to immerse themselves and navigate in digital models, providing a deeper understanding of spatial relationships, design intent, and potential safety risks [1]. This capability fosters improved interdisciplinary coordination and significantly reduces design-related errors, particularly in complex projects such as hospitals, industrial facilities, and transportation infrastructure.

Conversely, AR offers dynamic overlays of digital content onto the physical condition of a job site. Unlike VR, which creates an entirely virtual environment, AR enriches the real world, enabling workers, inspectors, and engineers to

visualize and dialogue with BIM elements directly on site. This facilitates tasks such as installation alignment, layout verification, clash detection, quality assurance (QA/QC) [10] and expands the understanding of physical reality. AR technologies, accessible on tablets, smartphones, or wearable headsets like the Microsoft HoloLens, represent a significant advancement in bridging the gap between digital project information and physical construction activities.

2.3 Emergence of data-driven intelligence

While VR and AR enhance visualisation, they do not inherently provide predictive or analytical capabilities. The next phase of digital transformation in construction is characterised by the integration of AI, which automates, enables learning, and supports data-driven decision-making across construction workflows [11].

Machine learning algorithms can analyse historical and real-time data to forecast schedule delays, optimise material quantities, and identify patterns that indicate safety risks or structural anomalies. Additionally, computer vision systems can automatically detect defects, such as cracks, misalignments, corrosion, or missing components, in images, videos, or drone-captured data [12]. Advanced deep learning architectures enable precise segmentation of point clouds, thereby improving the accuracy of digital twins and supporting as-built verification.

AI effectively shifts the construction industry from reactive to predictive and proactive methodologies. When paired with VR and AR, AI serves as the analytical engine that enriches immersive data visualization, allowing construction teams to access predictions, alerts, and recommendations directly within simulated or physical environments [13].

3 Technologies in detail

The integration of VR, AR, and AI represents one of the most significant advancements in the construction industry's digital transformation. Although these technologies are often examined independently, their combined potential can be fully understood only by examining their technical foundations, operational capabilities, and inherent limitations. VR provides fully immersive and interactive digital synthetic environments that enhance spatial comprehension, facilitate design validation, and allow teams to simulate construction sequences or safety scenarios before project execution [14]. AR extends these capabilities into the physical jobsite by overlaying digital information, such as BIM components, annotations, or quality-control indicators, onto real-world environments, supporting precision during installation, onsite verification, and real-time problem-solving [7]. AI, meanwhile, introduces powerful predictive and analytical capabilities through computer vision, machine learning, and data-driven optimization, enabling automated defect detection, progress monitoring, and resource forecasting. Taken together, these technologies form a complementary ecosystem in which immersive visualization enhances the interpretation of AI insights, and AI algorithms, in turn, strengthen the performance of VR and AR applications through real-time analytics and intelligent feedback loops [13].

Understanding the evolution, applications, and constraints of each technology is therefore essential for evaluating their synergistic impact on construction

workflows. Over the past decade, VR and AR tools have advanced significantly in terms of hardware performance, rendering capabilities, and device portability, making immersive environments more accessible to design teams and field personnel alike [14]. Similarly, AI techniques, particularly deep learning, computer vision, and natural language processing, have matured to process increasingly complex datasets captured through drones, mobile devices, LiDAR, and IoT sensors. However, challenges remain, including interoperability gaps across platforms, computational requirements, limitations in data quality, and workforce training needs. By examining the strengths and weaknesses of VR, AR, and AI collectively, this section lays the groundwork for a holistic understanding of how these technologies can be integrated into a unified digital framework capable of transforming construction planning, execution, and lifecycle management.

3.1 Virtual Reality (VR)

VR is a computer-generated, three-dimensional environment that immerses users in a fully digital world, allowing them to perceive, navigate, and interact with virtual elements as if they were physically present in the simulated space [6]. Unlike traditional visualization methods that rely on flat, two-dimensional screens, VR creates a sense of presence, often described as "being inside" the digital environment, by using head-mounted displays (HMDs), motion-tracking systems, and stereoscopic rendering techniques [15]. These systems track the user's head and body position and orientation in real time, adjusting visual and auditory stimuli accordingly to create a natural and intuitive experience [1]. VR can also be enhanced in full-body environments so-called CAVE (Cave Automatic Virtual Environments) using audiovisual content, projections, voice recognition and lightning.

VR environments are designed to replicate real-world conditions or generate simulated scenarios that may not yet exist, making them particularly valuable for construction applications [16]. Through VR, users can explore full-scale digital models, assess spatial layouts, examine constructability, and identify potential design conflicts long before any physical work begins [1]. The ability to move freely within the virtual environment enhances depth perception and spatial understanding, helping stakeholders visualize geometric relationships, structural configurations, and architectural features with far greater clarity than traditional drawings or flat-screen 3D models. The modularity of VR technologies expands the range of human visual perception with x-ray, wireframe, thermic and conflict-based scenarios.

Moreover, VR supports interactive behaviors within these environments. Users can manipulate objects, test different design alternatives, simulate construction sequences, rehearse safety procedures, or evaluate logistical constraints [14]. Advanced VR systems integrate haptic feedback, providing tactile sensations that further enhance realism and user engagement [1]. By creating a high-fidelity representation of the built environment, VR enables more informed decision-making, improves interdisciplinary coordination, and reduces the cognitive effort required to interpret complex technical information.

This combination of immersion, interaction, and realism makes VR one of the most transformative technologies in the construction industry, capable of bridging the gap between digital design and physical execution [1].

3.1.1 Types of VR in construction

VR systems employed in construction can be categorized into three primary formats:

- **Immersive VR** [17]: Utilizes HMDs such as Oculus Quest, HTC Vive, or Meta XR, allowing stakeholders to virtually “walk through” a building before construction begins. Immersive VR is beneficial for design validation, safety training, and stakeholder engagement.

- **Semi-immersive VR** [17]: Involves large projection screens or CAVE systems, providing partial immersion. These setups support collaborative design review among multiple users.

- **Non-immersive VR (desktop VR)** [17]: Relies on traditional monitors and offers simpler navigation through 3D environments. Though less immersive, it is more accessible and frequently used for preliminary design analysis.

3.1.2 Applications of VR in construction

VR enables a wide range of applications across the construction lifecycle by providing immersive and interactive digital environments that support planning, training, decision-making, and communication [17]. One of the most prominent uses of VR lies in design and planning optimisation, where immersive visualisation allows teams to evaluate spatial layouts, circulation patterns, sightlines, and ergonomic considerations at early project stages. Unlike traditional 2D drawings or non-immersive 3D models, VR enables users to experience the space at full scale, walk through rooms and corridors, assess design alternatives, and identify potential conflicts related to geometry, accessibility, or human behaviour [18]. This capability not only improves design quality but also reduces the likelihood of costly modifications during construction.

VR also plays a critical role in safety training, an essential aspect of construction management due to the high-risk nature of many onsite activities. Through realistic simulations of hazardous scenarios, such as falls from heights, equipment collisions, unstable scaffolding, or confined-space risks, VR provides workers with controlled environments in which to practice appropriate responses without exposure to real danger [16]. Immersive safety training has been shown to improve risk perception, knowledge retention, and situational awareness, ultimately contributing to fewer accidents and safer job sites.

In addition, VR enhances construction sequencing and logistics planning by enabling teams to visualise the step-by-step progression of activities before work begins. Construction managers can simulate equipment movements, crane positioning, delivery routes, material staging areas, and temporary structures within the virtual environment [15]. These simulations enable stakeholders to identify spatial conflicts, optimise workflows, and evaluate alternative strategies to reduce bottlenecks. By visualising construction processes in 4D, integrating time as a simulation component, teams gain a clearer understanding of sequencing dependencies and potential impacts on schedule and cost.

Another key application of VR is stakeholder communication and engagement, particularly with clients, facility managers, or community members who may not possess technical backgrounds. VR simplifies the interpretation of complex design information by enabling non-experts to understand architectural intent, structural features, interior layouts, material options and the effect of natural light in an intuitive, immersive way [16]. This

capability reduces misunderstandings, facilitates more informed decision-making, and strengthens collaboration between project teams and stakeholders. VR also supports remote participation, enabling geographically dispersed individuals to join virtual walkthroughs, evaluate design proposals, and provide real-time feedback.

VR environments can visualise “buildings as material banks,” showing material provenance, bill of quantities, and disassembly procedures to support future reuse and recycling. Material and components can be viewed and advertised digitally, thereby implementing a digital market of used construction elements. A number of hidden features can be added to the VR model and be triggered during navigation to provide information about hidden or inaccessible elements. This is an important feature of VR when designing for assembly and disassembly, helping to program sequences of separation and calculate the potential of building circularity [19].

Overall, VR serves as a powerful tool that enhances design quality, improves planning accuracy, strengthens safety culture, and fosters collaborative decision-making. Its ability to merge visualisation with simulation provides a foundation for more efficient, transparent, and informed construction processes.

3.1.3 Limitations and Challenges of VR

Despite its transformative potential, VR adoption in the construction industry faces several technical, organisational, and practical challenges that limit its large-scale implementation. One of the primary constraints relates to hardware and computational requirements. High-fidelity VR environments demand significant processing power to render large BIM models, complex geometries, and realistic lighting conditions at interactive frame rates [15]. Many construction projects involve intricate structural components and high-resolution textures that can overload standard VR systems, causing latency, reduced image quality, or motion sickness among users [16]. These performance constraints require advanced graphics cards, powerful processors, and optimised modelling practices, which can increase implementation costs and raise the barriers to widespread adoption.

Another challenge concerns integrating BIM models into VR environments. Although BIM provides detailed 3D representations of buildings, these models are often too heavy, fragmented, or semantically inconsistent to be used directly in VR applications [16]. Converting BIM data into VR-ready formats may require extensive preprocessing, such as model simplification, mesh optimization, or removal of non-essential elements [15]. These additional steps increase preparation time and demand specialized digital skills. Furthermore, inconsistencies between BIM authoring platforms and VR engines can create interoperability issues, hindering seamless information transfer between tools.

User-related limitations also play a significant role. Many construction professionals may experience cyber-sickness, characterized by dizziness or nausea resulting from visual-vestibular conflict when navigating virtual spaces [16]. Prolonged VR exposure can lead to fatigue, discomfort, and reduced productivity, which may discourage continued use. Additionally, operating VR systems requires a learning curve; not all workers or stakeholders possess the digital literacy necessary to interact effectively with immersive environments [15]. Organizations must therefore invest in training programs and digital upskilling to ensure effective adoption of tools.

Practical constraints at the jobsite level also hinder VR implementation. VR requires controlled environments where users can move safely without obstacles, which is difficult to ensure on active construction sites, where equipment, uneven surfaces, and safety risks abound [7]. This limits VR's use primarily to off-site design review, training facilities, or dedicated virtual coordination rooms [16]. While mobile VR devices exist, they often lack the fidelity, tracking accuracy, or robustness needed for construction-level applications.

Cost remains another significant barrier. High-quality VR headsets, motion trackers, and powerful computing hardware can be expensive, especially for small and medium-sized firms with limited budgets. Although technology prices are gradually decreasing, additional costs related to software licenses, training, and digital content creation still represent a substantial investment [16]. Without clear cost-benefit benchmarks or industry-wide guidelines, many companies struggle to justify VR adoption.

Finally, limited standardisation poses a strategic challenge. There is currently no universal framework for integrating VR with BIM, scheduling tools, or project management platforms [16]. As a result, VR solutions remain fragmented, with inconsistent data structures, varying levels of detail, and differing visualisation standards across projects [15]. This lack of standardisation reduces interoperability and complicates collaborative workflows.

3.2 Augmented Reality (AR)

AR enhances the physical environment by overlaying digital information, such as BIM components, annotations, construction tolerances, safety indicators, and geometric guidelines, directly into the user's field of view [20]. Unlike VR, which immerses users in a fully synthetic digital world, AR preserves the physical surroundings and enriches them with contextual digital content. This mixed visualisation allows users to simultaneously perceive actual construction conditions and the corresponding digital elements that guide, verify, or complement onsite activities [21].

AR systems operate by using devices such as tablets, smartphones, smart glasses, or optical see-through headsets (e.g., Microsoft HoloLens) equipped with cameras, depth sensors, and spatial mapping algorithms. These devices capture the physical environment in real time and superimpose virtual objects with precise geometric alignment, a process known as spatial registration [22]. Through advanced computer vision techniques, AR platforms detect surfaces, recognise patterns, and anchor digital elements to specific locations, ensuring that BIM-based overlays match the dimensions and orientation of physical components with high accuracy.

In the construction context, AR's primary value lies in its ability to bring design intent directly to the jobsite [23]. Workers can visualise structural elements, installation guidelines, reinforcement layouts, or alignment references directly on the actual building components, drastically reducing interpretation errors that often occur when relying solely on 2D drawings or static models. For instance, AR can highlight the exact location of conduits behind walls, indicate the correct position of steel reinforcements, or show the intended geometry of complex formwork systems [20]. This real-time guidance improves precision, accelerates installation processes, and minimises costly rework.

Furthermore, AR supports advanced quality assurance and quality control (QA/QC) workflows by enabling

inspectors to compare as-built conditions with BIM models in real time. Deviations, omissions, or misalignments can be identified visually on-site, reducing the need for manual measurements or prolonged inspection procedures [21]. AR also facilitates remote collaboration by enabling off-site experts to view the jobsite from the perspective of on-site workers, provide instructions, and annotate live video feeds, improving communication and reducing delays.

3.2.1 AR technologies and devices

AR technologies rely on a variety of hardware platforms that enable users to visualize digital information superimposed onto real-world environments [20]. These devices differ in terms of interface, mobility, precision, and immersive capability, allowing AR applications to be tailored to the diverse needs of construction sites. The most accessible entry point to AR is through smartphones and tablets, which utilize built-in cameras, gyroscopes, accelerometers, and depth sensors to detect surfaces and anchor virtual elements [23]. Their portability and low cost make them particularly suitable for rapid on-site checks, basic alignment verification, and the visualization of BIM elements directly on the device's screen [20]. Although these devices do not provide whole hands-free interaction, their widespread availability makes them a practical starting point for AR adoption in field operations.

Optical see-through headsets, such as the Microsoft HoloLens and Magic Leap, enable more advanced AR experiences. These devices use transparent lenses that overlay holographic content onto the user's natural field of view, enabling hands-free interaction with digital models while allowing complete awareness of the surrounding environment [20]. By integrating depth sensors, spatial-mapping algorithms, and gesture-recognition systems, these headsets create highly precise, stable overlays that are essential for tasks requiring acceptable positional accuracy, such as verifying as-built conditions, inspecting tolerances, or guiding workers during complex installations [21]. Their ability to process BIM data, display annotations, and support collaborative holographic reviews makes them particularly valuable for coordination meetings and advanced QA/QC workflows [22].

A third category consists of wearables and smart glasses, which offer lighter, more compact devices designed for continuous on-site use. These systems, such as Vuzix and RealWear headsets, typically prioritise durability, voice control, and real-time access to information over fully immersive holographic visualisation [20]. Although their AR capabilities are comparatively limited, they excel in environments where mobility, safety, and operational practicality are essential. Workers can receive remote expert assistance, capture field data, and access digital instructions without interrupting their workflows [21]. These devices enhance documentation efficiency, support field reporting, and enable rapid inspection cycles.

Together, these AR devices form a spectrum of technological solutions, ranging from entry-level visualisation tools to advanced holographic computing systems [23]. Their selection depends on the complexity of construction tasks, the precision required, environmental conditions, and the organisation's digital maturity [20]. As AR hardware continues to evolve, becoming lighter, more accurate, and more affordable, its integration into everyday construction activities is expected to become increasingly seamless and impactful.

3.2.2 Limitations and challenges of AR

Despite its significant potential to enhance onsite accuracy, coordination, and decision-making, AR faces several technical, practical, and organisational challenges that limit its widespread adoption in the construction industry [21]. One of the most prominent limitations relates to spatial registration accuracy, which refers to the ability of AR systems to align digital BIM elements with the real-world environment correctly [23]. Construction sites are dynamic, cluttered, and often subject to irregular lighting, dust, vibrations, and occlusions. These factors interfere with computer vision algorithms and depth-sensing capabilities, leading to digital overlays drifting or misaligning. Even minor registration errors can compromise measurement accuracy, mislead field workers, and diminish trust in the technology.

Another major challenge involves environmental variability. AR devices rely heavily on sensors, cameras, and surface recognition algorithms that are sensitive to changes in natural light, weather conditions, and material reflectivity [23]. Outdoor construction environments, with strong sunlight, shadows, glare, and uneven surfaces, often pose difficulties for AR tracking systems. Additionally, indoor environments may contain repetitive geometric patterns or insufficient visual features, which can hinder markerless AR recognition [22]. These environmental constraints limit the reliability and consistency of AR for precision-dependent tasks, such as rebar placement, installation alignment, or inspection verification.

The hardware limitations of AR devices also present significant obstacles. Although smartphones and tablets are widely accessible, their AR capabilities are constrained by limited battery life, processing power, and the need for handheld operation, which reduces usability in environments that require both hands [20]. More advanced see-through headsets, such as the Microsoft HoloLens, offer improved functionality but remain bulky, impact-sensitive, and less suitable for harsh job-site conditions. These devices can be uncomfortable during prolonged use and may require protective accessories that further restrict movement or visibility [21]. The cost of high-end AR hardware also remains a barrier for many construction firms, tiny and medium-sized enterprises with limited digital budgets.

Interoperability issues further restrict AR adoption. Many AR applications depend on proprietary file formats and do not seamlessly integrate with BIM authoring tools or project management software [22]. Model conversion, simplification, or segmentation is often necessary to prepare BIM content for AR visualization, which increases processing time and demands specialized technical skills [23]. Without standardized workflows or universal data formats, AR remains isolated within digital ecosystems, reducing its effectiveness in multi-stakeholder environments.

From an organizational perspective, the digital skills gap presents an additional challenge. Construction personnel may lack familiarity with AR devices, leading to low adoption rates, user resistance, or inconsistent implementation [21]. AR requires training not only in device operation but also in interpreting digital overlays, understanding tolerances, and integrating AR insights into daily construction workflows. Without strong leadership support and structured training programs, organizations may struggle to realize the full benefits of AR.

Safety and ergonomic concerns also warrant consideration. Wearing AR glasses on active construction sites can obstruct peripheral vision or distract users from physical hazards. Prolonged use may lead to eye strain,

fatigue, or discomfort, reducing operational efficiency [23]. Ensuring that AR enhances safety rather than compromises it requires careful workflow integration, device design improvements, and clear usage protocols [20].

3.3 Artificial Intelligence (AI)

AI refers to the development of computational systems capable of performing tasks that traditionally require human intelligence, such as learning from experience, recognising patterns, interpreting data, predicting outcomes, and making decisions [14]. Unlike traditional rule-based software, which operates strictly within pre-programmed instructions, AI systems adapt their behaviour based on the information they process. This capacity for autonomous learning, especially when combined with advanced data inputs from sensors, images, and BIM models, has positioned AI as a transformative force in the construction industry [3].

In this study, AI-based resource prediction encompasses forecasting material quantities, labour requirements, and equipment utilisation throughout the construction lifecycle. This process draws on three primary input data streams: (i) BIM-derived geometric and semantic data, including element quantities, material specifications, and spatial configurations; (ii) historical project records encompassing productivity rates, waste generation logs, and procurement datasets; and (iii) real-time site data captured through IoT sensors, drones, and photogrammetric systems. The prediction time horizon spans from short-term operational decisions, such as daily and weekly scheduling, to medium-term project planning at the monthly milestone level. Model accuracy is typically assessed using regression-based metrics, including Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE), while classification tasks, such as defect detection, are evaluated using F1-score and detection accuracy. These parameters define the operational scope within which AI contributes to resource-efficiency and circular-economy objectives in the integrated VR-AR-AI framework proposed in this study.

At its core, AI encompasses several subfields, each with unique capabilities that support different aspects of construction workflows. Machine Learning (ML) enables algorithms to identify statistical patterns in historical or real-time data, allowing systems to forecast potential delays, material needs, or safety risks. Deep Learning (DL), a subset of ML, uses neural networks with multiple layers to analyze complex data inputs such as images, videos, LiDAR point clouds, and sensor measurements, making it particularly useful for defect detection, progress tracking, and automated classification of construction components [7]. Computer Vision, another AI-affected domain, focuses on enabling machines to “see” and interpret visual information, allowing construction systems to evaluate artistry, detect anomalies, and monitor physical activities with unprecedented precision.

In the construction context, AI’s main contribution lies in its ability to convert raw, fragmented, and unstructured data into meaningful insights. Construction projects generate enormous amounts of information through BIM models, site photographs, drone captures, inspection reports, IoT sensors, and daily logs [24]. AI algorithms process this data to identify correlations, detect outliers, and generate predictions that support evidence-based decision-making. For example, computer vision models powered by AI can automatically identify cracks, misalignments, or missing reinforcements from site images, reducing the need for manual inspections [18]. Predictive algorithms can estimate project delays based on early productivity trends or optimise

material ordering to minimise waste and reduce environmental impact.

Moreover, AI supports the shift toward proactive construction management. Instead of responding to issues after they arise, predictive analytics allow teams to anticipate potential failures, safety hazards, or resource shortages before they disrupt progress [6]. This early-warning capability aligns with broader sustainability and circular economy goals by minimising rework, reducing waste, and extending the lifespan of structures through timely maintenance interventions.

Despite its potential, AI implementation faces challenges. High-quality datasets are necessary to train robust models, yet construction environments are highly variable and often lack standardised data collection protocols. Additionally, the opacity of some AI models, known as the “black-box” problem, raises concerns about transparency and trust among practitioners. Overcoming these barriers requires improved data governance, open datasets, explainable AI techniques, and training programs to enhance digital literacy among construction professionals.

3.3.1 Core AI techniques relevant to construction

AI encompasses a wide range of computational techniques designed to replicate human cognitive functions such as learning, perception, pattern recognition, and decision-making. In the construction industry, where large volumes of heterogeneous data are generated daily, AI plays a pivotal role in automating processes, improving prediction accuracy, and enabling data-driven insights. Several core AI subfields have emerged as particularly relevant to construction applications due to their ability to process complex visual, numerical, and textual data.

One of the most foundational techniques is ML, which enables algorithms to identify patterns and relationships within structured or unstructured datasets. ML models learn from historical project records, sensor data, and site observations to forecast outcomes such as project delays, cost overruns, productivity fluctuations, or material demand [7]. Common ML approaches include regression models, decision trees, random forests, and clustering techniques, each offering unique capabilities for classification, prediction, or anomaly detection. ML provides the analytical basis for developing intelligent systems that support proactive planning and real-time optimisation in construction workflows [25].

A more advanced subset of ML is DL, which leverages multi-layered neural networks to process high-dimensional data. DL has gained significant traction in construction due to its superior performance in analysing images, videos, and 3D point clouds, data types increasingly common in drone inspections, laser scanning, and photogrammetry-based workflows [7]. Convolutional Neural Networks (CNNs), for example, excel in tasks such as defect detection, reinforcement identification, segmentation of structural elements, and recognition of worker behaviours. Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks are used for temporal predictions, including forecasting schedule deviations or analysing equipment usage patterns.

Another key AI-affected domain relevant to construction is Computer Vision, which equips machines with the ability to “see” and interpret visual information captured from cameras or sensors. Computer vision techniques enable systems to automatically detect cracks, spalling, misalignment, missing components, improper installation, or

unsafe on-site behavior [7]. These methods enable automated QA/QC, remote inspection workflows, progress monitoring through photographic comparison, and integration with AR overlays to highlight deviations in real time. Computer vision underpins many emerging digital twin platforms, where as-built conditions are continuously compared with BIM models.

Beyond visual data, Natural Language Processing (NLP) has emerged as a valuable AI technique for managing the vast amount of textual and audible information generated throughout construction projects. NLP algorithms can extract insights from daily reports, specifications, emails, change orders, and safety documentation [25]. They can identify recurring issues, automate documentation, classify safety incidents, or detect contractual risks. Contributions include translating audio information, supporting business meetings and transcribing verbal interactions. NLP also supports voice-controlled interfaces in AR/VR systems, enhancing usability in hands-busy environments.

Complementing these techniques, Reinforcement Learning (RL) is increasingly used in construction automation and robotics, where algorithms learn optimal sequences of actions through trial-and-error interactions with their environment [7]. RL enables applications such as autonomous equipment navigation, crane path optimization, and robotic component assembly. Although still emerging in construction, RL holds significant potential for advancing automation in tasks that involve dynamic decision-making under uncertainty.

Finally, optimization and heuristic algorithms, such as genetic algorithms, swarm intelligence, and mixed-integer programming, play an important role in resource allocation, scheduling, structural design optimization, and energy performance assessments [7]. These methods enable construction teams to rapidly explore multiple configurations and identify optimal solutions based on specific performance criteria.

Collectively, these AI techniques form a robust computational foundation capable of transforming construction processes through automation, prediction, and intelligent decision support [24]. When integrated with immersive technologies such as VR and AR, AI capabilities are amplified, enabling real-time insights to be visualized within intuitive environments and directly applied to on-site workflows [25]. This synergy is essential for advancing the construction industry toward a more efficient, resilient, and sustainable paradigm.

3.3.2 Limitations and challenges of AI

Although AI has demonstrated remarkable potential to transform construction practices through automation, prediction, and advanced data analysis, its widespread adoption remains constrained by several key limitations. These challenges span technical, organizational, ethical, and economic domains, illustrating the need for a more mature digital ecosystem before AI can be fully embedded within construction workflows [24].

A primary challenge involves the scarcity and inconsistency of high-quality data, which are essential for training reliable AI models. Construction environments are highly variable, presenting fluctuating lighting, irregular geometries, occlusions, dirt, dust, and rapidly changing site conditions. As a result, images and sensor data captured onsite often contain distortions, noise, or incomplete information, which can negatively affect the performance of computer vision and deep learning systems [7]. Moreover,

the construction sector lacks standardized data collection protocols, leading to datasets that may differ significantly from one project to another in terms of format, labeling, structure, and content. This inconsistency limits the generalizability of AI models and increases the risk of inaccurate predictions or false detections [25].

Another critical limitation concerns the computational demands of AI technologies, particularly deep learning. Training and deploying large neural networks require significant processing power, high-performance GPUs, and continuous access to cloud computing platforms. Many construction firms, especially small and medium-sized enterprises, lack the infrastructure or financial resources to support such computational requirements [25]. Even when cloud solutions are available, issues such as latency, connectivity, and data upload restrictions on remote job sites can hinder AI performance, disrupt workflows, and reduce system reliability.

AI adoption also faces challenges associated with interpretability and transparency, often referred to as the “black-box problem.” Many advanced AI models, particularly deep neural networks, generate predictions without providing clear explanations of how they were derived [25]. This lack of interpretability creates hesitation among engineers, inspectors, and project managers who must justify decisions in safety-critical environments [7]. Without transparent or explainable AI techniques, users may struggle to trust AI recommendations, particularly when errors could have serious safety or economic implications.

From an organizational perspective, the construction industry continues to exhibit a significant digital skills gap. Most AI systems require specialized knowledge in data analytics, programming, cloud platforms, and algorithm interpretation, skills that are not traditionally part of construction training [24]. Many professionals feel overwhelmed by the perceived complexity of AI tools, leading to reluctance or resistance to adoption [7]. This skills gap highlights the need for comprehensive digital training programs, new competency frameworks, and collaborative partnerships between academia, industry, and technology providers.

Another organisational challenge is integration with existing workflows. Construction processes are highly fragmented, involving numerous stakeholders, subcontractors, and suppliers who often use a wide range of software systems and documentation styles. AI tools frequently operate in isolation and struggle to integrate seamlessly with BIM platforms, scheduling systems, quality control procedures, and field documentation. Without interoperability standards and unified data environments, AI solutions risk underutilization or misalignment with project needs [25].

Economic barriers also play a significant role in slowing AI adoption. Developing customised AI models, acquiring high-quality sensors, maintaining cloud subscriptions, and hiring specialised personnel can involve substantial upfront investment [24]. Many firms lack clear frameworks for quantifying the return on investment, making it difficult to justify long-term AI integration. Additionally, the construction industry is traditionally risk-averse; companies may hesitate to adopt emerging technologies without proven, widely accepted benchmarks of performance and reliability.

Finally, AI raises important ethical and privacy concerns. Data collected through cameras, drones, and wearable sensors may capture identifiable information about workers, raising issues of surveillance, consent, and compliance with data laws [25]. AI-driven automation also prompts concerns

about workforce displacement, equity, and the need to redefine roles and responsibilities across job categories. If not managed responsibly, AI adoption may lead to mistrust, resistance, or legal complications.

In summary, while AI holds enormous promise for enhancing efficiency, accuracy, and sustainability in construction, addressing these technical, organisational, economic, and ethical limitations is essential for realising its full potential [24]. Overcoming these challenges requires a combination of standardised data practices, transparent AI models, improved digital literacy, robust governance frameworks, and strategic investment in interoperable technologies [25]. Only with these foundational elements in place can AI evolve from isolated experimental applications into a central component of intelligent and integrated construction ecosystems.

4 Integration framework of VR, AR, and AI in construction

The successful adoption of VR, AR, and AI in construction requires a structured and progressive implementation strategy that aligns technological capabilities with organisational readiness, project requirements, and long-term digital transformation goals [24]. The following subsections outline key implementation dimensions, offering a holistic view of how the industry can gradually integrate these technologies into daily practice. Figure 1 illustrates the proposed multi-layer digital architecture that links the design, construction, quality control, and post-construction phases through a unified data ecosystem. BIM models, structured according to ISO 19650 and interoperable formats such as IFC and gbXML, are managed within a CDE and enriched with real-time and historical data sources. These inputs feed an AI engine combining machine learning, deep learning, computer vision, natural language processing, and reinforcement learning to enable predictive analytics and automated decision support. The outputs are operationalised through VR for immersive planning and coordination, and AR for on-site guidance, inspection, and maintenance. The framework establishes a continuous digital feedback loop in which field data and AI insights update BIM/CDE models, supporting improved accuracy, reduced rework, and enhanced lifecycle performance. The resulting system contributes to circular economy objectives, including reductions in material waste and emissions, improved resource efficiency, and extended service life. Interoperability standards and implementation constraints relevant to real-world construction contexts are also highlighted.

4.1 Establishing the digital foundation

A robust digital foundation is essential for the effective implementation of immersive and intelligent technologies in construction. These technologies rely on high-quality, well-structured, and consistently managed digital information. Without such a foundation, VR, AR, and AI workflows become disconnected, unreliable, and difficult to scale. Ensuring digital readiness begins with establishing standardised, interoperable, and well-governed data environments across the organisation [20].

One of the most important prerequisites is the adoption of reliable BIM practices with consistent modelling standards. BIM models serve as the central source of geometric and semantic information used by VR environments, AR overlays, and AI analysis pipelines [20]. Poorly structured

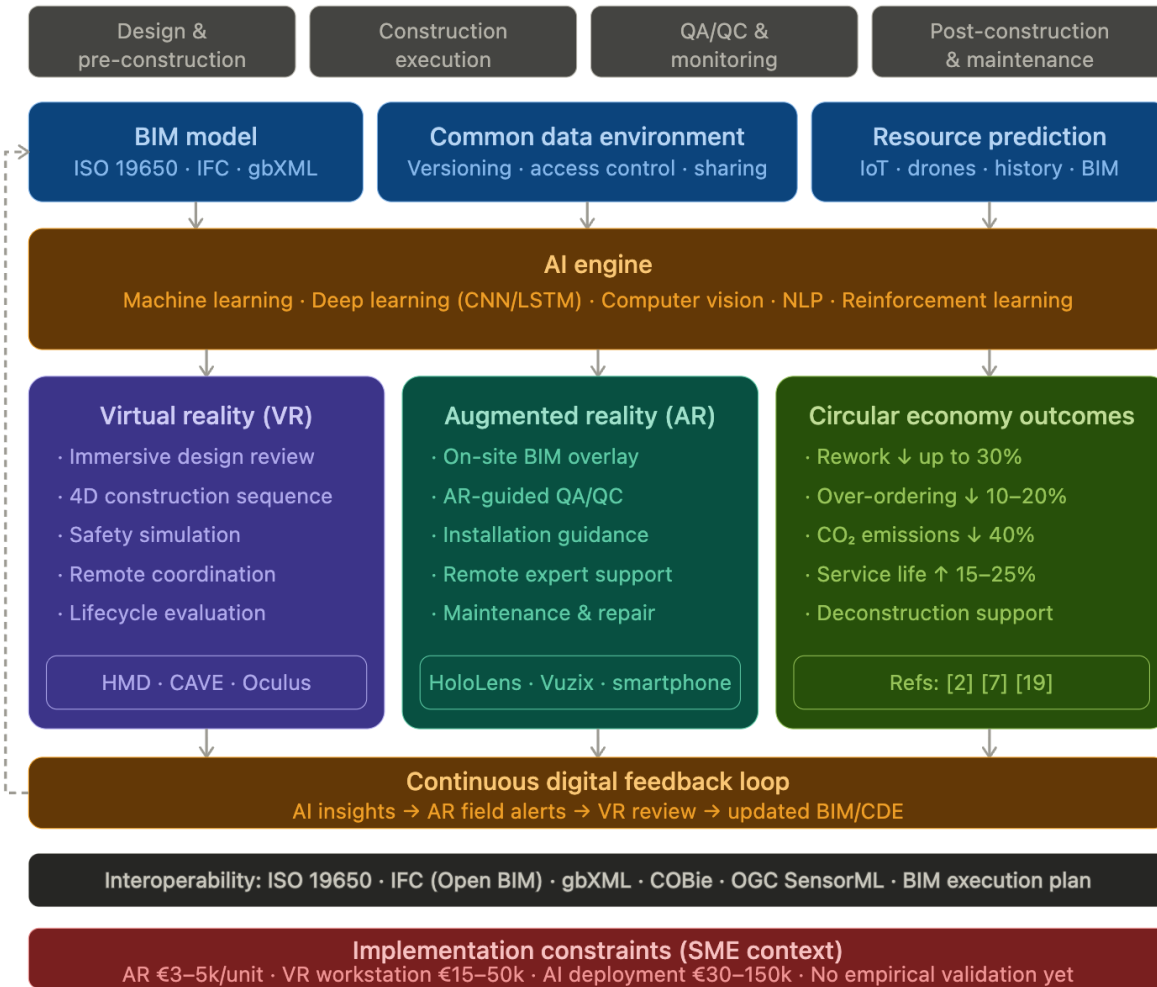


Figure 1. Proposed conceptual framework for the integrated deployment of VR, AR, and AI in circular and sustainable construction

BIM models, containing incorrect naming conventions, inconsistent levels of detail (LOD), or uncoordinated disciplines, create downstream problems that directly affect the accuracy of immersive visualisation and automated analytics. Establishing clear BIM execution plans (BEPs), defining model authorship responsibilities, and enforcing industry standards (such as ISO 19650) ensure that digital models remain coherent throughout the project lifecycle.

Equally important is the development of centralised data environments, such as Common Data Environments (CDEs). These platforms integrate project information from designers, contractors, suppliers, and clients into a single digital location. By maintaining documents, models, photos, drone captures, sensor datasets, and AI-generated reports in a structured environment, CDEs eliminate data fragmentation and ensure that all stakeholders have access to the most current information [24]. This level of centralisation is crucial for VR and AR tools, which require synchronised model updates, and for AI systems, which depend on consistent datasets for training and inference.

Another critical requirement is the establishment of interoperable file structures. Construction projects typically involve a variety of software platforms, BIM authoring tools, scheduling software, GIS, VR engines, AR viewers, drone capture systems, and AI algorithms. Without standardised file formats and workflows that enable smooth data

exchange between these systems, integration becomes extremely inefficient [25]. Interoperability can be strengthened through open formats such as IFC and gbXML, as well as through clear protocols for exporting and converting models for VR/AR use. Seamless data exchange ensures that immersive and intelligent tools operate on accurate, up-to-date digital representations.

Finally, organisations must implement clear information management protocols that establish how digital data is created, stored, updated, and accessed. This includes naming conventions for BIM objects and files, version control systems to prevent outdated model use, update frequencies, validation procedures, and defined access rights [25]. These protocols prevent inconsistencies that can lead to errors in AR overlays, incorrect VR simulations, or inaccurate AI predictions. Proper information governance also reduces duplication, prevents data loss, and enhances traceability for quality assurance and decision-making [20].

Together, these foundational components create the digital consistency necessary for effective VR, AR, and AI integration [24]. When these elements are in place, immersive and intelligent technologies can operate smoothly, share information reliably, and support high-impact applications across construction workflows. Conversely, without this foundational structure, implementation efforts risk fragmentation, producing

unreliable results, eroding user trust, and ultimately limiting the transformative potential of digital technologies in the construction industry.

4.2 Integration into design and pre-construction

The design and pre-construction phases provide the most structured and controlled environment for introducing immersive and intelligent technologies into construction workflows [7]. These early stages involve developing project concepts, coordinating multidisciplinary teams, planning logistics, and identifying potential risks, activities that benefit significantly from the combined use of VR, AR, and AI [25]. Integrating these technologies early in the project lifecycle establishes a solid digital foundation that enhances accuracy, reduces uncertainties, and improves decision-making long before physical work begins [17].

VR plays a central role during early design development by enabling stakeholders to immerse themselves in fully navigable digital models. Unlike traditional design review methods, which rely on drawings or flat-screen 3D visualisations, VR offers a full-scale representation of spaces, allowing designers and clients to assess spatial proportions, circulation paths, visibility, materiality, lighting, and user experience with greater clarity [20]. Through VR walkthroughs, teams can identify architectural inconsistencies, evaluate alternative layouts, and detect constructability issues that may not be apparent in conventional digital models [17]. This immersive environment enhances communication among architects, engineers, and clients, facilitating collaborative decision-making and early alignment on project goals.

AI enhances the design process by enabling automated and data-driven analysis of project models. Machine learning algorithms can evaluate design alternatives based on performance criteria such as energy consumption, structural efficiency, material quantities, or cost implications [25]. AI-based clash detection and rule-checking systems can assess BIM models for compliance with industry standards and project specifications, identifying potential conflicts earlier and with greater accuracy than manual reviews [7]. Predictive analytics provide insights on potential schedule risks, cost deviations, or constructability challenges, allowing project teams to make informed adjustments before committing to final designs [21].

AR complements VR and AI during pre-construction by providing real-world contextualization of digital components [25]. Early AR applications allow designers and engineers to visualise building elements within the actual site environment, enabling assessments of alignment, orientation, and interaction with surrounding structures [20]. For example, AR can be used during site walk-throughs to preview the placement of foundations, utilities, or site logistics zones, enabling more accurate planning and reducing the likelihood of conflicts during construction [21]. By bridging the digital and physical environments even before work begins, AR supports enhanced situational awareness and more precise early planning.

The integration of VR, AR, and AI also supports logistics planning and construction sequencing. VR-based 4D simulations allow teams to visualise step-by-step project progression, simulate crane operations, evaluate site access routes, and anticipate potential bottlenecks [17]. AI optimisation algorithms can analyse these simulations to propose more efficient sequencing strategies or resource allocations. AR can then be used during pre-construction

meetings to overlay planned layouts on the physical site, validating the feasibility of chosen logistics strategies.

In addition, these technologies improve stakeholder communication by presenting complex design, safety, and planning information in intuitive and interactive formats. Clients, community representatives, and non-technical stakeholders can participate in VR walkthroughs or AR-enhanced site tours to gain a clear understanding of the project vision and potential impacts [20]. AI-generated insights, such as risk predictions or construction performance indicators, can be visualised in VR dashboards or AR overlays, making them easier to interpret and act upon [17].

4.3 Onsite Deployment During Construction

The construction phase represents the most dynamic and operationally complex stage of a project, where multiple teams, equipment, materials, and work sequences converge in a constantly changing environment. It is during this stage that errors, miscommunication, and inefficiencies are most likely to occur, making it an ideal context for the combined deployment of VR, AR, and AI [25]. When integrated effectively, these technologies help bridge the gap between digital planning and physical execution, enabling real-time guidance, automated quality control, and more informed decision-making on-site [20].

AR serves as the primary interface for on-site operations, enabling workers to visualise digital information directly in the physical environment. Using mobile devices or see-through headsets, field personnel can overlay BIM components onto actual construction elements, ensuring precise alignment for installations such as structural components, mechanical systems, reinforcement layouts, or architectural finishes [21]. This capability reduces ambiguity and improves the accuracy of field tasks that traditionally rely on paper drawings or manual measurements [7]. AR-based instructions can also guide workers step-by-step through complex assemblies, reducing dependency on supervision and minimising the likelihood of errors or omissions.

AI plays a complementary, often invisible role during on-site deployment by processing field data collected from cameras, drones, wearables, and sensors [25]. AI-powered computer vision models can analyse photos or videos of the site to automatically detect defects, missing components, dimensional deviations, or unsafe behaviours [21]. These systems can operate continuously, providing real-time alerts that allow supervisors to intervene before problems escalate. AI also supports progress monitoring by comparing as-built conditions with BIM models or schedule baselines, enabling automated quantification of work completion and early identification of delays [25].

VR remains relevant during construction as a tool for remote coordination, issue resolution, and stakeholder communication. By integrating drone scans, 3D photogrammetry, or 360° site images into immersive environments, VR enables project teams to conduct virtual site walks, assess construction progress, and collaboratively resolve issues without requiring physical presence [21]. This is particularly valuable for large infrastructure projects or projects with geographically distributed teams. VR can also facilitate daily or weekly coordination meetings by presenting site conditions in an intuitive, navigable format that enhances understanding and accelerates decision-making [17].

The integration of VR, AR, and AI during onsite deployment creates a continuous feedback loop between field conditions and digital systems. For example, AI can

detect an alignment deviation in a structural element, which AR then displays to field inspectors as a visual highlight, allowing immediate correction [20]. The corrected condition can later be reviewed in VR by designers or managers to assess its implications for downstream tasks. This synergy enhances traceability, improves communication across disciplines, and reduces the time required to identify and resolve onsite issues.

However, successful implementation requires careful consideration of job-site conditions, device usability, and workflow integration. Construction sites are physically demanding environments where dust, vibration, weather conditions, and safety constraints can affect the performance and practicality of digital tools [7]. For this reason, AR hardware must be robust; AI algorithms must be adaptable to imperfect data; and VR coordination must complement, rather than replace, traditional site supervision [17]. Furthermore, digital workflows must be clearly defined so that field teams understand when and how to use each technology, ensuring compatibility with existing practices and minimising disruptions.

4.4 Quality assurance and quality control

Quality Assurance and Quality Control (QA/QC) are essential components of construction management, ensuring that projects meet design specifications, performance criteria, and safety requirements. Traditionally, QA/QC processes rely on manual inspections, paper-based checklists, and subjective assessments that can be time-consuming, inconsistent, and prone to human error [21]. The integration of AI, AR, and VR offers a transformative approach to improving the accuracy, consistency, and efficiency of quality control activities throughout the construction lifecycle [20].

AI plays a central role by automating defect detection and verifying compliance with digital models. By leveraging computer vision algorithms trained on large datasets of structural components, finishes, mechanical installations, and safety conditions, AI can analyse onsite images and videos to identify anomalies such as cracks, misalignments, missing reinforcements, surface defects, or nonconforming installations [25]. These systems can operate continuously via fixed cameras, drones, or wearable devices, providing real-time feedback that allows construction teams to address issues immediately [7]. Automated classification and segmentation models can also compare as-built conditions with BIM models, highlighting deviations that may compromise structural integrity or future performance.

AR enhances QA/QC processes by enabling inspectors to visualise digital information directly over the physical environment. Using mobile AR devices or see-through headsets, inspectors can overlay BIM elements, measurement guidelines, tolerance bands, or installation sequences onto the actual construction site. This allows precise verification of dimensions, alignment, and placement without relying solely on manual tools like tape measures or printed drawings [21]. AR supports immediate detection of differences between design intent and field execution; for example, highlighting a mispositioned cable tray or reinforcing bar in real time [20]. By providing intuitive visual cues, AR reduces ambiguity, accelerates inspections, and enhances communication between inspectors and field workers.

VR further supports QA/QC by enabling remote, interdisciplinary review. By converting site scans, such as 360° imagery, LiDAR point clouds, or photogrammetry

models, into immersive VR environments, teams can conduct virtual inspections, review progress, and assess corrective actions without being physically present on site [7]. VR is particularly valuable for complex infrastructure projects, large-scale facilities, or worksites with restricted access [20]. Designers, engineers, and quality managers can jointly explore an immersive representation of the site, analyse issues detected by AI, and collaboratively validate proposed solutions. This virtual collaboration enhances coordination across disciplines and reduces scheduling delays for physical inspections.

When combined, VR, AR, and AI enable a comprehensive, end-to-end QA/QC system. AI-driven insights identify potential quality deficiencies; AR provides field teams with visual tools to verify and correct these deficiencies; and VR creates a platform for comprehensive review and documentation [17]. The synergy of these technologies ensures that corrective actions are taken promptly, deviations are minimised, and quality standards are maintained throughout the project lifecycle.

Additionally, digital QA/QC solutions generate detailed records, including annotated images, AI-generated reports, and AR-based verification logs. These digital records improve traceability, support compliance with regulatory standards, and serve as valuable documentation for facility handover and future maintenance [20]. Over time, accumulated QA/QC data can also be used to train improved AI models, creating a self-reinforcing cycle of continuous improvement [25]. Overall, integrating VR, AR, and AI into QA/QC processes enhances construction quality, reduces rework, minimises waste, and supports the long-term durability and performance of built assets [20]. By establishing a more precise, transparent, and efficient quality control framework, these technologies directly contribute to safer, more sustainable construction practices.

4.5 Post-construction and maintenance

Once construction is complete and the asset enters its operational phase, integrating VR, AR, and AI becomes essential to ensure long-term performance, durability, and sustainability. Post-construction activities, such as facility management, routine inspections, predictive maintenance, and lifecycle assessment, benefit significantly from digital technologies that enable continuous monitoring, intuitive visualisation, and data-driven decision-making [20]. These tools support the transition from reactive maintenance to proactive, predictive asset management aligned with circular economy principles and resilience objectives.

AI forms the analytical core of post-construction operations by processing data from sensors, inspections, historical records, and environmental monitoring systems [16]. Machine learning models can identify deterioration patterns, forecast component failures, and estimate remaining service life based on factors such as temperature, humidity, load variations, and material ageing [25]. AI-powered anomaly detection systems analyse sensor streams from structural health monitoring (SHM) devices, such as accelerometers, strain gauges, or corrosion sensors, to flag unusual behaviour, whether caused by fatigue, cracking, excessive deformation, or environmental stressors [7]. These predictive capabilities enable maintenance teams to intervene before failures occur, reducing downtime, minimising repair costs, and extending asset lifespan.

AR supports maintenance workflows by overlaying digital information directly onto the physical asset during inspections and repair tasks. Technicians can visualise

internal elements, such as reinforcement layouts, embedded utilities, and previous repair histories, that are not visible to the naked eye [25]. By accessing BIM-linked AR overlays, maintenance personnel can see component specifications, deterioration predictions, and step-by-step repair instructions, reducing the likelihood of errors and accelerating interventions [20]. AR also facilitates remote support, allowing experts to guide onsite technicians through complex procedures via real-time annotations and visual cues [21]. This capability improves accuracy, reduces the need for specialist travel, and shortens response times.

VR remains valuable during the operational phase as a platform for training, planning, and scenario simulation. Facility managers can use immersive VR environments to understand the building's systems, rehearse maintenance procedures, and evaluate "what-if" scenarios related to natural hazards, system failures, or emergency responses [17]. For significant or critical infrastructure, VR enables safe exploration of hard-to-access areas, facilitating risk-free assessments and improving preparation for real-world interventions. VR also supports lifecycle evaluation by integrating updated digital models with operational data, enabling teams to visualize how the asset evolves [16].

Together, the integration of VR, AR, and AI creates a comprehensive digital ecosystem that enhances post-construction asset management [25]. AI provides continuous analytical insights; AR brings actionable, context-aware information directly to the jobsite; and VR supports immersive understanding and strategic planning [17]. This combination improves the quality and efficiency of maintenance activities, enhances safety, and reduces the environmental impact associated with premature deterioration and inefficient repair cycles.

Moreover, the digital records generated during post-construction, such as AI analysis reports, AR inspection logs, and VR-based maintenance simulations, form a valuable asset for future renovation, rehabilitation, or deconstruction efforts [21]. By maintaining a detailed, continuously updated digital history of the asset, organisations can adopt more circular, sustainable strategies, maximise material reuse, reduce waste, and support informed decision-making throughout the lifecycle.

4.6 Final remarks on implementation

The effective integration of VR, AR, and AI in construction requires not only technological readiness but also organisational alignment, structured planning, and a long-term commitment to digital transformation [20]. While each technology offers unique benefits when applied independently, their combined implementation yields a synergistic digital ecosystem that enhances accuracy, reduces waste, improves safety, and supports sustainable lifecycle management across the built environment.

A successful implementation strategy must be progressive, beginning with foundational digital practices, such as standardised BIM models, reliable data environments, and interoperable systems, and gradually evolving toward more advanced workflows that employ AI analytics, AR-guided execution, and VR-enabled coordination [25]. The transition from traditional methods to integrated digital processes cannot occur overnight; it requires iterative refinement, pilot programs, and deliberate capacity building to ensure that technologies are adapted to the specific needs and conditions of each project.

Moreover, implementation efforts must be supported by a clear vision of how these technologies align with organisational goals, project delivery strategies, and sustainability objectives [16]. VR, AR, and AI should not be treated as isolated "add-ons" but as interconnected tools that collectively enhance decision-making and operational performance [17]. Integrating them into routine planning meetings, onsite inspections, QA/QC workflows, and maintenance procedures ensures that their benefits become embedded in day-to-day operations.

Equally important is the development of a skilled workforce capable of leveraging digital tools effectively. Training programs, knowledge-sharing initiatives, and structured onboarding are essential to overcoming cultural resistance and building user confidence [25]. When construction personnel understand the value of immersive and intelligent technologies and are provided with intuitive workflows that complement their expertise, the adoption process becomes smoother and more impactful.

Finally, the successful implementation of VR, AR, and AI must be grounded in continuous evaluation and improvement [20]. As technologies evolve and new capabilities emerge, organizations should update their digital strategies, refine their workflows, and integrate new functionalities into existing systems [16]. This iterative process ensures that implementation remains aligned with industry advances and responsive to emerging challenges, including sustainability demands, regulatory changes, and evolving stakeholder expectations [21].

In summary, integrating VR, AR, and AI represents a strategic pathway toward a more efficient, accurate, and sustainable construction industry [25]. When supported by strong digital foundations, organisational readiness, and a structured implementation roadmap, these technologies can transform the entire lifecycle of construction projects, from design and planning to execution, quality control, and long-term maintenance, paving the way for next-generation digital construction ecosystems.

It is important to acknowledge the inherent limitations of this conceptual framework. The proposed integration model has not yet been empirically validated through controlled case studies; performance indicators referenced throughout this paper are drawn from individual pilot implementations in the literature rather than from systematic trials of the integrated system. Real-world adoption of the VR-AR-AI ecosystem also entails significant implementation costs that deserve explicit consideration. High-end AR headsets, such as the Microsoft HoloLens 2, range from approximately €3,000 to €5,000 per unit; professional VR workstation environments suitable for project coordination may require investments of €15,000–€50,000 per project node; and AI model development and deployment, including data infrastructure and cloud computing subscriptions, can demand between €30,000 and €150,000 in initial setup costs, depending on organisational digital maturity. Scalability is further constrained by connectivity requirements on remote or underground construction sites, interoperability gaps between proprietary software platforms, and the digital literacy levels typical of small and medium-sized enterprises (SMEs) in the construction sector. Future research should therefore prioritise empirical validation through structured pilot projects, standardised performance benchmarking across diverse project typologies, and the development of cost-benefit frameworks that support evidence-based adoption decisions at the firm level.

5 VR, AR, and AI for sustainability and the circular economy in construction

The integration of VR, AR, and AI offers a powerful pathway to align construction practices with sustainability objectives and circular economy principles [20]. As the built environment continues to account for a substantial share of global greenhouse gas emissions, resource consumption, and waste generation, digital technologies can play a crucial role in transforming traditional linear construction models, based on extraction, use, and disposal, into circular models that prioritise material efficiency, waste reduction, and lifecycle optimisation [25]. This section explores how each technology contributes to sustainability and how their combined application forms a robust framework capable of accelerating the transition toward circular construction systems.

To ground this analysis in measurable outcomes, it is instructive to reference quantitative benchmarks reported in the literature for individual technology applications. Studies integrating AI-driven quality control with AR-guided installation workflows have reported reductions in material rework of up to 30% [7], while predictive maintenance enabled by AI has been associated with extensions of asset service life of 15–25% compared with reactive maintenance strategies [7]. AR-assisted precision installation has been linked to reductions in material over-ordering of approximately 10–20%, directly contributing to lower construction waste levels [19]. Furthermore, BIM-integrated digital workflows have demonstrated CO₂ emission reductions of up to 40% per project lifecycle through optimized material procurement and reduced design iteration cycles [2]. While these figures derive from individual pilot implementations rather than from empirical validation of the present conceptual framework, they establish quantitative benchmarks against which future research should assess the integrated VR-AR-AI model proposed here. Recommended performance indicators for such validation include: percentage reduction in material waste and rework; improvement in material-use efficiency (kg of material per unit of completed work); reduction in CO₂-equivalent emissions per project; and extension of the mean service life of maintained assets.

5.1 Waste reduction through predictive insights and early error detection

One of the major contributors to waste in construction is rework, often caused by errors, misalignments, and inconsistencies between design and onsite execution. AI-powered computer vision enables early detection of these deviations by comparing progress photos, 3D scans, or video feeds against BIM models [21]. When deviations are identified promptly, corrective measures can be implemented before significant material or labour resources are wasted [25].

VR and AR enhance this process by providing intuitive visual interfaces that allow workers and engineers to inspect discrepancies more effectively [20]. AR overlays guide onsite teams with precise installation instructions, reducing mistakes that would otherwise lead to demolition or reinstallation. VR walkthroughs enable project teams to identify design inconsistencies before construction begins, preventing material waste later in the project [7]. Combined, these technologies support a predictive and preventive approach that drastically reduces rework, thereby

decreasing energy use, emissions, and waste generation across the project lifecycle.

5.2 Resource efficiency and optimised material use

The efficient use of materials is a central pillar of circular construction. AI enhances resource optimisation through predictive analytics that estimate material consumption with greater accuracy [20]. Machine learning models can anticipate demand variations based on historical data, design complexity, and on-site productivity patterns, minimising over-ordering and unnecessary stockpiling.

AR facilitates precise installation processes, reducing the likelihood of errors that require additional materials. VR simulations also help project teams evaluate alternative materials, construction methods, and design configurations before execution, allowing for better-informed decisions that optimise resource use [16].

By integrating AI predictions with immersive VR/AR guidance, projects can maintain resource efficiency while improving overall productivity and reducing the environmental footprint associated with material production, transport, and waste [25].

5.3 Lifecycle optimisation and predictive maintenance

Circular economy principles emphasise extending the useful life of buildings and infrastructure through proactive maintenance, rehabilitation, and reuse strategies. The combination of VR, AR, and AI offers valuable support for lifecycle management [21].

AI-driven predictive maintenance algorithms analyse sensor data and inspection images to identify early signs of deterioration, such as cracks, corrosion, or excessive deformations [20]. These insights help asset managers schedule maintenance interventions before minor issues escalate into major failures, extending the service life of structures and reducing the need for resource-intensive repairs [7].

VR enables immersive evaluation of maintenance scenarios, facilitating safe exploration of confined or hazardous environments and allowing teams to plan interventions effectively [16]. AR provides a real-time overlay of structural conditions during inspections, guiding technicians to areas requiring immediate attention and enabling them to validate completed repairs with high precision [21]. These capabilities support a lifecycle-oriented approach that aligns with circular principles by reducing premature demolition, improving material reuse options, and maximizing the functional lifespan of assets.

5.4 Enhancing circular design and deconstruction practices

Circular construction requires not only efficient building processes but also designs that facilitate the reuse, remanufacture, or recycling of materials at the end of life [20]. VR plays a crucial role in evaluating design-for-disassembly strategies by enabling immersive testing of how components can be dismantled safely and efficiently.

AI can support deconstruction planning by identifying materials, estimating quantities, and predicting the recyclability or reuse potential of structural elements [17]. Meanwhile, AR allows onsite workers to visualise hidden components, such as reinforcement bars or embedded elements, reducing accidental damage during selective demolition [25]. Together, these tools support the transition from demolition-based practices to planned deconstruction,

enabling the recovery of valuable materials and reducing landfill waste.

AR, when integrated with BIM, VR and AI, plays a critical role in operationalising material passports and enabling the implementation of buildings as material banks. By overlaying digital information onto physical assets, AR enables stakeholders to access detailed material data in situ, such as composition, disassembly potential, and reuse value. AR facilitates the visualisation of lifecycle information directly on building components, supporting more accurate identification, classification, and recovery of materials during maintenance and end-of-life phases [26]. This capability effectively bridges the gap between static material databases and real-world construction environments, transforming material passports into actionable tools. Consequently, AR enhances decision-making in selective deconstruction processes, reduces information loss across the lifecycle, and strengthens the traceability required for circular material flows.

6. Conclusions

The integration of VR, AR, and AI represents a transformative opportunity for the construction industry as it seeks to address persistent challenges in efficiency, sustainability, and digital modernisation. This paper provides a comprehensive theoretical analysis of how these three technologies, when strategically combined, can reshape construction workflows and support the transition toward circular, sustainable built environments.

The review of current technological capabilities demonstrates that VR enhances immersive visualisation and design comprehension, AR improves precision through real-time onsite guidance and augmented inspections, and AI introduces powerful analytical mechanisms that automate detection, optimise resource allocation, and support predictive decision-making. Individually, each technology offers valuable improvements; however, their true potential emerges when deployed as an integrated system. The conceptual framework proposed in this paper illustrates how data acquisition, intelligent analytics, and immersive interaction can be combined to create a continuous digital feedback loop that improves coordination, reduces rework, and supports lifecycle-oriented management.

The analysis also highlights how this integrated ecosystem aligns with circular economy principles by reducing waste, optimizing material use, extending the lifespan of assets through predictive maintenance, and enabling more efficient design and deconstruction practices. Despite its potential, the widespread adoption of VR, AR, and AI remains limited by several challenges, including interoperability constraints, computational demands, skill gaps, organizational resistance, and the high initial implementation costs [21]. Ethical considerations related to privacy, data governance, and workforce impacts also require careful attention. Addressing these barriers will require coordinated efforts from researchers, industry practitioners, policymakers, and technology developers.

Future directions identified in this study indicate that integrating immersive and intelligent technologies with digital twins, IoT sensing networks, and open data standards will be crucial to enabling fully intelligent and sustainable construction ecosystems. Continued research is necessary to improve robust AI models, generate standardized datasets, enhance the usability of immersive tools in real construction environments, and refine digital workflows that support circularity across the entire building lifecycle.

Overall, this work contributes to the growing body of knowledge on digital transformation in construction by articulating a unified theoretical perspective on how VR, AR, and AI can jointly support sustainable, efficient, and circular practices. The proposed framework serves as a foundation for future empirical studies and offers practical guidance for stakeholders seeking to implement advanced digital technologies in the construction sector.

Author Contributions

Conceptualisation, G.C.C.P., B.M.R. and L.B.; methodology, G.C.C.P.; software, G.C.C.P.; formal analysis, G.C.C.P.; investigation, G.C.C.P.; resources, and L.B.; writing—original draft preparation, G.C.C.P. and B.M.R.; writing—review and editing, G.C.C.P., B.M.R. and L.B.; visualisation, G.C.C.P.; supervision, L.B.; project administration, L.B.; funding acquisition, L.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] M. Noghbaei, A. Heydarian, V. Balali, and K. Han, "Trend analysis on adoption of virtual and augmented reality in the architecture, engineering, and construction industry," *Data*, vol. 5, no. 1, Mar. 2020, doi: 10.3390/data5010026.
- [2] I. Campo Gay, L. Hvam, A. Haug, G. Q. Huang, and R. Larsson, "A digital tool for life cycle assessment in construction projects," *Developments in the Built Environment*, vol. 20, p. 100535, Dec. 2024, doi: 10.1016/j.dibe.2024.100535.
- [3] I. Atta, E. S. Bakhoun, and M. M. Marzouk, "Digitizing material passport for sustainable construction projects using BIM," *Journal of Building Engineering*, vol. 43, p. 103233, Nov. 2021, doi: 10.1016/j.jobee.2021.103233.
- [4] F. P. Cambeiro, F. P. Barbeito, I. G. Castaño, M. F. Bolibar, and J. R. Rodríguez, "Integration of Agents in the Construction of a Single-family House through Use of BIM Technology," *Procedia Engineering*, vol. 69, pp. 584–593, 2014, doi: 10.1016/j.proeng.2014.03.029.
- [5] J. P. Carvalho, F. S. Villaschi, and L. Bragança, "Assessing life cycle environmental and economic impacts of building construction solutions with BIM," *Sustainability (Switzerland)*, vol. 13, no. 16, Aug. 2021, doi: 10.3390/su13168914.
- [6] M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen, "Digitalisation as an Enabler of Circular Economy," in *Procedia CIRP*, Elsevier B.V., 2018, pp. 45–49. doi: 10.1016/j.procir.2018.04.027.

- [7] A. Arsiwala, F. Elghaish, and M. Zoher, "Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings," *Energy and Buildings*, vol. 284, 2023, doi: 10.1016/j.enbuild.2023.112851.
- [8] K. Bäcklund, P. Lundqvist, and M. Molinari, "Showcasing a digital twin for higher educational buildings: developing the concept toward human centricity," *Frontiers in Built Environment*, vol. 10, 2024, doi: 10.3389/fbuil.2024.1347451.
- [9] D. Boyd, "A critical inquiry into the hyperreality of digitalization in construction," *Construction Management and Economics*, vol. 39, no. 7. Routledge, pp. 549–564, 2021. doi: 10.1080/01446193.2021.1904515.
- [10] C. A. S. Alves, C. A. M. Figueiredo, and J. Sanjurjo, "What Is Darapskite? Some Reflections on How Artificial Intelligence Could Promote an Academic Gap," *Engineering Proceedings*, vol. 56, no. 1. Multidisciplinary Digital Publishing Institute (MDPI), 2023. doi: 10.3390/ASEC2023-15329.
- [11] A. Addas, M. Tahir, and N. Ismat, "Enhancing Precision of Crop Farming towards Smart Cities: An Application of Artificial Intelligence," *Sustainability (Switzerland)*, vol. 16, no. 1. Multidisciplinary Digital Publishing Institute (MDPI), 2024. doi: 10.3390/su16010355.
- [12] G. Angiulli, P. Burrascano, M. Ricci, and M. Versaci, "Advances in the Integration of Artificial Intelligence and Ultrasonic Techniques for Monitoring Concrete Structures: A Comprehensive Review," *Journal of Composites Science*, vol. 8, no. 12, 2024, doi: 10.3390/jcs8120531.
- [13] M. Kim, D. Kim, and J. Shim, "The Association Between Aggressive Driving Behaviors and Elderly Pedestrian Traffic Accidents: The Application of Explainable Artificial Intelligence (XAI)," *Applied Sciences (Switzerland)*, vol. 15, no. 4. Multidisciplinary Digital Publishing Institute (MDPI), 2025. doi: 10.3390/app15041741.
- [14] Y. R. M. A. DBioethics and G. M. Gutman, "Aging, artificial intelligence, and the built environment in smart cities: Ethical considerations," *Gerontechnology*, vol. 22, no. 2. International Society for Gerontechnology, 2023. doi: 10.4017/gt.2023.22.2.rya.08.
- [15] F. X. Duorinaah, S. O. Olatunbosun, J.-H. Won, H.-L. Chi, and M.-K. Kim, "Assessment of construction workers' fall-from-height risk using multi-physiological data and virtual reality," *Automation in Construction*, vol. 176, p. 106254, Aug. 2025, doi: 10.1016/j.autcon.2025.106254.
- [16] K. Patil, S. K. Ayer, S. Bhandari, M. R. Hallowell, and L. A. Perry, "Bringing reality to virtual reality: the role of environmental richness in improving construction practitioners' VR experience," *Construction Innovation*, vol. 25, no. 7, pp. 358–383, Dec. 2025, doi: 10.1108/CI-01-2025-0014.
- [17] B. E. Özel and M. K. Pekiçli, "Construction site hazard recognition via mobile immersive virtual reality and eye tracking," *Automation in Construction*, vol. 173, p. 106080, May 2025, doi: 10.1016/j.autcon.2025.106080.
- [18] A. Sabir, R. Hussain, A. Pedro, and C. Park, "Personalized construction safety training system using conversational AI in virtual reality," *Automation in Construction*, vol. 175, p. 106207, Jul. 2025, doi: 10.1016/j.autcon.2025.106207.
- [19] T. M. O'Grady, N. Brajkovich, R. Minunno, H.-Y. Chong, and G. M. Morrison, "Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction," *Energies*, vol. 14, no. 13, p. 4065, Jul. 2021, doi: 10.3390/en14134065.
- [20] Z. Xu, Z. Feng, M. Babaeian Jelodar, and B. H. W. Guo, "Augmented reality applications in construction productivity: A systematic literature review," *Advanced Engineering Informatics*, vol. 62, p. 102798, Oct. 2024, doi: 10.1016/j.aei.2024.102798.
- [21] J. O. Toyin, A. Sattineni, E. M. Wetzel, A. A. Fasoyinu, and J. Kim, "Augmented reality in U.S. Construction: Trends and future directions," *Automation in Construction*, vol. 170, p. 105895, Feb. 2025, doi: 10.1016/j.autcon.2024.105895.
- [22] S. Arvikar, P. P. W. Aung, G. Cha, and S. Park, "Augmented Reality-based construction site management using optimized BIM and project schedule integration," *Automation in Construction*, vol. 175, p. 106204, Jul. 2025, doi: 10.1016/j.autcon.2025.106204.
- [23] H. Liu, D. Liu, and J. Chen, "Natural language-extracted and BIM-referenced knowledge base for construction quality inspection via augmented reality," *Automation in Construction*, vol. 179, p. 106500, Nov. 2025, doi: 10.1016/j.autcon.2025.106500.
- [24] R. Balakrishnan *et al.*, "Remote insects trap monitoring system using deep learning framework and iot," *Sensors*, vol. 20, no. 18. MDPI AG diversity@mdpi.com, pp. 1–17, 2020. doi: 10.3390/s20185280.
- [25] M. Abouelela, C. Lyu, and C. Antoniou, "Exploring the Potentials of Open-Source Big Data and Machine Learning in Shared Mobility Fleet Utilization Prediction," *Data Science for Transportation*, vol. 5, no. 2, 2023, doi: 10.1007/s42421-023-00068-9.
- [26] C. Keles, F. Cruz Rios, and S. Hoque, "Digital Technologies and Circular Economy in the Construction Sector: A Review of Lifecycle Applications, Integrations, Potential, and Limitations," *Buildings*, vol. 15, no. 4, p. 553, Feb. 2025, doi: 10.3390/buildings15040553.



Original scientific paper

Perceptions of brazilian construction industry professionals regarding a BIM-based materials passport: A qualitative exploratory study

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ABSTRACT

The construction industry is responsible for approximately one-third of greenhouse gas emissions and over 50% of natural resource consumption. In this context, the Circular Economy (CE) emerges as a strategy to promote economic development while reducing dependency on natural resources. Tools such as the Materials Passport (MP) are crucial in facilitating this transition. The MP is a digital solution that collects data on materials, aiming to facilitate their recovery and reuse. In Brazil, it is still underutilized. Therefore, understanding the perceptions of Brazilian professionals regarding this tool is crucial for its broader implementation in the sector. This study analyzes the views of four professionals on the concept and process of modeling an MP, based on interviews. The interviews consist of a validation method defined as a functional test, which examines the desired parameters from the user's perspective without requiring the user to understand the system's internal structure. The results highlight two main obstacles. First, modeling processes and information management still need to evolve to achieve market applicability. Second, tools applicable to CE in construction, such as the MP, must be accompanied by greater awareness of CE, MP, and sustainability concepts within the sector.

1 Introduction

Since the Industrial Revolution, the Linear Economy (LE) has predominated as the model of production and consumption [1]. This model, characterized by the “extract–produce–use–dispose” process, remains widely applied in the built environment, even with industrial advances, improvements in energy efficiency, and the development of new construction processes [2]. As a result, the construction industry stands out as one of the largest consumers of natural resources and raw materials worldwide [2]. It is estimated that this industry uses more than 50% of the planet's natural resources [3]; is responsible for one-third of greenhouse gas emissions [4]; and that its demand is expected to grow due to population increase [5].

The Circular Economy (CE) emerges as an alternative model of production and consumption that decouples economic growth from the extraction of natural resources [5], [6], keeping materials and products in use for as long as possible and at their highest value [6]. The creation of circular solutions involves the development of the Materials Passport (MP), a tool for incorporating CE principles [7]. Similarly, Digital Product Passports (DPP) represent a broader regulatory-driven concept that aims to provide

comprehensive, product-level information across multiple industries [8], whereas the MP, as adopted in this study, are construction-specific tools focused on material-level data to support circular economy strategies within the built environment. In the construction sector, the MP is still not widely adopted [1], and there are few studies dedicated to introducing circular practices in this field [8].

In the construction sector, the MP is still not widely adopted [1], and there are few studies dedicated to introducing circular practices in this field [9].

In the context of the built environment, the MP is a digital documentation tool [10], [11] functioning as a set of data and information detailing the characteristics of materials, assigning them value for recovery and reuse [7]. The information contained in an MP must be useful, accessible to users, and able to effectively communicate the level of information related to a product in a dynamic, living document. This document must be capable of reflecting the material's value throughout its entire life cycle and, therefore, requires an understanding of the Life Cycle Assessment of the material in question [12]. According to the Smart Waste Portugal Association (2021) [13], the data contained in an MP provide technical information about a construction

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product, enabling the identification of both its environmental impacts and its potential for recovery, reuse, and recycling.

Building Information Modeling (BIM) can be considered an enabler for integrating circular principles into building projects [14], as it encompasses technologies and processes for an integrated design practice. Modeling consists of creating a physical and operational representation of a building, with the capacity to store information and share essential data throughout the entire lifecycle of the project [15]. Thus, BIM has the potential to support the effective development and management of an MP [16]. Rahla et al. (2021) [17] highlight that many studies address issues related to the use of MP and BIM technologies to monitor and manage materials and components throughout the lifecycle in the construction industry, as well as to assess the level of circularity of these elements in buildings. Additional benefits of integrating BIM and MP have also been identified, such as error reduction, saving time and effort, and facilitating the sharing of sustainability information [18].

Despite the growing body of research addressing the technical development of MP and their integration with BIM, most existing studies primarily focus on conceptual frameworks, data structures, and technological solutions. However, there is still a limited understanding of how construction industry professionals perceive the applicability, usability, and practical value of the MP in real-world design and construction contexts. Since the successful implementation of digital and circular tools depends not only on their technical robustness but also on user acceptance and professional engagement, the lack of empirical studies exploring practitioners' perceptions represents a relevant research gap.

In this context, this article aims to investigate the perception of construction industry professionals regarding an innovative tool such as the Materials Passport. Understanding professional perception is critical, as designers, engineers, and decision-makers play a central role in the adoption and effective use of digital tools within the construction sector. To achieve this objective, a modeled MP is presented in the section "Application of Materials Passport," developed using Revit and Dynamo. This MP was conceptually proposed by Munaro and Tavares (2021) [1] and modeled in Revit by Alves (2025) [19] using automations developed with Dynamo. A validation protocol based on a functional test was conducted through interviews with construction industry professionals, enabling the identification of opportunities and challenges for incorporating the MP into the Brazilian construction industry.

2 Methodology

2.1 Application of Materials Passport

Munaro and Tavares (2021) [1] propose an MP model that includes the information needed to recover and reuse secondary components and materials in construction. The passport data are structured into: (1) general data, including the manufacturer's name, material composition, commercial name, among others; (2) health and safety data, such as information on toxicity, flammability, and related aspects; (3) sustainability data, including life cycle assessment, renewability of the material, among others; (4) design and production data, such as manufacturing processes and techniques, type of installation, certifications, among others; (5) use and operation phase data, covering material cleaning and maintenance, location and position in buildings, monitoring of energy and water consumption, among others; (6) disassembly guidelines, including instructions for disassembly and transportation, among others; (7) data on the reuse and recycling potential of materials, including end-of-life destination and possible reuse/recycling types; (8) material use history, such as recent maintenance and previous uses; and (9) other information that complements the material data.

Alves (2025) [19] develops the modeling and visual programming of this MP using Revit software and the Dynamo tool for automation scripting, with the support of Microsoft Excel. Revit, developed by Autodesk, is used to design, document, visualize, and deliver projects in architecture, engineering, and construction. Dynamo, also developed by Autodesk, was created to expand Revit's capabilities. It is a tool that uses visual programming, eliminating the need for prior programming knowledge. This enables the creation of scripts to automate repetitive tasks, interact with the Revit model, and develop new models based on complex rules and external data [20]. Figure 1 shows the BIM-based MP.

The proposed MP [1], [19] is composed of 49 parameters divided among the nine categories of information. Table 1 presents the categorized parameters that make up the MP, specifying the input of data formats in the BIM platform, as defined by the authors. The parameters were defined according to the MP proposed by Munaro and Tavares (2021) [1], except for the Sustainability parameters, which were adjusted according to data availability. The parameters defined for Sustainability include the Product Environmental Declaration (EPD), embedded energy and water data, and the circularity index.

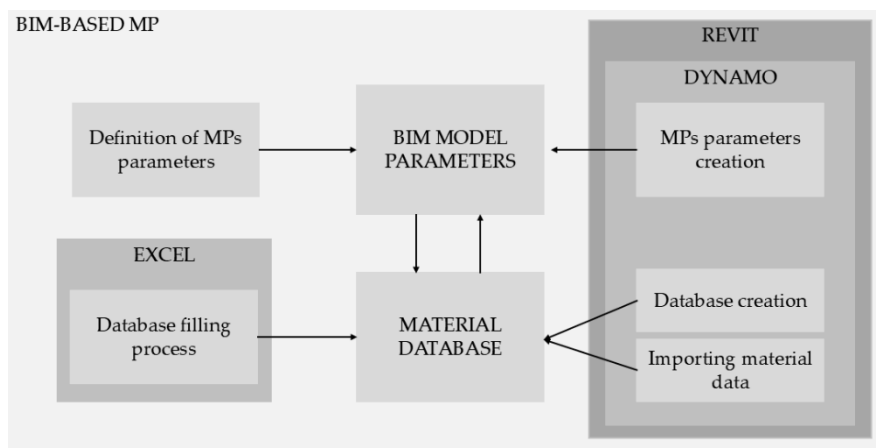


Figure 1. MP development [19]

Table 1 presents the MP parameters. The parameterization structure adopted for the MP in this study was developed by the authors and did not explicitly follow existing international standards for data templates and interoperability, such as ISO 23387 (Data Templates for Construction Objects) [21] or ISO 16739 (IFC) [22].

Initially, the parameters of the BIM model are specified and implemented directly within the BIM environment through visual programming routines developed in Dynamo (version 2021). Subsequently, a material database is structured using Dynamo scripts derived from the materials already available in Revit. This database is hosted in Microsoft Excel (version 2021), where the material information is manually entered. Once completed, the

database is imported into the BIM model, and the information is embedded in the material parameters, enabling its use, exchange, and transmission among project stakeholders.

Figure 2 presents the Dynamo workflow along with the nodes employed in the visual programming process. Each node operates based on predefined input requirements. The concluding stage, referred to as “Material data import,” consists of a routine with two nodes: one responsible for transferring the Excel-based database into the BIM environment, and another for mapping the imported data to the corresponding material parameter. The subsequent sections provide a detailed description of the MP development process.

Table 1. Materials Passport Parameters

Category	Parameter	Format
General data	Commercial name	Text
	Manufacturer's name	Text
	Material composition	Text
	Physical properties	Number
	Chemical Properties	Text
	Biological Properties	Text
	Product image	Image
	Main function	Text
Material health (safe data sheets)	Warnings (safety information)	Text
	Recommendations (safety information)	Text
	Toxicity (material composition)	Text
	Fire hazard rating	Text
	Hazard rating (other)	Text
Sustainability	EPD (Environmental Product Declaration)	URL
	Embodied Energy (EE)	Number
	EE in transport	Number
	Embodied water (EW)	Number
	GWP (Global Warming Potential)	Number
	ODP (Ozone Depletion Potential)	Number
	AP (Acidification Potential)	Number
	EP (Eutrophication Potential)	Number
	POCP (Photochemical Ozone Creation Potential)	Number
	ADP-elements	Number
	ADP-fossil fuels	Number
Circularity Index	Number	
Design and production	Recycled/reused/renewable material?	Text
	Manufacturing process and techniques	Text
	Installation and handling instructions	URL
	Certifications (energy labeling, material testing)	Text
	Traceability (RFID tags, barcodes)	Text
	Transportation requirements	Text
	Packaging characteristics	Text
Supply chain information	Text	
Use and operate phase	Positioning and location in the building	Text
	Cleaning instructions	Text
	Maintenance instructions	Text
	Connections details and requirements	URL
	Warranties and expected use times	Text
	Water consumption	Number
Disassembly guide	Energy consumption	Number
	External influences	Text
	Disassembly instructions (removal/replacement of pieces)	URL
	Packaging/storage requirements	URL
Recycling and reuse potentials	Transportation instructions	Text
	End-of-life considerations (reuse/recycling/remodeling)	Text
	Disposal Options	Text
History	Decomposability	Text
	History	Text
Others	Others	Text

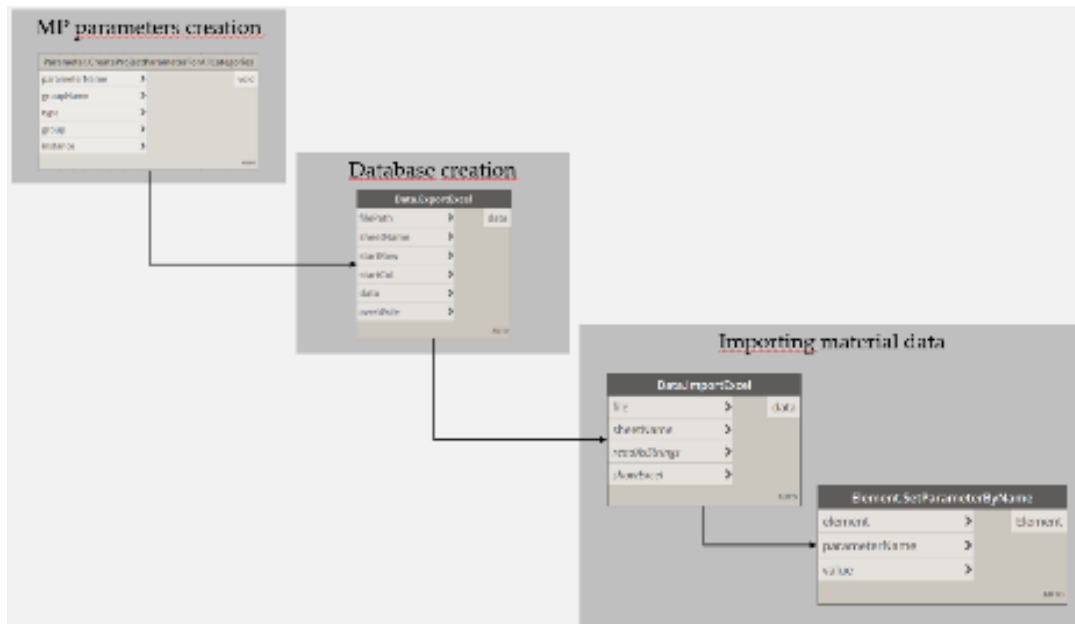


Figure 2. Dynamo workflow [19]

2.2 Functional test

The development of the proposed MP and its validation are part of the research conducted by Alves (2025) [19]. The author presents the step-by-step process of modeling the MP and validates it using validation strategies based on Dresch, Lacerda, and Junior (2015) [23]. Thus, this article presents only the proposed MP in the section “Application of Materials Passport” and applies one of the validation methods used in the study, defined as a functional test.

This type of validation, a black-box functional test, examines the desired parameters from the user’s perspective without requiring the user to understand the internal structure of the system. Its purpose is to test the functionality and usefulness of the MP [24]. In addition, the functional test makes it possible to identify potential failures and detect defects in it [23]. To achieve this, an interview protocol was used to evaluate the MP.

The questions were developed considering: (1) whether or not participants had prior knowledge of the topic; (2) whether these topics became clearer after the presentation of the MP; and (3) whether the presented MP is easy to use, efficient, and operational within the construction industry. Thus, the responses revealed the level of maturity and understanding regarding the topic, as well as identifying the positive or negative perception of the MP within the construction market.

Table 2 presents the interview protocol. It was divided into four stages. The first stage contained four questions, answered before the presentation of the MP. In the second stage, the concept of the MP and the modeling of the proposed MP were presented to each participant individually and remotely, in the form of a lecture. The content of the lecture begins with the concept of CE [2], [5], then it goes with the MP definition and examples in the literature [7], [10], [12], [25] and finishes with the application of MP as it is shown in section 2.1 “Application of Materials Passport”.

The third and fourth stages consisted of 12 and three questions, respectively, which were answered after the

presentation of the MP. All questions were answered remotely through online forms.

The term ‘artifact’ is adopted in accordance with Design Science Research terminology, referring to the developed MP [23].

DSR literature does not establish a minimum number of specialists for artifact validation, since the evaluation should be appropriate to the type of artifact, the maturity stage, and the research objective [26]. This perspective allows for the assessment of an artifact by one or more experts (e.g., Delphi study), as the sufficiency of evidence in DSR is often a matter of community agreement and persuasive argumentation rather than a fixed numerical rule [26]. In this study, the selection prioritized diversity of experience and mastery of the problem over sample size, aligning with recommendations on validity in DSR [27]. This choice is based on the application of criterion characteristic validity, which is considered ideal when human agents are involved in judging the properties and usefulness of the artifact, rather than relying solely on automated numerical measurements [27].

This study adopts an exploratory qualitative approach within a DSR framework, aiming to generate initial insights into the perception and applicability of the MP rather than statistically generalizable results. Thus, the professionals interviewed were selected through purposive (non-probabilistic) sampling. According to Creswell (2014) [28], purposive sampling is widely employed in qualitative research to intentionally select individuals with direct experience of or knowledge of the phenomenon under investigation. In this context, the selection of four participants was intentional, aiming to identify information-rich cases with diverse professional backgrounds that combine academic and industry perspectives. The focus was placed on depth of understanding and the richness of expert insights rather than sample size.

Furthermore, the study does not aim to achieve theoretical saturation, as commonly pursued in grounded theory approaches, but rather to explore early-stage perceptions and identify key challenges and opportunities for

Table 2. Interview protocol

INTERVIEW PROTOCOL	
STAGE 1	
Question 1	What do you understand by Circular Economy in construction?
Question 2	What do you understand by Materials Passport as a technological tool for the integration of Circular Economy in the construction industry?
Question 3	What do you understand by the use of technology and technological tools to achieve more sustainable building and construction projects in the construction industry?
Question 4	What do you understand by the use of BIM to achieve more sustainable building and construction projects in the construction industry?
STAGE 2	
Presentation of the Material Passport (the concept and modeling)	
STAGE 3	
Question 1	What do you understand by Circular Economy in construction?
Question 2	What do you understand by Materials Passport as a technological tool for the integration of Circular Economy in the construction industry?
Question 3	What do you understand by the use of technology and technological tools to achieve more sustainable building and construction projects in the construction industry?
Question 4	What do you understand by the use of BIM to achieve more sustainable building and construction projects in the construction industry?
Question 5	What do you understand by the use of technology and technological tools to incorporate circular concepts in the construction industry?
Question 6	What do you understand by the use of BIM to incorporate circular concepts in the construction industry?
Question 7	Is it possible to identify, based on your professional practice, how the presented approach can improve the sustainability of projects and constructions?
Question 8	Is it possible to identify, based on your professional practice, how the presented approach can improve the circularity of projects and constructions?
Question 9	Is it possible to identify flaws and/or defects in the resource?
Question 10	Is it possible to incorporate the artifact presented in the building design practice to make it more sustainable?
Question 11	Is it possible to incorporate the artifact presented in the building design practice to obtain a material database?
Question 12	How can this method improve the design practice of buildings?
STAGE 4	
Question 1	Suggestions for system improvement.
Question 2	Can you identify, based on the resource presented, professional practices that can be incorporated into your routine to promote more sustainable and/or circular constructions?
Question 3	Other comments.

future research. This approach is consistent with the exploratory and interpretive nature of qualitative inquiry, where the aim is not statistical generalization but the in-depth understanding of meanings, perspectives, and processes. The limited number of participants should therefore be interpreted in light of the exploratory nature of the study and the DSR-oriented validation of the proposed artifact.

The interviewed professionals had professional qualifications in the construction sector and prior knowledge of sustainability in the built environment and/or BIM. Also, the profiles selected for the interview combine Academy/Research and professional practice. The study intentionally focused on exploring and introducing MP concepts and modelling approaches in the Brazilian context,

rather than statistically assessing the maturity of MPs in the construction sector.

The qualifications of each professional are presented in Table 3. Interviewee I is a civil engineer who is self-employed, primarily engaged in design work using Revit. His professional profile reflects a focus on technical design and BIM workflows, and adopts a more conventional, technically oriented approach to engineering practice rather than one driven by environmental considerations.

Interviewee II is an environmental engineer with a specialization in sustainable construction and a master's degree in civil engineering. He is a partner-owner of a sustainable architecture firm and actively integrates sustainability into their professional practice. His work involves design using Archicad, along with knowledge of

Table 3. Professional profiles of the interviewees

Interviewees	Professional qualification
Interviewee I	Civil engineer
	Self-employed professional
	Works as a designer using Revit software
	Is not involved with sustainability topics in professional practice
Interviewee II	Environmental engineer with specialization in Sustainable Construction and a master's degree in Civil Engineering
	Partner-owner of a sustainable architecture firm
	Works as a designer using Archicad and has knowledge of Revit and energy simulation software.
	Works with sustainability in professional practice
Interviewee III	Civil engineer holding a Ph.D. in Civil Engineering
	University professor invited to various institutions
	Partner and owner of a traditional construction company
	Partner and owner of a modular construction company
Interviewee IV	Works with sustainability in professional practice
	Civil engineer with specialization in Engineering Project Management and a master's degree in Civil Engineering.
	University professor
	Works as an independent designer using BIM and Revit software
	Works with sustainability in professional practice

Revit and energy simulation software, highlighting a strong command of digital tools for environmentally responsive design. His profile demonstrates a clear alignment between academic training and professional practice, with sustainability as a central component of his work.

Interviewee III is a civil engineer with a PhD in civil engineering and a university professor, invited to lecture at various institutions. In addition to his academic role, he is a partner and owner of both a traditional and a modular construction company, reflecting significant entrepreneurial activity and industry engagement. His professional activities include working on sustainability in practice and advocating for the integration of advanced academic knowledge with real-world applications, particularly across conventional and innovative construction methods.

Interviewee IV is a civil engineer with a specialization in engineering project management and a master's degree in civil engineering, currently working as a university professor. Alongside his academic responsibilities, he serves as an independent designer, using BIM methodologies and Revit. His professional practice incorporates sustainability, indicating a commitment to integrating environmental considerations into both design and project management. His profile reflects a balance between academic expertise, digital design proficiency, and sustainability-oriented engineering practice.

2.3 Data analysis and analytical categories

To analyze the interview responses, two analytical categories were defined: (i) maturity level and (ii) perception of the use of the MP. The maturity level category was used to assess the degree of conceptual understanding demonstrated by the interviewees and was classified into two levels: Good maturity and Partial maturity. Responses classified as Partial maturity were general in nature and/or contained conceptual inaccuracies, whereas responses classified as Good maturity were more specific, conceptually

accurate, and demonstrated greater confidence and clarity regarding the topic. The responses from Stage 1 and the first four questions of Stage 3 of the interview protocol were analyzed using this category.

The perception of the use of the MP category aimed to evaluate whether the application of the MP in the construction sector was perceived positively or negatively by the interviewees. Responses were classified as Positive when no limitations or problems were identified; Partially positive when both challenges and positive perspectives were mentioned; Negative when the feasibility of using the MP was not recognized; and Partially negative when challenges outweighed the perceived benefits. The responses to Questions 5–12 in Stage 3 were analyzed using this category.

The interview responses were analyzed using a qualitative content analysis approach. Initially, the main researcher conducted a systematic reading of all responses and classified them according to the predefined analytical categories based on their semantic content, considering conceptual accuracy, level of specificity, and alignment with the objectives of the study. To enhance the reliability of the analysis, two secondary researchers independently reviewed the classifications. This triangulation among researchers contributed to increasing the credibility and rigor of the qualitative analysis.

3 Results

3.1 Perception of Maturity Level

Based on the responses of the interviewed professionals, it was possible to assess their level of maturity regarding the topics discussed. In Stage 1, in which none of the participants had previously been introduced to the concept of the MP or to the theoretical concepts presented by the authors, it became evident that the concept of CE (Question

1) is not well understood. In all responses, CE was limited to the idea of waste reduction, as illustrated by Interviewee I: "The issue of reuse and all forms of reducing environmental impact related to materials that encompass all stages of construction".

Regarding the MP (Question 2), although all participants were able to express the concept, it was not entirely clear, as illustrated by Interviewee II: "One of the main objectives of the MP in construction would be awareness, information, and especially the validation of sustainability and circularity parameters of a given material." In addition, a lack of confidence in the responses emerges, as indicated by Interviewee IV: "Honestly, I will say that I know very little about this subject. What I know comes from a lecture I once heard from a master's student in the same graduate program we attended. I would not say that it reflects what I truly understand, because I may be assuming premises that are not necessarily correct."

On the other hand, when the topic shifts to technology and BIM (Questions 3 and 4), all participants demonstrate greater confidence and understanding, as evidenced in Interviewee III's response: "The development of a new tool such as BIM was not designed with sustainability in mind. However, with this tool, it is possible to incorporate sustainability aspects into its use." Interviewee IV's response also reflects confidence and comprehension of the concepts, stating: "All the foundations of BIM, information, coordination, clash detection, data exchange, and integrated management, are fully aligned with the possibility of envisioning a more sustainable construction industry, with less impact and greater efficiency."

In Stage 3, the authors repeated the four questions from Stage 1 (Questions 1–4) to verify whether there was progress in participants' understanding of the topics addressed. Only Interviewee I had previously admitted not having sufficient knowledge when answering the questions in Stage 1. When analyzing this interviewee's development, it was observed that the concept of the MP had been assimilated, as evidenced by the statement: "It is a means that enables the application of circular economy principles within the construction industry. The Materials Passport consists of a digital set of data containing information about a material. The idea is that, based on this information, the material can be directed to a new use or properly managed at the end of its life, thereby closing the loop. In this way, the more information the passport contains about a material, the better." However, the understanding of CE remained limited to the idea of non-generation of waste, as shown in the response: "It is an economic model whose principle is the elimination of waste generation at any stage of construction processes."

Questions 5 and 6 of Stage 3 address the relationship between technology, BIM, and circular construction. When analyzing these questions, Interviewees II, III, and IV provided more confident and assertive responses compared to Interviewee I, demonstrating a deeper and more structured understanding of how technological tools support circularity in construction. Interviewee I emphasized the role of technology mainly as a support mechanism for information management, stating that "to achieve a circular economy model, it is necessary to have information about materials, and in a sector such as construction, where products are often complex and designed to last for decades, the use of

technologies and tools can greatly contribute, not only to storing but also to analyzing this information."

In contrast, Interviewee II articulated a broader and more systemic perspective, highlighting not only the importance of technological development but also the need for organizational, educational, and regulatory alignment: "I believe it is essential to develop technologies and new tools to incorporate circularity in the construction industry. However, I only see the real feasibility of these tools within companies if there is first a broad process of awareness-raising and environmental education among stakeholders". The interviewee further stressed that circularity requires coordinated action across the entire value chain, noting that "the circular economy does not work if only a few actors have the necessary knowledge and technology; everyone needs to understand its importance and participate for the chain to truly be circular."

Similarly, Interviewee IV clearly linked circular construction to the effective use of technology and BIM-based methodologies, stating that "without technology and tools, the implementation of circularity concepts becomes much more complicated," and emphasizing that while circularity begins as "a different way of thinking," it ultimately requires "specific methodologies and techniques, making technology extremely necessary for the process." These responses indicate a higher level of maturity among Interviewees II, III, and IV, as they connect technology and BIM not only to data handling but also to systemic change, professional practice, and the operationalization of circular construction principles. Table 4 presents the interviewees' level of understanding of the topics addressed in Stage 1 (Questions 1–4) and Stage 3 (Questions 1–6).

3.2 Perception of the Use of the Materials Passport

The analysis of Stage 3 (Questions 7–12) was conducted based on the interviewees' perceptions regarding the use of the MP. These questions addressed the applicability of the MP in professional practice and within the design context of the Architecture, Engineering, and Construction (AEC) industry.

Interviewees I, II, and IV expressed perceptions that were classified as partially positive. Their responses indicated openness to the use of the MP, while also highlighting limitations or challenges for its practical application. For example, Interviewee I stated that "certainly, the artifact provides great benefits and makes it easier to assess the sustainability of the materials to be used," but emphasized that sustainability in construction projects involves additional aspects beyond materials, such as "comfort and energy efficiency conditions, system performance, urban and social impact at the construction site, resource and labor optimization, [and] economic feasibility." This type of response reflects recognition of the MP's potential benefits alongside perceived constraints.

Interviewee II also demonstrated a partially positive perception, acknowledging the relevance of the MP while indicating that challenges related to implementation remain. Similarly, Interviewee IV recognized the potential contribution of the MP to professional practice but identified obstacles that prevent its immediate and full integration into routine workflows.

Table 4. Assessment of interviewees' maturity level based on the classification of responses as "Partial maturity" or "Good maturity" across Stage 1 (Q1–Q4) and Stage 3 (Q1–Q6)

		Interviewee I	Interviewee II	Interviewee III	Interviewee IV
Question		Stage 1			
Understanding the concept of EC	Q1	PARTIAL	PARTIAL	PARTIAL	PARTIAL
Understanding the concept of PM	Q2	PARTIAL	PARTIAL	PARTIAL	GOOD
Understanding of technology for sustainable constructions	Q3	PARTIAL	GOOD	GOOD	GOOD
Understanding of BIM technology for sustainable construction	Q4	GOOD	GOOD	GOOD	GOOD
		Stage 3 – Q1 to Q6			
Understanding the concept of EC	Q1	PARTIAL	PARTIAL	PARTIAL	PARTIAL
Understanding the concept of PM	Q2	GOOD	PARTIAL	PARTIAL	GOOD
Understanding of technology for sustainable constructions	Q3	PARTIAL	GOOD	GOOD	GOOD
Understanding of BIM technology for sustainable construction	Q4	GOOD	GOOD	GOOD	GOOD
Understanding of technology for circular construction	Q5	PARTIAL	GOOD	GOOD	GOOD
Understanding of BIM technology for circular construction	Q6	PARTIAL	GOOD	GOOD	GOOD

In contrast, Interviewee III expressed a perception classified as negative regarding the use of the MP. This interviewee emphasized the complexity of the MP and the effort required to compile and manage the associated information, stating that "the MP is complex and requires a lot of time to make use of this information and compile all the data." The interviewee further noted that such demands do not align with the current dynamics of the construction industry, highlighting limitations related to available time, human resources, and the scale of material information

involved: "there are no resources available to dedicate time to information such as embodied energy via MP in a universe of three thousand different types of materials."

Across all interviews, references were made to barriers associated with the use of the MP. These included difficulties related to data collection, availability, structuring, and organization, as well as constraints related to time and financial resources. Table 5 summarizes the interviewees' perceptions of the use of the MP, classified according to the predefined analytical categories.

Table 5. Interviewees' perceptions of the use of the Materials Passport based on Stage 3 (Questions 7–12)

		Interviewee I	Interviewee II	Interviewee III	Interviewee IV
Questions		Stage 3 – Q7 to Q12			
Applicability of the artifact in professional practice	Q7, Q8	PARTIALLY POSITIVE	PARTIALLY POSITIVE	NEGATIVE PERCEPTION	PARTIALLY POSITIVE
Applicability of the artifact in the practical design of the AEC industry	Q9, Q10, Q11, Q12	PARTIALLY POSITIVE	PARTIALLY POSITIVE	NEGATIVE PERCEPTION	PARTIALLY POSITIVE

4 Discussion

The responses from construction professionals raise relevant discussions about the applicability of the MP, which are not addressed in the tool's practical development. First, the questions from Stage 1 reveal that the interviewees have only a superficial understanding of the definitions of CE and MP, although they recognize the importance of technology and BIM in this context. This limited baseline awareness directly influences the perceptions expressed throughout the interviews, as initial evaluations of the MP may partially reflect conceptual uncertainty rather than a fully informed assessment of the tool itself. When the Stage 1 questions were repeated at the beginning of Stage 3, it was observed that only the interviewee who does not work directly with sustainability was able to advance in the understanding of the concepts presented. Thus, tools applicable to CE in construction, such as the MP, must be accompanied by greater awareness of CE, MP, and sustainability concepts within the sector, so that professional perceptions are based on a clearer understanding of the proposed approach.

The analysis of questions five and six from Stage 3 indicates that the interviewees generally recognize technology and BIM as essential enablers for implementing the MP and supporting the transition from a linear to a circular model. These elements are seen as enablers that can accelerate the process, and they are not the main limitation factor, at least at a conceptual level. However, when considering questions seven and eight, the perceptions shift toward the limited feasibility of introducing the MP into professional practice, particularly in large-scale projects. In this context, it is important to note that part of this perceived infeasibility may also be related to the interviewees' limited prior exposure to CE and MP concepts, which affects how they interpret the tool's potential and limitations. The interviewed designers acknowledge the relevance of the MP but do not perceive its full applicability, identifying several stages that must be overcome before its direct implementation. The contractor's representative, in turn, does not see how the tool can be incorporated, as it would require time and financial resources that the market currently lacks. These differences indicate that professional role and prior experience shape how the MP's potential and limitations are interpreted.

The responses to questions nine through twelve highlight that the main obstacle lies in data collection. First, the artifact suggests a manual data-gathering process; additionally, such data are not widely available in the market. These limitations were perceived both as technical constraints of the MP and as challenges related to the broader context in which the tool would be applied, particularly given the interviewees' varying levels of conceptual maturity regarding CE. Preliminary issues must be resolved before the tool can be effectively used. Questions such as: "At which stage of the design workflow should the MP be used?"; "How can the MP be integrated with other sustainability tools (such as energy efficiency analyses)?" and "Will the MP technology simplify or increase bureaucratic workload in professional practice?" raised from the interviewees' responses and indicate the need for continued research on CE and MP in the construction sector, since the present study did not aim to answer them. Problems related to the use of the MP in professional practice therefore extend beyond the artifact itself and are also associated with the current level of awareness and systemic organization of the construction industry. Consequently, isolated solutions may mitigate part of the problem, but they are unlikely to fully resolve it. As a

recommendation, cooperation among governmental decisions, regulations, and market actors is essential for tools like the MP to have a practical impact on everyday construction workflows.

Another important point highlighted in Stage 3 was financial cost. One of the obstacles to adopting the MP in design practice is the process's monetization. On one hand, time and financial resources are limited, and work must remain productive, especially for construction companies. On the other hand, building users must understand the relevance of sustainability, CE, and the MP to be willing to pay for these concepts and services, which is not yet a market reality. This reinforces the argument that professional perception of the MP is closely linked not only to its technical characteristics, but also to the broader dissemination of CE-related concepts within the sector. Nevertheless, environmental certifications such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and AQUA-HQE may encourage the use of such solutions, by providing market-driven incentives for the adoption of tools that support sustainability assessment.

Finally, Stage 3 suggests that more sustainable practices, including those related to circularity, are already present on the professional agenda. However, the effective application of these practices remains conditioned by both systemic constraints and the current level of conceptual awareness within the Brazilian construction context, indicating that broader educational and institutional efforts are necessary alongside the development of technological tools.

5 Conclusion

This study contributes to the literature by providing an empirical assessment of construction professionals' perceptions of a BIM-based Materials Passport in the Brazilian context, highlighting how baseline conceptual maturity and systemic industry conditions shape the evaluation and potential adoption of circular economy tools. The research was conducted to bring professionals closer to CE and the MP, and, through this approximation, advance investigations into the tool. Moreover, the interview responses, used to validate the artifact, revealed the MP's flaws and shortcomings, whether as a concept or in its practical application.

Based on the interviewees' responses, it is possible to propose that the implementation of the MP still faces challenges in the AEC sector. Despite the importance of the tool for the transition from a linear economy to a circular one [7], modeling processes and information management still need to evolve to achieve market applicability. Other issues were identified, including the need for training in sustainability in the built environment, as well as the integration of additional sustainable and circular practices into the market. The findings indicate that professional perception of the MP is strongly mediated by baseline awareness of CE concepts and by systemic conditions of the construction sector.

This study presents limitations to consider. First, the number of interviewees is not significant and, consequently, does not determine how the Brazilian construction sector understands CE and the MP. The answers obtained in the interview protocol are qualitative and do not represent the broader context of the Brazilian construction industry. However, the protocol provides a foundation for future research to obtain increasingly robust results. In addition, the

MP was developed independently of international open standards. New development cycles are required to incorporate standardized data structures into the MP.

The main findings of this qualitative analysis, considering the entire research (including Alves (2025) [18]), highlight the need to improve materials data management within the construction sector. Future studies may further advance automation in the MP modeling process, particularly by enhancing materials data collection through the use of artificial intelligence (AI). As indicated by the interviewees, the perceived unfeasibility of the MP is strongly associated with limitations of time and financial resources; in this context, technological solutions can play a key role in streamlining routine processes and facilitating data collection. Therefore, the integration of digital automation and intelligent data management emerges as a critical pathway for increasing the practical viability of the MP in professional practice.

CRedit authorship contribution statement

Conceptualization, G.F.A., M.R.M. and S.F.T.; Data curation, G.F.A.; Formal analysis, G.F.A.; Funding acquisition, S.F.T.; Investigation, G.F.A., M.R.M. and S.F.T.; Methodology, G.F.A., M.R.M. and S.F.T.; Project administration, S.F.T.; Resources, S.F.T.; Software, G.F.A.; Supervision, M.R.M. and S.F.T.; Writing - original draft, G.F.A.; and Writing - review & editing, G.F.A., M.R.M. and S.F.T. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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References

- [1] M.R. Munaro, S.F. Tavares, Materials passport’s review: challenges and opportunities toward a circular economy building sector, *Built Environ. Proj. Asset Manag.* 11 (2021) 767–782. <https://doi.org/10.1108/BEPAM-02-2020-0027>.
- [2] EMF, ARUP, First steps towards a circular built environment, Ellen MacArthur Foundation, 2022.
- [3] DEFRA, Digest of Waste and Resource Statistics – 2015 Edition, UK Government, 2015. <http://www.gov.uk/government/collections/waste-and-recycling-statistics> (accessed 3 May 2024).
- [4] IRP, Assessing Global Resource Use: A Systems Approach to Resource Efficiency and Pollution Reduction, United Nations Environment Programme, Nairobi, 2017.
- [5] ARUP, The Circular Economy in the Built Environment, ARUP, London, 2016.
- [6] EMF, Towards a Circular Economy: Business Rationale for an Accelerated Transition, Ellen MacArthur Foundation, Cowes, UK, 2015.
- [7] L.M. Luscuere, Materials passports: optimising value recovery from materials, *Proc. Inst. Civ. Eng. Waste Resour. Manag.* 170 (2016) 25–28. <https://doi.org/10.1680/jwarm.16.00016>.
- [8] European Parliament and Council of the European Union, Regulation (EU) 2024/1781 of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC, *Off. J. Eur. Union L* (2024) 2024/1781. <https://data.europa.eu/eli/reg/2024/1781/oj>.
- [9] M.R. Munaro, S.F. Tavares, L. Bragança, Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment, *J. Clean. Prod.* 260 (2020) 121134. <https://doi.org/10.1016/j.jclepro.2020.121134>.
- [10] D.I. Bokkinga, The Influence of a Material Passport on the Value of Real Estate within the Circular Built Environment, Master’s Thesis, Delft University of Technology, Delft, 2018.
- [11] EPEA Nederland BV, SundaHus i Linköping AB, Framework for Materials Passports, Brussels, 2017. <https://www.bamb2020.eu/wp-content/uploads/2018/01/Framework-for-Materials-Passports-for-the-webb.pdf> (accessed 2 December 2025).
- [12] M.R. Munaro, A.C. Fischer, N.C. Azevedo, S.F. Tavares, Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil, in: *IOP Conf. Ser.: Earth Environ. Sci.*, IOP Publishing, 225 (2019) 012018. <https://doi.org/10.1088/1755-1315/225/1/012018>.
- [13] Smart Waste Portugal Association, Circular Buildings – Guideline for Creating Circular Material Passports, Porto, Portugal, 2021.
- [14] A. Aguiar, R. Vonk, F. Kamp, BIM and circular design, in: *IOP Conf. Ser.: Earth Environ. Sci.*, IOP Publishing, 225 (2019) 012068. <https://doi.org/10.1088/1755-1315/225/1/012068>.
- [15] D. Smith, An introduction to building information modeling (BIM), *J. Build. Inf. Model.* (2007). <https://www.brikbases.org/content/introduction-building-information-modeling> (accessed 20 April 2024).
- [16] A. Talla, S. McIlwaine, Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste, *Smart Sustain. Built Environ.* 13 (2024) 179–198. <https://doi.org/10.1108/SASBE-03-2022-0050>.
- [17] K.M. Rahla, R. Mateus, L. Bragança, Selection criteria for building materials and components in line with the circular economy principles in the built environment: a review of current trends, *Infrastructures* 6 (2021) 49. <https://doi.org/10.3390/infrastructures6040049>.
- [18] I. Atta, E.S. Bakhoun, M.M. Marzouk, Digitizing material passport for sustainable construction projects using BIM, *J. Build. Eng.* 43 (2021) 103233. <https://doi.org/10.1016/j.jobbe.2021.103233>.
- [19] G.F. Alves, A.K. Gripp, M.R. Munaro, S.F. Tavares, L. Bragança, Application of materials passport to the wood frame construction system using Revit and Dynamo, *Buildings* 15 (2025) 4323. <https://doi.org/10.3390/buildings15234323>.
- [20] Autodesk, Autodesk Revit: BIM software to design and make anything. <https://www.autodesk.com/products/revit/overview?term=1-YEAR&tab=subscription> (accessed 3 December 2025).

- [21] International Organization for Standardization (ISO), ISO 23387:2025 – Building information modelling (BIM) — Data templates for objects used in the life cycle of assets, ISO, Geneva, Switzerland, 2025. <https://www.iso.org/standard/85391.html>.
- [22] International Organization for Standardization (ISO), ISO 16739-1:2024 – Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema, ISO, Geneva, Switzerland, 2024. <https://www.iso.org/standard/84123.html>.
- [23] A. Dresch, D.P. Lacerda, J.A.V.A. Júnior, Design Science Research: Método de Pesquisa para Avanço da Ciência e Tecnologia, Bookman, Porto Alegre, 2015.
- [24] M.E. Khan, Different approaches to black box testing technique for finding errors, *Int. J. Softw. Eng. Appl.* 2 (2011) 31–40. <https://doi.org/10.5121/ijsea.2011.2404>.
- [25] M. Honic, I. Kovacic, H. Rechberger, Concept for a BIM-based material passport for buildings, in: *IOP Conf. Ser.: Earth Environ. Sci.*, IOP Publishing, 225 (2019) 012073. <https://doi.org/10.1088/1755-1315/225/1/012073>.
- [26] K. Peffers, T. Tuunanen, M.A. Rothenberger, S. Chatterjee, Design science research evaluation, in: *International Conference on Design Science Research in Information Systems*, Springer, Berlin, Heidelberg, 2012, pp. 398–410.
- [27] K.R. Larsen, M. Niederman, S. Gregor, Validity in design science, *MIS Q.* 49 (2025) 1267–1294. <https://doi.org/10.25300/MISQ/2024/18064>.
- [28] J.W. Creswell, *Investigação Qualitativa e Projeto de Pesquisa: Escolhendo entre Cinco Abordagens*, Penso Editora, Porto Alegre, 2014.



Review paper

Assessment methods as strategic tools to advance circular economy in the construction sector

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ABSTRACT

The construction sector faces pressing environmental challenges driven by high resource consumption, elevated waste generation, and significant greenhouse gas emissions. The circular economy (CE) has emerged as a restorative and regenerative alternative to traditional linear models, promoting resource efficiency, material recirculation, and long-term sustainability. Effective integration of CE principles into the built environment, however, depends on the availability of assessment methods capable of measuring circularity, evaluating material flows, and identifying regeneration opportunities. This paper presents a theoretical analysis of existing sustainability assessment methods, including BREEAM, LEED, and DGNB, and evaluates their capacity to operationalise circularity in the construction sector. Results show that while current tools incorporate aspects of sustainability, they lack specific metrics to measure circularity indicators, such as material loops, design for disassembly, resource recovery potential, and system regeneration. A conceptual framework and an expanded set of indicators are proposed to enhance the assessment of circularity and support transitions toward circular construction practices. The paper contributes to the theoretical foundations needed to guide policy development, industry adoption, and collaborative strategies in circular built-environment systems.

1 Introduction

The construction sector remains one of the most resource-intensive industries worldwide, responsible for substantial raw material extraction, high energy consumption, and a significant share of global waste generation. This long-standing dependence on linear resource flows, characterized by extraction, production, use, and disposal, has amplified environmental pressures and exposed the structural inefficiencies of a throughput-oriented development model [1]. As urbanisation accelerates and the global building stock continues to expand, the sector faces increasing challenges related to resource scarcity, embodied carbon, waste management, and long-term environmental degradation [2].

In this context, the Circular Economy (CE) has emerged as a transformative paradigm that can decouple economic growth from resource depletion. Applied to the built environment, CE promotes strategies such as high-value reuse of construction and demolition waste (CDW), design for adaptability and disassembly, modular construction, material recirculation through industrial symbiosis, and the

integration of digital product information via Material Passports (MPs), Digital Product Passports (DPPs), and Building Logbooks [3], [4]. These strategies aim to extend the life cycles of materials, conserve value, and minimise environmental impacts across all project phases [5].

Despite the growing interest in CE, its operationalisation within the construction sector remains limited and inconsistent. A central challenge lies in the absence of harmonised, robust, and quantifiable assessment methods capable of evaluating circularity at the material, component, and building scales [6]. Existing sustainability frameworks, such as LEED, BREEAM, DGNB, HQE, and Level(s), provide essential metrics for environmental performance but were not originally designed to assess circularity [7]. As a result, many circularity-related aspects, including material flow tracking, component recoverability, regeneration potential, and value-retention efficiency, remain only partially captured or entirely unaddressed.

Assessment tools exhibit several methodological and practical shortcomings:

- **Insufficient material flow transparency** limits the ability to evaluate circular strategies throughout the life cycle;

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- **Lack of consistent indicators for reuse, disassembly, and reparability**, which are essential in CE-aligned design processes;

- **Oversimplified end-of-life (EoL) modelling**, often based on generic recycling rates rather than project-specific recovery pathways;

- **Fragmented data structures and limited interoperability** between sustainability tools, Building Information Modelling (BIM), and LCA/LCC databases;

- **Weak integration with emerging digital infrastructures**, such as Digital Product Passports and building-level materials databases required under new European regulatory frameworks.

These gaps highlight the need for a new generation of assessment methods that are positioned not only as evaluative instruments but also as strategic tools to steer design, procurement, construction, and maintenance toward circular and regenerative outcomes [8].

This paper critically examines the current state of assessment methods in the construction sector and evaluates their capacity to support the implementation of CE. It identifies structural limitations, conceptual inconsistencies, and digitalisation bottlenecks that hinder circularity measurement and decision-making [2]. Building on this analysis, the paper proposes a set of enhanced CE-aligned indicators and methodological considerations to strengthen assessment frameworks and position them as strategic enablers of circularity. By advancing more consistent, transparent, and interoperable assessment practices, the study aims to contribute to the ongoing transition toward a more resource-efficient and circular construction sector [2].

This study advances the current body of knowledge by moving beyond descriptive comparisons of sustainability assessment tools and providing a structured analysis of their limitations in operationalising circularity. Unlike previous reviews, which primarily assess environmental performance, this work conceptualises assessment methods as strategic instruments for enabling circular transitions. Furthermore, it proposes a preliminary set of circularity-oriented indicators and identifies key requirements for integrating digital traceability, life cycle thinking, and value-retention mechanisms into future assessment frameworks.

2 Theoretical background: circular economy in construction

2.1 From linear to circular systems

The construction sector has historically operated under a linear resource model, characterised by intensive raw material extraction, energy-intensive manufacturing processes, short utilisation periods for many building components, and large volumes of construction and demolition waste (CDW) disposed of at the end of the life of buildings [2]. This extract–produce–consume–dispose pathway results in significant material losses and exerts increasing pressure on natural ecosystems, especially as global demand for buildings and infrastructure continues to rise. Urbanisation trends, the expansion of building stock, and the need for continuous upgrades of aging infrastructure amplify the limitations of this model, making its long-term viability increasingly untenable [9].

In contrast, CE principles seek to redefine material and resource flows by maintaining value within the system for as long as possible. CE models emphasise strategies such as reuse, refurbishment, remanufacturing, design for

disassembly, high-quality recycling, and regenerative material cycles [9]. These approaches aim to extend service life, reduce dependency on primary resource extraction, and minimise environmental impacts associated with material production and disposal. Transitioning to CE therefore challenges the construction industry to replace traditional demolition practices with selective deconstruction, prioritise long-life components, and enable future adaptability, reversibility, and transformation of building systems [9].

To conceptualise these transitions, CE frameworks, including the widely referenced Ellen MacArthur Foundation's butterfly diagram, provide a structured representation of how materials circulate through biological and technical cycles [2]. Biological cycles refer to renewable, biodegradable materials that can safely return to natural systems, supporting regenerative processes such as composting, nutrient cycling, and the renewal of bio-based materials [10]. Technical cycles, by contrast, involve industrial materials such as metals, polymers, ceramics, and concrete, which must circulate through processes that retain or restore value: maintenance, repair, reuse, refurbishment, remanufacturing, and recycling. CE models emphasise value retention hierarchies, favouring high-value strategies (reuse, remanufacturing) over lower-value ones (downcycling), thereby aiming to maximise material utility across multiple life cycles.

Within the construction sector, strengthening technical cycles is particularly critical due to the long lifespan of built assets, the capital-intensive nature of building components, and the substantial embodied carbon and environmental impacts associated with the use of mineral and industrial materials [9]. Long service life, however, does not inherently ensure circularity. Without material traceability, disassembly-oriented design, and efficient recovery infrastructure, many materials ultimately follow a linear degradation pathway, ending up in landfills or low-value recycling streams.

Transitioning from linear to circular systems, therefore, requires integrating CE principles across all stages of the building lifecycle, from concept design and procurement to construction, operation, maintenance, renovation, and end-of-life planning [9]. Achieving this transition depends on enabling conditions, such as robust, harmonised data structures, digital workflows that embed circularity considerations (e.g., BIM-based material tracking), and assessment tools capable of consistently and at scale quantifying circularity performance. Without reliable data and metrics, circularity remains aspirational rather than operational, reinforcing the need for new methodologies that align design, material selection, and lifecycle management with CE objectives.

2.2 Barriers to circularity in construction

Despite growing interest in CE principles and a steady increase in pilot initiatives worldwide, the transition toward circular construction remains hindered by a series of persistent structural, regulatory, technical, cultural, financial, and organisational barriers [10]. These obstacles affect all stages of the value chain, from material sourcing and manufacturing to design, procurement, construction, operation, renovation, and end-of-life processes, limiting the scalability and mainstream adoption of CE practices. The complexity of these barriers reflects the deeply embedded linear logic that has shaped construction industry practices for decades.

A central constraint lies in the limited availability, quality inconsistency, and market immaturity of secondary

materials. Although CDW is one of the most significant waste streams globally, only a small fraction is recovered at a quality suitable for high-value reuse or remanufacturing. Contamination, inefficient sorting technologies, and the prevalence of composite materials complicate recovery processes [9]. Additionally, the absence of controlled and selective deconstruction practices, often replaced by rapid demolition, results in a loss of material integrity, limiting opportunities for component reuse. These challenges hinder the development of robust secondary material markets and prevent circular practices from becoming economically viable [10].

Regulatory and institutional barriers further inhibit circularity. Building codes, safety standards, and liability rules often restrict the reuse of structural or non-structural components due to concerns about performance reliability, traceability, warranties, and compliance [9]. Many standards still privilege virgin materials, and national regulations frequently lack harmonisation, making it challenging to apply circular strategies consistently across regions. Public procurement systems, which influence a large share of construction demand, often prioritise cost minimisation or traditional compliance pathways over circular performance, reinforcing linear procurement habits.

Another critical barrier is the lack of material traceability across the building lifecycle. Most construction products currently enter the built environment without digital identities or persistent data records. As buildings typically last several decades, the loss of information regarding material composition, embodied impacts, hazardous substances, and potential reuse pathways renders high-value recovery nearly impossible [9]. Frequent changes in ownership, fragmented documentation practices, and insufficient integration of digital tools across the value chain intensify this issue.

Digitalisation gaps compound this challenge. Many organisations lack digital infrastructures and platforms capable of recording, updating, and transferring material history in interoperable formats. Integration with tools such as Building Information Modelling (BIM), life-cycle assessment (LCA) software, and emerging frameworks like Material Passports (MPs), Digital Product Passports (DPPs), and digital building logbooks remains limited [3]. Data interoperability, inconsistent ontologies, and proprietary file formats hinder the integration of circularity criteria into decision-making processes during design and procurement, thereby restricting the flow of adequate information.

Economic and market-related barriers also persist. Circularity often requires higher upfront costs, investments in new technologies, development of reverse logistics, and the establishment of refurbishment or remanufacturing facilities [10]. These costs, combined with the uncertainty of resale markets for reclaimed components and the inconsistent supply of secondary materials, create perceived financial risks that discourage stakeholders from engaging in circular practices. The absence of mature business models, such as product-as-a-service, leasing, or material take-back schemes, further limits adoption.

Cultural and behavioural barriers contribute to the slow pace of the transition. The construction industry remains highly conservative, risk-averse, and oriented toward conventional supply chains. Designers, contractors, and clients often lack awareness, expertise, or confidence in circular strategies [10]. Limited training, insufficient knowledge transfer, and traditional performance indicators (e.g., cost and delivery time) overshadow circularity considerations. These cultural norms perpetuate linear

practices and hinder experimentation with innovative circular approaches.

Finally, one of the most fundamental limitations is the absence of transparent, harmonised, and widely accepted metrics for measuring circularity. Existing sustainability certification systems were developed under environmental paradigms and therefore lack dedicated definitions, indicators, and benchmarks for circularity [1]. This results in fragmented measurement approaches, superficial inclusion of circularity-related credits, and a general inability to quantify material recovery potential, design reversibility, value-retention capacity, or systemic regeneration. Without shared definitions and standardised metrics, circularity remains difficult to compare across projects, assess consistently, or incorporate into regulatory frameworks [11].

Within this context, assessment methods emerge as strategic tools. By establishing clear definitions, harmonised data requirements, measurable indicators, and traceable documentation structures, robust assessment methods can mitigate many of these barriers [10]. They can support informed decision-making, facilitate regulatory alignment, enhance digital interoperability, and guide the construction industry toward a systematic transition to linear-to-circular and regenerative practices.

3 Review of sustainability assessment methods

3.1 LEED

The Leadership in Energy and Environmental Design (LEED) system, developed by the U.S. Green Building Council (USGBC) [12], is the most internationally recognised and widely adopted sustainability certification framework [13]. LEED evaluates buildings through a credit-based structure that covers energy performance, indoor environmental quality, water efficiency, site sustainability, and materials and resources. Within this structure, the Materials and Resources category aims to improve environmental performance by encouraging responsible material sourcing, increasing the use of recycled content, promoting effective construction waste management, and enhancing transparency through Environmental Product Declarations (EPDs) and material ingredient reporting programs.

From a circularity perspective, LEED contributes indirectly by guiding project teams toward environmentally conscious decisions, such as reducing construction waste, favouring materials with lower embodied impacts, and encouraging the reuse of existing structures [14]. Requirements related to construction and demolition waste management, for instance, aim to divert waste from landfills [15]. At the same time, credits for reducing building life-cycle impacts incentivise adaptive reuse and renovation over new construction. Similarly, promoting EPDs increases the availability of life-cycle information on materials, potentially supporting informed decision-making in the early design stages.

Despite these positive contributions, LEED's alignment with CE principles remains limited. LEED was initially conceived to address environmental sustainability, and its material-related credits focus primarily on waste diversion rates, recycled-content proportions, and product transparency [15]. These indicators reduce environmental burdens but do not reflect deeper circularity objectives such as value retention, loop closure, multi-cycle material performance, or long-term adaptability [6]. For example, although LEED rewards the reuse of existing buildings, it

does not explicitly incentivise design strategies that would ensure future recoverability of components, such as modular construction systems, reversible connections, or design for disassembly [15]. Consequently, the framework encourages the reuse of past building elements but does not prepare buildings for future reuse cycles.

Another critical limitation relates to end-of-life considerations. LEED evaluates waste management during construction but does not assess the recovery potential of materials during future renovation or demolition [12]. End-of-life scenarios are not explicitly modelled, nor does the system provide methods for estimating the long-term recirculation potential of materials. This short-term focus prevents LEED from capturing the temporal dimension of circularity, where materials and components are expected to circulate through multiple life cycles over several decades [15].

Material traceability is also insufficiently addressed. Although EPDs and material ingredient disclosures promote transparency, they do not offer persistent digital identities for materials or components. LEED does not incorporate digital systems such as Material Passports, Digital Product Passports, or building-level logbooks that record material attributes throughout the building's lifespan [12]. Without such tools, it becomes difficult to trace materials over time, undermining future opportunities for reuse, refurbishment, or high-value recycling.

Additionally, LEED's assessment approach is static. Certification occurs at a single point in time, typically upon project completion. Circularity, however, is dynamic by definition: materials age, degrade, are replaced, and may re-enter new cycles [12]. A one-time certification cannot capture these transformations, nor can it evaluate whether buildings remain adaptable or suitable for future disassembly. Therefore, LEED's structure is incompatible with the continuous monitoring required for operational circularity [6].

Finally, the LEED system's structural characteristics limit its potential to drive circular change. Its flexible points-based approach allows projects to obtain certification without prioritising material-related credits, thereby weakening the influence of circularity-enabling strategies [6]. Moreover, its criteria rely heavily on market availability of products with specific certifications, which vary widely by region, creating inconsistent opportunities for circular practices across project locations.

3.2 BREEAM

The Building Research Establishment Environmental Assessment Method (BREEAM) is one of the most established and influential sustainability certification frameworks, widely implemented across Europe and internationally [13]. Compared to other systems, BREEAM offers a broader and more detailed coverage of material-related criteria, integrating sustainability considerations across categories such as management, energy, water, materials, waste, health and wellbeing, and pollution. Within its materials domain, BREEAM places particular emphasis on LCA, responsible sourcing of construction products, material efficiency, construction site resource management, and the use of EPDs [16]. These elements collectively enable a more comprehensive evaluation of embodied impacts than other frameworks, particularly by encouraging reductions in resource consumption and promoting transparency in material supply chains.

The inclusion of LCA within BREEAM is particularly noteworthy, as it enables a systematic analysis of the

environmental burdens associated with building components throughout their entire life cycle. This supports informed decision-making at early design stages and fosters the selection of materials with lower embodied impacts [17]. Additionally, BREEAM's focus on responsible sourcing and material efficiency reflects a broader effort to reduce primary resource extraction and minimise waste generation across project phases. In these respects, BREEAM provides a more robust assessment structure than LEED for examining material-related environmental performance.

However, when evaluated through the lens of CE, several limitations become apparent. Although BREEAM encourages resource-efficient design, it does not provide structured mechanisms to track dynamic material flows throughout a building's life cycle [6]. The system does not quantify reuse potential, assess the reversibility of building components, or map realistic end-of-life recovery routes [17]. This lack of material-flow modelling limits projects' ability to anticipate multiple life cycles for building components, a core principle of CE.

Moreover, BREEAM does not fully integrate circularity-specific design strategies. While certain credits indirectly support principles such as durability or adaptability, explicit recognition of design for disassembly, modular construction, remanufacturing potential, or long-term material value retention remains limited [16]. BREEAM's methodology continues to focus primarily on reducing environmental impacts, rather than enabling the regenerative, multi-cycle approaches central to CE implementation.

Material traceability within BREEAM is also fragmented. Although requirements for EPDs and responsible sourcing improve transparency, they do not provide the persistent and structured information needed to track materials throughout the building's lifespan [17]. The system does not incorporate digital tools such as Material Passports, Digital Product Passports, or building-level digital identities that would support long-term documentation of material attributes, facilitate selective deconstruction, or enable high-value reuse in future cycles [16]. Without such traceability mechanisms, circularity remains difficult to operationalise beyond the construction stage.

End-of-life considerations represent another critical gap. BREEAM addresses waste management during construction and operation; however, its treatment of the end-of-life stage is static and simplified [17]. The system does not evaluate realistic scenarios for component recovery, reuse in secondary markets, or integration into industrial symbiosis networks. This limitation restricts BREEAM's ability to support multi-cycle material strategies and fails to account for the logistical and economic complexities associated with future material recovery.

In summary, BREEAM provides a stronger foundation for evaluating embodied impacts and resource efficiency than LEED, particularly through its integration of LCA and responsible sourcing criteria [16]. Nevertheless, its methodological structure remains oriented toward environmental sustainability rather than circularity. The absence of dedicated indicators for material recirculation, long-term traceability, building adaptability, value-retention strategies, and lifecycle-integrated recovery pathways means that BREEAM falls short of enabling the systemic shift required for CE implementation [13]. While it helps reduce environmental impacts, it does not provide the tools needed to assess or accelerate the transition from linear to circular construction systems.

3.3 DGNB

The German Sustainable Building Council (DGNB) certification system is widely regarded as one of the most comprehensive and methodologically robust sustainability assessment frameworks currently in use. Its distinguishing feature lies in the balanced integration of environmental, economic, sociocultural, technical, and process-related performance criteria, reflecting a holistic understanding of building performance [18]. Unlike LEED or BREEAM, DGNB adopts an explicitly life-cycle-oriented perspective, incorporating both LCA and Life-Cycle Costing (LCC) as central components of its methodology [19]. This long-term approach enables a systemic evaluation of environmental burdens, operational and maintenance requirements, and economic implications throughout the building's lifespan, positioning DGNB as one of the most analytically rigorous certification systems available.

DGNB also incorporates optional criteria that are particularly relevant to CE principles, including adaptability, convertibility, and disassembly [19]. These criteria encourage design strategies that support flexible spatial configurations, facilitate future modifications, and enable the recovery of building components at the end of life. In doing so, DGNB acknowledges the importance of designing buildings as dynamic systems that can respond to evolving functional needs and material recovery pathways [6]. This makes DGNB the closest among existing sustainability certification systems to aligning with CE objectives.

Yet, despite these strengths, DGNB is not fully operationalised within a circularity framework. Several substantive gaps remain that limit its ability to support or measure long-term material recirculation. For instance, DGNB does not quantify the recirculation potential of materials or components beyond general assessments of recyclability [19]. The system lacks indicators that evaluate the feasibility of reintroducing materials into technical loops through reuse, refurbishment, or remanufacturing. Consequently, DGNB cannot assess whether materials retain functional value across multiple life cycles, an essential dimension of CE.

Similarly, although DGNB addresses adaptability and disassembly, it does not systematically evaluate whether recovered components can enter secondary markets or whether their properties, durability, and condition are suitable for high-value reuse [18]. The framework also lacks explicit metrics for value-retention strategies, including the durability of materials across multiple cycles, residual value forecasting, and quantification of the long-term economic benefits associated with material conservation [19]. These omissions limit DGNB's ability to assess whether buildings support regenerative material flows or merely reduce their environmental impacts.

Material traceability is another significant limitation. While DGNB encourages transparency through LCA and LCC, it does not integrate emerging digital tools, such as Material Passports, Digital Product Passports, or digital building logbooks, which record material attributes throughout the building's service life. Without such tools, the system cannot support long-term tracking of materials, documentation of component-level information, or data-sharing mechanisms essential for circularity. This lack of traceability undermines the ability to plan for future reuse, manage material stocks, or operationalise disassembly strategies.

Taken together, these limitations demonstrate that DGNB, although more advanced than LEED or BREEAM in addressing long-term design and material considerations,

remains primarily a sustainability assessment framework. Its partial alignment with CE principles reflects an evolution toward circularity, but not a complete integration of circularity metrics into its core methodology [19]. The system advances several essential preconditions for circularity. Still, it does not yet provide a comprehensive evaluation of material recirculation, multi-cycle value retention, or the systemic transformation required for circular construction [18]. As such, DGNB remains a sustainability-oriented tool with circularity features, rather than a method for assessing circularity.

4 Comparative analysis of LEED, BREEAM, and DGNB

A comparative examination of LEED, BREEAM, and DGNB reveals fundamental differences in scope, methodological depth, and alignment with CE principles [19]. While all three systems aim to improve the environmental performance of buildings, their capacity to support circularity varies significantly due to the historical context in which they were developed, the ecological paradigms they prioritise, and the types of indicators they include.

LEED remains the most widely recognised framework globally, mainly due to its accessibility, market penetration, and emphasis on environmental transparency and resource efficiency. However, its material-related credits primarily focus on waste diversion, recycled content, and responsible procurement. These indicators encourage reductions in environmental impact but do not fully address the value-retention strategies, multi-cycle material flows, or design-for-disassembly principles required for circularity [18]. LEED evaluates materials primarily now of construction, with minimal attention to long-term recovery potential or future reuse scenarios.

BREEAM offers a more comprehensive approach, particularly through its integration of LCA and responsible sourcing criteria. This positions BREEAM closer to systemic material evaluation than LEED does. Nevertheless, BREEAM still approaches materials from an environmental performance perspective rather than a circularity perspective [6]. While BREEAM encourages the efficient use of materials and reduction of construction-phase waste, it falls short of quantifying dynamic material flows or assessing whether components can be disassembled and recovered at the end of their life [17]. Material traceability remains fragmented, and digital documentation systems capable of supporting long-term recovery, such as Material Passports or Digital Product Passports, are not incorporated into the framework.

DGNB stands out as the most advanced system in terms of life cycle thinking, due to its explicit integration of LCA and LCC as core components of its methodology. DGNB goes further than LEED and BREEAM in recognising the importance of adaptability, convertibility, and disassembly, elements that are closely aligned with CE principles [18]. However, DGNB also falls short of fully operationalising circularity. Despite addressing long-term design strategies and offering credits for reversibility, DGNB does not quantify the potential for material recirculation, long-term value retention, or multi-cycle reuse scenarios. Traceability tools, digital identities for materials, and data structures for managing building-level material stocks are similarly absent.

Viewed collectively, the three systems demonstrate the limitations of sustainability-driven certification approaches when applied to circularity assessment. LEED provides transparency; BREEAM provides environmental optimisation; DGNB provides life cycle thinking. Yet none of them measure circularity holistically or operationally [18].

None of the frameworks quantify how materials circulate across multiple life cycles, evaluate the conditions that support reuse and remanufacturing, incorporate digital documentation tools for material traceability, or assess regenerative outcomes. These systems were designed to reduce environmental harm, not to manage circular material flows.

Thus, although LEED, BREEAM, and DGNB contribute valuable structures for improving sustainability performance, they do not capture the systemic, regenerative, and multi-scalar nature of CE. Their methodologies remain grounded in environmental sustainability rather than in circularity, leaving significant gaps in material flow tracking, end-of-life modelling, and design strategies for value retention [17]. This comparative analysis highlights the need for new assessment methods or substantial adaptations of existing ones to better reflect CE requirements, integrate digital data infrastructures, and support the development of circular construction practices at scale.

5 Limitations of current tools

A comparative analysis of existing sustainability assessment frameworks, such as LEED, BREEAM, and DGNB, reveals structural limitations that hinder their ability

to support a meaningful transition toward CE practices in the construction sector [19]. Although these systems have substantially advanced environmental performance evaluation and contributed to reducing operational and embodied impacts, their methodological foundations were not conceived with circularity in mind [18]. Consequently, they overlook several core dimensions required for the systemic transformation envisioned by CE principles.

A primary limitation is the absence of an explicit, comprehensive definition of circularity within these frameworks. While concepts such as resource efficiency, waste minimisation, and responsible sourcing are recurrent elements, none of the systems articulate circularity in terms of value retention, loop closure, design for disassembly, building components, or long-term material recirculation [6]. The lack of conceptual clarity leads to sustainability credits being misinterpreted as proxies for circularity, even though they pursue fundamentally different objectives.

Another critical gap is the absence of metrics capable of capturing material flow loops across multiple life cycles. Current tools do not quantify the ability of materials to circulate through reuse, repair, refurbishment, or remanufacturing pathways [17]. They also lack indicators for assessing component reversibility, selective deconstruction performance, recovery efficiency, or integration into secondary material markets. Instead, existing systems rely

Table 1. Comparative overview of LEED, BREEAM, and DGNB with respect to circular economy principles

Criterion	LEED	BREEAM	DGNB
Primary focus	Environmental performance, transparency, waste reduction	Life-cycle environmental optimisation, responsible sourcing	Holistic sustainability with strong life-cycle integration (LCA + LCC)
Integration of LCA	Optional and limited in scope	Mandatory for several credits; more detailed	Central component of the methodology; highly developed
Material efficiency	Addresses waste management and recycled content	Emphasises efficient use of materials and construction-phase waste reduction	Integrated through LCA/LCC; includes resource efficiency
Circularity definition	Not defined; circularity treated indirectly	Not explicitly defined; partially integrated	Not fully defined, but closest to CE concepts due to adaptability and disassembly credits
Design for Disassembly (DfD)	Not evaluated	Limited or indirect consideration	Included as an optional criterion; strongest among the three
Adaptability/flexibility	Not systematically assessed	Addressed indirectly (e.g., durability, longevity)	Explicitly discussed as part of design strategies
Material traceability	Relies on EPDs and HPDs; no long-term tracking	EPDs used, but no persistent traceability	No integration of digital passports or long-term tracking
Digital product data (MPs, DPPs)	Not integrated	Not integrated	Not integrated, despite forward-looking potential
End-of-life modelling	Evaluates construction waste only	Limited modelling; static assumptions	Includes disassembly criteria, but without complete recovery modelling
Value-retention strategies	Not assessed	Not assessed	Acknowledged conceptually but not quantified
Evaluation approach	Static, project-level, one-time certification	Static; focuses on environmental optimisation	Life-cycle oriented but not dynamic across multiple cycles
Overall alignment with CE	Low	Moderate	Highest, but still partial and sustainability-driven

on static, one-time indicators, such as recycled-content percentages or construction-phase waste diversion, that do not account for the dynamic, multi-cycle behaviour central to CE implementation.

The frameworks also fail to assess regenerative potential, which is essential for circularity in both technical and biological cycles [17]. While sustainability approaches prioritise impact reduction, circularity emphasises strategies that restore and regenerate systems. Yet, factors such as biogenic carbon cycling, ecosystem regeneration potential, renewable material replenishment, and positive environmental contributions are rarely incorporated into assessment methodologies.

A further limitation arises from insufficient integration of digitalisation trends. Existing systems do not adopt tools such as Material Passports, Digital Product Passports, digital building logbooks, or BIM-integrated circularity datasets, which are fundamental for long-term material traceability and future resource recovery [17]. Without such tools, buildings remain data-poor assets, and materials cannot be effectively tracked, documented, or reintroduced into technical cycles at the end of life.

Collectively, these limitations demonstrate that current sustainability assessment methods evaluate environmental performance rather than circularity [6]. They reduce harm but do not enable regenerative, multi-cycle material management. As a result, they fall short of capturing the systemic transformations required for CE implementation [17]. This confirms the methodological gaps identified in the broader literature and underscores the urgent need for new or adapted assessment tools capable of quantifying circularity, supporting material traceability, and enabling value retention across the entire building life cycle.

6 Identified gaps in measuring circularity

The theoretical analysis of existing assessment frameworks reveals several foundational limitations that prevent current systems from accurately reflecting the principles and operational requirements of the CE in the construction sector, as shown in Table 2 [17]. Although sustainability certification schemes have advanced environmental evaluation practices, they continue to be shaped by linear design assumptions and impact-reduction paradigms that are not compatible with multi-cycle,

regenerative material flows. As a result, the measurement of circularity remains incomplete, fragmented, and conceptually inconsistent.

The first gap concerns the predominance of waste-centric metrics, which reduce circularity to construction-phase waste diversion, recycled content percentages, or general waste minimization efforts. While useful from a sustainability standpoint, these metrics do not capture the systemic nature of circularity, which depends on materials' ability to retain value across multiple life cycles [6]. This narrow focus risks equating circularity with recycling efficiency rather than recognising it as a broader regenerative strategy that prioritises reuse, durability, and high-value recirculation.

A second limitation arises from the static nature of current assessment frameworks. Most certification systems evaluate buildings at a single point in time, typically at design completion or project delivery, without considering how materials and components evolve over decades of use, maintenance, replacement, and eventual disassembly [6]. Because circularity is inherently temporal and requires ongoing monitoring of material condition, performance, and recoverability, static assessments cannot capture the dynamic pathways through which materials may circulate over extended lifespans.

A third gap relates to the lack of systematic material traceability. Circularity depends on robust, long-term documentation of material attributes, provenance, chemical composition, embodied impacts, and potential hazards. However, current tools do not incorporate digital mechanisms such as Material Passports (MPs), DPPs, or digital building logbooks [17]. Without persistent data structures, the possibility of recovering and reusing high-value materials is severely constrained, and buildings remain opaque repositories of materials that are difficult to reintroduce into technical cycles.

Fourth, existing assessment systems provide insufficient recognition of design-for-circularity strategies. Approaches such as modular design, reversible connections, adaptable spaces, and selective deconstruction are key to implementing CE [17]. Yet, most frameworks include these criteria only in optional, qualitative, or minimally weighted forms [6]. The absence of clear, quantifiable indicators for design decisions that influence future recoverability limits the integration of circular principles during early project stages, where they are most impactful.

Table 2. Critical gaps in current circularity assessment within sustainability frameworks

Gap Identified	Description	Implications for Circularity
Waste-centric metrics	Focus on recycling rates, waste diversion, and construction-phase waste reduction, rather than on value retention or multi-cycle material loops.	Circularity becomes equated with waste management; high-value reuse, refurbishing, and remanufacturing remain unmeasured.
Static assessment frameworks	One-time evaluations at design or delivery stages that do not track materials over decades of use, replacement, or transformation.	Inability to assess material lifespan, future recoverability, or multi-cycle performance; the temporal dimension of circularity is ignored.
Limited material traceability	Absence of digital tools such as MPs, DPPs, or logbooks that provide persistent, structured material information.	Materials become impossible to recover at high value; lack of long-term documentation prevents technical loop closure.
Insufficient focus on design strategies	Weak or optional treatment of modularity, reversibility, adaptability, and design for disassembly.	Projects miss out on early-stage decisions that enable future reuse; design strategies central to CE are neither incentivised nor measured.
Absence of regeneration indicators	Lack of metrics for ecological regeneration, biogenic cycles, or positive environmental contributions.	Circularity remains limited to impact reduction; regenerative potential—key to CE—is not captured.

Finally, the absence of regeneration-oriented indicators represents a significant conceptual gap. Circularity is not solely about closing loops; it also encompasses the capacity of built systems to regenerate biological cycles, renew biogenic materials, and create positive ecological outcomes [17]. Current frameworks prioritise impact reduction over value creation or regeneration, thereby overlooking opportunities for buildings to contribute to environmental restoration, renewable material cycles, and carbon sequestration.

Together, these gaps demonstrate that existing sustainability assessment tools measure sustainability rather than circularity [17]. They fail to capture the multi-dimensional, systemic, and regenerative ambitions of CE, underscoring the need for new or adapted metrics that support value retention, digital traceability, material adaptability, and long-term recirculation across the entire building lifecycle.

Building on the identified gaps, this study proposes a preliminary framework of circularity indicators to address the limitations of current assessment methods. The proposed indicators are structured across key dimensions, including material flow dynamics, design for circularity, value retention, digital traceability, and regenerative capacity. Table 3 presents this framework, intended as a conceptual foundation for developing more robust operational circularity assessment tools.

7 Discussion

The findings of this review show that current sustainability assessment systems, despite their contributions to reducing environmental impacts, do not adequately capture the systemic, regenerative, and multi-cycle principles that underpin the CE. The gaps identified across LEED, BREEAM, and DGNB reveal that these frameworks continue to operate within a linear paradigm, privileging environmental optimisation rather than long-term material value retention, regenerative design, and multi-scalar resource circulation.

These limitations are not inherent to individual tools, but rather reflect the historical evolution of sustainability frameworks, most of which were conceived before the concept of CE thinking emerged as a guiding paradigm for the built environment.

The proposed indicator framework provides a structured response to the gaps identified in current assessment systems. By translating conceptual limitations into measurable dimensions, it enables a shift from descriptive sustainability assessment toward operational circularity evaluation. It addresses the absence of dynamic material flow metrics, long-term traceability mechanisms, and value-retention strategies highlighted in the previous sections. This transition is essential to move from assessing impacts to managing material performance across multiple life cycles.

Although certification systems incorporate critical sustainability dimensions such as waste minimisation, responsible sourcing, and life-cycle assessment, their methodologies are fundamentally impact-reduction-oriented. In contrast, circularity requires a structural redesign of how materials, components, and systems are conceived, used, managed, and recovered across successive life cycles. While sustainability seeks to “do less harm,” circularity aims to preserve and regenerate value, keeping materials in technical or biological loops for as long as possible. This conceptual distinction underscores the need for new assessment approaches that go beyond environmental optimisation.

The introduction of circularity-oriented indicators also has important methodological implications. Unlike traditional sustainability metrics, which are often static and evaluated at a single point in time, the proposed indicators require dynamic data structures, longitudinal monitoring, and integration with digital tools such as Building Information Modelling (BIM), material passports, and digital product documentation systems. This suggests that future assessment frameworks must evolve from one-time certification schemes toward continuous, data-driven evaluation models capable of tracking material conditions, transformations, and recovery potential over time.

Table 3. Critical gaps in current circularity assessment within sustainability frameworks

Dimension	Indicator	Description	Measurement approach
Material Flow	Recirculation Potential	Ability of materials to re-enter technical cycles	% reusable components, recovery scenarios
Design	Disassembly Index	Ease of separating components without damage	qualitative + connection typology
Value Retention	Residual Value	Economic value after first life cycle	LCC + secondary market estimation
Traceability	Material Transparency	Availability of digital material data	presence of MP/DPP
Adaptability	Functional Flexibility	Capacity to accommodate future uses	adaptability scoring
Regeneration	Biogenic Renewal Potential	Capacity to restore biological systems	% bio-based renewable materials
Material intensity	Desmaterialisation	Rate of reduction in material consumption per functional unit	Comparison between the baseline design and the optimised design
Waste generation	Waste Generation Rate	Amount of waste generated at the end of construction (m ³ /m ²)	waste generation rate (mass or volume/building)

To enable a genuine transition from linear to circular practices, the assessment of material performance must move beyond static, one-time evaluations and embrace continuous, data-driven monitoring over the building life cycle. Several enabling conditions emerge from the analysis:

The first requirement is the collaboration of multiple stakeholders, including industry practitioners, policymakers, certification bodies, researchers, and digital technology providers. Circularity cannot be implemented through isolated efforts; it requires harmonised definitions, consistent data structures, and aligned incentives across the entire value chain. Without coordination, adoption remains fragmented, limiting the scalability of circular practices and the development of cross-sectoral material loops.

A second enabler is the integration of digital tools for material tracking. Digital infrastructures, such as Material Passports, Digital Product Passports, BIM-embedded circularity datasets, and digital building logbooks, serve as foundational mechanisms for documenting material attributes over the long term. Without long-term traceability, even buildings designed for reuse or disassembly cannot achieve high-value recovery at the end of life. Embedding CE indicators into BIM workflows is therefore essential to operationalising circularity across design, procurement, and maintenance.

The third enabler concerns emerging business models that prioritise reuse, refurbishment, leasing, and product-as-a-service arrangements. Circularity cannot function effectively within traditional procurement and ownership structures. Instead, the construction sector must support reverse logistics networks, refurbishment centers, selective deconstruction services, and secondary material marketplaces. Assessment methods must evolve to capture these dimensions, evaluating not only material properties but

the economic and organisational systems that support material circulation.

A fourth enabler is the development of regulatory frameworks that facilitate the recovery of materials. Current regulations often restrict the reuse of recovered components due to concerns about liability, safety requirements, or outdated standards. Circularity-aligned policies should promote performance-based approvals, establish quality standards for secondary materials, offer incentives for design for disassembly, and require mandatory documentation of material data. Assessment tools alone cannot shift practice unless they are supported by enabling regulations.

Table 4 highlights the differences between LEED, BREEAM, and DGNB in terms of their advantages, limitations, and opportunities for CE implementation. While DGNB provides the strongest methodological foundation, particularly through its life-cycle integration, none of the three systems offers a comprehensive assessment of circularity. Their limitations consistently relate to the absence of indicators for material recirculation potential, design reversibility, long-term value retention, and regenerative performance, as well as the insufficient incorporation of digital material traceability tools.

Overall, this analysis reinforces that current methods primarily evaluate sustainability, rather than circularity. They excel in reducing environmental burdens but fall short of capturing the dynamic, regenerative, and multi-cycle character of CE. Addressing these gaps requires a new generation of assessment tools that can quantify circularity, support digital traceability, and enable system-wide value retention throughout the entire building life cycle. Only through such tools will the construction sector be equipped to transition to a truly circular, regenerative built environment.

Table 4. Advantages, limitations, and opportunities of LEED, BREEAM, and DGNB with respect to circular economy implementation

System	Advantages (Current Strengths)	Limitations (Gaps for Circularity)	Opportunities (Potential for CE Integration)
LEED	Global recognition and widespread adoption.	Does not evaluate design for disassembly, modularity, or reversibility.	Integration of Material Passports and Digital Product Passports.
	Strong emphasis on material transparency through EPDs, HPDs, and Declare labels.	No assessment of long-term material recovery potential.	Inclusion of indicators for recoverability, reuse potential, and multi-cycle performance.
	Encourages the reuse of existing buildings and waste reduction during construction.	Material traceability is limited to one-time product disclosures.	Expansion of life cycle thinking beyond initial construction.
BREEAM	Encourages the reuse of existing buildings and waste reduction during construction.	End-of-life scenarios are not considered.	Development of circular credits in future LEED versions.
	Strong integration of LCA and responsible sourcing.	• No modelling of material flows over multiple cycles.	Potential to expand LCA to include circularity metrics (e.g., recirculation potential).
	Broader material-related coverage than LEED.	Circularity-specific design strategies are not explicitly evaluated.	Integration of digital traceability tools, such as MPs and DPPs.
	Emphasis on material efficiency and construction-phase waste management.	Traceability mechanisms are not integrated into long-term building documentation.	Development of credits on modularity, reusability, and component-level recovery.
	Encourages transparent supply chains.		

		End-of-life modelling is static and limited.	Strengthening of secondary material market incentives.
DGNB	Most advanced system regarding life-cycle integration (LCA + LCC).	Material recirculation potential is not quantified.	Ideal candidate for integrating circularity-specific metrics.
	Includes adaptability, convertibility, and disassembly criteria.	Reuse pathways and secondary markets are not systematically evaluated.	A strong methodological foundation enables the adoption of digital material documentation systems.
	A holistic sustainability framework covers environmental, economic, and sociocultural aspects.	Value-retention strategies are absent from the assessment criteria.	Potential to link LCC with residual value forecasting and material recovery planning.
	Encourages long-term performance and durability.	Digital identity and traceability tools are not incorporated.	Expansion of disassembly and adaptability credits into mandatory criteria.

As illustrated in Table 3, although DGNB demonstrates the most substantial methodological alignment with CE principles, none of the systems provides a complete framework for assessing multi-cycle material flows, value retention, or regenerative performance. This reinforces the need for new assessment mechanisms that support digital traceability, long-term design adaptability, and the systemic recirculation of materials.

8 Conclusions

This paper contributes to the theoretical development of circularity assessment in the construction sector by explicitly distinguishing sustainability-based evaluation from circularity-oriented assessment and by identifying the structural conditions required to operationalise circular economy principles within existing frameworks.

This study demonstrates that while current sustainability assessment frameworks, such as LEED, BREEAM, and DGNB, have played an essential role in guiding environmental performance improvements, they remain insufficient for evaluating or enabling CE practices in the construction sector. The analysis reveals that these tools were developed within a sustainability paradigm centred on impact reduction, resource efficiency, and transparency, but not on the regenerative, multi-cycle, and value-retention principles that define circularity.

Across all systems, circularity is often treated indirectly or superficially, with an excessive emphasis on waste minimization and recycled content, and limited consideration of material recirculation potential, design for disassembly, component adaptability, or long-term value retention. Material flow loops are not modelled, digital traceability is absent, and regenerative outcomes are not assessed. As a result, sustainability certifications continue to focus on measuring *environmental performance* rather than *circularity, revealing a conceptual and methodological gap that hinders* progress toward a circular built environment.

Closing this gap requires a fundamental rethinking of how buildings are evaluated, documented, and designed. The findings highlight four strategic enablers for future CE-oriented assessment methods: (1) multi-stakeholder collaboration to harmonise definitions, data structures, and incentives; (2) integration of digital tools such as Material Passports, Digital Product Passports, and BIM-based circularity datasets to enable long-term material traceability;

(3) alignment with emerging business models that support reuse, refurbishment, and reverse logistics at scale; and (4) regulatory frameworks that facilitate material recovery, secondary-material markets, and performance-based acceptance of reused components.

Together, these elements suggest that future assessment frameworks must evolve beyond static certification models and adopt dynamic, data-rich, life-cycle-integrated methodologies capable of capturing the circulation, transformation, and regeneration of materials over time. Only by using new or substantially adapted tools will the construction sector operationalise circularity, optimise value retention, and support the transition toward a regenerative, resource-resilient built environment.

Ultimately, this review highlights the pressing need to develop indicators and digital infrastructures specific to circularity, enabling traceable, verifiable, and future-proof material cycles. Advancing circularity is not simply about extending existing sustainability metrics; it requires a paradigm shift that redefines how buildings are conceived, assessed, and managed throughout their life cycles. Such a shift is essential for achieving the systemic transformation needed to align the construction sector with the goals of a Circular Economy.

Author Contributions

Conceptualisation, G.C.C.P., M.R.M. and L.B.; methodology, G.C.C.P.; software, G.C.C.P.; formal analysis, G.C.C.P.; investigation, G.C.C.P.; resources, and L.B.; writing—original draft preparation, G.C.C.P. and M.R.M.; writing—review and editing, G.C.C.P., M.R.M. and L.B.; supervision, L.B.; project administration, L.B.; funding acquisition, L.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.





References

- [1] S. F. Abdulai, G. Nani, R. Taiwo, P. Antwi-Afari, T. Zayed, and A. O. Sojobi, "Modelling the relationship between circular economy barriers and drivers for sustainable construction industry," *Building and Environment*, vol. 254, p. 111388, Apr. 2024, doi: 10.1016/j.buildenv.2024.111388.
- [2] A. AlJaber, P. Martinez-Vazquez, and C. Baniotopoulos, "Barriers and Enablers to the Adoption of Circular Economy Concept in the Building Sector: A Systematic Literature Review," *Buildings*, vol. 13, no. 11, p. 2778, Nov. 2023, doi: 10.3390/buildings13112778.
- [3] I. Atta, E. S. Bakhom, and M. M. Marzouk, "Digitizing material passport for sustainable construction projects using BIM," *Journal of Building Engineering*, vol. 43, p. 103233, Nov. 2021, doi: 10.1016/j.jobe.2021.103233.
- [4] A. R. Costa, R. Hoolahan, and R. Charef, "Eight recommendations to adopt materials passports and accelerate material reuse in construction: insights from academia and practice," *npj Mater. Sustain.*, vol. 3, no. 1, p. 33, Oct. 2025, doi: 10.1038/s44296-025-00079-3.
- [5] I. Campo Gay, L. Hvam, A. Haug, G. Q. Huang, and R. Larsson, "A digital tool for life cycle assessment in construction projects," *Developments in the Built Environment*, vol. 20, p. 100535, Dec. 2024, doi: 10.1016/j.dibe.2024.100535.
- [6] A. Ferreira, M. D. Pinheiro, J. de Brito, and R. Mateus, "A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings," *Journal of Building Engineering*, vol. 66, May 2023, doi: 10.1016/j.jobe.2023.105825.
- [7] N. G. Akhimien, E. Latif, and S. S. Hou, "Application of circular economy principles in buildings: A systematic review," *Journal of Building Engineering*, vol. 38, p. 102041, June 2021, doi: 10.1016/j.jobe.2020.102041.
- [8] S. Banihashemi, S. Meskin, M. Sheikhhoshkar, S. R. Mohandes, A. Hajirasouli, and K. LeNguyen, "Circular economy in construction: The digital transformation perspective," *Cleaner Engineering and Technology*, vol. 18, p. 100715, Feb. 2024, doi: 10.1016/j.clet.2023.100715.
- [9] M. Dąbrowski, V. Varjú, and L. Amenta, "Transferring Circular Economy Solutions across Differentiated Territories: Understanding and Overcoming the Barriers for Knowledge Transfer," *UP*, vol. 4, no. 3, pp. 52–62, Sept. 2019, doi: 10.17645/up.v4i3.2162.
- [10] L. C. M. Eberhardt, M. Birkved, and H. Birgisdottir, "Building design and construction strategies for a circular economy," *Architectural Engineering and Design Management*, vol. 18, no. 2, pp. 93–113, Mar. 2022, doi: 10.1080/17452007.2020.1781588.
- [11] J. Kanters, "Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector," *Buildings*, vol. 10, no. 4, p. 77, Apr. 2020, doi: 10.3390/buildings10040077.
- [12] U.S. Green Building Council, "LEED rating system." Accessed: Mar. 29, 2024. [Online]. Available: <https://www.usgbc.org/leed>
- [13] O. Suzer, "Analyzing the compliance and correlation of LEED and BREEAM by conducting a criteria-based comparative analysis and evaluating dual-certified projects," *Building and Environment*, vol. 147, pp. 158–170, Jan. 2019, doi: 10.1016/j.buildenv.2018.09.001.
- [14] U.S. Green Building Council, "LEED for Cities and Communities." Accessed: Aug. 13, 2024. [Online]. Available: <https://www.usgbc.org/leed/rating-systems/leed-for-cities-communities>
- [15] "LEED for Cities and Communities | U.S. Green Building Council." Accessed: Oct. 01, 2024. [Online]. Available: <https://www.usgbc.org/leed/rating-systems/leed-for-cities-communities>
- [16] C. O'Malley, P. A. E. Piroozfar, E. R. P. Farr, and J. Gates, "Evaluating the efficacy of BREEAM code for sustainable homes (CSH): A cross-sectional study," in *Energy Procedia*, Elsevier Ltd, 2014, pp. 210–219. doi: 10.1016/j.egypro.2014.12.382.
- [17] A. Ferreira, M. D. Pinheiro, J. de Brito, and R. Mateus, "A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings," *Journal of Building Engineering*, vol. 66, May 2023, doi: 10.1016/j.jobe.2023.105825.
- [18] S. Ferrari, M. Zoghi, T. Blázquez, and G. Dall'O', "New Level(s) framework: Assessing the affinity between the main international Green Building Rating Systems and the European scheme," *Renewable and Sustainable Energy Reviews*, vol. 155, p. 111924, Mar. 2022, doi: 10.1016/j.rser.2021.111924.
- [19] D. Kouka, M. Russo, and F. Barreca, "Building sustainability assessment: A comparison between ITACA, DGNB, HQE and SBTool alignment with the European Green Deal," *Heliyon*, vol. 10, no. 14, p. e34478, July 2024, doi: 10.1016/j.heliyon.2024.e34478.



Original scientific paper

Theoretical relationships between circular economy practices and the agile approach in construction projects

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ABSTRACT

The construction industry is a major consumer of natural resources and a generator of waste, resulting in significant environmental impacts. At the same time, the sector faces management challenges, including project inconsistencies, missed deadlines, budget overruns, and environmental degradation. The Circular Economy (CE) has shown promise in addressing inefficient resource use and minimizing negative environmental impacts, while agile project management aims to deliver more successful and efficient projects. This paper explores the synergy between the agile approach and CE in the construction industry through a content analysis of CE practices and agile attributes for construction projects, examining positive and negative interactions. The results show a positive synergy between the two approaches, highlighting the use of digital technologies to promote CE and the design of modular buildings, focusing on the early phase of the life cycle (design), which has the most relationships. Flexibility and transparency were the agile attributes most associated with CE practices, with the "management processes" category highlighted as the most interactive. The study suggests adapting the Scrum agile framework to manage circular innovation projects in parallel with construction to promote the transition from a linear to a CE model in the construction industry.

1 Introduction

The construction industry is a major global consumer of natural resources, requiring large volumes of raw materials and generating significant amounts of waste. Continuous reliance on non-renewable resources has turned the built environment into a vast stock of accumulated materials while contributing to future resource scarcity. Under current production patterns, waste generation is expected to increase substantially by 2050, intensifying environmental pressures associated with construction activities [1]. In this context, the implementation of the Circular Economy (CE) in the sector emerges as a promising solution to combat inefficient resource use and minimize negative environmental impacts [2]. Amid forecasts of rising global greenhouse gas emissions, CE in construction plays an essential role in contributing to national climate goals, promoting practices that include waste reduction, process improvement, and material reuse [1].

The EU proposes a paradigm shift regarding the linear economic system of "take-make-dispose", aiming for

innovation, waste mitigation, and efficiency in material use [3]. However, the implementation of these practices is still in development [2]. Incorporating circular strategies into construction projects requires changes and overcoming obstacles, but it can make economic growth independent of excessive natural resource use, promoting more efficient use of materials and minimizing waste generation [4]. Nevertheless, resistance to change, product complexity, and technological barriers have hindered the adoption of circular principles in the construction industry [5].

The current landscape of the construction industry faces challenges that negatively impact the efficiency and success of projects, such as inconsistencies in designs, overlapping deadlines, excessive budgets, and environmental disadvantages [6]. In addition to low productivity and rigidity in adopting innovations [7]. In this regard, researchers have been seeking tools and methods to achieve more successful projects [6]. Given the rapid technological changes, the application of agile project management models has proven to be a promising approach to address these specific challenges in the construction sector [7].

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The pursuit of increased efficiency in project delivery changes necessitates modifications to the traditional construction management method. To overcome the obstacles of change management, maximize project value, and manage risks, agile methods have stood out as effective techniques. Agile is an iterative methodology that plans and guides project development and has been widely used across various industries, including construction [8].

Among agile methods, Scrum is the most widely used in construction projects [9]. Scrum is an agile approach designed to support collaborative work through iterative and incremental development. The framework organizes activities into recurring cycles that promote adaptability, continuous feedback, and progressive improvement throughout the development process. With proper training, project teams can gain agility in decision-making, resulting in transparent and effective communication, which contributes to better control of costs, schedules, and project quality. Scrum's flexibility enables adaptations to meet the specific needs of each team, ensuring an agile implementation across projects of different scales [10].

This article's main objective is to investigate the interactions between the agile approach and the CE in the construction industry through content analysis. To achieve this, the fundamentals of Bardin's method (1977) [11] were adopted, aiming to answer the following question: "What are the theoretical relationships between the Agile approach and the CE in projects within the Architecture, Engineering, and Construction (AEC) sector?" Considering the socioeconomic importance of civil construction, its environmental impact, the sector's complexity, and the challenges related to change, adopting agile practices and the CE can lead to more efficient and sustainable management of construction projects. Therefore, it is of utmost importance to investigate the synergy between the CE and agility to enable them to collaborate in the implementation of the construction industry.

This research contributes to the advancement of knowledge about the application of agile management in CE projects within the construction industry, enabling the development of more efficient and sustainable management strategies and models. Based on the discussions presented, the main theoretical relationships identified are explored, and possible practical applications of this synergy are suggested. With these results, it is hoped that this study will stimulate future investigations and initiatives that promote the joint adoption of these innovative approaches in the pursuit of a more sustainable and efficient construction sector. The article is organized into four parts: introduction, methods, results, relevant discussions, and principal conclusions.

2 Method

The method adopted in this research was content analysis, following the premises of Bardin (1977) [11] to investigate the interactions between the Agile approach and the CE in the Architecture, Engineering, and Construction (AEC) sector. Since few studies have addressed this combination of targeted concepts, it was decided to study them separately and then analyze their interactions. As the starting point will be the investigation of the existing literature on both topics, the research is classified as qualitative.

Through content analysis, relevant texts on the subject will be examined to identify and understand the potential correlation between the CE and Agile in construction projects.

Bardin's (1977) content analysis is divided into pre-analysis, exploration of the material, and treatment of results and interpretations. The pre-analysis phase involves steps such as a floating reading of the materials, defining objectives and/or hypotheses, establishing indices or analysis categories, and preparing the material for the coding process. In the exploration phase, the researcher codes the content, assigning relevant theoretical codes to predefined categories established during the pre-analysis. The final stage consists of treating the results, making inferences, and interpreting the data, which involves studying the coded data, analyzing the connections between categories, and extracting meaningful insights related to the research objectives.

For the pre-analysis, preliminary readings were conducted on the concepts of agility and on CE practices in the construction industry. After that, the following objective was established: to identify the interactions between the attributes of agile management and the CE practices applied to the construction industry.

Based on the literature review conducted by Enembreck et al. [12], the main agile attributes for construction projects were identified. The most frequently mentioned attributes among the authors became the categories for analyzing the agile concept in this content analysis. Regarding the CE, the pre-analyzed material included the study by Benachio et al. (2020) [13] and a complementary literature review. The literature review included 52 articles, and 12 additional practices were mapped.

Concluding the pre-analysis phase, the material was prepared. Table 1 was created, which is a compiled list of CE practices. To complement the analysis of the relationships, the practices were separated into categories based on the first stage of the project lifecycle they impact.

The categorization was based on the life cycle stages outlined in the EN 15804 [14] standard and on the classification of phases performed in the article by Benachio et al. (2020) [13]. An additional stage was also considered, as proposed in the article, to be added to the existing phases in the standard, previously called A0, to include activities related to the conception, planning, and design stage, adapting the model proposed by CEN [14]. Under EN 15804, stage A3 refers to the manufacturing of construction products and all processes from cradle to gate, considering both goods and services used during the life cycle of a building as "construction products" [15]. However, it is observed that reaching stage A3 requires a planning and design phase, for example, to determine which materials will be used. Therefore, the CE practices were subdivided into the following stages: Design (practices where A0 would be the first impact phase); Product (practices focused on manufacturing); Construction; Use; and Benefits and burdens beyond the life cycle.

This list of practices is related to Group 6 of the created codes, called "Characteristics" in the Agile Methodology category, which encompasses the main characteristics of agility and is presented in Table 2. These characteristics were also divided into three categories: project delivery, team and/or stakeholders, and management processes.

Table 1. Coding of the circular economy theme in the construction industry. Adapted from (*) [12] and (**) [13]

Key	CE practice in the construction industry	Life Cycle Stage
1	Use of digital technologies to support the promotion of the circular economy (*).	Design (Stage "A0")
2	Energy efficiency project (*).	
3	Modeling and Application of Life Cycle Cost (*).	
4	DfMA approach in manufacturing and assembly design (*).	
5	Design and use of modular buildings (**).	
6	Project for the adaptability of existing buildings (**).	
7	Project for dismantling building structures (**).	
8	Use of a scale to analyze the level of implementation of Circular Economy practices in the company (**).	
9	Use of a simulation in a BIM model to analyze the potential for reusing materials from different types of projects at the beginning of the project (**).	
10	Use of life cycle assessment to find the benefits of reusing different types of materials during the design phase (**).	
11	Use of inventory data to assist in the reuse of materials from a new building (**).	
12	Use of water management practices (**).		Product (Stage A1-A3)
13	Use of bio-based materials (*).	
14	Hazardous materials management (*).	
15	Use of local materials (*).	
16	Change in the use of materials, giving ownership to manufacturers to reuse the materials after the end of the first building's lifespan. (**).	
17	Development of materials passports (**).	
18	Reuse of secondary materials in the production of building materials (**).	
19	Reuse of construction materials in a new building (**).	Construction (Stage A4-A5)
20	Use of BIM for Construction and Demolition Waste Management (*).	
21	Waste reduction (**).	
22	Off-site construction (**).	Use (B1-B7)
23	Use of BIM to improve operation, maintenance, and asset management (*).	
24	Operational management of building space occupancy (*)	
25	Use of a tool to assess the condition of materials during the lifespan and end of life of a building (**).	
26	Minimize corrective maintenance with preventive maintenance (**).	
27	Use of BIM for building deconstruction (*).	End of Life (C1-C4)
28	On-site waste recycling (*).	
29	Analyze the potential for reuse or recycling of existing materials and whether it is feasible compared to using new materials (**).	
30	Demolition Waste Management (**).	
31	Deconstruction of structures and building materials (**).	Benefits and burdens beyond the end of life (D)
32	Use of a circularity tool to assess existing buildings and provide the best possible solutions for rehabilitation (**).	

Table 2. Coding of the agile management theme in the construction industry. Adapted from [12]

Key	Agile attribute	Category of attributes
A	Add value / Deliver with maximum value	Project delivery
B	Increase in delivery efficiency	
C	Time management / Shorter deadlines	
D	Customer satisfaction	
E	Budget control / Cost reduction	
F	Increase in team productivity	Team and/or stakeholders
G	Team self-organization	
H	Colaboration	
I	Improvement in communication / quick feedback	
J	Easy implementation / Simplicity	Management processes
K	Flexibility	
L	Change Management	
M	Inspection	
N	Continuous improvement	
O	Improvement / Sustainable development	
P	Effective risk resolution / Risk management	
Q	Transparency	

After defining the codifications described in Tables 1 and 2, the material exploration phase was initiated, guided by Bardin (1977) [11], with coding operations in which each CE practice is related to each agile attribute. In this phase, a qualitative assessment is made to determine if there is synergy between the CE and agility, based on the analysis of the author's relationships, through the development of a contingency matrix. Each row of the matrix corresponds to one of the CE practices, and the columns represent the characteristics of agility. To assist in organizing the matrix, numeric keys were established for the rows and alphabetic keys for the columns, according to the keys in Tables 1 and 2. Additionally, at the intersection of a row and a column, when identified, the number referring to the interaction found was recorded.

To conclude the content analysis based on Bardin (1977) [11], there is the "treatment of results and interpretations" phase. In this phase, systematic confrontations and inferences of the relationships in the matrix are performed, allowing the establishment of theoretical relationships between concepts, whether in positive interactions, when benefits arise from the combination, or in negative interactions, when the association of variables results in disadvantages. Based on this content analysis, inferences and interpretations of the obtained results were made. The quantitative results were also treated to map the frequency of relationships between the concepts.

3 Results

This section presents the mapping of interactions through content analysis by Bardin (1977) [11]. The qualitative results consisted of a contingency matrix and the respective interactions between CE practices and agile attributes. An interaction is defined as the conceptual relationship identified between a CE practice and an agile attribute based on their

alignment or complementary characteristics. The contingency matrix was composed of positive interactions between the concepts and negative interactions. The establishment of interactions was made through inferences and interpretations between the categories, identifying theoretical relationships between the themes of CE and agile methodology in the construction industry based on the current state of the literature. A total of 153 interactions were identified, including 146 positive and seven negative. The complete contingency matrix is available in full in the dissertation presented in [16].

Through the contingency matrix, the incidence of interactions by CE practices was quantitatively analyzed through a frequency-based aggregation, in which each interaction identified between a CE practice and an agile attribute was coded and counted as a unit of occurrence. Figure 1 graphically shows the number of interactions for each practice, including positive interactions (in green) and negative interactions (in red).

Regarding positive interactions, Practice 1, related to the use of digital technologies to support the promotion of the CE, had the highest number of interactions, totaling positive interactions with 12 different agile attributes. Practice 5, related to the design and use of modular buildings, received 11 positive interactions. The practices with the fewest positive interactions were Practice 15 (use of local materials) and Practice 18 (reusing secondary materials in the production of building materials), each totaling one interaction.

Analyzing the negative interactions, only five distinct practices were negatively related to agile characteristics. Practices 22 (Off-site construction) and 31 (Deconstruction of structures and building materials) had two negative each. One negative interaction was mapped for practices 3 (Modeling and application of Life Cycle Cost), 7 (Design for disassembly of building structures), and 12 (Use of water management practices).

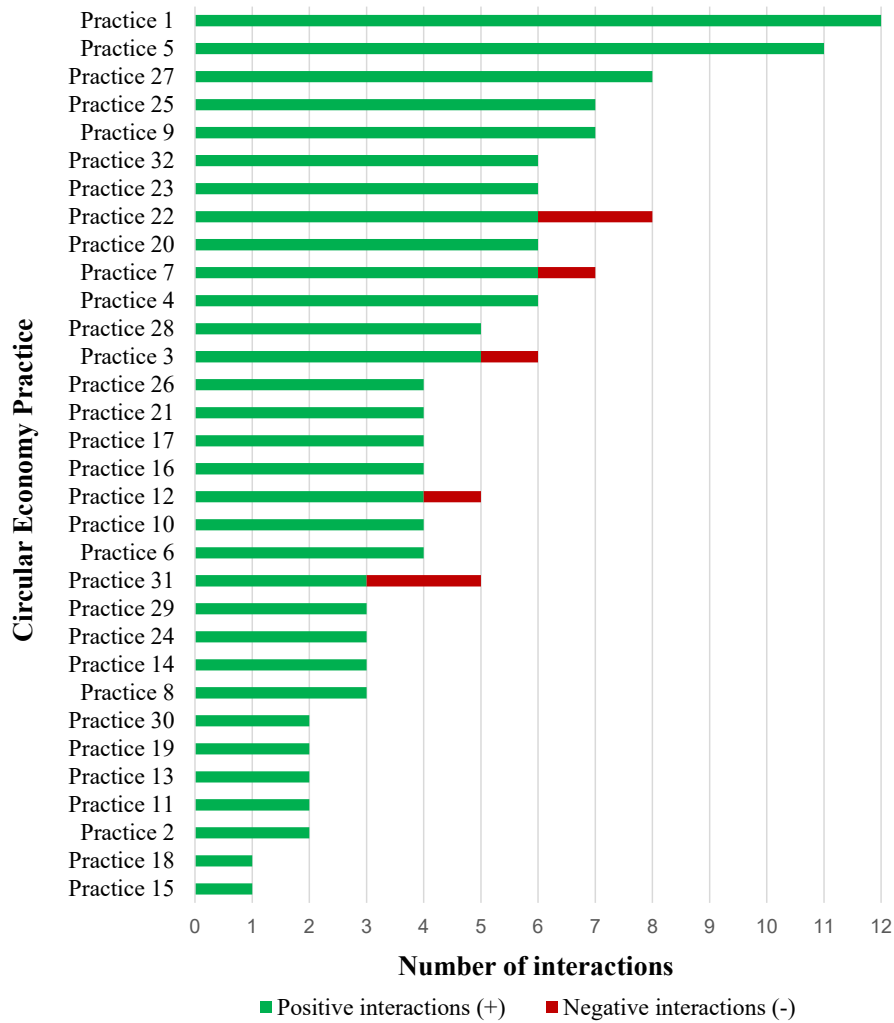


Figure 1. Incidence of interactions by CE practice

The incidence of interactions was also analyzed by agile attributes. The number of interactions for each agility characteristic in the construction industry was assessed and graphically represented in Figure 2.

Regarding positive interactions, the agile attributes with the highest occurrence were flexibility and transparency, each with 16 positive interactions. Next, among the most related attributes, there are budget control, continuous improvement, and risk management each with 14 positive interactions. The team self-organization attribute, however, did not have any mapped interactions.

The identification of negative interactions occurred in four different agile attributes, with the attribute “easy implementation/simplicity” having four negative relationships with CE practices. The attributes “budget control”, “flexibility”, and “shorter time management/deadlines” each showed one negative interaction.

In the context of the initial phases of the building's life cycle, which are impacted by the considered practices, the interactions present at each stage were investigated. For this analysis, both positive and negative interactions were considered, since unfavorable interactions are infrequent and the total volume of interactions is already significant.

Figure 3 shows that the design stage had the highest number of interactions, totaling 66 positive and three negative interactions (Project), which accounts for 45% of the total relationships identified (values derived from the contingency matrix, which comprises a total of 153 interactions). In contrast, the stage of benefits and loads beyond the end of life recorded the fewest interactions, representing only 4% of the total identified, that is, six positive interactions.

Based on the categories of CE practices at different stages of the lifecycle (design, product, construction, use, end of life, and post-end-of-life benefits), along with the agile attributes influenced by specific characteristics (project delivery, team and/or stakeholders, and management processes), an analysis was conducted to understand the interactions between these variables.

Figure 4 illustrates this analysis and reveals that the relationships related to agile attributes in the context of management processes are predominant in all stages of the lifecycle. On the other hand, agile attributes associated with the team and stakeholders show fewer interaction occurrences in almost all stages, except in the “benefits and post-life charges” phase, where the “project delivery” category had the lowest frequency of interactions.

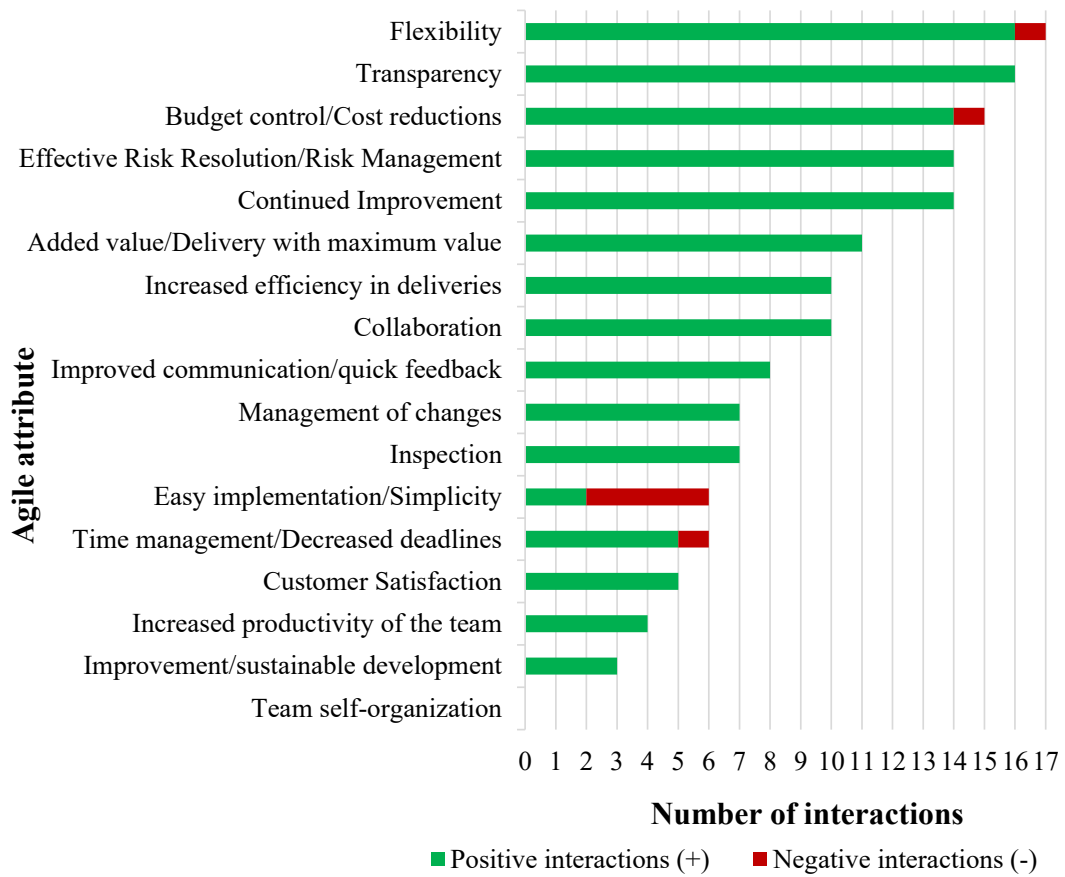


Figure 2. Incidence of interactions by agile attribute

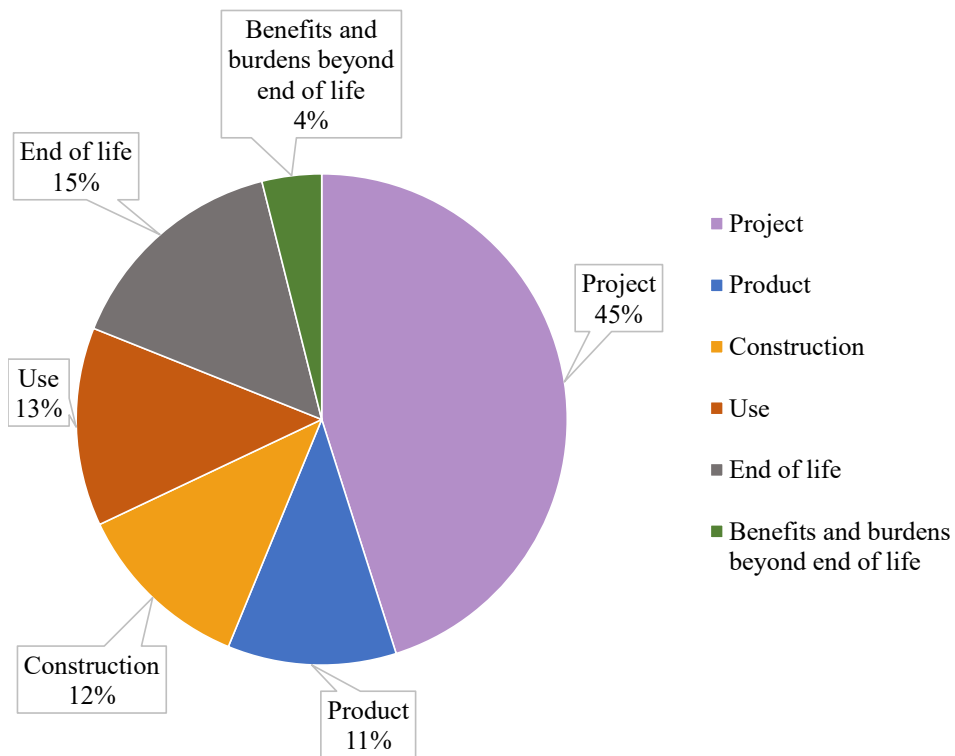


Figure 3. Incidence of interactions by life cycle stage

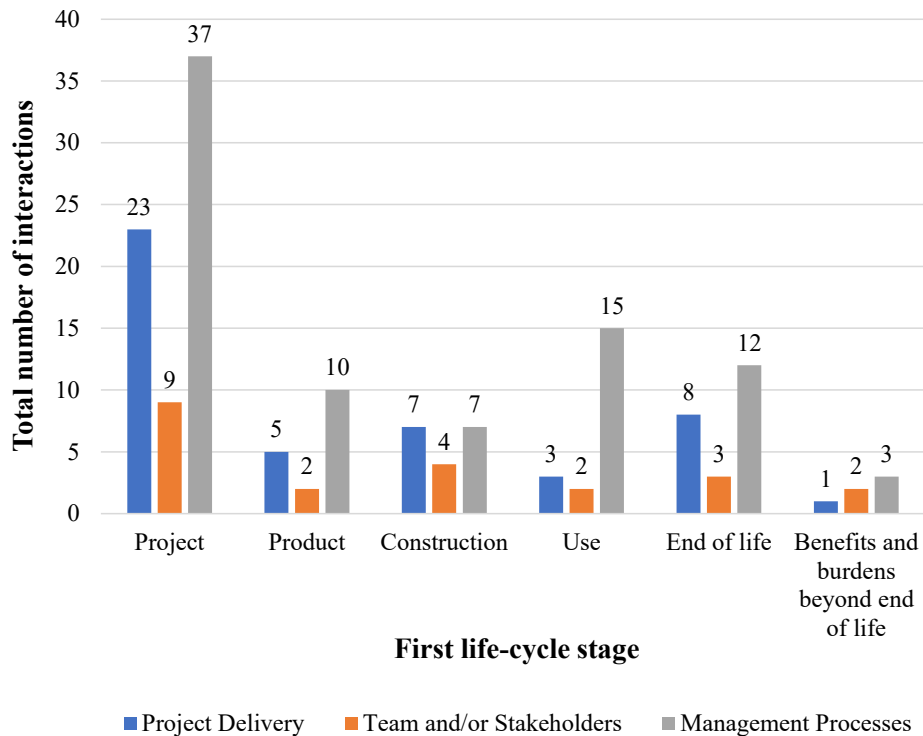


Figure 4. Incidence of interactions by stages of the life cycle and by categories of agile attributes

Based on the results presented in this section, the discussions in the following section were based on the analyses carried out.

4 Discussion

This section addresses the main discussions about the theoretical relationships between CE practices and agile attributes in construction projects found in the literature. Additionally, it highlights the main research gaps for future studies.

From Figure 1, it was observed that Practice 1 (“use of digital technologies to support the promotion of the circular economy”) had the highest number of interactions, totaling 12 positive responses. Overall, Industry 4.0 technologies such as the Internet of Things (IoT), robotics, BIM, Artificial Intelligence (AI), blockchain, and augmented reality (AR) have the potential to bring benefits to the CE in the construction industry throughout the project lifecycle [17]. These digital technologies are essential for transitioning from a linear economy to a CE. The recurring association between Practice 1 and agile management stems from the benefits these technologies can bring to project management.

These benefits include innovation; greater efficiency and quality in delivery; optimization of CE practices; flexibility to incorporate circular measures; tracking and monitoring of information; identification of improvements; centralization of information and agility in communication among stakeholders; sustainable development; collaboration in risk management; and increased transparency and visibility in data management [18]. Additionally, the theory is associated with the origin of the agile methodology, which emerged in the information technology (IT) and software development fields, bringing the values established in the Agile Manifesto [19] into the practice of using technologies to promote the CE.

The design and use of modular buildings (Practice 5) was the second most interactive practice. The construction and utilization of buildings offer an efficient, high-quality construction solution with greater process control [20]. Prefabrication of components improves quality control and delivery efficiency, reducing costs and minimizing waste. Additionally, the modular approach allows for adaptations, promotes transparency in the process, and enables continuous improvements, making it a flexible and satisfying solution for clients. A similarity was identified with the research by Benachio et al. (2021) [20], as the authors also mapped this practice as the second most interactive with the principles of Lean. Based on this analogy, similarities between the principles of Lean and Agile are observed, such as simplicity, continuous improvement, flexibility, and transparency.

The practices with the fewest positive interactions were Practice 15 (use of local materials) and Practice 18 (reusing secondary materials in the production of building materials). Both practices are alternatives for material substitution and make it difficult to correlate them with agile management characteristics. These practices are present in decisions to be made at the beginning of the project, whose benefits for the subsequent phases are not associated with managerial terms.

When examining negative interactions, it was found that only six distinct practices showed unfavorable associations with agile characteristics. The practices of “off-site construction” and “deconstruction of structures and building materials” had two negative interactions. Off-site construction conflicts with simplicity because it involves complexities in transporting large and heavy parts and in planning [20]. Additionally, the lack of flexibility to make changes during assembly is a limitation resulting from this construction approach. Regarding deconstruction, compared to conventional demolition, it requires more complex

planning, additional steps at the end of the structure's lifespan, and is a more time-consuming and meticulous process [21].

Based on Figure 2, an analysis was conducted on the recurrence of the theoretical relationships of each agile attribute. The attributes with the most positive interactions were flexibility and transparency. Flexibility is essential for applying CE practices, especially in transitioning from linear to circular models. Additionally, having flexible scenarios throughout the product lifecycle is necessary to achieve more sustainable projects. Transparency is fundamental for decision-making during the project, establishing visibility and trust among stakeholders. Therefore, transparency becomes indispensable for most CE practices to ensure successful implementation.

The team's self-organization attribute did not interact with any mapped CE practices. Although it is an attribute that can offer advantages in the transition to a CE, there were no interactions because the practices do not establish specific management guidelines, unlike this agile characteristic. However, it is evident that the self-management of the involved professionals provides competitive advantages to the project, and future studies may identify hypotheses about relationships with the CE. The agile attribute "easy implementation/simplicity" had the highest number of negative interactions. This stems from complexities attributed to the related practices, which require additional challenges for successful implementation, such as robust planning, detailed analysis, and specific techniques.

Regarding the analysis of the categories, it was observed that the interaction between CE practices and agile attributes, especially those related to management processes, plays a significant role in the early stages of the building's lifecycle, namely the design phase. Emphasizing the importance of adopting sustainable planning from the initial conception stage of a building. This can involve, for example, incorporating circular design from the CE and integrating construction project processes to incorporate innovations. By combining the concept of the circular economy with project management processes early in the project's initial phase, the substantial interaction between this stage and the mentioned approaches is addressed.

A low frequency of interactions was observed in the "team and/or stakeholders" category, which is related to the weak presence of solid management guidelines in CE models. The CE has not yet reached a level of maturity that enables adequate characterization of the essential qualities of a team and the development of strategies to improve communication with stakeholders. In this context, this study is relevant because it proposes a synergy between agile project management and the CE, allowing them to complement each other and fill gaps.

Regarding the "Benefits and loads beyond the end of life" phase, the low incidence of interaction with the "project delivery" category occurs because the practices related to this stage aim to go beyond the client-focused deliverable by considering what happens after the end of life. The fact that this stage was the least related to agile practices is also due to the characteristics of agile methodologies, which typically consider project management only until the completion of the active phase. This limited interaction arises from post-project issues, such as the need for extended planning and changes in stakeholders and end users. The reduced connection between agile project management and this specific phase highlights the importance of adapting management approaches according to the nature and distinct characteristics of each life-cycle stage. This situation may

also indicate the need to develop specific strategies to address the challenges and benefits that emerge after a project's formal completion. Due to the complexities involved in implementing practices in this stage, the agile approach stands out as an alternative for managing such complex issues, given its flexible and adaptive capabilities.

In summary, the results indicated that there is synergy between the CE and agile project management. Based on the interactions found, which were mostly positive, it was observed that the combination of both concepts has the potential to bring benefits to construction projects. Therefore, a proposed application, to corroborate and validate this synergy in real-world scenarios, is to adapt an agile framework for managing the implementation of one or more CE practices in the construction project.

To promote the transition from a linear economy to a CE in the construction industry, it is suggested to do so gradually and in a well-coordinated manner. Therefore, the agile approach can contribute with its iterative and incremental methodology, just as the construction industry needs to become familiar with agile methodology to expand its use in an increasing number of projects. For this, it is proposed to create a circular innovation project within the company for each building project, and these projects will be managed according to the agile methodology. Authors such as Lalmi, Fernandes, and Souad (2021) mention that the most used agile framework in the civil construction landscape is Scrum. Due to this, the present research recommends the Scrum framework for developing a management model aimed at implementing CE practices in construction projects. To exemplify agile management of CE practices through a parallel innovation project related to a specific construction, an adapted framework is proposed, considering the roles, ceremonies, and artifacts of Scrum as described in the Scrum guide [22]. This allows for adaptation regarding the daily meeting proposed by Scrum, which can be changed to weekly meetings, as there are phases in which the process of a construction project proceeds more slowly than software development in its original form. It is recommended to start the circular innovation project simultaneously with the conception of the construction project. For this, a Scrum team is established with a multidisciplinary team to handle activities related to the innovation project, including a Product Owner (suggestion: design engineer) and a Scrum Master (a professional trained in Scrum). It is also necessary to identify the main stakeholders of the project, such as the business owner, company management, engineering and architecture professionals, among others. The proposed approach is supported by recent studies indicating that agile methodologies enhance collaboration, adaptability, and sustainability performance in construction project environments [23].

It is important to emphasize that a framework provides guidelines for project management, but it is not a rigid process, allowing for flexibility depending on the type and phase of the project. It is also important to highlight the role of the Scrum Team in adjusting the sprint duration in accordance with the phase of the product development cycle. For example, extending the sprint time during the construction phase proportionally to the duration of the selected activities. The goal of the adapted framework is to practically demonstrate the synergy between the CE and agile methodologies, presenting agile as a driver for implementing CE business models in the construction industry.

5 Conclusions

The research adopted the content analysis and relationship method proposed by Bardin (1977) [11] to answer the question, "What are the theoretical relationships between the Agile approach and the CE in projects within the Architecture, Engineering, and Construction (AEC) sector?" Through a literature review, practices of the CE and agile attributes for construction projects were mapped. Content analysis identified 146 positive interactions and seven negative interactions between CE practices and agile attributes. The results indicated a synergy between the two concepts, highlighting the use of digital technologies to promote the CE and the design of modular buildings.

The agile attributes with the highest incidence of positive interactions were flexibility and transparency. On the other hand, the attribute "easy implementation/simplicity" had the highest number of negative interactions. The analysis of the results indicated that the combination of the agile approach and the CE can bring benefits to construction projects, due to the synergy between the concepts.

Agile characteristics such as flexibility, transparency, budget control, risk management, and continuous improvement are synergistically related to the practices of the CE, as detailed:

- Flexibility allows for the quick adaptation needed for CE strategies, responding to changes in the market and customer needs;
- Transparency promotes the dissemination and sharing of information to optimize sustainable practices;
- Budget control comes from the efficient allocation of resources, reduction of waste, and the reintegration of materials into the economy after their end of life through circular solutions;
- Risk management enables the identification and mitigation of environmental, social, and economic impacts associated with the circular model; and
- Continuous improvement supports the ongoing pursuit of innovations that make processes more sustainable and contribute to a circular cycle with the maximum value of materials.

It has been found that the combination of agility and the CE promotes the adoption of circular practices in the construction industry, as well as being a way to introduce agile methodology into the sector.

The analysis of the categories revealed the importance of the interaction between CE practices and agile attributes, especially concerning management processes during the early phases of a building's lifecycle, with a focus on the design phase, highlighting the need to adopt sustainable planning from conception. A limited interaction was observed in the "team and/or stakeholders" category due to the nascent presence of management guidelines in CE. In the "Benefits and burdens beyond the end of life" phase, the low connection with project delivery suggests a broader approach. The "Benefits and burdens beyond the end of life" phase shows less interaction with agility, reflecting the distinct characteristics of this stage and emphasizing the essential adaptation of management approaches. This finding underscores the need for specific strategies to address post-project challenges, highlighting the importance of considering the nuances of different lifecycle phases in the pursuit of more effective and sustainable practices. In this context, the agile approach stands out for its flexible and adaptive capacity, gaining relevance.

Based on the results, the adaptation of the Scrum agile framework is proposed for managing circular innovation

projects in parallel with construction, aiming to promote the transition from a linear economy to a circular one in the construction industry. The proposed association between agile and the CE in a company's innovation project intends to familiarize AEC professionals with both topics without causing a sudden change in the entire management process. This approach allows for the gradual and coordinated implementation of CE practices in construction projects, with agile management providing an iterative and incremental approach to achieve more sustainable projects. In this way, it is possible to overcome resistance to change and invest in innovation, which are crucial steps toward achieving more sustainable and efficient construction industry projects.

Finally, the synergy between the CE and agility presents an opportunity to promote the adoption of sustainable practices in the construction industry, fostering innovation and continuous improvement. It is emphasized that the establishment of these interactions was made through inferences and interpretations between the categories, identifying the theoretical relationships between the themes of CE and agile methodology in the construction industry based on the current state of the literature. Therefore, the scope of this research did not include proving or providing practical evidence through case studies about the theoretical interactions identified. For this reason, it is recommended that future studies explore this practical approach to validate its actual effectiveness and further enhance the integration between the CE and agile management in construction projects.

Furthermore, during the analysis of the interactions, a close relationship between Agile and Circular Economy construction was observed, as both approaches share principles and characteristics. Therefore, the relationship between Agile and Circular Economy construction is identified as a promising topic for further research, providing insights for improving project management in the construction industry.

References

- [1] M. Ghobadi, S.M.E. Sepasgozar, Circular economy strategies in modern timber construction as a potential response to climate change, *Journal of Building Engineering* 77 (2023) 107229. [10.1016/j.jobbe.2023.107229](https://doi.org/10.1016/j.jobbe.2023.107229).
- [2] M.S. Hassan, et al., Risk assessment of circular economy practices in construction industry of Pakistan, *Science of The Total Environment* 868 (2023) 161418. [10.1016/j.scitotenv.2023.161418](https://doi.org/10.1016/j.scitotenv.2023.161418).
- [3] M. Kucukvar, How circular design can contribute to social sustainability and legacy of the FIFA World Cup Qatar 2022™? The case of innovative shipping container stadium, *Environmental Impact Assessment Review* 91 (2021) 106665. <https://doi.org/10.1016/j.eiar.2021.106665>.
- [4] B. Piotrowska, D. Słyś, Comprehensive Analysis of the State of Technology in the Field of Waste Heat Recovery from Grey Water, *Energies* 16(1) (2023) 137. <https://doi.org/10.3390/en16010137>.
- [5] C. Illankoon, S.C. Vithanage, Closing the loop in the construction industry: A systematic literature review on the development of circular economy, *Journal of Building Engineering* 76 (2023) 107362. <https://doi.org/10.1016/j.jobbe.2023.107362>.

- [6] A. Shah, et al., Influence of Agile Leadership on Project Success: A Moderated Mediation Study on Construction Firms in Nepal, *Engineering Letters* 30(2) (2022).
- [7] P. Vaz-Serra, F. Hui, L. Aye, Construction Project Managers Graduate Agile Competencies Required to Meet Industry Needs, *Lecture Notes in Civil Engineering* 94 (2020) 601–607. https://doi.org/10.1007/978-981-15-7222-7_49.
- [8] K.N. Mohammed, S.C. Karri, An analytical approach in usage of agile methodologies in construction industries – A case study, *Materials Today: Proceedings* 33 (2020) 475–479. <https://doi.org/10.1016/j.matpr.2020.05.045>.
- [9] A. Lalmi, G. Fernandes, S.B. Souad, A conceptual hybrid project management model for construction projects, *Procedia Computer Science* 181 (2021) 921–930. <https://doi.org/10.1016/j.procs.2021.01.248>.
- [10] S.S. Jethva, M.J. Skibniewski, Agile project management for design-build construction projects: A case study, *International Journal of Applied Science and Engineering* 19(1) (2022) 1–11. https://doi.org/10.6703/ijase.202203_19%281%29.001
- [11] L. Bardin, *Análise de Conteúdo*, Edições 70, Lisboa, 1977.
- [12] F.L.P. Enembreck, M.C.D. Freitas, L. Bragança, Explorando o potencial da gestão ágil na indústria da construção: uma revisão sistemática da literatura, *Gestão & Tecnologia de Projetos* 19(2) (2024) 175–199. <https://doi.org/10.11606/gtp.v19i2.212579>.
- [13] G.L.F. Benachio, et al., Circular economy in the construction industry: A systematic literature review, *Journal of Cleaner Production* 260 (2020) 121046. <https://doi.org/10.1016/j.jclepro.2020.121046>.
- [14] CEN, EN 15804+A2 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, 2019.
- [15] BRE Group, BRE Global Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012+A1:2013, Watford, UK, 2014.
- [16] F. L. P. Enembreck, Sinergia na aplicação da abordagem ágil associada à economia circular na gestão de projetos, *Dissertação de Mestrado*, Universidade Federal do Paraná, Curitiba, 2023. Available at: <https://acervodigital.ufpr.br/xmlui/bitstream/handle/1884/85741/R%20-%20D%20-%20FLAVIA%20LUIZA%20PIRES%20ENEMBRECK.pdf> (accessed 10 May 2025).
- [17] F. Setaki, A. Van Timmeren, Disruptive technologies for a circular building industry, *Building and Environment* (2022) 109394. <https://doi.org/10.1016/j.buildenv.2022.109394>.
- [18] S. Çetin, et al., Circular Digital Built Environment: An Emerging Framework, *Sustainability* 13(11) (2021) 6348. <https://doi.org/10.3390/su13116348>.
- [19] K. Beck, et al., *Manifesto for Agile Software Development*, 2001. Available at: <http://agilemanifesto.org> (accessed 15 August 2022).
- [20] G.L.F. Benachio, et al., Interactions between Lean Construction Principles and Circular Economy Practices for the Construction Industry, *Journal of Construction Engineering and Management* 147(7) (2021). [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002082](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002082).
- [21] A.S. Allam, M. Nik-Bakht, From demolition to deconstruction of the built environment: A synthesis of the literature, *Journal of Building Engineering* 64 (2023) 105679. <https://doi.org/10.1016/j.job.2022.105679>.
- [22] K. Schwaber, J. Sutherland, *The Scrum Guide*, 2020.
- [23] A. M. Zamil, M. Alhusban, Agile Project Management for Sustainable Construction: A Systematic Review, *Civil Engineering Journal* 11(1) (2025). <https://doi.org/10.28991/CEJ-2025-011-01>



Review paper

Governance in built environment: Development and monitoring of circular policies in the sectorSimone do Amaral Cassilha^{*1)} , Sergio Fernando Tavares¹⁾ ¹⁾ Federal University of Paraná, Postgraduate Program in Civil Construction Engineering - UFPR, Rua Evaristo F. Ferreira da Costa, 369-377 – Polytechnic Center, Curitiba, Brazil*Article history**Received:* 02 December 2025
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Available online: 01 June 2026*Keywords*circular economy,
construction sector,
built environment,
policy evaluation,
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The transition toward a Circular Economy (CE) in the construction sector is essential for addressing escalating pressures related to resource scarcity, climate change, and environmental degradation. This study investigates the development and monitoring of circular policies within the built environment by examining international initiatives and evaluating policy instruments through a multi-level governance perspective. A systematic literature review was conducted to identify regulatory frameworks, strategies, and evaluation tools implemented across different regions. The findings reveal that CE policies remain predominantly focused on end-of-life waste management, while upstream strategies—such as design for disassembly, modularity, material traceability, and digital integration—are still underutilized. Most initiatives lack comprehensive monitoring indicators and rarely integrate micro (local), meso (regional), and macro (national) levels in a cohesive feedback loop. The analysis demonstrates that effective CE implementation requires synergistic policy packages supported by robust data, digital technologies, and multi-stakeholder collaboration. The study concludes that advancing circularity in the built environment depends on the development of adaptive, evidence-based policies capable of aligning national agendas with local realities and ensuring continuous evaluation across the construction life cycle.

1 Introduction

Globally, resource consumption continues to rise as both population and income levels increase. According to the McKinsey Global Institute [1], the rapid economic expansion of countries such as China and India could bring nearly three billion people into the global middle class over the next two decades, significantly accelerating the demand for urban infrastructure. The institute estimates that China alone could add each year the equivalent of 2.5 times the total existing floor area of the city of Chicago.

The persistent growth in the demand for and use of natural resources has made these materials increasingly scarce and costly, compromising their long-term availability. Until the twentieth century, governments and companies primarily focused on capital and labor; however, in the coming decades, natural resources will need to be placed at the center of public policies and corporate strategies [2].

According to the One Planet Network [3], countries with large territorial areas and abundant natural resources face fewer pressures to transition toward a Circular Economy (CE) compared with European and Asian nations, which operate under stronger spatial and resource constraints. In

Belgium and the Netherlands, for example, the scarcity of raw materials makes recycling particularly attractive [4]. Figure 1 illustrates the difference between linear, recycling, and circular economies.

Unlike the linear economy—based on extraction, production, and disposal—the CE seeks to reduce and preserve material use, decrease carbon footprints, and establish a balanced relationship among economic, environmental, and social pillars [5]. One of the main barriers to implementing circular strategies in the built environment is the lack of regulatory frameworks and guidance. Guerra [6] identifies the absence of local regulations as a critical gap, noting that such instruments are essential for enabling effective territorial action.

Nonetheless, recent years have seen the development of guidelines aimed at enhancing resource efficiency and promoting the adoption of CE-aligned practices, particularly in Europe and Asia [7]. China, for instance, has introduced CE-based regulations since 2013, including the CE Promotion Law, the CE Development Strategy, and a short-term action plan. In Europe, the European Commission launched its CE Action Plan in 2015 [8].

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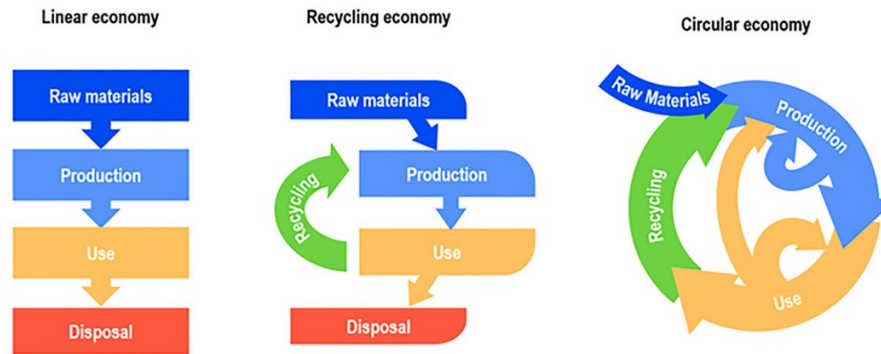


Figure 1. Linear, recycling and circular economies (Downes, 2018).

In the context of construction and demolition (C&D) activities, a significant number of old buildings are being demolished due to inadequacy to contemporary requirements [10]. The substantial volume of waste generated makes increasing recycling and reuse rates an urgent priority.

In the construction sector, regulatory frameworks are widely recognized as essential for guiding market behavior and shaping industry practices [11]. Political leadership is therefore critical for advancing circularity; however, the success of any regulatory instrument depends on the cooperation and commitment of all stakeholders involved [12].

Regulatory instruments can either remove or create barriers. Soininen et al. [13] observe that legal instruments are often oversimplified, offering limited support for the effective adoption of sustainable practices. Policymakers must carefully consider the guidance and acceleration roles of regulations, as well as potential obstacles at each intervention point [14].

The CE offers a promising pathway to address environmental challenges in the construction industry, yet achieving a circular built environment requires strong policy support and governance. Significant gaps remain in the formulation of CE policies in the construction sector [15], and knowledge about instruments capable of enabling an effective transition is still limited [16].

2 Circular policy instruments in the built environment

Across the world, CE policies for the construction sector are emerging, although practical evidence of their implementation remains limited. A critical issue within this global CE landscape is that many policies continue to rely predominantly on conventional regulations associated with the recycling of construction and demolition waste (C&DW) [17].

As highlighted by Hao et al. [18], certain regulations have failed to achieve the desired increases in resource efficiency, let alone generate added value or reach broader socioeconomic objectives. Bolger et al. [19] illustrate this gap by pointing to ambitious national recovery targets for C&DW that do not specify how such levels should be achieved by local actors in practice.

In Italy, for example, although recycling rates are relatively high, the practice of reuse remains limited due to the lack of regulations concerning the quality and performance of secondary materials [21]. Policy integration and harmonization remain underexplored in the built

environment. This challenge is directly linked to the disconnection frequently observed between policy formulation and implementation.

Yu et al. [22] note that policy implementation is generally perceived as a top-down approach, with limited consideration for evaluation and feedback from local actors. Effective policy design and evaluation must incorporate local knowledge and implementation experiences, contributing to refinement and redefinition of subsequent policy agendas. Evaluation is fundamental for establishing a virtuous cycle, ensuring continuous alignment between policy design and the sector's adherence to established parameters [23].

The authors contend that newly proposed policies are never perfect, as information and knowledge remain incomplete during formulation. To improve policy effectiveness, governments must learn from successes, failures, and unexpected outcomes. Moreover, a considerable time gap may exist between policy design and implementation. During this interval, the implementation environment may change—particularly in a sector characterized by long building lifespans and the involvement of multiple actors. Therefore, adaptive policy adjustments are essential to ensure relevance over time [24].

There remains a lack of robust evaluation indicators to assess CE policy performance at different organizational levels [26]. To address this, transparent and collaborative environments are needed in which diverse actors can communicate and assess regulatory measures effectively.

A comprehensive understanding of the entire supply chain is necessary to address the sector's complexity, while the various actors involved must recognize the economic, social, and environmental benefits associated with CE adoption. Policies should shift away from the traditional waste-centered perspective and move toward "designing from waste" regulatory approaches [27].

CE-oriented policies must therefore incorporate this shift: information from actors directly involved should be integrated at the micro level; supply chain evaluations should be conducted at the meso level, with a regional focus; and policy refinement should occur at the macro level, aligned with national agendas [28]. Such a configuration can foster more effective and robust public policy frameworks.

Given the importance of ongoing assessments, as emphasized by numerous authors, this study aims to examine the extent to which CE-related policies and regulatory instruments include mechanisms for evaluation and monitoring.

The effective implementation of circularity requires rigorous consideration of local specificities, the engagement of all actors, and continuous monitoring and evaluation. In a

global scenario marked by resource scarcity, climate change, and escalating environmental degradation, integrating CE practices into urban planning emerges as a promising strategy for building more sustainable and resilient cities [30].

3 Methodology

This study initially conducted a systematic literature review to identify works related to development of circular policies in the construction sector. Identified studies were subsequently screened to determine whether they referenced evaluation or monitoring tools for the policies under analysis.

Diagram 1 illustrates the research steps followed by the study. The procedure followed a structured workflow comprising successive stages of selection and analysis:

Research objective: evaluate the development and monitoring of circular policies within the construction sector.

Literature review: exploratory literature review was performed, complemented by case-study analyses to

capture practical instances of policy development and monitoring.

Study selection: articles were filtered based on their relevance to policy development and the presence of explicit references to monitoring or evaluation mechanisms. Inclusion criteria prioritized studies that discussed both policy formulation and instruments for assessing policy performance.

Descriptive analysis: selected studies were subjected to a descriptive analysis that involved the identification and definition of key variables, followed by the selection of appropriate methods for data analysis. This stage aimed to summarize the scope, objectives, and evaluation approaches of the reviewed policies.

Tool analysis: identified evaluation and monitoring instruments were analyzed through the lens of Yu et al. [31] bidirectional policy-making framework (Figure 2). This analytical step examined how each instrument aligned with micro (local), meso (regional), and macro (national) levels of policy operation and feedback.

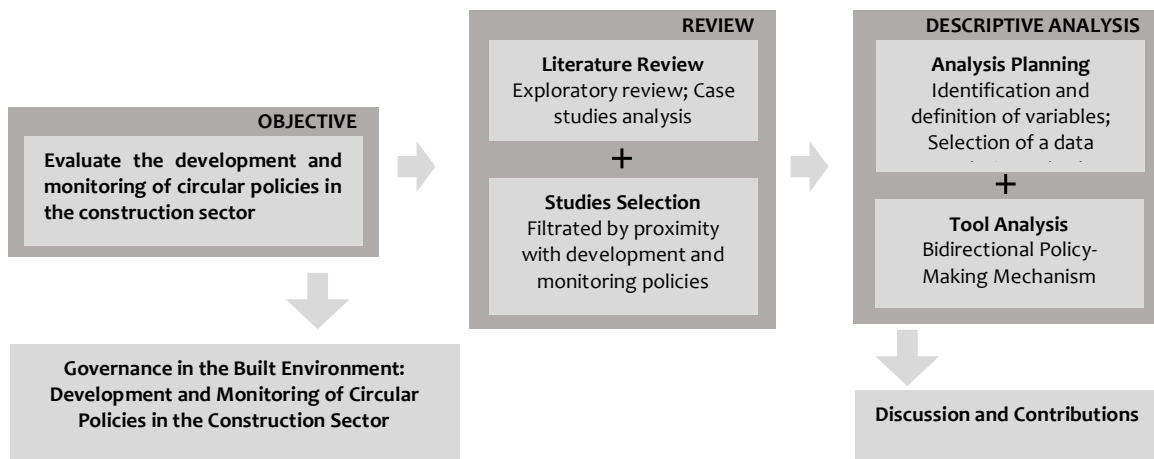


Diagram 1. Research process steps

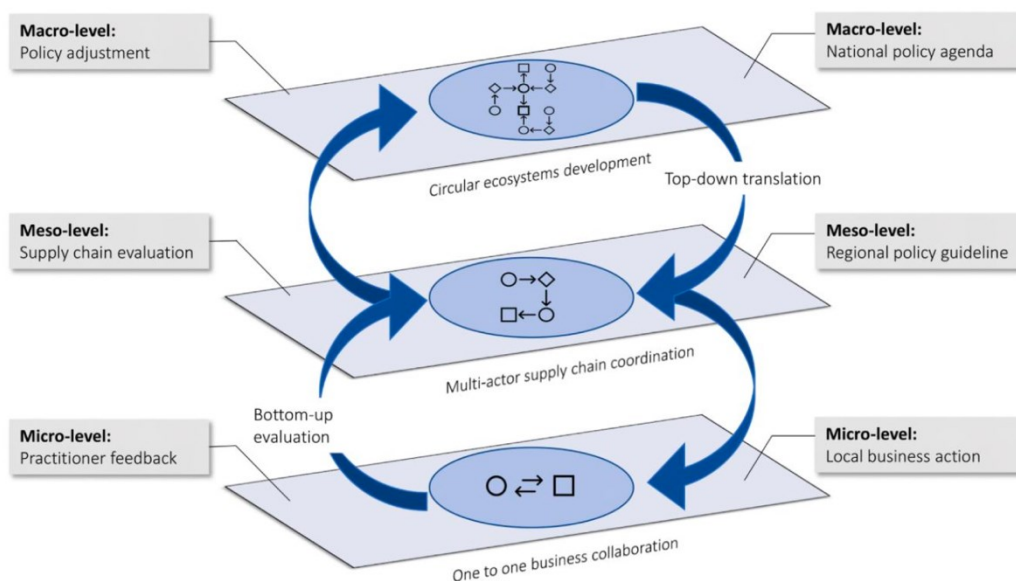


Figure 2. Bidirectional policy-making mechanism (Yu et al., 2022)

Discussion and contributions: Findings were synthesized to inform the governance discourse on circularity in the built environment, highlighting strengths, gaps and opportunities for improving the development and monitoring of circular policies.

4 Analysis of policy instruments and international initiatives

The scientific studies analyzed, which presented examples of policy evaluation and monitoring within the Circular City (CC) context, are briefly introduced below to provide an overarching understanding of how the selected works are grouped. Table 1 synthesizes the articles, emphasizing existing initiatives and their respective strategies, policies, and monitoring mechanisms.

Table 1. Evaluation and monitoring strategies

	INITIATIVE	STRATEGIES	POLICY	EVALUATION / MONITORING
EUROPEAN UNION	CE action plan (2020)	Regulation for construction products: durable, repairable, recyclable, reusable.	Digital passport for products; technological infrastructure; industrial symbiosis; secondary-material markets.	Implementation of CE across different sectors, alignment with the ReSOLVE framework.
NETHERLANDS	CE by 2050	Four levels of transition management: Transition Arenas, Transition Agendas, Transition Experiments, Monitoring and Evaluation	Regional leadership integrating with cross-border strategies; facilitating cross-sectoral partnerships.	Assessment limited by availability and accessibility data; Material flow analysis of construction and demolition.
CHINA	Sustainable use of resources	BIM modeling to reduce waste; Flexible design, prefabrication	Life-cycle monitoring; Regulations for waste prevention; Policies for C&D recycling.	Standardizing practices; Life-cycle monitoring system.
SAUDI ARABIA	Waste management regulation	Regulations for recycling, sustainable practices and quality materials; Reduce impacts of cement and concrete industries; Efficiency in design and construction.	Recycling programs; Collaborative policy development; Energy-performance for new cement factories; Carbon taxes to energy efficiency and technology.	Research institutions to monitor and provide data to actors; Tracking system to monitor C&D waste management; GHG reductions in cement and concrete industries.
FINLAND	Circular Economy in the Built Environment	Expand on CE: develop indicators and measures, stakeholder collaboration.	CE goals for the construction sector; Land Use incorporate CE;	CE implementation monitored; Target for space efficiency; CE activities rewarded.
GERMANY		Integration C&D material stocks; Reduce material demand and increase secondary-material supply by 2030; Policy for CE implementation.	Taxes on primary resources and waste disposal; Environmental awareness in educational curriculum.	Integrating material-flow modeling with stakeholder perspectives; Analysis impacts of CE policies.
HONG KONG		Modular design and deconstruction strategies; Maintenance, dismantling and end-of-life treatments.	Increase reuse of modular components; Recognize steel's recycling potential.	Sobol indices to identify parameters for LCA results.
INDIA		Circular supply chain framework; Integrate smart technologies to CE decision-making.	CE principles when renovating buildings; CE design on urban local governments; CE responsibilities to all levels of governance.	Material flows through IoT; responsible supply chain systems.
UNITED KINGDOM		CE in design, construction, and renovation; Building passports; CE into urban planning processes.	CE s at design stage; Regulatory frameworks for CE adoption; Supportive planning for CE implementation.	CE requirements to the sub-regional level; CE principles into national and local planning policies.

SOMALIA		Integrate CE into national development strategies.	Regulation for construction waste management.	Evaluate results aligned with the 11 pillars of the IG-ADAPT framework.
QATAR		Reduce construction waste via prevention, reuse, and recycling; Adoption of private-sector CE strategies.	Partnerships between research institutions and municipalities; Use of recycled aggregates; C&D waste recycling hubs.	Alignment circular city initiatives with national strategic objectives; Monitoring public-private partnerships in the waste sector.
GHANA		Increase recycling and material recovery rates; Enhance waste management; Market development for secondary materials.	Economic incentives for recycling enterprises; Regulations for responsible landfilling; Guidelines for sustainable C&D waste.	Quantitative analysis and qualitative feedback from stakeholders; Scenario-based modeling for evaluating policy.
DENMARK		Reduce material consumption in construction; Energy efficiency and waste minimization; CE practices across the life cycle.	Landfill taxation; Building renovation to extend lifespan; Guidelines for CE-based building design.	Bottom-up stakeholder input with top-down supply chain evaluation; Monitoring micro, meso, and macro levels, feeding results into policymaking.
SINGAPORE & INDONESIA		Cooperation for CE adoption; Reduce C&D waste and increase recycling; Private-sector participation in circular practices.	Industrial symbiosis; Standards for recycled construction materials; Waste-to-resource industrial networks.	Assessment of cross-border CE collaborations; Performance through life-cycle-based indicators.
CENTRAL AND EASTERN EUROPE		Building renovation and aging stock; CE principles into construction practices; Reuse and recycling of key materials.	C&D waste directives for member states; Harmonization of C&D classification systems; Pre-demolition audits and material passports.	C&D management relation to EU circular transition; Monitoring platforms to assess EU waste directives; Gaps and opportunities for C&D circularity.

The initiatives reviewed highlight a wide range of circular strategies implemented across different regions, including the European Union, Asia, and Africa. Among the regulatory evaluation and monitoring mechanisms examined, tools were identified across the three organizational levels proposed by Yu et al. [32]: micro, meso, and macro. However, one noticeable issue is that many analytical tools only encompass two levels—typically micro and meso—while few incorporate the macro level, which represents national agendas.

Two strong examples that integrate micro and meso levels include: (i) Pilot projects designed to test and advance CE-oriented approaches; (ii) The involvement of local research institutions responsible for monitoring waste management practices and generating data for stakeholders.

Integrating coordination with national-level agendas would support adaptive policy adjustments, offering meaningful feedback to high-level policymakers and reinforcing the policy cycle as a dynamic, iterative mechanism.

A full integration of CE principles is essential for effective policymaking, given that different circular mechanisms are more effective at distinct phases of the construction life cycle. The absence of a universal solution reflects the need to articulate prevention, recycling, and waste management strategies according to project stages. The market competitiveness of secondary materials depends on

reducing recovery costs and ensuring consistent material quality—conditions that necessitate economic policy interventions such as subsidies, tax reductions, and incentives for technological innovation.

A synergistic combination of policy instruments is therefore fundamental to generating value across the life cycle. Additionally, advances in Information and Communication Technologies (ICT) strengthen digital governance by enhancing transparency, collaboration, and traceability, all of which support continuous policy evaluation [33].

5 Discussion

The analysis of international initiatives reveals that the transition toward a CE in the built environment remains uneven and highly dependent on contextual factors such as governance structures, technological capacity, regulatory maturity, and market readiness. While many countries have advanced significantly in establishing CE frameworks—particularly within the European Union—implementation gaps persist, especially in regions where institutional capacity is limited or where regulatory mechanisms remain fragmented.

A notable finding across the reviewed studies is the predominance of waste-centric approaches, despite the well-established understanding that the most effective circular strategies occur upstream, particularly during the design and

planning phases. This persistent focus on end-of-life (EoL) waste management reinforces linear practices, while opportunities for waste prevention, modularization, design for disassembly, and material traceability remain underexploited.

The structure proposed by Yu et al. [34], which organizes policy formulation and evaluation according to micro, meso, and macro levels, proves to be an insightful analytical lens for understanding governance dynamics. However, only a

limited number of countries integrate mechanisms across all three levels:

- Micro level: municipal regulations as pilot projects, local data, life-cycle tracking.
- Meso level: inter-municipal coordination as regional supply chain, interoperability measures.
- Macro level: national policy agendas, legislative frameworks, and long-term CE.

Table 2. Evaluation and monitoring levels

	EVALUATION / MONITORING		
	MICRO LEVEL individual corporate collaboration	MESO LEVEL multi-actor supply chain	MACRO LEVEL development of circular ecosystems
EUROPEAN UNION	Alignment of CE with ReSOLVE framework		
NETHERLANDS	Evaluation limited by availability of material flows and resource use		
CHINA	Department for standardizing practices; monitoring system for life cycle and demolition waste		
SAUDI ARABIA	Local research institutions to monitor C&D and provide data to stakeholders	Achieve significant GHG reductions in the cement and concrete industries	Tracking system to monitor and regulate CDW management
FINLAND	CE implementation will be monitored; definition of target levels; CE activities will be rewarded		
GERMANY	Combining material-flow modeling with stakeholder perspectives to identify effective policy measures, improving efficiency and resource economy		
HONG KONG	Sobol indices identify parameters influencing LCA		
INDIA	Blockchain to life-cycle monitoring, traceability, process automation, closed-loop, recycling and remanufacturing		
UNITED KINGDOM	Multi-level transformative urban model to reshape technology, construction, and waste sectors		
SOMALIA	Real-time monitoring and data-driven decision through circular principles		

QATAR	Monitoring statistics, blockchain applications, and data blocks to support CE in built environment and urban spaces
GHANA	Integrated management of waste influences CE activities
DENMARK	Pilot projects to test and advance CE approaches
SINGAPORE & INDONESIA	Assessment potential for urban mining, recovery, and reuse of building components
CENTRAL & EASTERN EUROPE	Convergence of legislative changes, technological advances and sustainability in design competitions signals a profound evolution in the architecture and construction sector.

The absence of mechanisms connecting these three levels jeopardizes policy coherence. Without structured feedback loops, policies tend to remain generic and disconnected from ground-level realities. This reinforces one of the primary challenges identified in the literature: the lack of iterative cycles that enable continuous improvement, recalibration of goals, and adaptation to emerging conditions.

Moreover, the lack of robust indicators for evaluating CE policies in the construction sector is a recurring limitation. Existing tools often focus on recycling rates or landfill metrics that capture only a fraction of circularity's potential benefits. Broader indicators are needed to assess: resource efficiency gains across the life cycle, material circulation and quality assurance, design-stage circularity criteria, market competitiveness of secondary materials, carbon reduction impacts, and technological innovation related to CE.

Another important trend is the increasing reliance on ICT-based tools, including digital twins, BIM-integrated material databases, IoT tracking devices, and blockchain-enabled material passports, which allow for greater transparency, traceability, and informed decision-making. These tools can strengthen data quality and significantly enhance monitoring systems. However, their adoption remains uneven, often limited by financial constraints, lack of interoperability, or insufficient technical capacity.

Across the global cases examined, economic instruments alone, such as subsidies, tax reductions, and incentives for secondary material use, are not sufficient to drive systemic change. Their effectiveness depends on complementary regulatory, institutional, and informational instruments. Policymakers therefore need to adopt synergistic policy packages, tailored to the life-cycle characteristics of the construction sector, while fostering collaboration between public and private stakeholders.

Although the development and implementation of CE policies in the construction sector have intensified, the

analysis conducted shows that the effectiveness of these approaches, as well as their monitoring mechanisms, could be further improved. The sector still relies heavily on linear models, with a predominant focus on waste management rather than preventive strategies throughout the life cycle.

A key weakness observed is the insufficient integration among local, regional, and national governance levels. The literature demonstrates that the absence of structured feedback mechanisms undermines the adaptation and improvement of public policies.

Significant limitations are also evident in monitoring systems. Recent studies advocate for the incorporation of life-cycle assessments, material traceability, and carbon metrics as more robust control criteria.

Despite the identified gaps, the literature highlights criteria that exemplify good practices, such as multi-level governance integration with coordination across institutional scales; circular design strategies, such as design for disassembly; digital monitoring through BIM, traceability, and data-driven models; policies that combine regulatory and economic instruments; and active stakeholder engagement in policy implementation and evaluation.

The effective transition toward a CE in the built environment depends on life-cycle-oriented approaches, evidence-based adaptive governance, multidimensional performance indicators, and the integration of regulatory, economic, and technological instruments.

Finally, the literature shows that successful CE implementation depends on aligning national strategies with local realities. This means acknowledging the heterogeneity of construction markets, regional material flows, and diverse governance capacities. Only through multi-level coordination, continuous evaluation, and evidence-based adjustments can CE policies achieve lasting and meaningful transformations in the built environment.

6 Conclusions

The CE policy in the construction sector is neither uniform nor particularly advanced, despite a decade of institutional interest. The initiatives reviewed reveal a field caught between aspirational frameworks and operational constraints. Countries that have developed sophisticated regulatory language frequently lack the monitoring infrastructure to assess whether that language translates into material change. Countries with monitoring capacity, conversely, often operate without the upstream design mandates that would make data collection meaningful. This asymmetry points to a structural misalignment in how CE policy for the built environment has been conceptualized.

The predominance of waste-centric approaches across virtually every region examined is the most persistent and arguably the most consequential finding of this review. Recycling rate targets, favored by the EU, Saudi Arabia, Ghana, and Qatar, quantify one narrow slice of circularity. Downstream management of materials have already completed their linear journey through extraction, production, use, and disposal. What such metrics systematically ignore is the regulatory architecture governing material choices at the earliest project stages, where the greatest resource-efficiency gains are available.

Yu et al. [15] established that CE implementation in the construction sector has remained focused on end-of-life waste, while design-stage interventions (design for disassembly, modular construction, pre-demolition audits, material passports), remain marginal in most national frameworks. The cases reviewed here confirms that even among countries with explicit commitments to upstream circularity, regulatory enforcement mechanisms for design-stage compliance are conspicuously absent or voluntary. The United Kingdom's multi-level transformative model represents a partial exception, but its sub-national planning inconsistency limits its scalability. The Netherlands' CE by 2050 strategy is architecturally sophisticated yet constrained, in its own monitoring assessments, by data availability at the material-flow level.

The framework proposed by Yu et al. [34], which organizes CE policy evaluation across micro (local), meso (regional), and macro (national) levels, provides the most analytically productive lens available in the literature for examining the cases reviewed. Its application, however, reveals a pattern more troubling than a simple absence of integration: what exists in many jurisdictions is the formal appearance of multi-level coordination without the operational mechanisms that would make feedback loops functional.

China's case is instructive precisely because it inverts the typical pattern. The national government has deployed a comprehensive standardization and life-cycle monitoring system, while local feedback mechanisms remain structurally subordinated. The result is a top-down policy architecture with significant data-collection capacity but limited adaptive responsiveness to ground-level implementation realities. Denmark demonstrates the opposite configuration. Its pilot-project approach explicitly tests CE interventions at the micro level before generating data for meso-level supply chain evaluation and, ultimately, macro-level legislative adjustment.

Germany's model occupies a middle position that is perhaps the most replicable for industrialized economies outside Northern Europe. Material-flow modeling at the meso level is integrated with stakeholder perspectives to identify effective policy measures, while economic instruments (taxes on primary resources, waste disposal fees) operate at the macro level. The critical weakness, also present in Finland's approach, is the absence of binding design-stage requirements capable of shifting construction market behavior rather than merely adjusting waste management incentives. Germany monitors material flows efficiently but does not yet mandate the design decisions that would make those flows circular rather than linear.

The increasing adoption of ICT-based tools (digital twins, BIM-integrated material databases, IoT tracking, blockchain-enabled material passports) represents one of the more technically coherent trends in the evidence reviewed. India's deployment of blockchain for life-cycle traceability and closed-loop manufacturing, Qatar's use of blockchain and data analytics for CE monitoring in built environments, and Saudi Arabia's real-time C&D waste tracking system all demonstrate that technological capability to monitor circular performance exists and is diffusing beyond high-income contexts. Somalia's case introduces a real-time data-driven governance infrastructure that is documented in a context where the broader regulatory and institutional framework for CE remains absent.

The observation challenges a common assumption in the governance literature, namely that monitoring tools are downstream outputs of mature regulatory systems. The evidence suggests the relationship can be reversed, with implications for policy sequencing. In contexts of limited institutional capacity, investments in digital monitoring infrastructure may generate the evidence base needed to justify and design the regulatory frameworks that should logically precede them. Whether this inversion constitutes an adaptive strategy or a structural limitation depends on whether the data generated is institutionally actionable.

Despite the heterogeneity of the cases reviewed, the evidence converges on a set of criteria that differentiate more advanced CE policy systems from those that remain largely symbolic. These criteria are not merely descriptive of what exists in high-performing jurisdictions. They are operationalizable as benchmarks for evaluating and improving CE governance frameworks in any construction sector. Table 3 synthesizes these criteria, with specific country exemplars and policy implications derived from the evidence reviewed.

Some patterns found could be highlighted:

- Governance integration without instrument synergy produces coordination without policy traction; instrument synergy without governance integration produces locally coherent packages that fail to scale;
- the secondary material market development criterion exposes what may be the most underaddressed structural barrier in the entire policy landscape;
- governance design failure reflects the absence of political commitment to adaptive policy cycles;
- input-oriented evaluation permits governments to claim policy success without demonstrating behavioral change in construction markets.

Table 3. Summary of criteria found in the analyzed cases

CRITERION	DEFINITION	CASES	POLICY IMPLICATIONS
MULTI-LEVEL GOVERNANCE INTEGRATION	Coordinated regulatory mechanisms operating simultaneously at micro, meso, and macro levels	Denmark: pilot projects feeding supply chain evaluation and legislative adjustment; Netherlands: Transition Arenas and formal monitoring	Establish inter-institutional coordination protocols and structured feedback loops between governments levels
UPSTREAM CIRCULAR DESIGN MANDATE	Regulatory requirements for design for disassembly, modularity, and material traceability prior to construction permit issuance	United Kingdom: multi-level integrating technology, construction, and waste sectors; EU: digital product passports and design requirements	Embed circularity criteria in planning permission frameworks; modular prefabrication through procurement standards
DIGITAL MONITORING INFRASTRUCTURE	ICT-enabled traceability systems (BIM, IoT, blockchain) linked to policy evaluation mechanisms across governance levels	India: blockchain for life-cycle and closed-loop manufacturing; Qatar: blockchain and data analytics for CE monitoring; Saudi Arabia: real-time C&D waste tracking	Mandate interoperable digital standards for material passports; invest in shared data infrastructure accessible to all governance levels
SYNERGISTIC POLICY PACKAGES	Combination of regulatory, economic, and informational instruments designed as a coherent system rather than isol	Finland: CE implementation with reward mechanisms and land-use criteria; Germany: material-flow integrated with tax instruments and policy	Replace single-instrument approaches with adaptive packages; establish regular review cycles tied to quantified performance thresholds
SECONDARY MATERIAL MARKET DEVELOPMENT	Policy instruments designed to reduce recovery costs, assure quality of secondary materials, and enable competitive market formation	Singapore & Indonesia: urban assessment for building component recovery; Central & Eastern Europe: legislative reform with deconstruction incentives; Italy: high recycling rates but reuse constrained	Establish quality certification frameworks for recycled aggregates and components; combine landfill taxation with subsidies for secondary material procurement in public projects
ADAPTIVE EVALUATION CAPACITY	Institutionalized mechanisms for continuous policy assessment, including life-cycle metrics, carbon performance, and stakeholder feedback	Denmark: feedback loop integrating local data into national legislative; China: national life-cycle monitoring system for demolition waste; Somalia: real-time data-driven governance through circular digital infrastructure	Develop multidimensional indicator sets beyond recycling rates; institutionalize periodic policy review cycles with mandatory stakeholder input

Advancing CE governance in the built environment therefore depends less on the invention of new policy instruments than on resolving the institutional conditions under which existing instruments are evaluated, revised, and politically sustained. That resolution is, ultimately, a governance challenge rather than a technical one. And it is, by the evidence reviewed here, the challenge most consistently evaded.

The study concludes that the successful implementation of CE in the built environment depends on the continuous alignment of political agendas with local realities, the active participation of stakeholders across all levels, and the establishment of adaptive regulatory systems capable of

evolving alongside technological, environmental, and socio-economic transformations. Only through holistic, coordinated, and evidence-based approaches can CE policies contribute effectively to creating more sustainable, resilient, and resource-efficient cities.

Future research should advance on multidimensional evaluation frameworks, assessing CE performance on construction life cycle, to incorporate design-stage strategies, material traceability, carbon reduction performance, and digital integration. Empirical studies should examine how multi-level governance structures operate in practice, analyzing feedback mechanisms linked to micro, meso and macro-level policy.

CRediT authorship contribution statement

Simone Cassilha: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, review & editing. Sergio Tavares: Conceptualization, Supervision, Validation.

Declaration of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] McKinsey Global Institute (2011). *Resource Revolution: Meeting the World's Energy, Materials, Food and Water Needs*. McKinsey and Company, New York, NY, USA.
- [2] ADAMS, Carol. *The Sustainable Development Goals, integrated thinking and the integrated report*. 2017.
- [3] PLANET, One et al. *One Planet Multi-Partner Trust Fund for SDG 12 Report 2020*. 2021.
- [4] GIORGI, Serena; LAVAGNA, Monica; CAMPIOLI, Andrea. Circular economy and regeneration of building stock in the Italian context: Policies, partnership and tools. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 2019. p. 012065
- [5] MACARTHUR, Ellen. *Rumo à economia circular: O racional de negócio para acelerar a transição*. Ellen MacArthur Foundation, 2015.
- [6] GUERRA, Beatriz C. et al. Circular economy applications in the construction industry: A global scan of trends and opportunities. *Journal of cleaner production*, v. 324, p. 129125, 2021
- [7] JONES, Holly P. et al. Restoration and repair of Earth's damaged ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, v. 285, n. 1873, p. 20172577, 2018.
- [8] BAI, Xiong et al. ESG performance, institutional investors' preference and financing constraints: Empirical evidence from China. *Borsa Istanbul Review*, v. 22, p. S157-S168, 2022.
- [9] ABABIO, Josephine Ofosu-Mensah et al. Sustainable energy for all: the link between financial inclusion, renewable energy and environmental sustainability in developing economies. *International Journal of Energy Sector Management*, n. ahead-of-print, 2023.
- [10] BANIHASHEMI, Saeed et al. Critical success factors (CSFs) for integration of sustainability into construction project management practices in developing countries. *International*
- [11] VAN BUEREN, Bart JA et al. The circular economy operating and stakeholder model "eco-5HM" to avoid circular fallacies that prevent sustainability. *Journal of Cleaner Production*, v. 391, p. 136096, 2023.
- [12] KANTERS, Jouri. Circular building design: An analysis of barriers and drivers for a circular building sector. *Buildings*, v. 10, n. 4, p. 77, 2020.
- [13] SOININEN, Niko et al. A brake or an accelerator? The role of law in sustainability transitions. *Environmental Innovation and Societal Transitions*, v. 41, p. 71-73, 2021.
- [14] ENTSALO, Hanna et al. Analysing regulatory instruments in sustainability transitions: A combined 'intervention points' and 'roles of law' approach to the European Union's Ecodesign framework. *Sustainable Production and Consumption*, v. 42, p. 125-137, 2023.
- [15] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [16] NUßHOLZ, Julia et al. From circular strategies to actions: 65 European circular building cases and their decarbonisation potential. *Resources, Conservation & Recycling Advances*, v. 17, p. 200130, 2023.
- [17] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [18] WU, Haitao et al. Does environmental pollution inhibit urbanization in China? A new perspective through residents' medical and health costs. *Environmental Research*, v. 182, p. 109128, 2020.
- [19] BOLGER, Kathleen; DOYON, Andréanne. Circular cities: exploring local government strategies to facilitate a circular economy. *European planning studies*, v. 27, n. 11, p. 2184-2205, 2019.
- [20] AKOMEA-FRIMPONG, Isaac et al. A review of circular economy models and success factors on public-private partnership infrastructure development. *Built Environment Project and Asset Management*, v. 14, n. 1, p. 109-126, 2024.
- [21] DALHAMMAR, Carl et al. Enabling reuse in extended producer responsibility schemes for white goods: legal and organisational conditions for connecting resource flows and actors. *Circular economy and sustainability*, v. 1, n. 2, p. 671-695, 2021.
- [22] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [23] BOLGER, Kathleen; DOYON, Andréanne. Circular cities: exploring local government strategies to facilitate a circular economy. *European planning studies*, v. 27, n. 11, p. 2184-2205, 2019.
- [24] ALVO-PORRAL, Cristina; LÉVY-MANGIN, Jean-Pierre. The circular economy business model: Examining consumers' acceptance of recycled goods. *Administrative Sciences*, v. 10, n. 2, p. 28, 2020.
- [25] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [26] PASCHOALIN FILHO, João Alexandre; BEZERRA, Claudia Maria da Silva; GUERNER DIAS, Antonio José. Environmental indicators proposal for construction solid waste management plans assessment. *Management of Environmental Quality: An International Journal*, v. 31, n. 6, p. 1623-1645, 2020.
- [27] HAITHERALI, Hammadhu; ANJALI, G. Circular economy in construction sector—a guideline for policy makers from global perspective. *Circular Economy and Sustainability*, v. 4, n. 2, p. 1285-1313, 2024.
- [28] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.

- [29] HAITHERALI, Hammadhu; ANJALI, G. Circular economy in construction sector—a guideline for policy makers from global perspective. *Circular Economy and Sustainability*, v. 4, n. 2, p. 1285-1313, 2024.
- [30] CERVANTES PUMA, Genesis Camila; SALLES, Adriana; BRAGANÇA, Luís. Exploring the Potential of Circular Economy Strategies in Urban Planning: A Comparative Analysis of Successful Case Studies. In: *International Conference "Coordinating Engineering for Sustainability and Resilience"*. Cham: Springer Nature Switzerland, 2024. p. 491-500.
- [31] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [32] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.
- [33] CORDELLA, Antonio; BONINA, Carla M. A public value perspective for ICT enabled public sector reforms: A theoretical reflection. *Government information quarterly*, v. 29, n. 4, p. 512-520, 2012.
- [34] YU, Yifei et al. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resources, Conservation and Recycling*, v. 183, p. 106359, 2022.



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Examples

Reference to a journal publication:

[1] V.W.Y. Tam, M. Soomro, A.C.J. Evangelista, A review of recycled aggregate in concrete applications (2000-2017), *Constr. Build. Mater.* 172 (2018) 272-292. <https://doi.org/10.1016/j.conbuildmat.2018.03.240>

Reference to a book:

[3] A.H. Nilson, D. Darwin, C.W. Dolan, *Design of Concrete Structures*, thirteenth ed., Mc Graw Hill, New York, 2004.

Reference to a chapter in an edited book:

[4] J.R. Jimenez, Recycled aggregates (RAs) for roads, in: F Pacheco-Torgal, V.W.Y. Tam, J.A. Labrincha, Y. Ding, J. de Brito (Eds.), *Handbook of recycled concrete and demolition waste*, Woodhead Publishing Limited, Cambridge, UK, 2013, pp. 351–377.

Reference to a website:

[5] WBCSD, The Cement Sustainability Initiative, World. Bus. Counc. Sustain. Dev. <http://www.wbcscement.org/pdf/CSIRecyclingConcrete-FullReport.pdf>, 2017 (accessed 7 July 2016).

SUPPLEMENTARY MATERIAL

Supplementary material such as databases, detailed calculations and the like can be published separately to reduce the workload. This material is published 'as received' (Excel or PowerPoint files will appear as such online) and submitted together with the manuscript. Each supplementary file should be given a short descriptive title.

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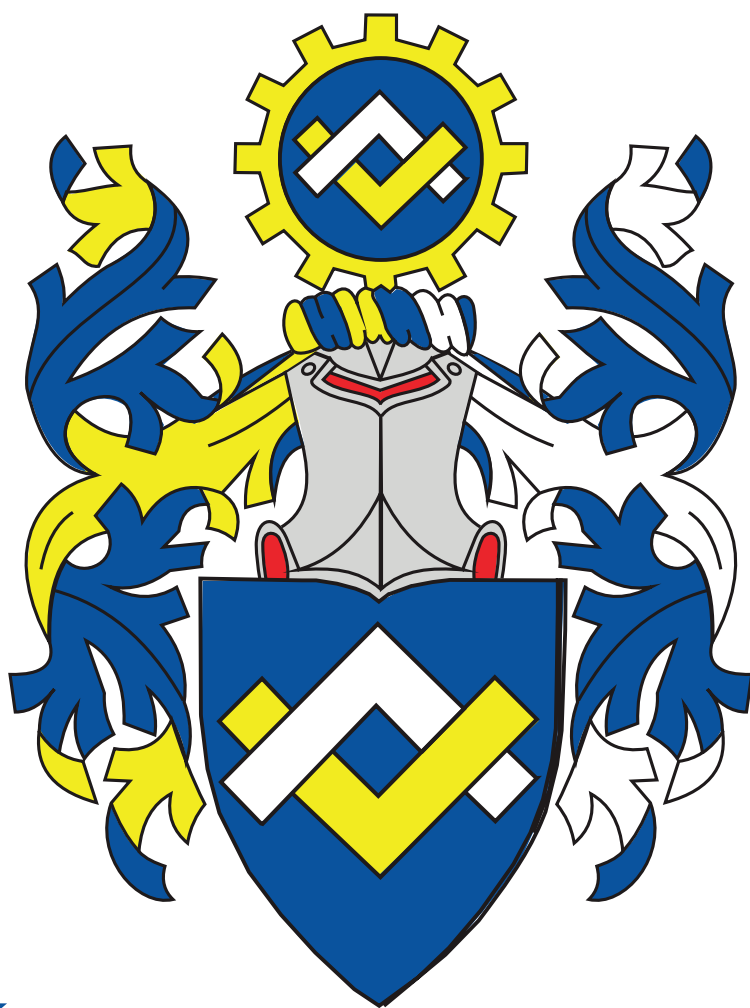


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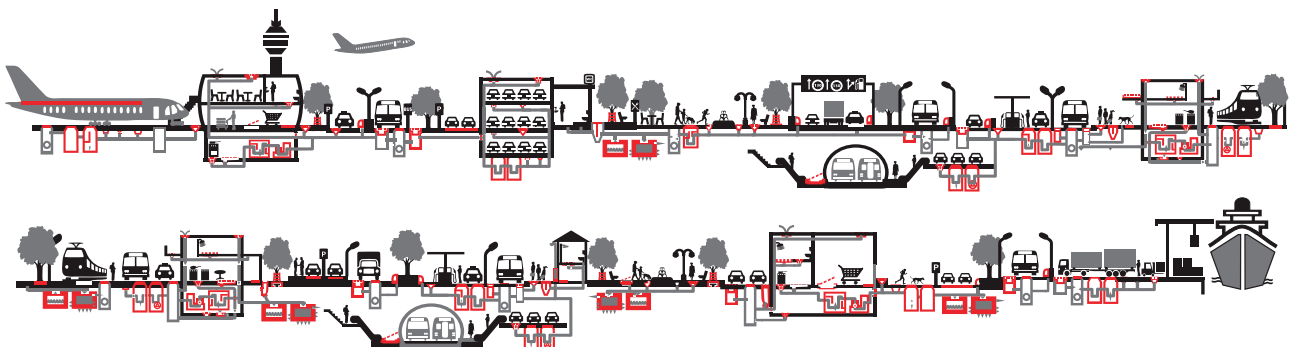
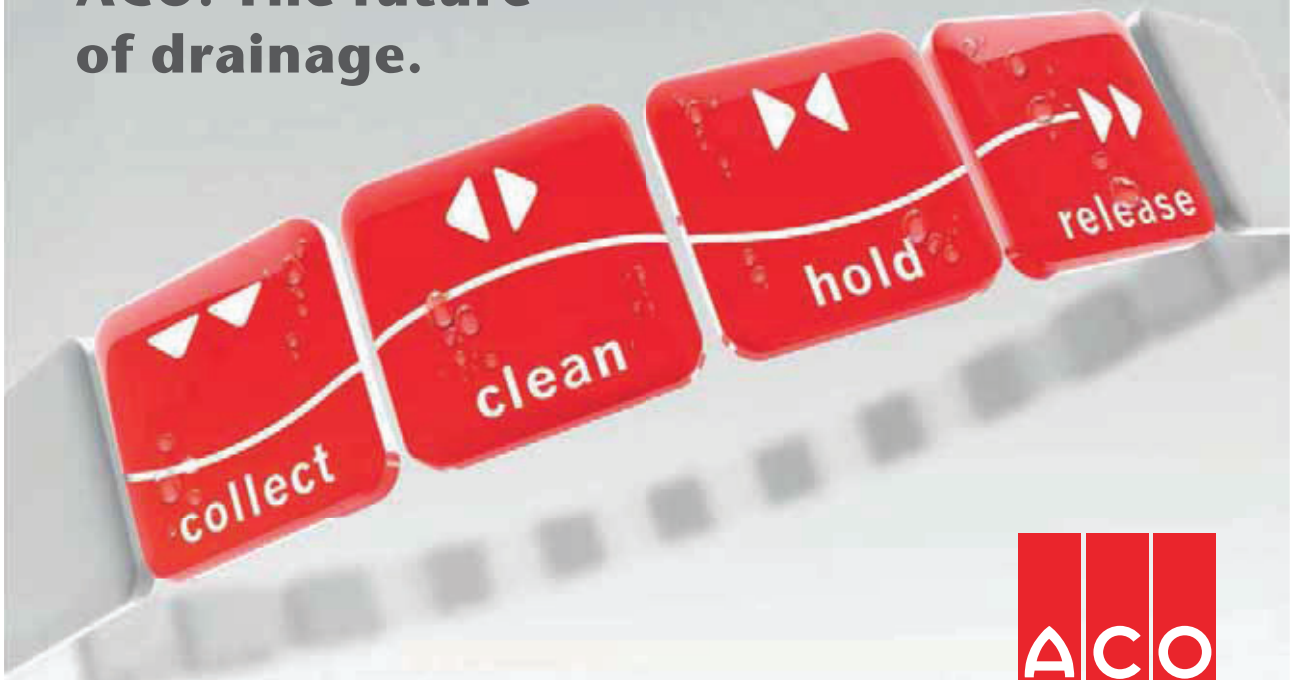
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CENTAR ZA PUTEVE I GEOTEHNIKU

U okviru centra posluju odeljenja za geotehniku, nadzor i terenska ispitivanja, projektovanje saobraćajnica, laboratorija za puteve i geotehniku. Značajna aktivnost centra usmerena je ka terenskim i laboratorijskim geološko - geotehničkim istraživanjima i ispitivanjima terena za potrebe izrade projektno - tehničke dokumentacije, za različite faze i nivoe projektovanja objekata visokogradnje, niskogradnje, saobraćaja i hidrogradnje, kao i za potrebe prostornog planiranja i zaštite životne sredine. Stručni nadzor, kontrola kvaliteta tokom građenja, rekonstrukcije i sanacije objekata različite namene, izrada studija, ekspertiza, konsultantske usluge, kompletan konsalting u oblasti geotehničkog inženjeringa, neke su od delatnosti centra.



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- **SLT metoda (Static load test)**
- **DLT metoda (Dynamic load test)**
- **PDA metoda (Pile driving analysis)**
- **PIT (SIT) metoda (Pile (Sonic) integrity testing)**
- **CSL - Crosshole Sonic Logging**



- **Ispitivanje šipova**
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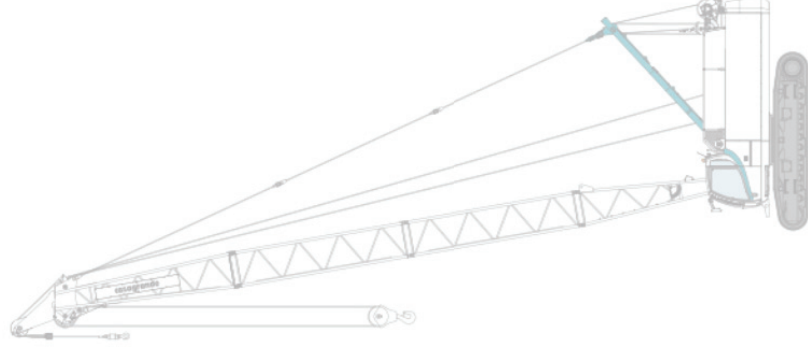


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PUT INŽENJERING



Put inženjering d.o.o punih 25 godina radi kao specijalizovano preduzeće za izgradnju infrastrukture u niskogradnji i visokogradnji, kao i proizvodnjom kamenog agregata i betona. Preduzeće se bavi i transportom, uslugama građevinske mehanizacije i specijalne opreme.

Koristeći inovativne tehnike i kvalitetan građevinski materijal iz sopstvenih resursa, spremni smo da odgovorimo na mnoge zahteve naših klijenata iz oblasti niskogradnje.



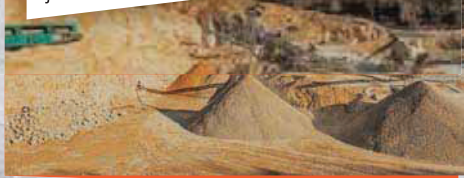
Osnovna prednost prefabrikovane konstrukcije jeste brzina kojom konstrukcija može biti projektovana, proizvedena, transportovana i namontirana.



Izvodimo hidrograđevinske radove u izgradnji kanalizacionih mreža za odvođenje atmosferskih, otpadnih i upotrebljenih voda, izvođenjem hidrograđevinskih radova u okviru regulacije rečnih tokova, kao i izvođenjem hidrotehničkih objekata.



Površinski kop udaljen je 35 km od Niša. Savremene drobilice, postrojenje za separaciju i sejalice efikasno usitnjavaju i razdvajaju kamene agregate po veličinama. Tehnički kapacitet trenutne primarne drobilice je 300 t/h.



Za spravljanje betona koristimo drobljeni krečnjački agregat sa našeg kamenoloma, deklariranih frakcija, kontrolisane vlažnosti. Kompletan proces proizvodnje i kontrole kvaliteta vršimo prema važećim standardima.



Obradu armature vršimo brzo, stručno i kvalitetno, sa kompjuterskom preciznošću i dimenzijama po projektu.



Naša kompanija u oblasti visokogradnje primenjuje sistem prefabrikovanih betonskih elemenata koji u odnosu na klasičnu gradnju ima brojne prednosti.



Prednapregnute šuplje ploče su konstruktivni elementi visokog kvaliteta, proizvedeni u fabrički kontrolisanim uslovima.



Izrađujemo betonske "New Jersey profile" koji se u svetu koriste za preusmeravanje saobraćaja i zaštitu pešaka u toku izgradnje puta, kao i Betonblock sistem betonskih blokova.



Uslugu transporta vršimo automikserima, kapaciteta bubnja od 7 m³ do 10 m³ betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 m³/h, sa dužinom strele od 36 m.



Kao generalni izvođač radova, vršimo koordinaciju svih učesnika na projektu, planiranje, praćenje i nabavku materijala, kontrolu kvaliteta izvedenih radova, poštujući zadate vremenske rokove i finansijski okvir investitora.



Osnovi princip našeg poslovanja zasniva se na individualnom pristupu svakom klijentu i pronalaženje najoptimalnijeg rešenja za njegove transportne i logističke potrebe.



Usluge građevinske mehanizacijom vršimo tehnički ispravnim mašinama, sa potrebnim sertifikatima kako za rukovoce građevinskim mašinama tako i za same mašine.



Raspoložemo opremom i mašinama za sve zemljane radove, kipere i dampere za rad u teškim terenskim uslovima, automiksere i pumpe za beton, autodizalice, podizne platforme.



Sakupljanje i privremeno skladištenje otpada vršimo našim specijalizovanim vozilima i deponujemo na našu lokaciju sa odgovarajućom dozvolom. Kapacitet mašine je 250 t/h građevinskog neopasnog otpada.



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Strastvenost, timski duh i vizija budućnosti. Mapei aktivno doprinosi najvažnijim svetskim projektima u oblasti arhitekture, infrastrukture i stanovanja, kao i obnovi kulturno-istorijskih građevina. S predanošću radimo svakog dana, kako bismo oblikovali održivu budućnost građevinske industrije.



Više na: www.mapei.rs i www.mapei.com



MATEST "IT TECH" KONTROLNA JEDINICA



JEDNA TEHNOLOGIJA MNOGO REŠENJA

IT Touch Technology je Matestov najnoviji koncept koji ima za cilj da ponudi inovativna i user-friendly tehnologiju za kontrolu i upravljanje najmodernijom opremom u domenu testiranja građevinskih materijala

Ova tehnologija je srž Matestove kontrolne jedinice, software baziran na Windows platformi i touch screen sistem koji je modularan, fleksibilan i obavlja mnoge opcije

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JEDNOM SHVATIŠ - SVE TESTIRAŠ



NAPREDNA TEHNOLOGIJA ISPITVANJA ASFALTA

- | GYROTRONIC - Gyrotory Compactor
- | ARC - Electromechanical Asphalt Roller Compactor
- | ASC - Asphalt Shear Box Compactor
- | SMARTRACKER™ - Multiwheels Hamburg Wheel Tracker, DRY + WET test environment
- | SOFTMATIC - Automatic Digital Ring & Ball Apparatus
- | Ductilometers with data acquisition system

MULTIFUNKCIONALNI RAMOVI ZA TESTIRANJE

- | CBR/Marshall digital machines
- | Universal multispeed load frames
- | UNITRONIC 50kN or 200kN Universal multipurpose compression/flexural and tensile frames

OPREMA ZA GEOMEHANIČKO ISPITVANJE

- | EDOTRONIC - Automatic Consolidation Apparatus
- | SHEARLAB - AUTOSHEARLAB - SHEARTRONIC
- Direct / Residual shear testing systems
- | Triaxial Load Frame 50kN

MIXMATIC - Automatic Programmable Mortar Mixer