Comparative Case Analysis of Waste Sorting and Processing Models for Advancing Circular Construction in Europe

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Abstract. Construction and demolition waste (CDW) represents one of Europe's largest materials flows and a critical challenge for achieving circularity in the built environment. Drawing on comparative case studies from Latvia, Estonia, Greece, Cyprus, Slovenia, Romania, and Turkey, this paper analyzes how diverse CDW management models: centralized recycling hubs, on-site demolition processing, closed-loop manufacturing systems, public-led circular construction initiatives, and digital or technology-enabled waste prevention strategies influence material recovery outcomes, environmental performance, and market dynamics. Using a structured cross-case analytical framework, the study compares technological, regulatory, and operational features across cases to understand how collection, sorting, and processing systems shape circularity potential. Results demonstrate that advanced automated sorting, integrated value-chain models, and digital tools can substantially increase landfill diversion rates, reduce CO_2 emissions, and preserve virgin resources. However, persistent barriers including insufficient market demand for secondary materials, lack of end-of-waste criteria, regulatory inconsistencies, and cultural resistance, limit broader uptake. Stakeholder insights further

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highlight the role of political incentives, economic competitiveness, and technological readiness in enabling or constraining CDW circularity. The findings contribute to a clearer understanding of how European CDW sorting and processing practices can support a high-value circular construction transition and identify priority areas for policy and industry action.

Keywords: Construction and Demolition Waste (CDW) · Circular Construction · Waste Sorting and Processing · Secondary Raw Materials · Recycling Technologies · Industrial Symbiosis · Circular Economy Models

1 Introduction

Construction and demolition waste (CDW) constitutes a major global waste stream and is widely reported to represent 30–40% of total waste generated worldwide [7, 11]. Although the European Union has introduced regulatory instruments and recovery targets, the sector continues to face challenges related to fragmentation, inconsistent regulatory enforcement, and limited market demand for secondary materials [6].

Studies examining global CDW trends emphasise that rapid construction activity and inadequate waste management practices significantly increase waste loads and environmental pressures [5]. In parallel, systematic reviews of CE strategies in CDW demonstrate that circularity depends on coordinated interventions across demolition practices, sorting infrastructure, and secondary material market development [8]. Research on recycled concrete aggregates further shows that these materials can effectively replace natural aggregates with acceptable structural performance when properly processed [1], contributing to measurable reductions in CO_2 emissions [9]. CDW valorisation supports sustainable business models by enhancing resource efficiency and enabling closing-the-loop strategies, as outlined by Bocken et al. [2].

A growing body of research highlights selective demolition [3], automated sorting technologies [12], and material-specific closed-loop recycling processes such as concrete and gypsum recovery [13] as key enablers of improved circularity. However, most scientific contributions focus on single technologies, individual material streams, or isolated national contexts. As a result, limited attention has been given to how different CDW management models perform under contrasting operational, regulatory, and market conditions across Europe. This paper addresses this gap, through a comparative analysis of fourteen operational CDW management cases from seven countries. The study examines how technological configuration, logistics organization, governance support, and market conditions shape material recovery efficiency, circularity outcomes, and overall system performance. It also identifies the enabling conditions and systemic barriers that influence the scalability of high-value recycling practices. The central argument emerging from the comparison is that strong circularity performance depends not on technology alone, but on the alignment between sorting capacity, market demand, regulatory clarity, and proximity-based reuse opportunities.

2 Methodology

The methodology was designed to ensure a systematic, transparent, and comparative assessment of CDW management models across seven European and neighbouring countries. Fourteen case studies were selected on the criterion that each must represent an operational, documented CDW sorting or processing activity, including facilities in Latvia, Estonia, Slovenia, Cyprus, Greece, Turkey, and six Romanian cases covering demolition-based recovery, cement co-processing, closed-loop material systems, and manufacturing reuse strategies. Scientific publications were used to interpret technological performance and situate findings in broader circular economy research.

A structured analytical framework of five interconnected dimensions was applied: (1) collection and logistics organization; (2) sorting and processing technologies; (3) circular economy contribution and material loop integration; (4) measurable performance indicators such as recovery rates, diversion rates, and CO_2-related impacts; and (5) enabling conditions and constraints, including regulatory environments, market factors, and public-sector support. Cases were coded according to this structure and categorized into five CDW management model groups: centralized high-automation hubs, on-site demolition processing systems, industrial closed-loop or co-processing systems, public-led circular construction hubs, and digital-enabled or technology-driven circularity systems.

This approach enabled synthesis of heterogeneous case information into a cohesive comparative assessment evaluating both how CDW is managed and what impacts these models produce under real operational conditions. The comparison is constrained by differing reporting formats and indicator availability. Indicators such as diversion rates were not normalized but reported as provided by each source; cross-case comparisons should therefore be read as indicative rather than strictly equivalent.

3 Results

The fourteen case studies examined in this research represent a wide spectrum of operational approaches to CDW management. The CDW case studies show substantial variation in logistics, technological maturity, and integration with industrial processes. Centralized high-automation hubs, including CleanR Verso in Latvia and Green Marine AS in Estonia, report diversion rates above 70% and produce multiple certified fractions, though their effectiveness depends heavily on stable waste inflows and functioning market demand. In contrast, on-site demolition systems such as BS Recycling in Romania reduce transport-related emissions and enable immediate reuse of aggregates, albeit with fewer and less refined material fractions. Closed-loop industrial systems, for example, gypsum recycling by Saint-Gobain or ceramic reuse by Wienerberger, achieve high material purity and predictable output quality by reintegrating CDW into established manufacturing processes. Public-led circular hubs, such as Nigrad in Slovenia, demonstrate how municipalities can use CDW to support territorial regeneration and localized reuse loops. Digital-enabled models, including blockchain-based concrete monitoring and CO_2-reactive aggregate upgrading, illustrate innovative mechanisms for waste prevention and quality improvement, though they remain in early implementation stages.

Collectively, the results show that CDW performance outcomes arise from interactions among logistics, technological capacity, market structure, and regulatory conditions.

By grouping the cases according to shared operational principles, the analysis provides a clearer understanding of how different models contribute to Europe's circular construction transition and how each model's strengths and constraints shape its performance. The aim is not to reduce the complexity of each case but to make visible the structural relationships between organizational form, technological infrastructure, and circularity outcomes.

Table 1. Summary of CDW management model types and representative cases.

Model type	Representative cases	Key operational characteristics
Centralized high-automation hubs	CleanR Verso (Latvia); RRC Fasoula (Cyprus); Green Marine AS (Estonia); Romania Mixed Facility A; Romania Mixed Facility B; Romania Mixed Facility C	Large-scale mixed CDW reception; automated mechanical and sensor-based sorting; high throughput capacity; stable secondary material outputs.
On-site demolition processing systems	BS Recycling (Romania)	Mobile crushing and separation equipment brought to demolition sites; reduced transportation needs; immediate reuse of aggregates in infrastructure projects.
Industrial closed-loop / co-processing systems	Geocycle (Romania); CRH (Romania); Wienerberger; Saint-Gobain Rigips (Romania)	Integration of CDW into cement kilns or manufacturing lines; processing of non-recyclable fractions as alternative fuels or feedstock; mono-material recycling loops (gypsum, clay products).
Public-led circular construction hubs	Nigrad / Maribor CE Hub (Slovenia)	Municipal reuse and recycling operations; reclaimed materials used in local building, road, and embankment projects; community access to secondary raw materials markets.
Digital-enabled and technology-driven systems	SKYRODEMA (Greece); CO_2-reactive aggregates (Turkey)	Blockchain-enabled traceability, fresh concrete waste prevention, accelerated carbonation, and material upgrading technologies.

Table 1 ssummarizes the five model types identified in the comparative analysis and highlights the operational logic that differentiates them. Centralized high-automation

facilities possess strong material-sorting capabilities and deliver high-quality recycled outputs but depend heavily on consistent waste inflows and supportive market conditions. On-site demolition systems function effectively in large-scale demolition projects and significantly reduce the environmental burden associated with material transportation. Industrial closed-loop systems are highly efficient for specific material flows, such as gypsum or brick residues, though they are constrained by their reliance on uniform waste types and internal industrial demand. Public-led hubs demonstrate how municipal actors can use CDW management to revitalize degraded areas, develop local reuse markets, and support community-level circularity. Finally, digital-enabled models offer novel approaches to waste prevention and quality enhancement, although most remain at early stages of practical adoption. Taken together, these models illustrate the diversity of pathways available for improving CDW management in Europe. They also demonstrate that circularity can be achieved through different forms of governance, technology, and business models, depending on local conditions, material streams, and institutional capacity.

The case studies reveal that performance differences among CDW systems arise primarily from how waste is collected, transported, and sorted, and from the technological maturity of processing infrastructures. Centralized high-automation hubs such as CleanR Verso in Latvia and Green Marine AS in Estonia rely on structured logistics that consolidate mixed waste flows into large-scale sorting facilities, where automated optical sensors, magnetic separators, and multi-stage mechanical systems enable diversion rates above 70% and the production of multiple certified fractions. In contrast, mobile on-site processing, represented by BS Recycling in Romania, integrates demolition logistics with material recovery at the source, minimizing transport emissions and enabling rapid reuse of aggregates in nearby infrastructure projects. Cyprus applies a hybrid model where partial on-site sorting is supported by centralized mechanical and manual separation, illustrating how mixed systems evolve in regions with fragmented markets and developing regulatory frameworks.

Differences in sorting technologies strongly influence circularity outcomes. High-automation lines in Latvia and Estonia demonstrate superior precision and throughput, whereas material-specific loops, such as Saint-Gobain's gypsum recovery and Wienerberger's ceramic reuse, achieve high purity and full reintegration of CDW into industrial manufacturing cycles. Co-processing facilities in Romania and Turkey extend circularity into cement production by converting CDW into alternative fuels or clinker substitutes, with the Turkish carbonation process additionally reportedly capturing up to 250 kg CO_2 per tonne of aggregate processed. Digital technologies introduce new forms of circularity: Greece's blockchain-based system prevents fresh concrete waste by tracking its age and redirecting surplus material before hardening, reportedly achieving nearly full recovery of aggregates.

Circular economy contributions differ across contexts. Municipal reuse hubs such as Nigrad in Slovenia demonstrate high levels of local material recirculation, in some reported applications reaching 100% reuse for specific fractions, by integrating CDW into public works and urban regeneration projects. Industrial closed-loops generate high-value products such as plasterboards and bricks, while centralized hubs predominantly supply recycled aggregates to construction markets. Environmental benefits include

reduced emissions from avoided virgin extraction and transport optimization, particularly in Slovenia and Turkey, where material loops operate within short geographic radii. Social and economic impacts vary: job creation is evident in Latvia, Estonia, and Slovenia, while Cyprus demonstrates that even well-designed systems face severe limitations when market demand for recycled materials is low. These findings collectively show that system performance depends on the alignment of logistics, technology maturity, market structure, and regulatory clarity. This relationship is synthesized in Table 2.

Table 2. Summary of CDW model outcomes across case studies.

Model type	Observed outcomes
Centralized high-automation hubs	High diversion rates (70–80%+); multiple sorted fractions; strong output quality; dependence on market demand and steady inflows.
On-site demolition processing systems	Reduced transport emissions; immediate reuse; fewer output fractions; variable purity depending on demolition conditions.
Industrial closed-loop / co-processing systems	Stable integration into industrial processes; substantial substitution of virgin fuels and materials; high predictability; limited to specific waste streams.
Public-led circular construction hubs	Localized reuse; territorial regeneration; community access to materials; strong circularity for specific fractions.
Digital-enabled and technology-driven systems	Waste prevention; improved traceability; enhanced material properties; early-stage scalability but high innovation potential.

The comparative patterns summarized in Table 2 indicate that no single model dominates across all dimensions of circularity. Instead, performance depends on the interplay between technological capability, proximity-based logistics, regulatory support, and market readiness. Centralized hubs excel at material purity, on-site systems minimize emissions, closed-loops create stable industrial demand, public hubs localize circularity, and digital models prevent waste formation altogether. Together, these models highlight complementary pathways toward a more resilient and higher-value circular CDW system.

4 Discussion

The findings indicate that technological capacity alone does not determine CDW circularity; effectiveness depends on the alignment of sorting technologies, market readiness, and clear regulatory requirements. High-performance automated sorting systems support previous that sensor-based separation can significantly improve material recovery

quality [4, 12]. However, their impact remains constrained where demand for secondary materials is weak, as illustrated by the Cyprus and Romanian cases. Public-led reuse models, exemplified by Nigrad in Slovenia, show how local governance and municipal strategies can strengthen circular loops, while fragmented regulatory enforcement in Romania and the absence of end-of-waste criteria in Cyprus reflect structural barriers identified in previous research [7, 10]. Emerging digital innovations, such as blockchain traceability and CO_2-reactive aggregate upgrading, also appear promising for waste prevention, real-time quality verification, and lifecycle tracking, although their large-scale deployment remains limited. It should also be noted that scaling digital-enabled systems such as blockchain traceability to less digitally mature markets may face significant barriers, including high implementation costs, limited digital infrastructure, and low digital literacy among construction sector actors. Phased deployment models and targeted public investment would likely be required to extend such innovations beyond well-resourced pilot contexts across European regions. Overall, the comparison suggests that resilient CDW systems require not only technological advancement but also coherent policy frameworks, functioning end-markets, stakeholder awareness, and proximity-based reuse loops. The persistence of cultural and social barriers, particularly about the safety of recycled aggregates, further underscores the need for targeted education, certification systems, and market-building measures.

This study has several limitations. The cases are heterogeneous in scale, maturity, reporting depth, and regulatory context, which limits direct standardization of performance indicators across all models. In addition, some cases are reported through project or case-specific documentation rather than uniform datasets, meaning that the comparison should be interpreted as an analytically structured cross-case assessment rather than a statistically harmonized benchmark. Future research could strengthen the evidence base by applying common circularity indicators and longitudinal monitoring across a larger number of cases.

5 Conclusions

This comparative case study demonstrates that European CDW management systems are diverse, evolving, and increasingly oriented toward circularity. Centralized hubs excel in producing high-quality secondary materials, on-site demolition systems reduce transport-related impacts, industrial closed-loop processes secure stable material inputs for manufacturing, public-led hubs stimulate territorial circularity, and digital innovations enhance traceability, quality, and waste prevention.

Despite these advancements, persistent challenges remain. Market acceptance of secondary materials is inconsistent, regulatory frameworks are fragmented, and cultural reservations about recycled products undermine adoption. Technological readiness also varies widely across regions, and end-of-waste criteria remain unclear in several national contexts. For circular construction to become standard practice, policy and industry action should prioritize at least four areas: harmonized end-of-waste criteria, stronger quality certification and traceability systems, public procurement requirements for recycled materials, and targeted investment in selective demolition and advanced sorting infrastructure. Of these, harmonized end-of-waste criteria represent the most

foundational priority for regions currently showing regulatory inconsistencies – such as Romania and Cyprus – as the absence of clear end-of-waste status undermines market confidence in secondary materials and limits the effectiveness of the three remaining measures. Quality certification, public procurement, and sorting investment can only deliver systemic impact once a stable and consistent regulatory baseline is in place

No single model offers a universal solution. However, the comparative evidence shows that the strongest circularity outcomes emerge where technological capacity, stable-end markets, supportive regulation, industrial collaboration, and traceability mechanisms are aligned within locally appropriate reuse and recycling systems.

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