

Lecture Notes in Civil Engineering

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Christina Giarma · Ricardo Mateus ·
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ReShaping the Built Environment through Sustainability and Circularity

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Assessment of the Ecological Footprint of Construction and Demolition Waste in Residential Buildings

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Abstract. This research analyzes the feasibility of obtaining a real Construction and Demolition Waste (CDW) footprint by quantifying and analyzing waste generated in two residential developments. The aim is for the CDW footprint obtained during construction to serve as a reference for similar future projects, enabling more accurate waste management estimates. The methodology combines theoretical estimation and quantitative measurement of construction waste, comparing planned estimates with actual on-site data.

Calculating the CDW footprint revealed significant discrepancies between EGR and PGR estimates and actual waste: up to 18% and 27% less, respectively, for non-hazardous waste, and 400–900 times more than actual for hazardous waste. For Level I CDW, primarily generated during excavation, the footprint ranged from 3.83 m³/m² B/R for one basement to 4.60 m³/m² B/R for two basements. For Level II CDW, the footprint depended on the construction system: 0.50 m³/m² S/R for traditional construction and 0.30 m³/m² S/R for prefabricated or industrialized elements. Hazardous CDW was quantified in mass due to a lack of volumetric data, showing lower values in industrialized constructions (0.000046 t/m² S/R) than in traditional ones (0.000075 t/m² S/R).

These findings support compliance with current regulations and provide data-driven benchmarks that promote waste minimization and eco-efficient construction practices.

Keywords: Ecological footprint · building · recycling · sustainable construction · construction and demolition waste

1 Introduction

The implementation of new regulations and revisions of existing frameworks have advanced European targets for waste management, industrial sustainability, and the transition to a circular economy [1–9]. Reliable, real-world data remain essential to assess the effectiveness of these measures and to monitor progress [10–16].

Construction and demolition waste (CDW) requires proper traceability to prevent malpractice and verify circular economy practices, including reuse, recycling, and recovery, as mandated by legislation [17]. CDW represents the largest waste stream in the European Union, comprising approximately one-third of total waste generation [1].

The CDW footprint provides detailed information on waste generation and management, enabling strategies to reduce waste in the design phase, improve recycling and recovery during construction, and promote reuse, especially in demolition. It also contributes to reducing the ecological footprint, a measure of human impact on the environment [18].

Spain has recently updated its regulatory framework with Ley 7/2022, replacing Ley 22/2011 and repealing Orden MAM/304/2002. This law transposes European Directives (EU) 2018/851 and (EU) 2019/904 [2–6]. The law prioritizes waste prevention, reduces landfill disposal, ensures proper management of hazardous and non-hazardous waste, and assigns responsibilities to regional authorities for authorization, inspection, and data management. Digital tools are essential to ensure traceability and interoperability across administrative levels.

Despite regulatory advances and the proliferation of initiatives, significant uncertainties remain regarding the estimation of actual CDW generation, as well as the influence of building typology and the degree of industrialization on these rates. Recent studies highlight the need to validate and refine existing calculation methods through systematic comparisons with experimental on-site data.

In this context, the present study examines the accuracy of current CDW estimation methods used in Waste Management Studies (EGR) and Waste Management Plans (PGR), by comparing theoretical estimates with in situ experimental measurements and analysing the role of construction typology and industrialization level in waste generation.

2 Methodology

Conventional CDW estimation methods are generally based on standardized datasets, often producing generic values that may not reflect real on-site waste generation. Historically, regional construction practices played a major role in shaping waste outputs; in contemporary contexts, building typology and degree of industrialization have emerged as primary determining factors.

To address these limitations, a two-stage methodological framework was implemented, combining theoretical estimation with experimental validation. In the first stage, CDW generation was estimated using the indicators and coefficients defined in the corresponding Waste Management Studies (EGR) and Waste Management Plans (PGR). These documents provided project-level forecasts disaggregated by waste category and referenced surface area or built volume.

In the second stage, experimental data were collected directly on site. Waste was segregated by fraction, classified according to the applicable European waste codes, and weighed using calibrated equipment. The total CDW mass was subsequently normalized by constructed floor area to obtain standardized generation rates (e.g., $\text{t}\cdot\text{m}^{-2}$), enabling comparison with theoretical values.

The empirical study was conducted on two residential construction projects with comparable characteristics in terms of size, location, and regulatory context but differing in construction system and industrialization level. This design allows isolating the effect of construction typology and industrialization on CDW generation while ensuring that external boundary conditions remain as similar as possible. A comparative analysis was then carried out to assess deviations between theoretical and measured values and to identify systematic biases in current estimation practices.

2.1 Theoretical Estimation

The EEH-AURREZTEN tool developed by Ihobe was used and specifically adapted to comply with the regional regulatory requirements set out in Orden 2726/2009. This tool enables the standardized estimation and characterization of construction and demolition waste (CDW) at project level. In this study, it was applied to both the Waste Management Studies (EGR) and the Waste Management Plans (PGR) associated with the selected residential projects.

Using adapted EEH-AURREZTEN tool, the estimates reported in the EGR and PGR were systematically assessed for several key parameters: total waste generation (in terms of both mass and volume), material densities, waste classification by fraction and hazard level, proposed management and treatment routes (reuse, recycling, recovery, or disposal), and the associated management costs. In addition, the influence of these estimates on the overall construction budget (Construction Cost Estimate, PEM) was examined, in order to quantify the economic relevance of CDW management within the project's financial framework.

2.2 Experimental Data Collection

An experimental approach was implemented based on the systematic collection of on-site data throughout the entire construction process, from initial earthworks to completion. This continuous monitoring enabled a detailed and temporally resolved characterization of construction and demolition waste (CDW) generation at project level (Fig. 1).

The primary sources of information were:

- waste dispatch records, documenting each removal event, the type of container used, declared waste type, and estimated or measured volume;
- certificates issued by authorized treatment facilities, specifying the mass of waste received, the corresponding European Waste Catalogue (EWC/LER) codes, and the final treatment option;
- construction progress certifications, which provided a reliable record of executed work, allowing the allocation of waste flows to specific construction stages and work packages.

These datasets were cross-checked and harmonized to obtain consistent, project-wide waste balances. The combination of volumetric information from dispatch records and gravimetric data from facility certificates enabled the quantification of actual CDW in both mass and volume, and the derivation of effective material density coefficients for each waste fraction. All recorded flows were classified according to EWC/LER codes, and assigned to specific management routes (on-site reuse, off-site recycling, recovery, or landfill disposal).

Finally, unit costs reported in the treatment certificates and transport invoices were used to calculate the economic costs associated with each waste stream. These were then aggregated and related to the construction budget (PEM), allowing assessment of the budgetary impact of CDW management and comparison with the cost assumptions made in the project's waste management planning documents.



Fig. 1. Vallecas Construction Site (VA001). From left to right: Construction and Demolition Waste (CDW) plasterboard; Non-hazardous mix Level II CDW. Non-stony nature; Hazardous CDW.

2.3 Data Analysis and Comparison

Experimental results were systematically compared with estimates derived from EGR and PGR methods, as well as across the project sample, to evaluate the role of construction typology in CDW generation. The comparison exposed noteworthy divergences and underscored structural limitations of current estimation techniques.

3 Results and Discussion

The calculation of the construction and demolition waste (CDW) footprint provided quantitative evidence of substantial discrepancies between theoretical estimations and observed on-site waste generation at project level (Table 1). These deviations were detected for both non-hazardous and hazardous waste streams, revealing structural limitations in current estimation practices embedded in regulatory planning instruments.

For non-hazardous CDW, the comparison between design-stage documents and measured data showed that the Waste Management Study (EGR) systematically underestimates the total amount of waste generated by approximately 18%. The deviation is even larger for the Waste Management Plan (PGR), which underestimates non-hazardous CDW by up to 27%. Given that both EGR and PGR are mandatory, standardized tools

in the current regulatory framework, these results indicate that they do not adequately reflect real on-site conditions and may lead to insufficient dimensioning of downstream management infrastructure and budgets.

In contrast, for hazardous CDW, the mismatch presents an opposite pattern. Here, the theoretical estimations included in EGR and PGR grossly overestimate the quantities actually generated. Estimated hazardous waste quantities exceed measured values by factors of approximately 400 (EGR) and 900 (PGR), respectively. This overestimation suggests an overly conservative or poorly calibrated approach to hazardous waste forecasting, with potential implications for cost allocation, contracting of specialized treatment services, and the interpretation of compliance with legal thresholds. Together, these findings underscore the need to revise and recalibrate current CDW estimation methodologies to improve their accuracy and reliability.

Table 1. Total CDW estimates versus actual CDW generation.

	EGR	PGR
Non-hazardous CDW	−18% vs. actual	−27% vs. actual
Hazardous CDW	400× actual	900× actual

This systematic overestimation suggests a conservative approach in project documentation, likely driven by regulatory compliance requirements, but it also evidences a lack of precision in forecasting hazardous waste streams.

With respect to Level I waste (uncontaminated soil and inert materials), the CDW footprint is strongly influenced by building configuration, particularly the number of underground levels. The results indicate specific generation rates of 3.83 m³/m² of below-ground built area for buildings with one basement and 4.60 m³/m² for those with two basements. These findings confirm that excavation volume is the primary driver of Level I waste generation, rather than the construction methodology employed (Table 2).

Table 2. Level I waste footprint.

	CDW Footprint Level I (m ³ /m ² B/R)
One basement	3.83
Two basements	4.60

In contrast, Level II waste (including both inert and non-inert fractions) exhibits a clear dependence on construction typology. In buildings executed using conventional construction techniques, the CDW footprint attains 0.50 m³/m² of above-ground built area, whereas this value decreases markedly to 0.30 m³/m² in projects that incorporate prefabricated or industrialized systems (Table 3). This reduction provides quantitative evidence of the effectiveness of construction industrialization strategies in reducing waste generation during the execution phase.

Table 3. Level II waste footprint.

	CDW Footprint Level II non-hazardous (m^3/m^2 S/R)
Traditional	0.50
Industrialized	0.30

A comparable pattern is observed for hazardous Level II waste, although with much lower absolute values. Owing to the absence of reliable volumetric data, these waste streams were quantified exclusively in mass terms. The results indicate a hazardous Level II CDW footprint of 0.000075 t/m^2 for buildings constructed using traditional methods and 0.000046 t/m^2 for projects employing industrialized construction systems (Table 4). Although their contribution to total waste generation is relatively minor, the reduction associated with industrialized processes is consistent with the trends identified for non-hazardous waste, thereby reinforcing the positive influence of construction industrialization on overall waste minimization.

Table 4. Hazardous Level II CDW (mass).

	CDW Footprint Level II hazardous (t/m^2 S/R)
Traditional	0.000075
Industrialized	0.000046

The observed differences are also evident in the economic assessment of CDW management. The results indicate that a higher degree of industrialization leads to a substantial reduction in waste management costs, particularly for Level II inert and hazardous fractions. In the case studies analyzed, savings of approximately €35,700 were recorded for Level II inert waste and €850 for hazardous waste, corresponding to an overall cost reduction of around 20% in the more industrialized project. By contrast, the costs associated with Level I waste and non-inert Level II waste were not significantly affected by construction typology but were instead primarily governed by the volume of excavation.

Overall, the results show that current estimation tools (EGR and PGR) exhibit notable limitations in accurately predicting CDW generation, especially for hazardous waste. Moreover, the findings confirm that construction typology and the degree of industrialization are key determinants of both waste generation and management costs. These insights highlight the need to integrate real on-site data into estimation models and support the adoption of industrialized construction systems as an effective strategy to reduce both environmental impacts and economic costs (Table 5).

These results confirm that the current estimation tools (EGR and PGR) present notable limitations, particularly in the case of hazardous waste. The findings indicate that construction typology and the degree of industrialization are key determinants of both waste generation and associated management costs. Specifically, industrialized

Table 5. Economic assessment.

	Economic savings on total CDW management
Traditional	0%
Industrialized	20%

construction methods substantially reduce material waste, enhance the efficiency of recycling processes, and yield significant economic savings. Overall, these outcomes support the implementation of industrialized systems as an effective strategy to advance circular economy objectives in the construction sector.

4 Conclusions

This study provides a comprehensive assessment of construction and demolition waste (CDW) management within the current regulatory framework. Recent regulations are broadly aligned with European waste management targets; however, their implementation is still at an early stage and will require long-term, region-specific strategies to become fully effective. The findings highlight that digitalization is essential to ensure traceability and operational efficiency across the CDW value chain, and that strict compliance with Law 7/2022 (Spanish Law) is particularly critical for both transporters and waste managers.

Pre-construction review of the Waste Management Study (EGR) and Waste Management Plan (PGR) contributes to more accurate planning and improved stakeholder compliance, while training and awareness-raising activities are shown to enhance appropriate on-site waste management practices. During the construction phase, systematic verification of documentation helps maintain traceability, although a tendency to simplify European Waste Catalogue (EWC/LER) codes is observed in practice. In terms of waste streams, Level I waste (primarily uncontaminated soil and inert materials) predominates in the early project stages, whereas Level II waste increases significantly during the masonry phase. Circular economy practices, such as the reuse of excavated soil, are only partially implemented. Hazardous waste generation is substantially lower than initially estimated, and recycling routes prevail over final disposal.

The results confirm that industrialized construction systems reduce both total waste generation and associated CDW management costs by up to 20%. Overall, progress towards a circular economy in the construction sector depends on the combined effect of regulatory compliance, digitalization, active stakeholder engagement, and the adoption of industrialized processes. Under these conditions, the construction sector can play a decisive role in achieving broader environmental and sustainability objectives.

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