Special issue – The circular economy as a lever for decarbonization

Circular economy and decarbonization in construction: Evidence from life cycle costing in Italy

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Abstract

Purpose. The purpose of this work is to answer whether selective demolition is economically viable, as well as to highlight the limitations of the construction and demolition (C&D) waste management chain in Italy and make recommendations to overcome them.
Methods. An environmental Life Cycle Costing analysis is conducted to assess the costs of selective demolition and manufacturing recycled aggregates in the Lombardy Region (Northern Italy). The investigated system encompasses all management phases of inert waste originating from demolition activities, from its generation at the building end-of-life to the treatment phase in a recycling plant, till the market replacement as recycled aggregate.
Results and discussion. The economic inventory relating to 7 case studies shows that the average cost for demolition and C&D waste management is € 7.04 per m^3 of a demolished building. When a considerable proportion of metal waste stream is sold, this cost is minimised.
Conclusion. Following the results, it is possible to identify the criticalities of the C&D waste management chain and how to overcome them to close the loop in the construction sector. Future research should focus on expanding the market for high-quality recycled aggregates by encouraging their sale and usage in new buildings.

Keywords: Life Cycle Costing (LCC), selective demolition, construction and demolition waste, recycled aggregates, economic impact.

JEL classification: D15, L52, M11

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1. Introduction

Construction and demolition (C&D) waste represent 45.5% of the total production of special waste in Italy, according to the most recent ISPRA report (2021). Although the recovery rate is 78.1% (ISPRA, 2021), various regulatory, economic, technical, and cultural barriers (Cutaia et al., 2022) prevent the widespread use of recycled aggregates (RAs) produced by C&D waste recycling activities. Backfilling and excavated soil are not included in this proportion, which only refers to the preparation for reuse, recycling, and other types of material recovery (ISPRA, 2021). The intended usage of RAs might vary depending on their quality and performance characteristics. The Ministry of the Environment's Circular 15/07/2005 No. 5205 indicates the most appropriate uses for RAs according to specific properties. Therefore, respecting the characteristics described by the standard, embankments, road foundations, environmental restorations, fillers and bridges, additional layers with antifreeze, capillary, draining function, and finally concretes with resistance class Rck <15 Mpa, may consist of RAs. Among the limitations, market acceptance of products made using secondary resources as input material will only be ensured when production costs are lower than virgin materials (Cutaia et al., 2022). Nevertheless, even more critical, the presence of impurities in the RAs and the difficulty in guaranteeing their consistent production (Borghi et al., 2018; ICESP, 2020) preclude their use in structural concrete (Dhir et al., 2019). To produce high-quality RAs, the waste entering the recycling plant must be as homogeneous as possible. This requires that the materials be carefully sorted throughout the structure's demolition phase, a practice currently uncommon in Italy (Cárcel-Carrasco et al., 2021; Pantini & Rigamonti, 2020). For this reason, selective demolition should be encouraged along with expanding the market for RAs, which are currently not economically competitive with natural aggregates. In this context, Life Cycle Thinking methodologies (Life Cycle Assessment (LCA), Environmental Life Cycle Costing (eLCC), and Social Life Cycle Assessment (sLCA)) (Toniolo et al., 2020) can be valuable tools for investigating the economic, environmental, and social aspects of a product or process throughout its life (Jacob-Lopes et al., 2021). Recent studies highlight that circular economy strategies not only reduce waste and resource extraction but also represent an effective pathway towards decarbonization, with potential reductions of up to 39% of global emissions through material efficiency (Circle Economy, 2023). In this sense, the construction sector, as one of the largest consumers of energy-intensive materials, is crucial for aligning circular practices with climate neutrality targets (Pauliuk et al., 2021). In particular, The eLCC is currently seen as a "driver" for construction improvement (Manewa et al., 2021) since it allows better financial decisions to be made by taking into account all the relevant costs of an asset (Kelly and Hunter, 2009; Martinez-Sanchez et al., 2015).

2. eLCC overview and previous studies

Rebitzer et al. (2003) are among the first to define the eLCC as the evaluation of all costs associated with a product life cycle directly borne by more cycle stakeholders (e.g., supplier, manufacturer, user/consumer). The literature, however, shows that its application to building end-of-life is seemingly very limited, probably due to a lack of data access and reliability, standards and guidance documents, and unawareness among construction operators (Manewa et al., 2021). Indeed, the eLCC methodology, unlike the LCA, lacks regulation, expertise, and direction and is now only acknowledged (but not deeply described) in some current standards, like ISO 15663:2021, ISO 15686-5:2017, ISO 15643-4 and IEC 60300-3-3. To develop a general agreement for an international standard that parallels the ISO 14040 standard for LCA, the Society of Environmental Toxicology and Chemistry (SETAC) published, in 2011, a code of practice for eLCC (Swarr et al., 2011), which provides a framework for evaluating decisions with consistent, but flexible system boundaries as part of product sustainability assessment. To encourage further case studies and peer-reviewed research, the code of practice aims to provide readers with a firm knowledge of implementing eLCC in conjunction with LCA. The code offers recommendations that expand on the ISO 14040 standards' four-phase framework to make it easier to define and apply uniform system boundaries for LCC and LCA studies that complement one another on a particular product's system. As another example of methodology conjunction, Hoogmartens et al. (2014), in their research, describe the full environmental LCC (feLCC), which extends eLCC by incorporating monetised, non-internalised environmental costs that may be discovered using environmental assessment approaches such as LCA, to demonstrate explicitly that eLCC is not an equivalent of LCA or cost-benefit analysis. There are various examples in the literature of LCA and LCC being used together to thoroughly examine the environmental and financial sustainability of the C&D waste management chain. However, the two techniques have never been paired with the monetisation of environmental impacts, as the feLCC implies. Some analysed studies consider environmental and economic factors, while others examine only one. Hu et al. (2017), for example, employ LCC and LCA in a case study in the Netherlands for demolition, recycling, and new construction to identify the environmental and financial hotspots in selective demolition and waste management in the Dutch context. The findings indicate that integrating new construction with demolition projects to maximise reuse potentials, particularly metals, is essential for improving demolition's environmental and economic profiles and related material treatment. This best practice can save life cycle costs by 23%. The metal fraction is a key parameter since it has the highest economic value (despite representing 6% of total recovered material by weight). The use of RAs in new construction is environmentally favourable owing to the avoidance of raw material extraction and the reduction of aggregate supply transportation. The research by Mah et al. (2018) examines the quantity of concrete waste created throughout the construction and demolition stages of some structures in Malaysia, as well as the incorrect management of it, which frequently has a significant environmental effect. The primary goal of this research is to discover the most environmentally friendly scenario for concrete waste handling. The LCA modelling is used to assess the environmental impact and GHG (Greenhouse gases) emissions, whereas the LCC is used as an extension of LCA in terms of economic dimension. According to the findings, recycling concrete waste to replace natural aggregates in concrete production has the best eco-efficiency (reduced environmental and cost implications), whereas landfilling has the lowest. This analysis also shows that transportation distances and mining activities are the two most significant factors of GHG emissions and cost impact. To optimise environmental and financial savings, they suggest that mobile material recovery facilities should be built as close to the waste producer and recycled material demand point as feasible to offset the distance between the building site and the landfill. Furthermore, Di Maria et al. (2018) show that combining LCA and LCC data can highlight the environmental and economic drivers in C&D waste management in the Region of Flanders in Belgium. The integrated research findings can assist policymakers in promoting all the options contributing to sustainability and limiting those that create barriers. The results suggest that increasing high-quality C&D waste recycling can greatly lower the system's total environmental effect. A similar approach is used in Dahlbo et al. (2015) work, where the Finnish C&D waste management is evaluated holistically using LCA, LCC, and other methods. The findings show that the metal treatment performed well in all the assessments; thus, improving it would not significantly impact the system. Mixed C&D waste is the worst fraction regarding climate change impacts, prices, and material recycling. Other economic assessment approaches are employed in addition to the LCC approach. For example, Coelho and de Brito (2010) conduct a "global cost" study comparing selective demolition versus conventional demolition in Portugal. According to this study, selective demolition is more expensive than conventional demolition since labour expenses are about six times higher due to the increased time required to complete the operation and the limited usage of mechanical equipment. It is suggested that landfill prices in the Lisbon Region should be raised from 90% to 1500% to make most selective demolition operations economically like conventional demolitions. Also, in the Portuguese context, Coelho and de Brito (2013) conduct a cost-benefit analysis on inert recycling operations, demonstrating that the material input gate fee is the largest share, providing around 86% of all benefits. Table 1 summarises the scientific articles described above.

Table 1 – Summary of the studies analysed

Article	**Geographic location**	**Methodologies applied**	**System Boundaries**	**Costs investigated**	**Data collection method**	**Key economic findings & numerical benchmarks (standardized in €)**
Hu et al. (2017)	Netherlands	LCA LCC	Demolition, recycling, and new construction	Internal costs	Case study analysis	Integrating new construction with demolition projects to maximise reuse potentials, particularly metals, can reduce total life cycle costs by **23%**. Additionally, the implementation of traceability reduces management costs by **50%** through better waste sorting and lower treatment fees
Mah et al. (2018)	Malaysia	LCA LCC	Demolition, recycling, and new construction	Internal costs	Case study analysis, direct interviews	Recycling concrete waste to replace natural aggregates archieves the highest eco-efficiency (reduced environmental and cost implications), while landfilling has the lowest. Specifically, on-site mobile recycling (**3.35 €/t**) leads to a **68.1% cost reduction** compared to tratidional landfill disposal (**10.50 €/t**) by eliminating transport logistics.
Di Maria et al. (2018)	Belgium	LCA LCC	C&D waste end-of-life: Landfilling and Recycling	Internal costs	Sectorial reports, literature reviews and direct interviews	Increasing high-quality C&D waste recycling can significantly lower the system's total environmental effect.From an economic perspective, high landfill taxes in Flanders (**55 €/t**) act as the primary driver for recycling, making it more competitive than disposal despite high labor costs of **39.20 €/h**.
Dahlbo et al. (2015)	Finland	LCA LCC BAT (best available technology)	C&D waste end-of-life: Landfilling and Recycling	Internal costs	Analysis of market price data and general estimations	Metal treatment performs optimally across all environmental and economic assessments, where mixed waste was selected as the worst fraction in terms of climate change impacts, prices, and recycling potential. Material purity is the primary profit driver: while wood recovery involves a net cost of **~25€/t,** metal recovery generates substantial economic credits up to **450 €/t**

Article	**Geographic location**	**Methodologies applied**	**System Boundaries**	**Costs investigated**	**Data collection method**	**Key economic findings & numerical benchmarks (standardized in €)**
Coelho and de Brito (2010)	Lisbon	Global cost	Demolition	Internal costs	Case study analysis	Selective demolition is significantly more expensive (**~6x)** than conventional methods because it is **5.7 times more labor-intensive**. This is due to the increased time required for manual operations and the limited use of heavy machinery. Consequentely, selective demolition profitability relies heavily on the recovery of high-value materials, such as steel (**150 €/t**), to offset these higher personnel costs.
Coelho and de Brito (2013)	Lisbon	Cost-benefit analysis	C&D waste recycling	Internal costs	Case study analysis	Recycling plants are economically viable with a **2.1 year payback period**. The material input gate fee represents the largest share of revenue, providing around **86%** of all cost benefits. However, the system's efficiency is sensitive to disposal costs, as **79.5%** of operational expenses are linked to managing non-recyclable residuals (**7.50 €/t**).

Despite the increasing application of Life Cycle Costing (LCC) in construction and demolition contexts, existing studies exhibit considerable methodological heterogeneity and limited standardisation. Recent reviews highlight that LCC applications in this field vary widely in terms of system boundaries, cost categories included, and integration with circular economy principles, thereby limiting cross-study comparability (Vella et al., 2026; Shen et al., 2021). Although some studies integrate LCC with environmental life cycle assessment (LCA), they are often based on project-specific case studies with limited generalisability and do not systematically identify the key economic cost drivers of selective demolition practices (Cerchione et al., 2025). These limitations are further compounded by the intrinsic challenges of cost data collection: data are typically drawn from heterogeneous sources, may be business sensitive, and are often expressed using sector-specific cost models and terminology that require reconciliation within a unified inventory. In addition, cost data tend to be more volatile than physical flows, and results are strongly influenced by geographical location due to market fluctuations and regulatory differences (Islam et al., 2015; Di Maria et al., 2018; Swarr et al., 2011). Despite these challenges, a substantial share of the existing LCC literature relies on international datasets that may not adequately reflect the regulatory and economic specificities of the Italian construction sector. This study responds to these gaps by providing detailed, empirically grounded LCC data for both conventional and selective demolition, based on primary data collection and standardised cost categories with transparent assumptions, within the underrepresented Italian context. The originality of the work lies in its granular cost breakdown, which explicitly differentiates between selective and conventional demolition practices – a level of detail that is often missing in the current literature – and in the establishment of a realistic and updated economic benchmark for demolition and C&D waste management in Italy. As a first step towards a potential alignment with environmental life cycle assessment and the future application of the full environmental LCC (feLCC) framework proposed by Hoogmartens et al. (2014), the eLCC methodology is applied to multiple Italian case studies. In line with the objectives of European stakeholders aiming to promote circularity in the construction sector (ECESP, 2021), this work ultimately contributes to the development of context-specific scenarios to foster circular demolition practices from an Italian perspective, which has so far received limited attention in the academic literature.

3. The Italian context

3.1. C&D waste

C&D waste is codified in Chapter 17 of the European Waste Catalog (EWC) as "Waste from construction and demolition operations (including land reclamation)", where a related code (EWC code) is assigned to each waste flow (Eurostat 2010). Secondary raw materials (SRMs) in the form of RAs can be created by proper treatment of this specific type of waste (DGRV no. 1773/2012). SRMs offer several benefits, including greater supply security, reduced virgin material and energy usage, reduced climatic and environmental consequences, and lower production prices (European Parliament 2016). However, the quality of the RAs produced is strictly connected to the type and the homogeneity of waste generated during demolition and to the type and age of the building. As a result, it is critical to carry out a proper demolition procedure, including planning for waste sorting operations. By reducing the demand for virgin aggregates and the associated energy-intensive production processes, secondary raw materials contribute directly to lowering life-cycle carbon emissions, strengthening the nexus between resource efficiency and climate mitigation (Businge & Mazzoleni, 2023).

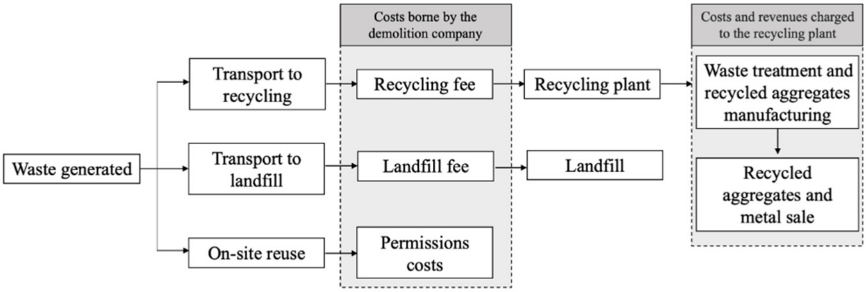
3.2. Selective demolition

At the beginning of 2020, the UNI website published the new voluntary code of practice UNI/PdR 75:2020, "Selective deconstruction - Methodology for selective deconstruction and waste recovery from a circular economy perspective". The standard defines selective demolition as "a series of sorting operations into homogeneous fractions, using machinery and equipment, with the primary goal of maximisation of reuse and recycling of the C&D waste" (UNI/PDR no.75/2020, p. 12). Conventional demolition operations should be replaced by selective disassembly and deconstruction operations aimed at obtaining mono-material fractions (e.g., concrete, bricks, cement, wood) suitable for treatment in recycling plants to get high-quality SRMs. According to UNI/PDR 75:2020, selective demolition is divided into three stages: planning, operational, and database implementation. The preliminary assessment and the executive project are part of the planning stage. The operative step includes preparing the areas on the construction site for temporary waste storage, deconstruction, and the selective demolition itself. Finally, the company must compile the documentation on the building materials database, which includes all flow-related information. The goal is to simplify the design phase in the case of an eventual new demolition, increasing the recycling and reuse rate. The presence of extraneous and dangerous substances and other materials that could reduce the recyclability of the C&D waste is checked during the preliminary assessment. The selective disassembly phase, which occurs before demolition, is designed to remove parts of the structure that can be reused immediately. A critical aspect of these activities is that all disassembled demolition materials must be put separately on the site for effective waste recovery and recycling (D.Lgs no.152/2006). Selective demolition necessitates reorganising the construction site to prepare for the dismantling and deconstruction operations aimed at obtaining homogeneous fractions and providing additional space for storing the separate scraps. Deconstruction also necessitates a significant increase in trained personnel. As a result, the cost of this type of demolition is estimated to be higher than conventional demolition techniques (Coelho and de Brito 2011; Mondini 2019). Therefore, industry operators still prefer to use conventional demolition methods.

3.3. C&D waste management chain

In Italy, sustainable C&D waste management is still in its early stages, and landfilling is the most common end-of-life destination for C&D waste (Di Maria et al. 2018) even if the situation is different in the different regions (see for example Pantini & Rigamonti 2020 for Lombardy region). Figure 1 schematises the typical path of inert waste from its generation to the destination with the costs that must be borne and to whom they compete. The C&D waste can be disposed of in a landfill, recycled, or reused on-site. In the first two cases, the demolition company must pay for transporting the waste to the appropriate treatment plant or sanitary landfill (transportation + gate fee). In the third case, however, the company is responsible for the costs of on-site waste treatment. The recycling plants bear the costs of treating the waste that enters the plants and manufacturing the SRMs, but they earn three incomes from the gate fee paid by demolition companies, the sale of the RAs and the sale of the metal fractions.

Figure 1 – Tracing scheme of waste flows and related costs to be borne



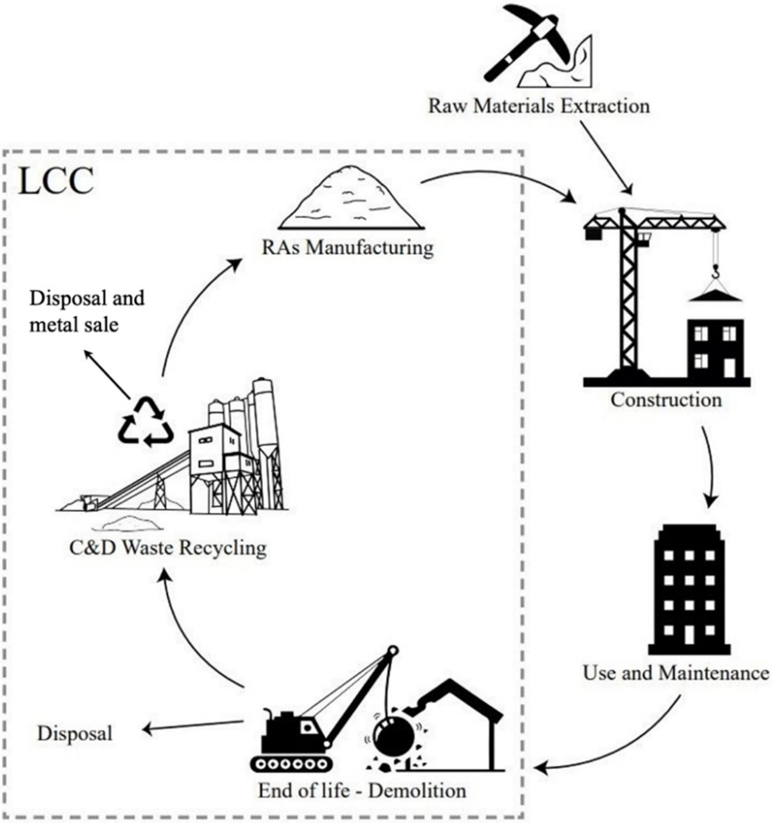
4. Material and methods

This research phase aimed to apply an eLCC, which draws on conventional LCC data, expanding it to include life cycle costs incurred by more than one actor (Hoogmartens et al., 2014), to the C&D waste management chain in Lombardy (Northern Italy). It will be described in the following paragraphs. In this case, the demolition companies and recycling plants were considered actors in the analysed system.

4.1. Goal and scope

As previously stated, this work aims to evaluate the internal costs of the C&D waste management chain in Italy. In this context, it is crucial to clarify the terminology and system boundaries used, as nomenclature in the LCC field is not yet fully homogeneous and the methodology is not highly standardized. Specifically, this study focuses exclusively on evaluating the internal costs directly borne by the actors involved int the C&D waste management chain (i.e., demolition companies and recycling plants). Consequently, external costs, such as monetized environmental or social externalities that are not internalized in current market prices, are excluded from this assessment to ensure a clear focus on the immediate economic viability for industry operators under current market conditions. To archieve this, the functional unit chosen for the system is the demolition of a cubic meter (m^3) building. The investigated system includes all management phases of inert waste originating from demolition activities, from its generation at the building end-of-life, during an ordinary or selective demolition, to the treatment phase in a recycling plant, till the market replacing as RAs (Figure 2). Any phase prior to the building's demolition is excluded. The reference year is 2019.

Figure 2 - The system boundaries represented by the hatching area



4.2. Data collection

The inventory is implemented for each process in the management chain, with the construction of two surveys, one for demolition businesses and the other for C&D recycling facilities. During the eight-month data-collecting period, 66 demolition companies and 27 recycling firms were contacted. It was feasible to obtain complete data for seven case studies on the demolition phase (with a response rate of 10.61%) and two mineral waste recycling facilities (with a response rate of 7.41%). The response rate demonstrates the high level of confidentiality of the information needed. The commercial building typology predominates among the collected demolition cases, with just one case belonging to the residential category and one to the school building type. Even though the questionnaire was sent to firms throughout Italy, all case studies were from the Lombardy region (Northern Italy). The cost per volume of demolished buildings (€/m^3) is calculated by adding the entire cost of demolition to the total cost of disposal (resulting from the questionnaires for demolition companies) and recycling (resulting from the questionnaires for recycling plants).

4.2.1 Setting up the questionnaire for demolition companies

The demolition case study survey is split into five macro-sections, including the general information and all the preliminary costs, machinery acquisition costs, operative costs, disposal, and recycling costs. Specific local taxes and potential financial incentives were excluded from the inventory to ensure the results reflect the intrinsic operational costs of the processes, making the findings more generalizable. Furthermore, overhead costs (e.g. administrative management, marketing, and office utilities) were omitted as they are highly dependant on the specific organizational structure and size of individual companies rather than the technical characteristics of the demolition method itself. By focusing on direct operational costs, the study provides a more standardized and transparent benchmark for comparing selective and conventional demolition techniques.

The questionnaire sections are detailed below, and Table 2 illustrates the survey structure with all the needed data.

Section 1: General information

The first section contains general information such as the demolition company name, the typology of demolished structure, the volume empty to full [m^3], the technique of demolition carried out, and the demolition duration [h].

Section 2: Preliminary costs

Depending on the type of building, the preparatory phase can be more or less expensive. In any case, the companies must bear the costs of the demolition project [€], the planning and preparation [€], the eventual reclamation of the building [€], the safety charges [€], and the cost of the environmental due diligence [€], which is the process of assessing the property for any potential risk of environmental contamination (Polidoro 2020).

Section 3: Machinery acquisition costs

The expected lifespan [h], purchase price [€], and hours of use [h] (referred to a specific demolition) is required for each piece of machinery used during the demolition activity. The total cost of the equipment, referred to as the single intervention, was determined by multiplying the hourly cost (purchase cost/lifespan) by the number of hours of usage during the demolition.

Section 4: Operative costs

This section includes the machinery maintenance costs [€/y], the annual salary for personnel [€/y], the insurance costs [€], as well as the use of electricity, fuel, and water with matching billing prices [€]. The reported annual costs were divided by the average number of working hours per year (2024 h) to convert machine maintenance and personnel wages to euros.

Section 5: Disposal and Recycling costs

The final section of the survey is separated into destination tabs based on whether the generated flow is directed to a landfill, for disposal with energy recovery, for recycling, reused on-site (after adequate treatment with crusher and mobile screen), or third-party managed. Each module requires the type of waste (using the EWC code) and the relative quantity, as well as the gate fee [€/t] and the relative transport costs [€/t].

Table 2 – Demolition company survey: Data required (the self-calculated values are in italics)

Section	**Data requested**	**Detailed requests and calculations**	**Unit**
1. General Information	Company name		
	Building typology	o Commercial o Residential o Services	
	Volume (empty to full)		m^3
	Type of demolition executed	o Selective o Conventional o Total o Partial	
	Demolition time		hours
2. Preliminary costs	Demolition project		€
	Setting of the demolition site		€
	Building reclamation		€
	Security wages		€
	Environmental due diligence		€
3. Machinery Acquisition costs	Typology	o Excavator o Tower crane etc.	
	Expected lifespan		years
	Acquisition cost o *Hourly cost*	*acquisition cost/lifespan*	€ €/hour
	Usage time		hours
	Total intervention cost	*hourly cost x usage time*	€
4. Operative costs	Machine maintenance o *Hourly cost* o *Total*	*annual cost / 2024* *hourly cost x demolition time*	€/year €/h €
	Personnel wages o *Hourly cost* o *Total*	*annual cost / 2024* *hourly cost x demolition time*	€/year €/h €
	Insurance		€
	Consumption	Energy o Bill cost o *Total*	kWh €/kWh €
		Fuel o Bill cost o *Total*	Litres €/litre €
		Water o Bill cost o *Total*	Litres €/litre €
5. Disposal and Recycling costs	Typology of waste	EWC code	-
	Destiny	o Landfill o On-site reuse o Recycling o Third-party management	
	Quantity		tonnes
	Gate fee		€/tonne
	Transport cost		€/tonne
	Total cost	*quantity x gate fee + quantity x transport cost*	€

4.2.2 Setting up the questionnaire for recycling facilities

The questionnaire for recycling plants is subdivided into six macro-sections. The six parts collect general information on the facility and all expenses related to preliminary costs, machinery investment costs, operating costs, and incoming and outgoing flows (such as RAs). The questionnaire sections are described in detail below, and Table 3 depicts the survey structure, including all relevant data.

Section 1: General information

The plant name, location, site area [m^2], plant type (moving, self-propelled, or fixed), expected lifespan [y], and treatment capacity [t/y] are all included in the general information. The actual tonnes treated in the reference year are computed by summing the tonnes of incoming waste declared by the plant.

Section 2: Preliminary costs

These are the costs borne for the acquisition of the plant site [€], insurance [€], and end-of-life machinery [€]. These expenses are incurred at the beginning of the year or on a one-time basis (as in the case of the machinery end-of-life). Therefore, the yearly cost is calculated by dividing them by the plant's expected lifespan.

Section 3: Machinery acquisition costs

The requests for each machinery in the inventory (e.g., jaw crushers, rotating or vibrating screens, iron and plastic removers, and other mechanical accessories) are the expected lifespan [y], the cost of purchasing [€], and the duration of usage during the year [h/y]. The total cost regarding the reference year (2019) is calculated by multiplying the cost of acquisition (previously divided by the lifespan) by the number of hours of usage during the year.

Section 4: Operative costs

The costs of machinery maintenance [€/y], annual personnel wages [€/y], security wages [€/y], and energy, fuel, and water consumption stand for the operative costs of a waste treatment facility. Furthermore, EU Regulation 305/11 on construction products placed on the market and the recent Legislative Decree 106/17 for construction products (including recycled ones) require the CE certification level of the aggregates produced. The survey requests the level of CE certification, which can be system 2+, which requires an initial inspection of the recycling plant as well as ongoing surveillance, assessment, and verification, and system 4, which requires the manufacturer's self-certification (EU Regulation 305/11), as well as the relative annual cost (€/y). The cost per tonne treated is determined by dividing the annual fee by the number of tonnes treated that year.

Section 5: Input flows

The incoming quantity [t] and the cost charged for admittance [€/t] (the so-called gate fee) are required for each incoming flow identified by the EWC code. The total revenue due to incoming flows is calculated by multiplying the incoming quantity by the relative gate fee.

Section 6: Output flows

This last section includes all streams separated from inert mineral waste that cannot be handled at the plant and thus have a different fate, as well as the production and sale of RAs. For these outflows, the type, destination, quantity [t] and landfill cost [€] or selling price (in the case of metal streams) are listed. The second part of this section is dedicated to RAs products, which include the type and particle size class d/D (ratio between the size of the lower and upper diameter), the typology, i.e., RAs mixed in a single fraction, of different granulometric size, from concrete or bituminous origin, the quantity produced [t], the selling price [€/t], and the selling rate.

Table 3 – Recycling facilities survey: data required (the self-calculated values are in italics)

Section	Data requested	Detailed requests and calculations	Unit
1. General Information	Plant name Localisation		
	Site area		m^2
	Treatment capacity		tonnes
	Tonnes treated per year		tonnes/year
	Expected lifespan		years
	Plant type	○ Mobile ○ Self-propelled ○ Fixed	
2. Preliminary costs	Purchase of the plant site ○ *Annual cost*	*purchase cost/plant lifespan*	€ €/year
	Insurance ○ *Annual cost*	*insurance cost/plant lifespan*	€ €/year
	Machinery end-of-life ○ *Annual cost*	*End-of-life cost/plant lifespan*	€ €/year
3.Machinery Acquisition costs	Typology	○ Jaw crusher ○ Vibrating screen ○ etc.	
	Expected lifespan		hours
	Acquisition cost ○ *Hourly cost*	*purchase cost/lifespan*	€ €/hour
	Usage time		hours
	Total intervention cost	*hourly cost x usage time*	€
4. Operative costs	Machine maintenance		€/year
	Personnel wages		€/year
	Security wages		€/year
	CE certification	○ Level 2+	€/year

Section	Data requested	Detailed requests and calculations	Unit
		○ Level 4	
	Consumption	Energy ○ Bill cost ○ *Total*	kWh €/kWh €
		Fuel ○ Bill cost ○ *Total*	Litres €/litre €
		Water ○ Bill cost ○ *Total*	Litres €/litre €
5. Input flows	Typology of waste	EWC code	-
	Quantity treated		tonnes
	Gate fee		€/t
	Total revenue	*Quantity treated x gate fee*	€
6a. Output flows	Typology of waste	EWC code	-
	Destiny	○ Landfill ○ Recycling	
	Quantity		tonnes
	Disposal cost/revenue		€/t
		Quantity x disposal cost/revenue ○ Landfill ○ Metal sale	€
6b. RAs	Typology and granulometric class	○ Mixed RAs in a single fraction ○ RAs of different grain sizes ○ RAs from concrete ○ Bituminous RAs	
	Quantity produced		tonnes
	Selling price		€/t
	Selling rate	quantity sold/quantity produced x 100	%

5. Results

The results of the arithmetic mean for each cost item of the seven cases are displayed in Tables 4 and 5. Regarding the demolition phase, the values in €/m^3 (Table 4) are determined by dividing each cost by the empty to full volume of the demolished structure. The values in €/t for the recycled plants (Table 5) are derived by dividing the costs incurred by the tonnes treated during the reference year, 2019. Starting from the demolition phase, with the data acquired, it is possible to calculate the costs of the macro-categories of preliminary costs, machinery acquisition, operation, and disposal costs. The highest costs, within the preliminary ones, are those borne for safety charges and removing hazardous materials from the building (particularly materials containing asbestos). Among all the machinery employed, the data shows that the excavator (including all the attachments) competes for 89% of the overall acquisition expenses. Instead, employee salary is the most significant regarding operative costs, more than fuel and electricity consumption. The average cost of demolition activities (excluding waste disposal costs) is 5.53 €/m^3. As previously stated, the costs borne by recycling plants are expressed in euros per tonne of waste processed at the facility during the reference year (2019). Based on the data, it emerges that the plant earnings are nearly entirely derived from the payment for the delivery of the waste to be treated (-12.28 €/t). The profit from the sale of RAs is -2.06 €/t, while the revenue from the sale of metals is -0.83 €/t, and these profits are insufficient to cover the treatment expenses (6.09 €/t).

To calculate the average cost of the entire supply chain (demolition and treatment of generated waste), all costs have been reported in €/m^3 demolished (FU). The calculation is done by multiplying the cost of recycling (including the revenue deriving from the sale of metal waste) and the sale of RAs expressed in €/t for the tonnes of inert waste sent for recycling that are present in a demolished cubic meter [t/m^3] (data extracted from the demolition companies' questionnaire). The gate fee of the recycling plant is excluded from the calculation to combine the two LCC analyses on demolition and recycling. The average overall cost of the whole chain is 7.04 €/m^3. It is also shown that correctly executed selective demolition results in higher total supply chain costs (the average value of the selective demolition cases is 8.81 €/m^3) compared to conventional demolition cases (the average value of the conventional demolition cases is 2.69 €/m^3). Figure 3 compares the average cost values between cases in which a correct selective demolition is performed and the cases closest to a conventional demolition (Cases 5 and 6). The figure shows that the most critical cost items across the management chain are those connected to the acquisition of demolition equipment and employee wages. Comparing the costs of the two demolition techniques shows that the costs of machinery acquisition, safety (which relates to personnel), and building reclamation are substantially higher in selective demolition.

Table 4 – Demolition company: Average costs

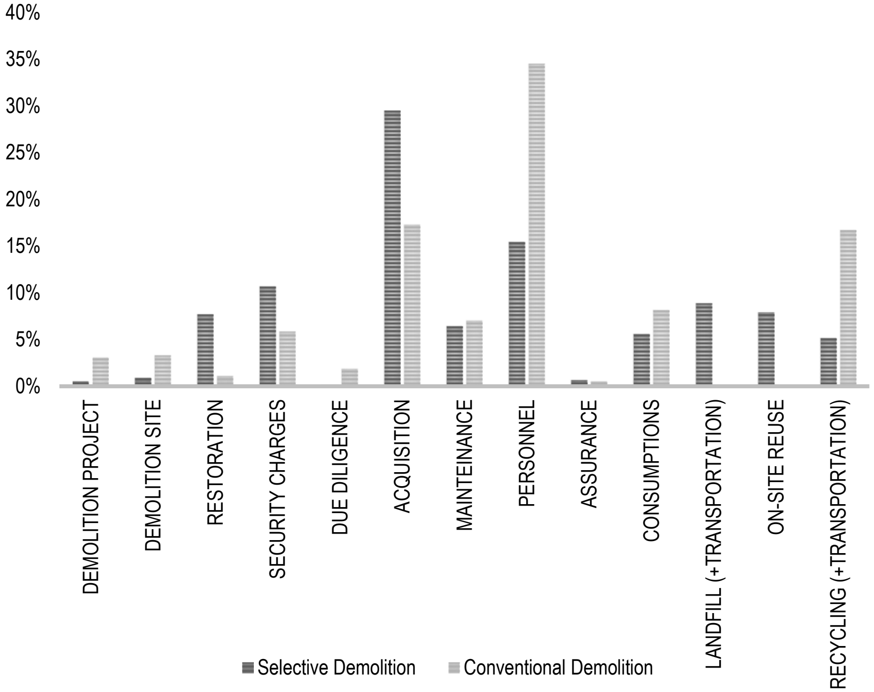
Section	Cost item	Average cost per m³ demolished
Preliminary costs	Demolition project	0.06 €/m³
	Setting of the demolition site	0.08 €/m³
	Building reclamation	0.50 €/m³
	Security wages	0.72 €/m³
	Environmental due diligence	0.02 €/m³
Machinery acquisition costs	Machinery acquisition	1.99 €/m³
Operative costs	Machine maintenance	0.46 €/m³
	Personnel wages	1.23 €/m³
	Insurance	0.05 €/m³
	Consumptions	0,42 €/m³
Disposal and recycling costs	Landfill fee	0.52 €/m³
	Transportation	0.25 €/m³
	On-site reuse	0.50 €/m³
	Recycling	0.24 €/m³
TOTAL	***eLCC (Demolition + Recycling)***	***7.04 €/m³***

Table 5 – Recycling facilities: Average costs

Section	Cost item	Average cost per tonne treated
Preliminary costs	Purchase of the plant site	0.51 €/t
	Insurance	0 €/t*
	Machinery end-of-life	0.26 €/t
Machinery acquisition costs	Machinery acquisition	0.83 €/t
Operative costs	Machine maintenance	0.73 €/t
	Personnel wages	2.53 €/t
	Security wages	0.01 €/t
	CE certification	0.15 €/t
	Consumptions	1.06 €/t
Input flows	Gate fee	-12.28 €/t
Output flows	Landfill	0.01 €/t
	Metals sale	-0.83 €/t
RAs	Selling price	-2.06 €/t
TOTAL	***Treatment operations***	***6.09 €/t***
	Revenues	***15.17 €/t***

* The value is insignificant.

Figure 3 – The contribution of individual expenditures on overall costs (in percentage) for selective and conventional demolition



5.1. Sensitivity analyses

Table 6 shows the range of variation between the minimum and maximum values for each cost item relating to the entire supply chain. Given that some of these have a significant variation, it was decided to proceed with a sensitivity analysis to see how the total cost of the supply chain would vary as costs vary within the ranges defined below. For simplicity, the chosen cost items have a difference between maximum and minimum greater than 2.00 €/m^3. Accordingly, the parameters with the most significant variability are the building reclamation, security wages, acquisition costs of machinery and personnel costs. Among these, the machinery acquisition cost and personnel reach a difference greater than 4.00 €/m^3.

Table 6 – eLCC – total range (min-max) and average value (wide range values are in italics)

	Cost item	**Min**	**Max**	**Average**
Demolition	Demolition project	0.03 €/m^3	0.13 €/m^3	0.06 €/m^3
	Setting of the demolition site	0.00 €/m^3	0.21 €/m^3	0.08 €/m^3
	Building reclamation	*0.00 €/m^3*	*2.86 €/m^3*	0.50 €/m^3
	Security wages	*0.12 €/m^3*	*2.51 €/m^3*	0.72 €/m^3
	Environmental due diligence	0.00 €/m^3	0.10 €/m^3	0.02 €/m^3
	Machinery acquisition	*0.27 €/m^3*	*4.90 €/m^3*	1.99 €/m^3
	Machine maintenance	0.00 €/m^3	1.31 €/m^3	0.46 €/m^3
	Personnel wages	*0.14 €/m^3*	*3.29 €/m^3*	1.23 €/m^3
	Insurance	0.00 €/m^3	0.21 €/m^3	0.05 €/m^3
	Consumptions	0.05 €/m^3	0.93 €/m^3	0.42 €/m^3
	Landfill fee	0.00 €/m^3	1.35 €/m^3	0.52 €/m^3
	Transportations	0.00 €/m^3	1.90 €/m^3	0.25 €/m^3
	On-site reuse	0.00 €/m^3	1.21 €/m^3	0.50 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3	0.32 €/m^3	0.08 €/m^3
	Recycling inert waste*	0.00 €/m^3	0.78 €/m^3	0.16 €/m^3
TOTAL	***Base-case scenario***			***7.04 €/m^3***
	Best-case scenario			***4.85 €/m^3***
	Worst-case scenario			***13.24 €/m^3***

* Data obtained from the LCC on recycling plants

The starting scenario is the one with the average costs resulting in the value chain cost of 7.04 €/m^3. The sensitivity analysis aims to compare the costs of the best- and worst-case scenarios. In the best-case scenario, the cost with the most significant variability margin is replaced with the minimums defined in table 6. The total cost of the supply chain in this way would be reduced by 31%, reaching the final cost of 4.85 €/m^3. On the contrary, in the worst-case scenario, the five cost items are replaced with the maximum values, resulting in an increase of 88% of the total cost up to 13.24 €/m^3.

Another sensitivity analysis is run to show the economic impact of separating metals at the demolition site. The metal is often transported for recycling and benefiting from scrap metal is a common activity. If the metal flows are substantial, the revenues from their sale can be sufficient to cover the demolition costs. By including metal scrap sales (-1.63 €/m^3), the whole cost is reduced by more than 20% on average (5.41€/m^3).

6. Discussion

One of the most significant criticalities of the management chain discovered after the analysis is that the average result of the seven demolition cases shows that the most significant proportion of all production (95%) is inert mineral waste (EWC 170904). Metal waste is 4% of overall waste, whereas organic materials (such as paper and wood) and hazardous waste (collected after building reclamation) constitute 1%. Table 7 illustrates the average percentage compositions of inert mineral waste, metals, and other materials. According to the waste composition obtained, inert mineral waste is almost entirely composed of a mixed stream of C&D waste (EWC 170904), with just 4% referring to a distinct cement stream (EWC 170101). Metals account for 96% of the flux of iron and steel (EWC 170405), with aluminium (EWC 170502) and cables accounting for the remainder (EWC 170411). The "other" category, which constitutes a tiny fraction of the total, is mainly composed of mixed packaging (EWC 150106) and insulating materials (EWC 170600). On the other hand, no organic material, such as wood, was identified (EWC 170201).

Table 7 – Percentage composition of the categories of inert mineral, metallic and other waste

	Total mass fraction %	Materials division (EWC code)	Mass fraction %
Inert waste	95%	170904 – Mixed C&D waste	96%
		170802 – Gypsum materials	0.1%
		170101 – Cement	3.9%
Metals	4%	170405 – Iron and steel	96%
		170502 – Aluminium	3%
		170411 – Cables	1%
Other	1%	150106 – Mixed packaging	56%
		170600 – Insulating materials	20%
		170302 – Bituminous Materials	8%
		170605* and 180603* - Hazardous materials (asbestos)	16%
		170201 – Wood	0%

Furthermore, although respondents stated selective demolition operations in all seven demolition cases, an assessment of the machinery used, demolition timeframes, and waste flow generated on-site revealed that only five cases out of seven were carried out appropriately. The fifth and sixth cases present a noticeable lack of material sorting and screening, as more than 90% of the flows generated refer only to the mixed C&D fraction (EWC 170904). A proper selective demolition would have involved a subdivision into distinct flows of concrete, bricks, metals, and organic substances (e.g., wood). In the first three cases, the inert fraction (EWC 170904) is reused on-site after adequate treatment with a small mobile plant owned by the firm, a procedure currently used in medium-large demolition activities in Italy. The remaining flows concern inert waste sorted and sent to treatment plants (nearly 0.4%) or landfills (about 1-2%). In the fourth case, 33% of the fluxes (all metal flows) are recycled. The remaining part, particularly hazardous waste, is disposed of in landfills or transferred to third-party disposal companies. The mixed C&D flow is isolated from the cement, iron, and steel in the last case, and the bituminous mixtures, representing 1% of total waste production, are disposed of in landfills.

The results above confirm the outcomes obtained from previous LCC studies on the C&D waste management chain, demonstrating that the studies are related even though the geographical context is different. Similar to the findings of Coelho and de Brito's (2010) study, it is shown that selective demolition is more expensive than conventional demolition, with the longer time required to complete the operation and the limited use of mechanical equipment. It is also confirmed that recycling plants' material input gate fee makes up the largest share (Coelho and de Brito (2013)). The metal fraction is a key parameter for Hu et al. (2017), Mah et al. (2018) and Dahlbo et al. (2015) because it has the highest economic value. This is supported by the sensitivity analysis on metal waste flows, which reveals that even though metal waste represents 4% of the total average waste, their selling can lower the cost of the full chain by nearly 20%. These findings confirm that circular strategies such as metal recovery and the replacement of virgin aggregates can deliver dual outcomes: economic value creation and substantial carbon savings. This dual benefit has been increasingly recognized in modelling studies and sectoral analyses across manufacturing and residential contexts (Bressanelli & Saccani, 2025; Businge & Mazzoleni, 2023; Pauliuk et al., 2021). Building on these findings and considering that the results of this study identify machinery acquisition, safety-related personnel costs, and building reclamation as the primary contributors to the higher cost of selective demolition, specific strategies must be implemented to enhance its economic competitiveness. For instance, the significant impact of machinery costs could be mitigated through the development of equipment sharing platforms or specialized rental markets for advanced sorting tools, reducing the initial capital expenditure for smaller firms. Additionally, streamlining the building reclamation phase through the integration of Building Information Modelling (BIM) - based pre-demolition audits (European Commission, 2018; Volk et al., 2014) could significantly reduce the time required for hazardous material identification. While the analysed buildings are often dated, the integration of modern Scan-to-BIM technologies allow for the creation of digital inventories of existing structures, enabling precise mapping of material volumes even in the absence of original digital documentation (Volk et al., 2014). This would, in turn, lower safety-related personnel costs and improve the overall efficiency of the selective process, making it a more viable alternative to conventional methods.

7. Conclusions

Enhancing selective demolition practices and fostering a stronger market for recycled aggregates are not only significant measures to close material loops in the construction sector, but also strategic levers for decarbonization, in line with international evidence on material efficiency and climate neutrality (Circle Economy, 2023). Expanding the market for high-quality recycled aggregates would not only improve the economic viability of recycling plants but also avoid the carbon-intensive production of cement and steel, thus generating co-benefits for both circularity and decarbonization (Oladapo et al., 2024; Santos et al., 2025).

During this study, several obstacles were encountered in acquiring data suitable for modelling the eLCC, owing to firms' unwillingness to share sensitive data such as their expenses or revenues. However, utilising the available data, it was possible to give a first estimation of the demolition chain costs in the Lombardy Region. According to the research, the average cost for demolition and C&D waste management is 7.04 € for each m^3 of a demolished building. When a considerable proportion of metal waste stream is sold, this cost is minimised. However, when a proper selective demolition is executed, the overall supply chain costs are higher (approximately 8.81 €/m^3) than when the demolition does not include selective disassembly and material sorting (around 2.69 €/m^3). It should be noted that selective demolition involves more manual effort and, as a result, a higher cost of security wages and equipment use. According to the interviews with demolition companies, the absence of material sorting is determined by the fact that it is difficult to have sufficient spaces accessible inside the demolition sites to keep the waste separate while waiting for transportation. As a result, sector operators prefer to deliver mixed waste in a single heterogeneous stream (EWC 170904). To mitigate these economic and logistical barriers, this study suggests a two-fold strategy. First, at a technological level, the integration of digital tools such as BIM for pre-demolition audits could optimize the identification of hazardous materials, thereby reducing reclamation type and safety related personnel costs. Second, the impact of high initial investments could be balanced by promoting equipment-sharing platforms should lower the capital barriers for smaller firms to access in advanced sorting tools, making selective practices more accessible for small and medium-size firms. Complementary to these measures, a possible solution for construction sites that cannot host individual flows of concrete, bricks, ceramics, and so on could be to classify the waste as EWC 170107 – mixtures of concrete, bricks, tiles, and ceramics, which collect most of the inert waste but, unlike EWC 170904 – mixed C&D waste, reduce the need to separate the various streams. By reducing the need to differentiate the multiple flows, recyclability and subsequent manufacturing of high-quality aggregates might be facilitated without demanding too personnel. The sensitivity analysis allows to determine which cost items had the most fluctuation and hence those on which it would be suitable to act using incentive mechanisms to obtain the best-case scenario. Future research breakthroughs include investigating the environmental implications of demolition using the LCA approach and then the monetisation of these impacts to implement the feLCC (according to Hoogmartens et al., 2014), which, hence, include other than the internal costs, some external costs that can be internalised in the short term (De Menna et al., 2016; Swarr et al., 2011). Future research should also be aimed at closing the loop in the C&D waste management chain by stimulating the market for high-quality RAs, promoting their sale and use in new buildings, proposing a solid financial incentive system and providing data and recommendations helpful to contracting authorities to include the correct disposal of demolition waste in public procurement.

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Data availability statements

All data generated or analysed during this study refer to aggregate and anonymous results and are included in this published article.

Declaration of 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.