Doctoral dissertation:

CIRCULARITY IN THE CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT CHAIN

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Doctoral dissertation of:

Federica Carla Carollo

2022- XXXV Cycle

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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

DOCTORAL PROGRAMME IN ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING

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ABSTRACT

The PhD project results from a collaboration agreement between Lombardy Region, the ENEA - National Agency for New Technologies, Energy and Sustainable Economic Development research centre and Politecnico di Milano. The result of the three-year PhD provides a comprehensive study of the construction and demolition waste management (C&D) chain with the goal of fostering the circular economy (CE) in the construction sector through the implementation of tools useful to public administrations to encourage circular practices. To reduce global impacts and preserve natural resources, a CE is essential in resource-intensive activities such as construction. The goal is achieved by implementing the Full-Environmental Life Cycle Costing (feLCC) methodology, which combines the Life Cycle Assessment (LCA) methodology with that of environmental Life Cycle costing (eLCC) through the monetisation of environmental impacts. Based on the study results, it is possible to suggest incentive mechanisms in favour of small and medium enterprises (SMEs) for the execution of private demolition works. C&D waste represents 45.5% of the total production of special waste in Italy. Although the high recovery rate (78,1%), various regulatory, economic, technical, and cultural barriers prevent the widespread use of recycled aggregates (RAs) produced by C&D waste recycling activities. Among the limitations, market acceptance of products made using secondary resources as input material will only be ensured when their production costs are lower than those of virgin materials. Nevertheless, even more critically, the presence of impurities in the RAs and the difficulty in guaranteeing their consistent production preclude their use in structural concrete. To produce high-quality RAs, the waste entering the recycling plant must be as homogeneous as possible. Through selective demolition, a practice not very common in Italy, the materials can be carefully sorted, which is why it should be encouraged. The project was developed in four successive macro phases, the application of the eLCC, the application of the LCA, the monetization of the environmental impacts and finally the definition of the proposals for the incentive mechanisms. The first research phase aimed to apply an eLCC to Lombardy's C&D waste management chain (Northern Italy). The functional unit chosen for the system is the demolition of a building per cubic meter (m^3). The investigated system includes all management phases of inert waste originating from demolition activities, from its generation at the end of building life, during an ordinary

or selective demolition, to the treatment phase in a recycling plant, till the market re-placing as RAs. The inventory is implemented for each process in the management chain, with two surveys issued to demolition companies and C&D recycling facilities, respectively. It is 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 LCA study of the selective demolition phase is performed under the same boundaries as the eLCC system. The system functional unit is the demolition of a cubic meter (m^3) of the structure. The Life Cycle Inventory is developed using data from the eLCC surveys, which included the consumption of diesel, water, and energy, the typology and quantities of waste leaving the demolition site for recycling/landfill and on-site reuse, and the distances that are driven. The model is developed using SimaPro 9.3 with the Environmental Footprint 3.0 characterisation method, which evaluates 16 impact categories. The union between the eLCC and the LCA occurs through the monetisation process of the environmental impacts. Four different monetisation methods are selected, i.e., De Nocker e DeBacker, Smith et al., Stepwise, and Environmental footprint. The monetised impact is calculated by multiplying the environmental impact indicator by the monetisation factor reported in the reference method. The final value of the eLCC is then added to the monetised impact to obtain the feLCC value. Starting from the results obtained, the incentive mechanisms for the benefit of selective demolition and the use of recycled aggregates are defined. In particular, the identified cost items on which it is possible to apply a discount on the cost incurred by demolition companies and recycling plants are the demolition project, the on-site reuse cost, the recycling fee, and the sale of RAs. The incentives are supposed to be payable by Public Administrations through tax relief and/or non-repayable grants. The recipients of these incentives are the SMEs for the execution of private works. The final step is to conduct a feasibility analysis on applying the incentives described above to real case studies. Multiple conversations with Lombardy Area workers have determined which available funds might be spent for this purpose, and how much volume demolished every year can be entitled to incentives. In conclusion, although many challenges are experienced in gathering data appropriate for the eLCC, owing to organisations' lack of confidence in revealing sensitive data such as expenditures spent, the feLCC has proved to be a useful tool for identifying the criticalities of a value chain such as that of C&D waste. Using the available data, it is feasible to evaluate all the costs of the demolition chain (both internal and external through the monetisation of the

impacts) and, as a result, develop some proposals to stimulate the market for recycled aggregates. The findings show that the average cost for demolition and C&D waste management is 7.04 €/m^3*. It was demonstrated that landfill expenses much outweigh recycling fees, and the cost of on-site reusing is equivalent to a landfill fee. However, it has the advantage of zero transportation expenses. The sensitivity analysis revealed that the total cost is lowered when the earnings from the sale of metal waste cover the expenses of transporting the other flows to the recycling plant or landfill. With the support of the LCA study, it has been revealed that when a more extensive breakdown of waste streams is accomplished, the outcome is opposite to the desired goal, i.e., increased environmental and economic impacts. Recommendations are made for operators in the sector on how to manage selective demolition better and which are the separable waste streams that bring greater benefits in both economic and environmental terms. A set of incentives is defined that can be directly used by public administrations in favour of SMEs in the execution of private works. The limits of the research provided are connected to the difficulties in gathering sufficient and representative data, and the geographical restriction to the Lombardy Area. As a result, one of the research's future directions is to expand the study to other Italian regions to gain an exhaustive case study of the current scenario and ensure that incentive programs are aligned throughout Italy and among all public administrations.*

CONTENTS

ABSTRACT

INTRODUCTION: Circularity in the construction industry 1

CHAPTER 1: The C&D Waste management chain 4

1.1 CONSTRUCTION AND DEMOLITION WASTE... 4

1.1.1 Italian C&D waste management 6

1.1.2 Recycling aggregates manufacturing and criticalities.. 7

1.1.3 End of waste decree 8

1.2 BUILDINGS CLASSIFICATION 10

1.2.1 Buildings with predominantly concrete/masonry structure 10

1.2.2 Buildings with predominantly metal structure 12

1.2.3 Intended function 12

CHAPTER 2: Demolition and C&D waste recycling.. 14

2.1 BUILDING DEMOLITION TECHNIQUES... 14

2.1.1 Conventional demolition.. 15

2.1.2 Selective demolition following the UNI/PdR 75:2020 17

2.1.3 Types of demolition machinery 21

2.2 RECYCLING PLANTS 30

2.2.1 Fixed plants... 31

2.2.2 Mobile plants 32

2.2.3 Operational phases.. 34

CHAPTER 3: Methodology: Full environmental Life Cycle Costing 41

3.1 LIFE CYCLE COSTING 42

3.2 LIFE CYCLE ASSESSMENT 45

3.3 MONETISATION OF ENVIRONMENTAL IMPACTS 49

3.3.1 Main monetisation models 52

CHAPTER 4: Previous LCT studies on C&D waste management 56

CHAPTER 5: Environmental Life Cycle Costing of the C&D waste management chain 64

5.1 GOAL AND SCOPE 64

5.2 INVENTORY 65

5.2.1 Setting up of the questionnaire for demolition companies 66

5.2.2 Setting up of the questionnaire for the recycling facilities 70

5.2.3 Case studies – Demolition 75

5.2.4 Case studies – Recycling plants 79

5.2.5 Destiny of the waste flows 80

5.3 RESULTS 82

5.3.1 Recycling plant costs 82

5.3.2 Full chain costs 84

5.4 SENSITIVITY ANALYSIS 86

CHAPTER 6: Life Cycle Assessment of the C&D waste management chain 90

6.1 GOAL AND SCOPE 90

6.2 LIFE CYCLE INVENTORY AND TRANSPOSITION ON SIMAPRO SOFTWARE . 93

6.3 LIFE CYCLE IMPACT ASSESSMENT 111

6.4 SENSITIVITY ANALYSIS **128**

6.4.1 The contribution of the metal flows 128

6.4.2 The contribution of the workforce 136

CHAPTER 7: ARCADIA Database **147**

CHAPTER 8: Full-Environmental Life Cycle Costing **153**

8.1 MONETISATION OF THE IMPACTS **153**

8.1.1 Smith et al., 2020 153

8.1.2 De Nocker e DeBacker, 2018 156

8.1.3 Stepwise 158

8.1.4 Environmental Prices 160

8.2 feLCC RESULTS **162**

CHAPTER 9: Incentive Mechanisms **165**

9.1 TYPES OF BUSINESSES IN LOMBARDY REGION **165**

9.2 PUBLIC WORKS: CAM EDILIZIA **167**

9.3 PRIVATE WORKS: PROPOSAL FOR INCENTIVES **169**

9.4 APPLICATION ON THE REAL STUDIES **170**

DISCUSSION AND CONCLUSION **174**

ACKNOWLEDGEMENT **180**

REFERENCES **181**

ANNEX I: Full chain costs of the single cases (1-7) **189**

A1.1 Case 1 .... **189**

A1.2 Case 2 .... **191**

A1.3. Case 3 193

A1.4. Case 4 195

A1.5. Case 5 197

A1.6. Case 6 199

A1.7. Case 7 201

ANNEX II: SimaPro models of single datasets 203

A2.1 Recycling of aluminium 203

A2.2 Recycling of Iron and steel 204

A2.3 Recycling of cables 205

A2.4 Recycling of gypsum-based materials 207

A2.5 Recycling of wood 210

A2.6 Recycling of mixed C&D waste 212

A2.7 Recycling of cement 216

A2.8 On-site reuse of C&D waste 217

A2.10 Landfill of C&D waste 219

A2.5 Landfill of mixed packaging 220

A2.11 Storage of Insulating materials 220

ANNEX III: Metadata sheets for BDI-LCA ARCADIA Project 223

INTRODUCTION

Circularity in the construction industry

Construction is a resource-intensive sector that calls for a circular economy (CE) to mitigate global impacts and preserve our precious resources (Ghufran et al. 2022). Businesses and consumers alike may benefit from a circular economy by optimizing resource usage, reducing raw material consumption, and recovering waste by recycling or reusing it as a new product. In this context, paying attention to the building's end of life, the generation of construction and demolition waste, and its fate is critical for closing the cycle. According to the 2021 ISPRA report, construction, and demolition (C&D) waste account for 45.5% of total special waste generation in Italy. Despite a recovery rate of 78.1% (ISPRA 2021), a variety of legislative, economic, technological, and cultural constraints (Cutaia et al. 2022) prohibit the widespread use of recycled aggregates (RAs) produced by C&D waste recycling activities. This fraction excludes backfilling and excavated soil and solely includes preparation for reuse, recycling, and material recovery (ISPRA 2021). RAs' intended applications may differ based on their quality and performance qualities. The Ministry of the Environment's Circular 15/07/2005 No. 5205 specifies the best usage for RAs based on their qualities. As a result, embankments, road foundations, environmental restorations, fillers and bridges, extra layers with antifreeze, capillary, and drainage functions, and concrete with resistance class Rck 15 Mpa may all be made using RAs while conforming to the standard's specifications. Among the constraints, the market acceptability of items produced with secondary resources as input materials will be ensured only when manufacturing costs are lower than those of virgin materials (Cutaia et al. 2022). Nonetheless, the presence of impurities in RAs, as well as the difficulties in ensuring consistent manufacture (Borghi et al. 2018; ICESP 2020), preclude their application in structural concrete (Dhir et al. 2019). The waste entering the recycling facility must be as homogeneous as possible to produce high-quality RAs. This necessitates meticulous sorting of the components during the demolition phase of the construction, a technique that is currently uncommon in Italy (Cárcel-Carrasco et al. 2021), called selective demolition. As a result, selective demolition should be promoted, as should the growth of the market for RAs, which are presently not economically competitive with natural aggregates. The 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 excellent tools in this circumstance for examining the financial, environmental, and social aspects of a product or process throughout its life (Jacob-Lopes et al. 2021). The eLCC, in particular, is now viewed as a “driver” for construction improvement (Manewa et al. 2021) since it enables better financial decisions by accounting for all relevant expenses of an asset (Kelly and Hunter 2009; Martinez-Sanchez et al. 2015). The results of the three-year PhD, which provides a complete assessment of the economic and environmental impacts of the C&D waste management chain, will be shown in the following chapters. The goal was achieved by applying the Full-Environmental Life Cycle Costing (feLCC) methodology, which combines the LCA methodology with the eLCC methodology by monetising environmental impacts. According to the findings, providing incentives for small and medium-sized enterprises (SMEs) to perform private demolition work was feasible to relaunch the frozen supply chain and encourage circularity in the construction industry. In order to reach the aim, the document is organized as follow: The first chapter introduces the C&D waste management chain, with a focus on the Italian context; the second chapter provides an overview of demolition techniques and C&D waste recycling; the third chapter presents the methodology at the core of the PhD project, i.e. feLCC; the fourth chapter reports on a series of previous studies on the application of the methodology; the fifth and sixth chapters show the application of the eLCC and LCA to a set of case studies; the ARCADIA project is described as one of the project's outputs in chapter seven; finally, in chapter nine, a set of incentive proposals for SMEs are presented.

CHAPTER 1

The C&D Waste management chain

1.1 CONSTRUCTION AND DEMOLITION WASTE

The European Waste Catalogue is a collection of waste categorisation codes based on Directive 75/442/EEC, which defines *waste* as *"any material or object that falls within the categories indicated in Annex I and which the owner discards, wants to discard, or is obligated to discard"* (also known as the European Waste Catalogue code, or EWC code). Any waste, whether intended for recovery or disposal, must comply with Annex I of the directive, often known as the European List of Wastes. In Chapter 17 of the European Waste Catalogue, C&D waste is categorised as "Waste from construction and demolition operations (including land reclamation)", and for each waste flow is allocated an EWC code (Eurostat 2010). The EWC codes are numerical sequences of six digits divided into three pairs (e.g., 17 01 06) that identify waste based on the manufacturing process from which it originated. Table 1 lists all the C&D waste EWC codes relative to the waste from C&D operations. Hazardous waste recognised by safety data sheets or laboratory examination is denoted by an asterisk "*" (e.g., 17 06 05* "Construction materials containing asbestos").

Table 1: Mineral waste from construction and demolition operations (EWC codes)

EWC Code		Description
17 01 concrete, bricks, tiles, and ceramics	17 01 01	Concrete
	17 01 02	Brick
	17 01 03	Tiles and ceramics
	17 01 06*	Mixtures of or separate fractions of concrete, bricks, tiles and ceramics containing hazardous substances

	17 01 07	Mixtures of concrete, bricks, tiles, and ceramics other than those mentioned in 17 01 06*
17 02	17 02 01	Wood
Wood, glass, and plastic	17 02 02	Glass
	17 02 03	Plastic
	17 02 04*	Glass, plastic, and wood containing or contaminated with hazardous substances
17 03	17 03 01*	Bituminous mixtures containing coal tar
Bituminous mixtures, coal tar and tarred products	17 03 02	Bituminous mixtures other than those mentioned in 17 03 01*
	17 03 03*	Coal tar and tarred products
17 04	17 04 01	Copper, bronze, brass
Metals (including their alloys)	17 04 02	Aluminium
	17 04 03	Lead
	17 04 04	Zinc
	17 04 05	Iron and steel
	17 04 06	Tin
	17 04 07	Mixed metals
	17 04 09*	Metal waste contaminated with hazardous substances.
	17 04 10*	Cables containing oil, coal tar and other hazardous substances
	17 04 11	Cables other than those mentioned in 17 04 10^
17 05	17 05 03*	Soil and rocks containing hazardous substances
soil (including excavated soil from contaminated sites), stones and dredging spoil	17 05 04	Soil and stones other than those mentioned in 17 05 03*
	17 05 05*	Dredging spoil containing hazardous substances
	17 05 06	Dredging spoil other than those mentioned in 17 05 05*
	17 05 07*	Track ballast containing dangerous substances
	17 05 08	Track ballast other than those mentioned in 17 05 07*
17 06	17 06 01*	Insulating materials containing asbestos

Insulation materials and asbestos-containing construction materials	17 06 03*	Other insulation materials consisting of or containing dangerous substances.
	17 06 04	Insulation materials other than those mentioned in 17 06 01* and 17 06 03*
	17 06 05*	Construction materials containing asbestos
17 08 Gypsum-based construction material	17 08 01*	Gypsum-based construction materials contaminated with hazardous substances
	17 08 02	Gypsum-based construction materials other than those mentioned in 17 08 01*
17 09 Other construction and demolition wastes	17 09 01*	Construction and demolition wastes containing mercury
	17 09 02*	Construction and demolition wastes containing PCB (e.g., PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, and PCB-containing capacitors)
	17 09 03*	Other construction and demolition wastes (including mixed wastes) containing dangerous substances
	17 09 04	Mixed construction and demolition waste other than those mentioned in 17 0 01*, 17 09 02* and 17 09 03*

1.1.1 Italian C&D waste management

In Italy, sustainable C&D waste management is still in its beginnings, with landfilling being the most typical destination for C&D waste (Di Maria et al. 2018). Figure 1 depicts the usual pattern of inert waste from source to destination, together with the expenses 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 circumstances, the demolition company is responsible for transferring the material to the proper treatment facility or sanitary landfill (transport plus gate fee). However, in the third situation, the firm is liable for the costs of on-site waste treatment. The recycling facilities share the costs of processing waste that enters the plants and producing secondary raw materials (SRMs). However, they gain three income streams: demolition companies' gate fees, the sale of RAs, and the sale of metal fractions.

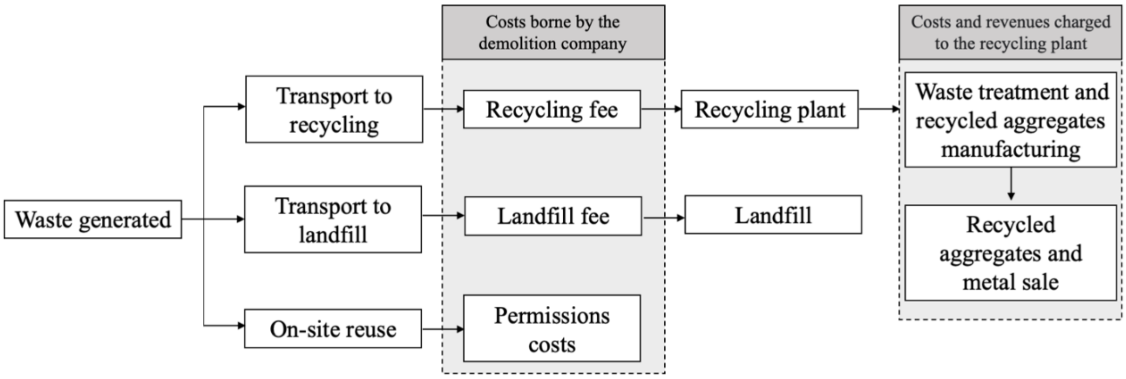


Figure 1: Tracing scheme of waste flows and related costs to be borne

1.1.2 Recycling aggregates manufacturing and criticalities

SRMs in the form of RAs can be manufactured by proper treatment of this specific type of waste (D.G.R.V. no. 1773/2012). However, the quality of the RAs produced is inextricably linked to the kind and homogeneity of waste generated during demolition, as well as the type and age of the structure. The Ministry of the Environments' Circular 15/07/2005 No. 5205 specifies the best applications for RAs based on their individual properties. As a result, the RAs can be utilised for the following use destinations while conforming to the characteristics stated by the standard:

C1: embankments

C2: road foundations

C3: foundations

C4: environmental restorations fillers and bridges

C5: additional layers with antifreeze, capillary, and draining function

C6: concretes with resistance class Rck <15 Mpa

As noted in the introduction, one of the limitations is the presence of impurities in RAs (Borghi et al. 2018; ICESP 2020), which restricts their use in structural concrete (Dhir et al. 2019). SRMs, on the other hand, have various advantages, including increased supply security, reduced raw material and energy use, reduced climatic and environmental consequences, and cheaper manufacturing costs (European Parliament 2016).

1.1.3 End of waste decree

One of the most recent critical issues that have emerged in preventing the circular economy in the construction industry is the current End of Waste (EoW) decree. The decree, published on September 27, 2022 (GU n.246 of 10/20/2022), specifies the criteria by which inert waste from C&D activities and other inert waste of mineral origin subjected to recovery operations cease to be classified as waste. Nonetheless, the 2018 sentence (State Council, 28/02/2018, n.1229) had already undermined the waste management balance by depriving Regions of the authority to grant authorisations to recycling facilities (Carollo & Rigamonti, 2019). On that occasion, the Council of State interpreted the European Waste Framework Directive (2008/98/EC), specifically art. 6 (or 184-ter of Legislative Decree 152/06), by reserving to the State the exclusive right to define the detailed criteria for the definition of the conditions that allow waste to become new products (Carollo & Rigamonti, 2019). Companies with all recycling activities, trade associations and regional governments have urged to create a new Decree to unblock the condition. After more than a year of blockade due to the Sentence of the Council of State, the Ministry of the Environment solved the situation by publishing the law of June 14, 2019, n. 55, converting the so-called “Sblocca Cantieri” Decree Law 32/2019. The authority to issue EoW permits to treatment facilities is returned to the regions under this legislation.

The critical issues identified by recovery operators members of ANPAR - the National Association of Producers of Recycled Aggregates - in the new EoW decree (GU n.246 of 10/20/2022) are related to the fact that it introduces constraints on the free movement of goods imposed by the European Union, does not provide clear indications on the methods of sampling and laboratory sample preparation, and introduces disparities concerning the limits set at other Member States' End of Waste decrees (ANPAR, 2022).

In particular, the Association points out that the decree:

- Introduces a check on the solid matrix, which sets concentration limits for contaminating substances that would prevent the use in Italy of RAs produced in other European Union countries, regularly provided with CE marking by harmonised European standards.
- It requires RAs to adhere to significantly stricter limitations than excavated soil and rocks or aggregates generated from bituminous conglomerates;
- Although it does not make direct reference to Table 1 of Annex 5 of Part IV of Legislative Decree 152/06, which establishes the limit concentrations of soils to be considered contaminated based on use (residential or commercial/industrial), it borrows limits to the physical matrix of recycled aggregates from that provision.
- For the sampling methods and sample preparation, it does not prescribe using the specific standard for aggregates (EN 932-1).

Furthermore, the decree specifies concentration limits for solvents and polycyclic aromatic hydrocarbons (PAHs). PAH or hexavalent chromium in recovered aggregates is due mainly to waste materials entering the recovery process (and hence necessary present in RAs), such as bituminous conglomerate or cement. The new Regulation's relative concentration limits are derived from the table relating to the uses of remedied land intended for residential or green areas: these values do not correspond at all to the prevalent use of RAs, which are used for more than 90% of infrastructural works (e.g., in embankments or foundations) (ANPAR, 2022). This is a mistake that risks inhibiting not only the recycling chain but also the construction chain, from which the waste in issue originates and to which the RAs are partly destined. Indeed, according to the new restrictions specified in the text of the EoW decree, waste generated by building demolition and restoration, even if correctly recycled, would yield items that do not comply with the decree above, leaving no alternative but landfill them as waste. In the worst-case scenario, inert waste might be dumped on the land, causing environmental and economic harm to the neighbourhood.

1.2 BUILDINGS CLASSIFICATION

Building material categorisation enables for the early identification of the type of C&D waste that will be generated. The most frequent building constructions in Italy may be divided into two categories: buildings with mostly masonry or concrete structure (see § 1.2.1) and buildings with a metal framework (see § 1.2.2). These two types of structures are examined in further detail below. As stated in § 1.2.3, another classification is based on the intended use of these buildings.

1.2.1 Buildings with predominantly concrete/masonry structure

Traditional masonry buildings refer to structures built in block and brick. The ceilings are often made of wooden, arched brick. The foundations are often conventional, such as stone with sand and brick mortar. Ties have also been employed in certain historical constructions. Contemporary masonry (Figure 2) buildings are constructed using modern materials i.e., with concrete-block joists, concrete slabs, and walls built of pressed brick, cement blocks, perlite, and so on. The foundations of these kind of structures are often made of concrete or steel. Materials used in masonry building include clay, sand, gravel, and stone. These materials are transformed into bricks and tiles, which are used to construct masonry structures (Aydenlou, 2020). Cement, water, and aggregates of sand and stones are combined in the proper proportions in liquid form for concrete constructions, which hardens quickly to produce a stonelike element with strong compressive strength called concrete (Aydenlou, 2020).

Figure 2: Buildings with concrete/masonry structure.

1.2.2 Buildings with predominantly metal structure

Buildings composed of iron and steel (Figure 3) are stronger, higher, and less costly than those made of stone, brick, or wood. Steel structures are stiff, continuous, and have solid connections that allow stresses to be distributed between beams and columns (Aydenlou, 2020). A steel structure is a flexible commercial space alternative.

Figure 3: Buildings with a metal structure

1.2.3 Intended function

Buildings, as noted in the introduction to this chapter, can be categorised, also, based on their intended function. The categorisation is available in the text of Presidential Decree 412/93 article 3 and is given together with the list of sub-categories, displayed in Table 2.

Table 2: Intended function of the buildings (Presidential Decree 412/93)

Intended function		
E.1	Buildings used for residences and similar.	E.1(1) dwellings used as permanent residences (e.g., civilian homes, rural, boarding schools, convents prisons, barracks);
		E.1(2) dwellings used as a residence with occasional occupation (e.g., holiday homes);
		E.1(3) buildings used as hotels, pensions, and similar activities;
E.2	Buildings used as offices and similar: public or private, independent, or contiguous to buildings also used for industrial or craft activities, provided that they can be separated from these buildings for the purposes of thermal insulation;	
E.3	Buildings used as hospitals, clinics or nursing homes and similar including those used for hospitalization or care of minors or the elderly as well as protected structures for the assistance and recovery of drug addicts and other subjects entrusted to public social services;	
E.4	Buildings used for recreational, associative or cult activities and similar;	E.4(1) such as cinemas and theatres, meeting rooms for congresses;
		E.4(2) such as exhibitions, museums and libraries, places of worship;
		E.4(3) such as bars, restaurants, dance halls;
E.5	Buildings used for commercial and similar activities: such as shops, wholesale or retail warehouses, supermarkets, exhibitions;	
E.6	Buildings used for sports activities;	E.6(1) swimming pools, saunas and similar;
		E.6(2) gyms and similar;
		E.6(3) sports support services;
E.7	Buildings used for school activities at all levels and similar;	
E.8	Buildings used for industrial and craft activities and similar.	

CHAPTER 2

Demolition and C&D waste recycling

2.1 BUILDING DEMOLITION TECHNIQUES

Demolition is the operation aimed at the partial or entire demolition of a structure constructed by a pre-planned sequence of actions performed on the building itself. Structures are often composed of several components (i.e., beams, lintels, support pillars, metal profiles, plates) constructed of various materials and coupled by constraint systems that assure the necessary stability and stiffness. Breaking these relationships is what demolition entails. This operation is a high-risk activity since, in most cases, demolished the building was not the one who built it and needed to know how the building itself or a piece of it could respond to solicitations. The demolition may concern the entire structure or a part of it (partial demolition), and it can be distinguished at the level of approach as selective demolition and conventional demolition. At the methodological level, it can be identified as manual or mechanical demolition (Mordà, 2011). A demolition intervention is the combination of the previous three aspects.

The choice of the most appropriate approach and means for the demolition of the structure in question is up to the demolition designer, who must be an experienced structural engineer and must analyse a slew of issues before proceeding with the operative phases. The factors follow these macro areas (Mordà, 2011):

- Operator safety and public safety.
- Environmental aspects.
- Economic aspects.
- Timing.
- Physical aspects relating to the property, such as those listed below:

a) The passage of time may have caused changes in the materials used in the construction: the iron may have oxidised, both in the load-bearing beams and in the crawl spaces or load-bearing walls; the wood may have degraded due to humidity and parasites; and the mortars may have been crushed or degraded due to humidity or chemical reactions caused by salts or other substances present.

b) Buildings are frequently constructed using diverse building techniques and materials during various eras. Furthermore, settling structures and foundations over time can cause unforeseen tensions, leading to abrupt collapses during demolition activities.

c) The buildings may have undergone numerous interventions, such as the opening or closure of rooms, the removal of pillars and columns, and the installation of extra floors, altering the static nature of the building.

An accurate analysis of the building being demolished must be carried out before proceeding with the demolition itself.

2.1.1 Conventional demolition

The conventional demolition approach is the quickest and cheapest way to destroy a structure. Apart from the mandatory hazardous material disposal, there is no specific recovery of building materials. A typical conventional demolition consists of the following four stages:

a. Survey of the building

Before demolition, industry specialists should inspect all aspects of the property, including the construction materials, design, building usage, and building codes. There should also be a study of the neighbourhood’s preference for noise and dust and any potential community implications of these types of operations. Furthermore, the structure should be inspected for dangerous, poisonous, radioactive, or flammable elements. The building should be structurally inspected for the construction technique, present structural condition, structural system, and design. This activity would make it easier to identify which strategies to apply safely and effectively dismantle the property.

b. Removing hazardous materials

If hazardous materials such as asbestos, minerals, radioactive substances, and flammable materials are found in the initial inspection, industry experts should be deployed to remove them safely before proceeding to demolition.

c. Preparation of the demolition plan

A thorough strategy for how the demolition should be carried out should be established. The demolition plan should include specifications on which demolition procedures should be used in each section of the structure and the sequence in which they should be carried out. Supporting information, such as the building’s location and distance from adjacent structures and roadways, as well as sensitive zones such as schools and hospitals, should be included. The demolition plan should also include all methods for managing health, safety, and waste disposal before, during, and after destruction.

d. Implementation of safety measures

To provide a safe, efficient, and cohesive approach to the demolition operation, all engaged workers should address preventive measures and engage in toolbox discussions. Furthermore, demolition safety indicators must be used correctly and consistently. Workers should also wear adequate Personal Protective Equipment (PPE) near the building. Failure to follow the reminders above and other critical safety precautions can result in various repercussions, including exposure to dangerous chemicals, a flash fire, or the development of occupational illness.

2.1.2 Selective demolition following the UNI/PdR 75:2020

The UNI website released the revised optional code of practice UNI/PdR 75:2020, “Selective deconstruction - Methodology for selective deconstruction and waste recovery from a circular economy viewpoint”, at the start of 2020. Selective demolition is defined in the standard as *“a sequence of sorting procedures into homogenous fractions, utilizing technology and equipment, with the primary purpose of maximizing reuse and recycling of C&D debris”* (UNI/PdR 75:2020, p. 12). To obtain high-quality SRMs, conventional demolition activities should be substituted with selective disassembly and deconstruction operations targeted at providing mono-material fractions (e.g., concrete, bricks, cement, wood) suitable for treatment in recycling facilities. The waste subdivision depicted in Table 3 should be obtained by adequately performing a selective demolition.

Table 3: Typical waste subdivision after a selective demolition

MATERIAL	EWC CODE
Reusable components	-
Wood	17 02 01
Glass	17 02 02
Plastic	17 02 03
Bituminous mixtures	17 03 00
Metals (including their alloys)	17 04 00
Lands and rocks	17 05 04
Insulating materials	17 06 00
Gypsum-based building materials	17 08 00
Cement	17 01 01

Bricks	17 01 02
Tiles and ceramics	17 01 03

According to UNI/PDR 75:2020, selective demolition is divided into three stages:

- Step 1: Planning,
- Step 2: Operational
- Step 3: Database implementation.

While the first two phases constitute the flow of selective demolition, the third is required to identify all the helpful information to maintain an inventory of materials and products used in the construction/renovation. The third phase's output enables the design phase to be simplified in the case of future deconstruction. The purpose is to simplify the planning procedure in the event of a new demolition, boosting the recycling and reuse rate.

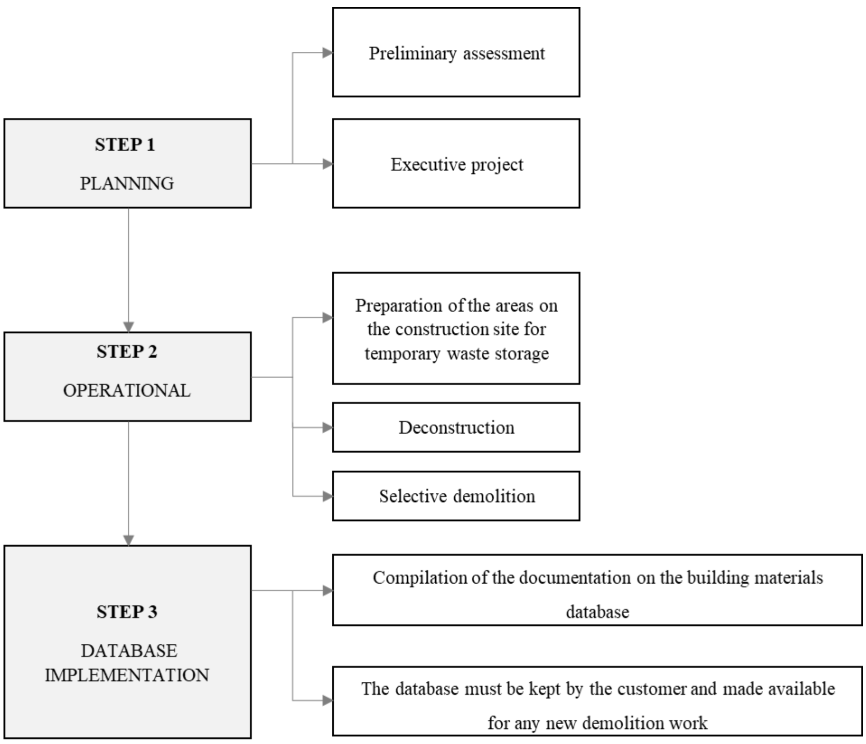


Figure 4: The stages of selective demolition according to UNI/PDR 75:2020

As the scheme in Figure 4 shows, the preliminary assessment and the executive project is 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. During the preliminary investigation, the presence of hazardous substances and other materials that could reduce the recyclability of the material from C&D and which, therefore, must be sent individually for recovery is verified. Before demolition, the selective dismantling phase aims to remove the parts of the structure (e.g., doors, windows, furnishings, possibly up to prefabricated and structural elements) which can be directly destined for reuse.

In many cases, even bricks, tiles, beams, railings and parapets, window frames, and similar, if disassembled with care and without damage, can be reused as they are or, after simple treatments that adapt them to a new use. While the first two phases are manual, the last phase is mechanical and requires specific machinery and equipment depending on the type of building. The movement of machinery and heavy vehicles must be carried out with particular attention to avoid any disturbance to the surrounding environment. The temporary accumulations of waste on the site must be left clean and tidy (D.Lgs no.152/2006, art. 183, letter bb). A critical aspect of selective demolition 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 & de Brito, 2011). Therefore, industry operators still prefer traditional demolition methods.

Table 4 compares conventional and selective demolition (Coelho & de Brito, 2011; Venugopal, 2022).

Table 4: Comparison between conventional and selective demolition (Venugopal, 2022)

Conventional Demolition	Selective Demolition
Costs are dependent mainly on the final disposal cost of CDW	Costs are uniform between labour, equipment, transport and final disposal cost of CDW
Skilled labour not required	Skilled labour required
Labour costs are lower	Labour costs are higher
Time saving	Time consuming
Highly dependent on mechanical equipment	Highly dependent on the workforce
Removal of hazardous materials only	Maximum recovery of building components

C&D waste has greater impurities making it difficult to recover materials	C&D waste include mono-material fractions, and is thus easily reuse/recycle
Unsustainable in the long run	Sustainable in the long run
Low quality of recycled materials often does not compensate for primary raw material dependence	Recycled materials are of good quality thus reducing the need of primary raw materials
Less space requirement	More space requirement for temporary storage deposits

2.1.3 Types of demolition machinery

The machines and tools used vary depending on the demolition technique. The following paragraphs describe typical machinery used for selective and conventional demolition, distinguishing between non-explosive and implosive methods.

Non-explosive method

The non-explosive method of demolition employs hand tools and machines. It is ideally suited for dismantling smaller to medium-sized constructions such as residences or businesses.

This method includes the use of:

- Sledgehammer

The sledgehammer is a heavy-duty hammer used for demolition activities that demand a lot of power. It is made up of a massive, flat metal head and a long wooden handle. (Figure 5).

Figure 5: sledgehammer

- Bulldozers

A bulldozer is a large tractor with a big blade-like shovel at the front and moves around using metal tracks over wheels. A bulldozer is a type of earthmoving machine primarily used to move earth and clear waste from a site (Figure 6)

Figure 6: Bulldozer breaking a bridge

- Wrecking balls

A wrecking ball is a giant steel ball generally suspended from a crane and is used to demolish massive structures. It was most popular throughout the 1950s and 1960s (Figure 7).

Figure 7: Wreking ball demolition

- Standard and high-reach excavators

Excavators are heavy construction equipment consisting of a boom, dipper (or stick), bucket and cab on a rotating platform known as the “house”. The high-reach excavator is a type of excavator that has a very long boom arm and is mainly used for demolition. The high-reach excavator (Figure 8) is designed to reach the upper storeys of buildings that are being destroyed.

Figure 8: High-reach excavator

The excavator has a series of attachments available, the most used of which are:

- demolition shears

They are the most often used demolition tool, at least in Italy; they are simple to operate, and only one person is required to complete the job. They are affordable, act on a particular section of the wall to be removed and are thus appropriate for selective demolition.

Figure 9: Excavator with demolition shear

- Fixed pulverisers

Pulverisers are tools that smash crushed material between one fixed and moving jaw to decrease particle size and extract iron from other materials.

Figure 10: Excavator with fixed pulveriser

- Sorting grapple

In addition to moving concrete blocks, grapples are commonly used to handle logs, wooden beams, pipes, and steel beams. They are available in two varieties on the market:

- hydraulics for equipping working equipment such as truck cranes, excavators, or any lifting means with a hydraulic circuit.
- electro-hydraulic complete with control unit, electric motor, and hydraulic pump, for quick connection to bridge cranes and port cranes.

Figure 11: excavator with sorting grapple

- Demolition bucket

Excavator buckets are commonly used for excavating, tearing, and loading various materials.

Figure 12: excavator with bucket

- Hydraulic breaker

A breaker is a large percussive hammer mounted to an excavator (Figure 13) that is used to smash concrete buildings or rocks. It is driven by the excavator's auxiliary hydraulic system, which is equipped with a foot-operated valve for this reason. Rock breakers are used by demolition crews for operations that are too large for jackhammering or in regions where blasting is not viable owing to safety or environmental concerns.

Figure 13: Excavator with hydraulic breaker

- electro-lifting magnet

The lifting magnet is flexible industrial handling equipment that can accommodate various ferrous objects, from little bundles of rod or waste to massive, heavy blocks. Lifting magnets, unlike slings and chains, may be used to raise loads that would ordinarily need two or more persons.

Figure 14: excavator with electro-lifting magnet

Implosive method

The explosive method is a type of demolition technique that employs explosives to destroy the building's structural supports and cause it to collapse. Explosives are used to demolish tall buildings with multiple floors when shears or a bucket are impractical due to construction times. Once the building has been undermined, it comes down in a few seconds, whereas demolition with a bucket or grapple would take much longer and thus increase costs.

Figure 15: Implosive controlled demolition

2.2 RECYCLING PLANTS

The two primary types of C&D recycling plants differ in the following ways: Fixed plants have foundations and, as a result, cannot be moved. On the other hand, mobile plants do not have foundations and can be moved to other areas, notably on demolition sites. Fixed systems, on the other hand, have more space at their disposal and are thus built to be more complex and ideal for producing a higher-quality product. Fixed plants are more expensive to install, i.e., they cost “turnkey” two or three times the cost of a mobile plant, and they also have the increase in transport costs from the demolition site to the quarry.

2.2.1 Fixed plants

Typically, the management of a fixed plant for C&D waste valorisation is directly integrated with extractive activity in a quarry. In fact, in the case of materials from demolitions that do not contain harmful, dangerous, or polluting materials (due to their elimination during the demolition phase), the quarry systems can be used, with some minor modifications that do not typically necessitate significant investments. There are, however, stationary factories designated solely for the recovery of inert waste from demolition and construction, which can be positioned in strategic places with production centres, with transportation costs being a critical item in the economics of enterprises in the field. Fixed plants are composed of fixed structures as opposed to mobile plants; nevertheless, the disadvantage of lack of mobility is offset by the higher product quality and more effective dust and noise control. This type of plant often features vast operational spaces that allow for more control over product quality and the option of blending recycled material with virgin aggregate to optimise final product performance. Using advanced technology, it is feasible to automatically separate the light fraction (mostly paper, plastic, and wood) included in crushed material. This refining of the product ensures the absence of contaminating components and significantly enhances its mechanical properties.

Figure 16: Fixed Plant

2.2.2 Mobile plants

The increasing spread of mobile plants on the territory is primarily due to their ease of transportation and the potential of being employed near building sites where C&D waste is generated. This capacity to *“follow”* the material to be valorised results in a significant decrease in transportation costs, which is a decisive factor in the economics of producing *“poor”* resources like building aggregates. Most quarry material treatment plant manufacturers provide potential users with at least one transportable unit that may be utilised for waste treatment or the valorisation of demolition materials. These devices are transportable but have a specific design and practical simplicity. The advantage of these machines, particularly the smaller ones ideal for city building sites, is the ability to grind at the same time as the demolition phase, allowing the aggregates generated to be reused on the same construction site or sold to third parties for other purposes. The decision to acquire one machine over another is influenced by several criteria. It is feasible to select machinery that, when placed in sequence, can provide crushing quality standards comparable to those of stationary plants' secondary phases (figure 17). However, if the production of inert waste is consistent, a fixed plant would be more competitive. It would guarantee, at the exact cost, a series of controls through which it is possible to ensure very high-quality standards for the final product.

Figure 17: Mobile plant

In Table 5 an author's elaboration summarizes the fundamental distinctions and characteristics of each system type.

Table 5: Characteristics of fixed and mobile plants

Fixed Plant	Mobile Plant
High customization of the system: it can be defined as a made-to-measure suit, high construction costs, little, if any, possibility of selling as used;	Portability and high flexibility in the implementation of treatment processes: the position within the treatment process can be chosen according to needs;
Installation area: rather large, minimum 1500-2000 m2, area authorized for industrial use, compliance with environmental impact standards;	Reduction of material transport costs, reduction of landfill costs in the case of disposal, reduction/elimination of transport within the quarry;
Operating process: the high degree of customization optimizes, but specializes the plant, different operating processes can rarely be implemented;	No need for connection to other external drive units, independent handling with savings on transport costs on site;
Management logistics: all the material to be treated must arrive at the plant, high transport costs.	High versatility: it can be used to work extreme types of materials; however it is less specialized.

2.2.3 Operational phases

The RAs derived from C&D waste go through a variety of manufacturing processes, which varies depending on the plants (which can be mobile or fixed) employed, as well as the technical advancements generated by the various companies:

- Feeding
- Crushing
- Dust abatement
- Iron removal

- Screening
- Washing

Before the treatment stages, the material passes through an initial step of quality control of the arriving waste to ensure its regulatory and technical admissibility to the facility.

Feeding

The facility is supplied by pouring demolition waste from storage heaps into special devices known as feeders. These machines, manufactured of solid steel to handle enormous pressures, mainly consist of a casing supported by special rubber shock absorbers. The material is divided into different parts using a spinning eccentric mass (at variable speed) required to create the vibrations and unique screens; specifically, the finer fraction is removed while the coarser fraction is transferred to the crushing unit. The feeder performs a preliminary screening of the material. There are numerous power systems to consider, including:

- grizzlies: which distinguishes itself by imposing an inclined push.
- Pre-screening: separating by imposing a circular/elliptical pattern.

Crushing

Crushing is the process of reducing the size of the materials flowing from the feeders to a marketable size. This step is crucial for the recycling process since it is within the crushing chamber that the construction scrap is recovered, which, in addition to shrinking in size, separates the ferrous components from the lithoid ones.

Crushing can occur in numerous ways:

- by the impact of rubble thrown against a resistant wall.
- by compression of the material between two jaws.
- by shredding caused by resistant elements (bars, heavy balls) set in motion together with the material to be shredded.

Typically, the cycle is split as follows:

a. Primary crushing: During this step, the material is reduced, either directly from the construction site or from the plant storage site, with dimensions of up to one meter in length and maximum output sizes of roughly 70 mm.
b. Intermediate crushing: in this step, the primary phase product is further reduced, resulting in product dimensions ranging from 6 to 70 mm.
c. Fine crushing: the result of the second stage is reduced to dimensions on the order of 2 mm (sand and filler).

Given the varied forms of crushing, different crushers will be employed at each step to distinguish between primary, secondary, and tertiary crushers.

Table 6 lists all of the crusher typologies.

Table 6: Crushing machineries

Crusher's typology	Brief description
aw crusher	They are among the most common machines because they are simple, cheap to produce, and long-lasting. Their working principle is simple: they crush the material between two jaws, or two plates, toothed or smooth, in steel or cast iron,

	one of which is fixed, coinciding with the internal surface of a wall of the machine's casing, and the other, called mobile jaw, which approaches and moves away from the previous one, causing the material placed between the two to disintegrate. Feeding occurs from the top; the shape and convergence of the jaws aid in the downward fall of the material, guiding it towards locations where the space between the two plates gradually decreases. This results in progressive crushing, with the end product's maximum size, determined precisely by the distance between the bottom walls of the jaws. The ability to modify this distance gives the machine some adaptability. Because of their sturdiness, these machines are ideally suited to primary crushing.
Gyratory crushers	The crushing principle is the same as that used by jaw machines, except that the fixed jaw, in this case, is in the shape of an inverted truncated cone, and inside it moves eccentrically the mobile jaw, which is also in the shape of a truncated cone, but not upside down. The movement obtained brings the mobile jaw towards and away from the fixed cone, against which it crushes the material fed from above. These are machines with excellent output but are more delicate than jaw crushers and are rarely employed for initial crushing. The output is controlled by raising and lowering the moveable cone. The shaft's lower end serves as the piston of a hydraulic cylinder positioned within the eccentric group. A hydraulic power unit with an inert gas pre-charged accumulator controls the shaft's vertical sliding and crushing shell. The inert substance's regulation and hardness also determine the grain sizes generated in this scenario.
Impact crushers	Crushing occurs in these machines due to the collision of a single element that is rapidly thrown by one or two rotors equipped with high rotation speed (400-1500 rpm) against the internal walls or bars of crushers or other similar devices. Much of the disintegration is caused by collisions between inert materials.
Hammermills	These machines use their impact against a sequence of high-speed revolving hammers attached to a flywheel to shatter the material. These are, without a doubt, the most often-used crushing machines. The impact mill has a crushing factor that

	is more than double that of a jaw crusher. However, it is more prone to wear depending on the materials handled (hammer replacement occurs on average after an output of 12,000 - 15,000 tonnes of debris). Thus, it has higher management expenses.
Roller mills	Two parallel-axed cylinders rotate in opposing directions: the material to be ground is dropped between them in a space bigger than the distance d between the lateral surfaces. The rotation of the cylinders, as well as the friction between the steel surfaces and the inert material, creates grip and, as a result, crushing by crushing. Due to low yields and significant wear, this machine rarely uses secondary crushing to obtain sand.
Rod mills	The material to be crushed enters a hollow, horizontal, revolving cylinder holding heavy metal bars that, as a result of the rotation, are elevated and fall back on the material, grinding it. Feeding can occur from one end, with discharge occurring from the other, or both ends, with discharge occurring in the centre. Sands with superior granulometry are produced using bar mills, making them ideal for castings used in concrete.
Mills for fillers	There are several sorts, ranging from roller mills forced against plates to steel ball mills that, like the previous ones, use bars with heavy balls as crushing agents.

Dust abatement

One of the primary issues encountered in such operations is the significant dust created by the crushing plant, mainly when impact mills are employed. Adopting specific steps to create a healthy work environment for the employees in charge is essential.

There are two types of dust removal systems:

- using nebulized water: it comprises a series of nebulizer nozzles that atomize and ionize the water using a high-pressure compressed airflow

- suction through air flows: comprises a succession of suction hoods outfitted with specific filters that suck up the fine and dusty portion of the material and deliver it into a silo via special ducts.

The material thus collected can be taken to a landfill or reused in suitable processing cycles. In some large plants (fixed plants), the two systems can be coupled to ensure greater efficiency in solving the problem.

The gathered material can then be disposed of or reused in processing cycles. In certain big plants (fixed plants), the two systems can be linked to improving issue resolution efficiency.

Iron removal

This technique permits the ferrous fractions in the crushed material to be removed. It is carried out by sophisticated systems that attract and transport the metallic fractions from the aggregates into particular bins using an electromagnet installed on a rubber roller in continuous motion.

Screening

The product received from the crusher is not marketable because it has not yet been split into various granulometric classes. Another procedure, *screening*, can be used to achieve this separation. This entails passing non-separated aggregates via components having a perforated surface (flat or cylindrical) that are only permitted to pass grains with a diameter less than the control one, as indicated by the hole dimensions. The amount of material that does not pass through the screen’s perforations is described as withheld, whilst what passes is characterized as passing. We can then differentiate in different screening machines listed in Table 7.

Table 7: Screen machineries typologies

Screens' typology	Brief description
Vibrating screens	They are made up of one or more overlapping perforated plates, having larger diameter holes on top and smaller diameter holes on the bottom; mounted on a suspended frame or resting elastically on a frame, they are put in vibration to allow the material to move. Categorizing the content in various sizes is accomplished by overlaying numerous screens.
Rotating screens	In this case, the screening operation is carried out by sending the material to be screened through a hollow cylinder with a perforated sheet metal surface that is placed in rotation; advancement is regulated by the combined effect of the rotating motion and an inclination of the drum axis. During this path, aggregates with diameters smaller than the sheet's perforations traverse and gather between the mentioned surface and the exterior casing, producing the loop. Instead, the held material will exit inside the perforated drum on the opposite side of the feed. Metal sheets can contain holes with varying diameters that grow in the direction of advancement; this results in a natural selection of the material into multiple classes.

Washing

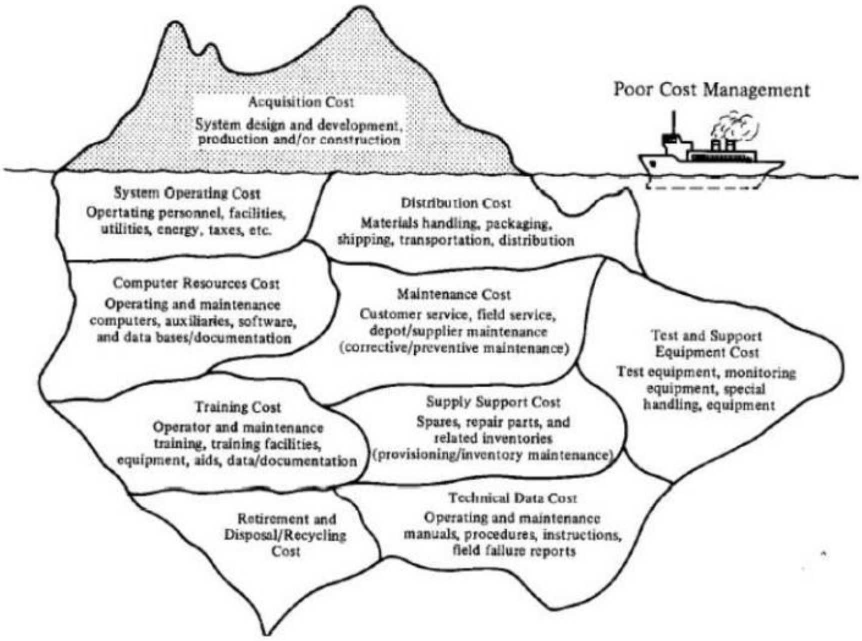
The grains are washed in the last phase to remove pollutants such as humus, clay, dust, and so on from aggregates. Three types of machines are often used: spray washers, cylindrical washing machines, and screw washing machines.

CHAPTER 3.

Methodology: Full environmental Life Cycle Costing

This thesis will present the application of the full environmental life cycle costing (feLCC) methodology. Hoogmartens et al. described the LCC in 2014, categorising it into four types: fLCC, eLCC, feLCC, and sLCC. Conventional LCC (also known as financial LCC (fLCC)) evaluations are limited to private investments by a single actor (a firm or consumer). The Environmental LCC (eLCC) draws on fLCC data, expanding it to include life cycle costs incurred by other actors (in this case, both the demolition companies and recycling plants are considered). In Societal LCC (sLCC), all expenses incurred by anybody in society, whether now or in the future, and related to a product's life cycle are considered. The feLCC methodology, instead, extends eLCC by incorporating monetised, non-internalised environmental costs that may be discovered using environmental assessment approaches such as Life Cycle Assessment (LCA). All the methods used to get the feLCC are provided in the following sub-paragraphs: the LCC, the LCA and the Monetisation of the environmental impacts.

3.1 LIFE CYCLE COSTING



Source: Life-Cycle Costing (Fabrycky and Blanchard, 1998).

Figure 18: Life cycle costing - cost typologies

Rebitzer et al. (2003) defined the LCC as the assessment of all costs associated with a product life cycle that one or more cycle stakeholders directly bear (e.g., supplier, manufacturer, user/consumer). The analysis is divided into four stages: goal and scope definition, inventory implementation, interpretation of the results, and lastly, reporting and review of the findings. The costs that are considered in the execution of an analysis of this type are divided into internal or direct costs and external or indirect costs. Internal or direct costs are incurred by the actors involved in the product's life cycle, whether the producer, supplier or user/consumer. Internal costs can be evaluated in terms of the market price, i.e., the price consumers will pay for the product at the time of purchase, or factor costs, which refer to the production costs incurred by a firm in producing goods and services. External or indirect costs are defined as "non-marketed goods or services" as they do not have a direct monetary value. External costs are, in fact, the result of monetising the social and environmental repercussions caused by the “product” along the entire life cycle. Finally, the so-called social (or societal) costs represent the sum of internal costs with external costs (Martinez-Sanchez et al., 2015). The first LCC application dates back to 1933 when the General Accounting Office of the United States developed a methodology for the purchase of tractors based on the rationale that purchasing decisions should not only be based on the initial acquisition cost but also on the for operation, and, to a lesser extent, for disposal. In 1960, the LCC became mandatory by law for US government procurement of weapons systems and government agency construction programs in several US states (Sherif and Kolarik, 1981). Almost simultaneously in Europe, the LCC began to attract attention in the public sector and was increasingly used to make political and business decisions (Hoogmartens et al., 2014). In 2011, the Society of Environmental Toxicology and Chemistry (SETAC) published a code of practice for LCC, which provides a general framework for evaluating the economic impacts of a decision. On this occasion, it was presented a complete model of all costs incurred by producers, consumers’ owning costs and the actual costs imposed on other stakeholders, aligning them with the requirements of an ISO 14040 compliant LCA (Hunkeler et al., 2008). In 2014, the directives on public procurement were issued (directive 2014/24/EU; directive 2014/25/EU) to encourage the use of the LCC approach and select, through this, the most economically advantageous competitor. Nowadays, although some standards mention the application of LCC, for example, ISO 15663:2021 (Petroleum and natural gas industries — Life-cycle costing — Part 3: Implementation guidelines), ISO 15686-5:2017 (Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing), IEC 60300-3-3 (Dependability management - Part 3-3: Application guide - Life cycle costing), a standard was never formally developed equivalent to ISO 14040/44 which regulate the environmental LCA.

Goal and scope

In this first step, it must be defined the type of LCC to be applied, according to the point of view, of the recipient and the potential objectives that can be linked to the identification of the total costs of a product or the monitoring and management of costs within of the company. In this phase, the functional unit is defined, i.e., the reference object of the study, to which all the data will then be normalised. Finally, depending on the point of view, the boundaries of the system are defined, i.e., which phases of the life cycle must be considered within the study (e.g., production and manufacturing, use and maintenance and end of life of a particular product).

Inventory

The study continues with identifying and quantifying all costs related to the product life cycle. The cost inventory must consider the latter's significant variability based on the reference time and location (Di Maria et al., 2018).

The cost elements to be identified are:

- Direct production costs: e.g., raw materials or direct labour.

- Indirect costs (or hidden costs): e.g., general expenses, indirect labour, waste treatment costs or pollutant abatement.

- Contingent costs: uncertain future costs for environmental damage caused (external costs), which also include external costs that are presumed to be internalised in the short term: for example, costs relating to CO_2 emissions (e.g., for carbon tax o purchase of tradable emission permits).

Depending on the objective, the field of application, and the adopted perspective, it is necessary to identify which of these costs to include and how to organise the data. The problems of data availability, quality and uncertainty make this phase the most critical of the whole methodology.

Interpretation

The purpose of the interpretation is to guarantee that the results and the information gathered from the results fit the requirements of the previously specified research goals. This phase also includes uncertainty and sensitivity studies, which should concentrate on the data with the most significant uncertainties owing to projected parameter changes or value choices.

Reporting and review

The last phase is dedicated to the presentation of the results to the decision-makers. It is necessary that the results are reported in a complete and accurate way and prepared for eventual revisions in view of scientific publications.

3.2 LIFE CYCLE ASSESSMENT

From a methodological point of view, the LCA definition proposed by SETAC, presently formalised in the ISO 14040, is as follows: "LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a product's life cycle from raw materials acquisition, through production, use, end-of-life treatment, recycling, and final disposal". An LCA research contains four phases that should be examined separately (Figure 19) but as part of an iterative process. During data collection, for example, the system becomes acquainted, and new requirements or constraints may emerge, necessitating a modification of the study's goal or scope. Similarly, the interpretation step may result in a review of the scope and the type and quality of the data gathered to meet the set goal.

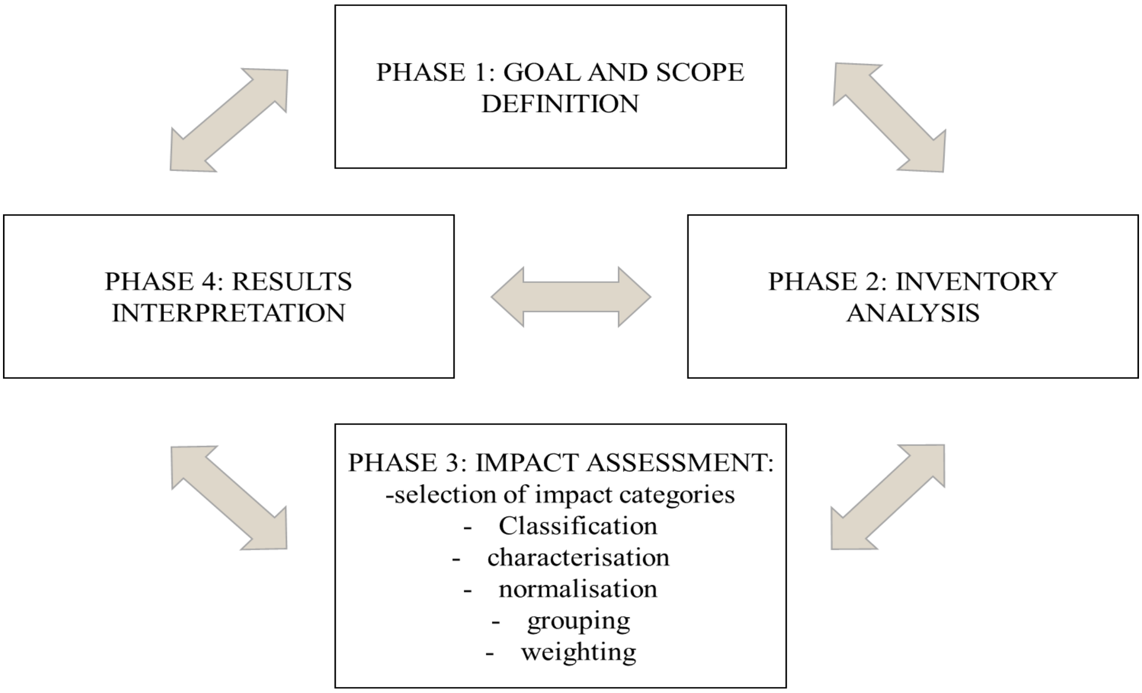


Figure 19: LCA structure

Goal and scope definition

The goal and scope definition distinguishes two separate stages: goal definition and scope definition. The aim definition includes a declaration of the intended application, the study's motivations, the target audience, and if the results will be utilized in comparison assertions. It is critical to grasp the decision-context scenario from the beginning of the research since it is related to distinct modelling principles and methodological choices for solving cases of multi-functionality. There are two modelling principles:

- Attributional modelling depicts the actual or forecasted specific or average supply chain plus its use and end-of-life value chain. The system is hence modelled as it is or was (or is forecasted to be);
- Consequential modelling: it depicts the generic supply chain as theoretically expected as a consequence of the analysed decision.

Many aspects must be defined while establishing the scope of an LCA. The product system to be investigated and its functions, the functional unit, the system boundary, the processes to handle multi-functionality instances, the life cycle impact assessment (LCIA) methodology and types of impacts, and the data quality requirements must all be specified. The system boundary specifies which unit processes are included in the analysis, and the system boundary must be chosen following the study's goal. A full LCA should encompass the whole life cycle (from cradle to grave or cradle to cradle), although some phases are occasionally ignored. The functional unit defines the quantification of the identified functions of the system, and it is defined as the "quantified performance of a product system for use as a reference unit". The functional unit shall be clearly defined and measurable.

Life cycle inventory analysis (LCI)

The inventory analysis is the second step of LCA research. It entails creating a model of reality that accurately represents all interactions between the individual processes of the system under consideration. The purpose of this phase is thus to quantify all of the input and output streams connected with the various stages of the product's life cycle. The functional unit must be referenced in the input and output data. The major headings under which data may be classified include energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products and waste, releases to air, water and soil, and other environmental aspects (e.g., land use).

Life cycle impact assessment (LCIA)

Using the LCI data, the third phase of LCA tries to identify and assess the magnitude and relevance of potential environmental impacts for a product system throughout its life cycle. This procedure entails linking inventory data with specific environmental impact categories and indicators to understand these impacts better. Issues such as choice, modelling and evaluation of impact categories can introduce subjectivity into the LCIA phase. Therefore, transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported. The LCIA phase must comprise the following elements:

- Selection of impact categories, category indicators and characterisation models: The selection of impact categories, category indicators and characterisation shall be justified and consistent with the goal and scope of the LCA. The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, considering the goal and scope.
- Assignment of LCI results to the selected impact categories (classification): this procedure leads to the assignment of the inventory results to the selected environmental impacts, represented by the established environmental impact categories.
- Calculation of category indicator results (characterisation): it involves the conversion of LCI results to standard units and aggregating the converted results within the same impact category.
- Normalisation is the calculation of the magnitude of the category indicator results relative to some reference information. The normalisation aims to understand better the relative magnitude for each indicator result of the product system under study.
- Grouping is the assignment of impact categories into one or more sets as predefined in the goal and scope definition, and it may involve sorting and ranking.
- Weighting: it is the process of converting indicator results of different impact categories by using numerical factors based on value choices. The purpose of this procedure is to get a result represented by a single index, which defines the global impact caused by the examined activity

Interpretation

The life cycle interpretation step includes multiple components:

- The identification of the significant issues based on the results of the LCI and LCIA phases of LCA: the objective of this element is to structure the results from the LCI or LCIA phases to help determine the significant issues, in accordance with the goal and scope definition. Examples of significant issues are:
    a. Inventory data, such as energy, emissions, discharges, waste.
    b. Significant contributions from life cycle stages to LCI or LCIA results, such as individual unit processes or groups of processes like transportation and energy production.
- The completeness, sensitivity, and consistency checks:
    a. Completeness check: its objective is to ensure that all relevant information and data needed for the interpretation are available and complete.
    b. Sensitivity check: its objective is to assess the reliability of the results and conclusions by determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results.
    c. Consistency check: its objective is to determine whether the assumptions, methods and data are consistent with the goal and scope
- Conclusions, limitations, and recommendations: the objective of this part of the life cycle interpretation is to draw conclusions, identify limitations and make recommendations for the intended audience of the LCA.

3.3 MONETISATION OF ENVIRONMENTAL IMPACTS

External environmental costs are externalities that fall on the community, not borne by those who generated them or defined as side effects of economic activities. In short, they reflect an effect exerted by the action of an agent, e.g., through the production or consumption of a good, on another agent (Di Giulio, 1962). The monetisation of externalities is rare since quantifying the external costs inherent in social and environmental factors in economic terms is not always easy and obvious. Externalities are usually categorised as positive (so-called external diseconomies) or negative (so-called external economies). According to Bazzani et al. (1994), an externality is positive when the utility of third parties increases without them having to compensate those who caused the increase in utility. On the other hand, an externality is said to be negative when it causes a decrease in an individual's utility, and no compensation is recognised to him (e.g., water, atmospheric, acoustic, visual pollution). If the effect of the externalities goes from who produces it to who receives it, these will be unilateral. Instead, they will be reciprocal in case each party involved in the externalities is both an active and a passive part. Their interaction leads to the creation of reciprocal benefits or damages. To address the "market failure" caused by those who exploit and pollute natural resources' unwillingness to cover the cost that inevitably falls on the community, legal systems have defined systems for internalizing environmental costs by utilizing the "whom polluter pays" principle (Directive 2004/35/EC). With the internalisation of environmental costs, a category of environmental impact is expressed in monetary value. This value can be based on costs associated with repairing the damage (e.g. Table 8) or prevention (e.g. the amount of money needed to prevent CO2 emissions through energy savings) (Durao et al., 2019).

Table 8: Damage costs due to emissions from different studies (Source: Environmental LCC 2008. (eds) Hunkeler et al. Chapter 4. SETAC)

Emission	UM	ExternE (Best estimate)	ExternE (low)	ExternE (high)	Pace study	Massachusetts study	EPS (2000d)
SO2	€/kg	9.2	1.3	27	3.70	1.24	3.27
NOx	€/kg	10.0	1.1	30	1.50	5.38	2.13
PM10	€/kg	17.0	1.9	50	2.17	3.31	36
Cd	€/kg	67.0	6.7	120	-	-	10.2
Pb	€/kg	10	5.0	15	-	-	2910
CH4	€/kg	0.2	0.043	1.6	-	-	2.72
CO2	€/kg	0.019	0.0038	0.139	0.012	0.018	0.108
CO	€/kg	-	-	-	-	0.72	0.331
VOC	€/kg	-	-	-	-	4.39	2.14
Dioxine	€/kg	290000	29000	520000	-	-	-

The major monetary valuation strategies for calculating the benefits and costs of environmental alterations are based on direct and indirect methodologies. Both techniques are based on the "willingness to pay and accept," also known as "willingness to pay/receive." They may be stated as how much people are willing to pay in exchange for a benefit and how much they are willing to take to bear a certain expense (Alberini et al., 2006). Among the direct approaches, the "Contingent Evaluation" method estimates the worth of a resource based on preferences stated directly by individuals. The evaluation consists of surveys administered to a representative sample of consumers who are asked to declare how much they are willing to pay to preserve a specific environmental asset or how much they would like to receive to renounce its use in a hypothetical market of the goods.

These methodologies serve as the foundation for quantifying the economic cost of air pollution harm to human health (e.g., “value of statistical life” (VSL)). Among the indirect methods, “Hedonic Costs” assumes that an individual’s choice to acquire a property, for example, is based on the environmental and geographical characteristics of the specific real estate market. The “travel cost method” (TCM) estimates an indirect measure of the availability pay for the attractions of a place. Then it quantifies the value using information collected on the frequency of visits of individuals to a specific site and the total costs incurred by them to reach it (e.g., travel, overnight stays).

3.3.1 Main monetisation models

Monetization models are consistent and transparent sets of weighting factors, expressed in currency. They have been proposed by different authors and some of them have been updated over the years. Each model uses different methods, which also follow different approaches, for determining the weights for the various impact categories. Some of the major monetary patterns are listed below (Durao et al., 2019; Lasperini et al., 2021).

- Eco-costs
- Ecotax
- Ecovalue
- Environmental Prices
- EPS
- ExternE
- LIME
- Stepwise

The weighting systems available in the literature have the benefit of being well-known, documented, and subject to expert assessment. They do, however, carry the risk of being employed uncritically, in unsuitable regions, and in circumstances other than those for which they are designed. Despite comprehensive literature on the various models, understanding and reconstructing the procedures used to determine the weights is not always simple. (Ahlroth, 2014).

Table 9 shows the key characteristics of the models indicated above.

Table 9: Monetisation models (Source: Durao et al. 2019)

Monetisation model	Brief description
Ecotax 2002	It is a monetization strategy based on Swedish eco-taxes and emissions and resource use taxes. It is assumed that political decisions reflect society beliefs about environmental issues. All weighing and tax information is given in Swedish crowns (SEK) (Swedish krona).
Stepwise 2006	It is a monetization approach based on the Ecoindicator99 LCIA (Life cycle impact assessment) method (endpoint method), which generates physical ratings for each of the three safeguard subjects: man, ecology, and resources.
Ecovalue 2008	The approach uses weighting parameters to aggregate midpoint indications on the influence of a monetized endpoint indicator at the mid-level (which evaluates impact from the perspective of who is ultimately impacted). It is based on resource depletion market evaluations and individual willingness-to-pay (WTP) estimations for environmental quality.
Eco-costs	The technique refers to the most often used environmental categories in the environmental evaluation of building materials and assemblies that are compatible with the environmental information contained in the EPD (Environmental Product Declaration).
Environmental prices	Indicates the loss of economic well-being deriving from each additional kilogram of pollutant released into the environment and often coincides with external costs.

Strategies in product design (EPS)	EPS is an approach for choosing between design options in product and process development. The results of the EPS impact assessment method are damage costs for emissions and use of natural resources expressed as ELU (Environmental Load Units). One ELU represents an externality corresponding to one Euro environmental damage cost.
External costs of energy (ExternE)	It is based on a European Commission-funded initiative that began in 1995 with the goal of monetizing the socio-environmental harm produced by various energy vectors. ExternE conducts a thorough and methodical analysis of the full cause-and-effect chain, from charges or emissions to environmental consequences and damages. Market pricing or "willingness to pay" are used to analyse the effects.
LIME	The method is based on endpoint indicator modelling and aims to develop a database to assist industries in implementing reliable LCA studies.
Social Costs of Carbon (SCC)	SCC represents the economic cost associated with climate damage resulting from the emission of an additional ton of carbon dioxide (tCO_2).

The final findings might vary greatly depending on the chosen and used model; thus, it is vital to describe the choices and assumptions clearly and transparently. Above all, it is important to consider these changes when evaluating the results of a study (Arendt et al., 2020; Lasperini, 2021). Because each model has unique characteristics in terms of place, culture, and time, it is impossible to directly compare the various weighting elements of the various models. These characteristics determine whether they are appropriate for specific evaluations and, as a result, give guidance on their potential uses. In reality, no model is superior to the others: it is required to assess which is more appropriate based on the features of the given scenario. In a complicated impact analysis including several environmental elements, it is therefore important to employ a variety of models tailored to the individual instance (Pizzol et al., 2015). According to the review carried out by Pizzol et al. (2015) (Lasperini, 2021) the LIME and Stepwise models are the best in the field of

LCA studies. However, it specifies that the evaluations expressed are in part subjective and at least valid only in the specific context examined. A crucial challenge is the lack of a strategy shared and accepted by the scientific community to define how the set of weights is derived and what the appropriate field of application is. This gap unavoidably makes selecting a weight system or systems less clear. Another point to consider is the impact categories: certain models include weights for damage categories derived from data about impacts that may be inserted in the final phase of the environmental mechanism. On the other hand, others supply monetary weights based on data related to occurrences observed at the beginning of the environmental mechanism. Furthermore, while certain impact categories have the same name in different models, they may not always correspond to the impacts and effects studied (Ahlroth et al., 2014).

CHAPTER 4.

Previous LCT studies on C&D waste management

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. In a case study in the Netherlands for demolition, recycling, and new construction, Hu et al. (2017) used LCC and LCA to determine the environmental and economic hotspots in selected demolition and waste management. According to the findings, combining new buildings 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 potentially reduce life cycle costs by 23%. The recovery of metal fraction is a necessary measure since it has the highest economic value (although accounting for just 6% of the total recovered material by weight). Using RAs in new construction is environmentally friendly since it avoids raw material extraction and reduces aggregate supply transportation. From an environmental perspective, the demolition phase bears 52% - 90% of the burden of the investigated impact categories. Mah et al. (2018) investigates the amount of concrete waste generated during various Malaysian projects' building and demolition stages and its improper management, which frequently has a substantial environmental impact. The primary purpose of this research is to identify the most environmentally favourable scenario for handling concrete waste. The LCA modelling is used to calculate the environmental impact and GHG (Greenhouse gas) emissions, whilst the LCC is employed as an economic extension of the LCA. In comparison to landfilling, recycling concrete waste to replace natural aggregates in concrete production offers the best eco-efficiency (lowest environmental and financial impacts). This study also revealed that transportation distances and mining operations are the two most important factors influencing GHG emissions and cost effects. Mobile recycling plants should be as close to the waste producer and recovered material demand point as possible to offset the distance between the building site and the landfill to maximise environmental and economic benefits. C&D waste should be recycled in mobile recycling facilities to reduce environmental consequences and reused as road substrate material rather than being sent to a landfill. Furthermore, Di Maria et al. (2018) demonstrates that integrating LCA and LCC data can reveal the environmental and economic drivers of C&D waste management in the Belgian Region of Flanders. The findings of the comprehensive research can help policymakers promote all alternatives that contribute to sustainability while minimising those that cause hurdles. The results suggest that boosting high-quality C&D waste recycling can significantly reduce the overall environmental impact of the system. When compared to landfilling, the recycling has an environmental impact reduction of 36%. The major environmental advantage of recycling is the avoidance of landfilling of C&D waste and the substitution of natural resources with recovered materials. The most significant benefit of selective demolition is the recovery of materials (metals and wood) during the demolition process. Finally, the authors show that LCC results are more successful than LCA results in identifying conflicts of interest among the various participants.

Dahlbo et al. (2015) take a similar approach, comprehensively evaluating Finnish C&D waste management using LCA, LCC, and other approaches. The data revealed that the metal treatment worked well in all assessments. In terms of climate change implications, costs, and material recycling, mixed C&D waste is the worst proportion. It was determined that the evaluation should be based on system-level rather than installation-level analyses. LCA might be used to supplement the evaluation in finding hot spots, i.e., activities or processes that contribute the most to the overall chain’s environmental performance. In addition to the LCC approach, other economic evaluation approaches have been used. For example, Coelho & de Brito (2010) conducted a “global cost” analysis in Portugal comparing selective demolition to conventional demolition. According to this study, selective demolition is more expensive than conventional demolition, with labour costs around six times higher in the latter due to the increased time required to complete the operation and the limited usage of mechanical equipment. It is proposed that landfill fees in the Lisbon Region be raised from 90% to 1500% to make most selective demolition operations economically comparable to conventional demolitions. Also, in the Portuguese context, Coelho & de Brito (2013) conducted 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. Cost data is typically gathered from a wide range of sources, making it challenging to create a uniform data set for a study. Furthermore, some data may be business sensitive. Different industry sectors have established cost models and language that may need to be reconciled while creating the inventory. Another challenge is that cost data can be more volatile than physical units, and geographic location significantly affects study results due to cost variability and market fluctuations (Islam et al. 2015; Di Maria et al. 2018; Swarr et al., 2011). The following research, which used just LCA analysis, all came to the same conclusion: recycling is only sometimes the best environmental choice due, especially to the high emissions deriving from the C&D waste transportation and the emissions of the recycling plants. The key points recommended by the studies to improve the environmental performance of the system, so, are the increase in the demand for recycled aggregates, supporting their use in the construction sector. In Lombardy, Borghi et al. 2018 demonstrated that, under the current scenario, the advantages associated with C&D waste recycling (owing to natural resource substitution) could not match the burdens caused by the other management stages (mainly from transport). Many evaluated alternatives revealed no or minimal gains over the present condition. Plants powered by electricity and with a shorter delivery distance for C&D waste are settings where some improvements can be found. The most significant benefit is achieved when all the RAs generated are of high quality, and the complete number is sold. Butera et al. (2015) showed that in the context of Denmark, using C&D waste in road construction as a substitute for natural gravel is preferable to landfilling in most environmental impact categories. Transportation of C&D waste and avoided transportation of natural aggregates are the most critical processes for most non-toxic categories and one toxic category (carcinogenic human toxicity), accounting for 60-95% of total impacts. Leaching contributed significantly to freshwater eutrophication and human and environmental toxicity. The Spanish study conducted by Mercante et al. (2012) indicated that the consumption of fuels and energy by transport, sorting, and landfilling contributes to higher environmental impact in all categories. The benefits are attributed to recycling plastics, metals, aggregates, cardboard, and wood, except for climate change for wood and cardboard, where recycling emissions are higher than those of comparable virgin materials. Rosado et al. (2019) highlighted the importance of avoiding impacts from recovered materials, particularly those associated with recycling steel, glass, and plastics. The findings of the various scenarios, on the scientific paper, show that increasing recycling and producing medium-quality RAs improves the impact categories of acidification and respiratory inorganics. However, even though the mineral fraction constitutes a significant amount of C&D waste, its recycling does not appear to be noteworthy in terms of avoided impacts. In contrast, its contribution to transportation impacts is significant, accounting for 76% of total crude oil used throughout the management system. Borghi et al. (2018), Mercante et al. (2012), and Rosado et al. (2019) proposed selective demolition in civil construction and demolition activities; however, it is not included in the system they analysed. Instead, Rigamonti and Pantini conducted a study in 2019 that evaluated the environmental performances of selective demolition: the results show that environmental sustainability is heavily dependent on the characteristics of the building to be demolished as well as local markets for recycled materials. Selective demolition alone cannot solve the problem because a good waste management system must follow it. Table 10 summarises the scientific literature discussed before.

Table 10: Summary of the studies analysed

Article	Geographic location	Methodologies applied	System Boundaries	Main findings
Hu et al. (2017)	Netherlands	LCC LCA	Demolition, recycling, and new construction	Integrating new construction with demolition projects maximises reuse potentials, especially materials, and may save up to 23% on life cycle costs. The demolition phase accounts for 52% - 90% of the environmental impact categories examined.
Mah et al. (2018)	Malaysia	LCA LCC	Demolition, recycling, and new construction	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.

Di Maria et al. (2018)	Belgium	LCA LCC	C&D waste end-of-life: Landfilling and Recycling	Increasing high-quality C&D waste recycling can significantly lower the system's total environmental effect. When compared to landfilling, the recycling has an environmental impact reduction of 36%. In the case of recycling, the main environmental benefit comes from the avoided landfilling of C&D waste and the substitution of natural resources with recycled materials. In the case of selective demolition, the most important benefit comes from the recovery of materials (metals and wood) during the selective demolition.
Dahlbo et al. (2015)	Finland	LCA LCC BAT (best availabl e technolo gy)	C&D waste end-of-life: Landfilling and Recycling	The metal treatment performed well in all the assessments, while mixed waste is selected as the worst fraction in terms of climate change impacts, prices, and material recycling.
Coelho & de Brito (2010)	Lisbon	Global cost	Demolition	Selective demolition is more expensive than conventional demolition, with labour costs around six times higher in the latter due to the additional time necessary to finish the operation and the restricted use of mechanical equipment.

Coelho & de Brito (2013)	Lisbon	Cost-benefit analysis	C&D waste recycling	The material input gate fee in recycling plants is the largest share, providing around 86% of all cost benefits.
Butera et al. (2015)	Denmark	LCA	C&D waste management	In most environmental impact categories, using C&D waste in road construction as a substitute material for natural gravel is preferable than landfilling. The transportation of C&D waste and the avoiding of natural aggregate transportation account for 60-95% of total impacts.
Borghi et al. (2018)	Italy	LCA	C&D waste management	The advantages of C&D waste recycling (owing to natural resource substitution) cannot offset the burdens imposed by the other management stages (mainly from transport). Instead, the greatest benefit is achieved when all the RAs generated are of excellent quality and the complete production is sold.
Mercante et al. (2012)	Spain	LCA	C&D waste management	For all impact categories, the main benefits are attributable to recycling of plastics, metals, aggregates, cardboard, and wood, except for climate change for wood and cardboard, where recycling emissions are higher than those of the comparable virgin products.
Rosado et al. (2019)	Brazil	LCA	C&D waste management	The findings highlighted the importance of avoiding impacts from recovered materials,

				particularly those linked to recycling steel, glass, and plastics. Although the mineral component represents a significant amount of C&D waste, its recycling is insignificant in terms of avoided impacts. In contrast, its contribution to transportation impacts is significant, accounting for 76% of total fuel consumption.
Rigamonti and Pantini (2019)	Italy	LCA	Demolition	The environmental sustainability is heavily dependent on the characteristics of the building to be demolished as well as local markets for recycled materials. Selective demolition alone cannot solve the problem because a good waste management system must follow it.

CHAPTER 5.

Environmental Life Cycle Costing of the C&D waste management chain

As indicated in Chapter 3, the first step in achieving a feLCC study is to apply the eLCC to the C&D waste management chain (to the demolition and recycling stages). This section explains how the approach is developed.

5.1 GOAL AND SCOPE

As stated in § 3.1 the goal and scope of the project must be defined. The goal of this eLCC is to evaluate all the internal costs of the C&D waste management chain in Italy. The functional unit chosen for the system is the demolition of a cubic meter (m^3) of building, to which all inventory data has been reported. Figure 20 shows the system boundary investigated. The hatching area, under examination, includes all management phases of inert waste originating from demolition activities, from its generation at the end of building life, during a demolition (that can be conventional or selective), to the treatment phase in a C&D recycling plant, till the market re-placing as RAs. All outputs with a destination other than recycling (e.g., disposal) have been examined, as well as transportation between phases.

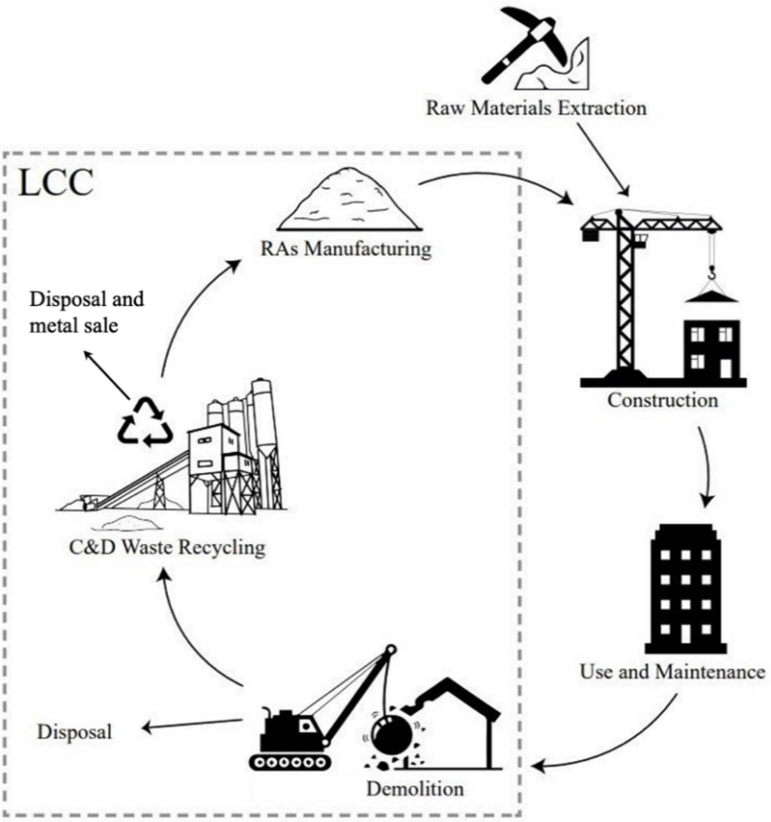


Figure 20: The system boundaries represented by the hatching area

5.2 INVENTORY

The inventory is implemented for each process in the management chain, with two surveys issued to demolition companies and C&D recycling facilities, respectively.

5.2.1 Data Collection

66 demolition businesses and 27 recycling companies were contacted over the eight-month data collection period. 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%) were obtained. The response rate reflects the information's high level of confidentiality. Among the gathered demolition cases, the commercial building typology predominates, with just one case belonging to the residential category and one to the school building type. Even though the questionnaire was distributed throughout Italy, all case

studies are from the Lombardy area (Northern Italy). Building materials are an important aspect of the building industry, and they have a substantial impact on construction output. 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. The choice of building material is determined by the client, designer, and contractor, considering technical parameters such as strength, and durability, as well as availability, cost, compliance with standards and codes, the familiarity of contractors with the technology, and the availability of a workforce with the necessary skills (Pheng & Hou. 2019). Concrete/masonry and metal structures are the two most common types of buildings depending on the principal material used in construction.

5.2.1 Setting up of the questionnaire for demolition companies

The demolition case study survey is divided into five macro-sections, which comprise basic information and all expenses related to the preliminary cost, machinery purchase costs, operational costs, and disposal and recycling costs. The questionnaire sections are described in full below.

Section 1. General information

The first section (Table 11) includes general information such as the demolition company name and the intended function (see § 1.2.3) of the demolished structure, i.e., the specific use for which a building is projected and built, which must be documented. The volume empty to full [m3], the technique of demolition (see § 2.1), and the duration [h].

Table 11: General information

Data requested	Detailed requests and calculations	Unit
Company name	-	-
Intended function	○ Commercial ○ Housing ○ Services	-
Year of construction	-	year
Volume (empty to full)	-	m^3
Type of demolition executed	○ Selective ○ Conventional ○ Total ○ Partial	-
Demolition timeframe	-	hours

Section 2: Preliminary costs

The preliminary phase might be more or less expensive depending on the type of building. In any case, the companies must face the costs of the demolition project [€], planning and preparation [€], eventual building reclamation [€], safety charges [€], and environmental due diligence [€], the procedure that examines the environmental conditions and dangers connected with a property (Polidoro, 2020) (Table 12). The Traditional Environmental Due Diligence (TEDD) ensures that hazardous materials and pollutants are properly found, handled, permitted, and mitigated.

Table 12: Preliminary costs

Data requested	Detailed requests and calculations	Unit
Demolition project	-	€
The setting of the demolition site	-	€
Building reclamation	-	€

Security wages	-	€
Environmental due diligence	-	€

Section 3: Machinery acquisition costs

Each piece of machinery employed during the demolition activity (see § 2.1.3) must have an estimated lifespan [h], purchase price [€], and hours of usage [h] (refer to a specific demolition). The equipment's overall cost, referred to as the single intervention, is calculated by multiplying the hourly cost (purchase price/lifespan) by the number of hours employed during the demolition (Table 13).

Table 13: Machinery acquisition costs

Data requested	Detailed requests and calculations	Unit
Typology	○ Excavator ○ Tower crane etc..…	
Expected lifespan		years
Acquisition cost		€
○ ***Hourly cost***	*acquisition cost/lifespan*	€/hour
Usage time		hours
Total intervention cost	*hourly cost x usage time*	€

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 [€] (Table 14). The reported annual costs are divided by the average number of working hours per year (2024 h) to convert machine maintenance and personnel wages to euros.

Table 14: Operative cost

Data requested	Detailed requests and calculations	Unit
Machine maintenance		€/year
○ ***Hourly cost***	*annual cost / 2024*	€/h
○ ***Total***	*hourly cost x demolition time*	€
Personnel wages		€/year
○ ***Hourly cost***	*annual cost / 2024*	€/h
○ ***Total***	*hourly cost x demolition time*	€
Insurance		€
Consumption	Energy	kWh
	○ Bill cost	€/kWh
	○ *Total*	€
	Fuel	Litres
	○ Bill cost	€/litre
	○ *Total*	€
	Water	Litres
	○ Bill cost	€/litre
	○ *Total*	€

Section 5: Disposal and Recycling costs

The final section of the survey is divided into tabs based on whether the produced flow is sent to a landfill, for disposal with energy recovery, for recycling, reused on-site (after proper treatment with a crusher and mobile screen), or third-party managed. Each module requires the type of waste (using the EWC code, see § 1.1, Table 1) and the relative quantity, as well as the gate fee [€/t] (with a negative sign if it represents revenue, e.g., metals sale) and the relative transport costs [€/t] (Table 15).

Table 15: Disposal and Recycling cost

Data requested	Detailed requests and calculations	Unit
Typology of waste	EWC code	-
Destiny	○ Landfill ○ On-site reuse ○ Recycling ○ Third-party management	
Quantity		tonnes
Gate fee		€/tonne
Transport cost		€/tonne
Total cost	*quantity x gate fee + quantity x transport cost* ○ Landfill ○ On-site reuse ○ Recycling ○ Metal sale	€

5.2.2 Setting up of the questionnaire for the recycling facilities

The recycling plant questionnaire is organized into six macro sections. The six sections collect general facility information as well as all expenses associated with preliminary costs, machinery investment costs, operational costs, and incoming and outgoing flows (e.g., RAs).

Section 1. General information

The basic information includes the plant name, location, site area [m^2], plant type (see § 2.2), estimated lifespan [y], and treatment capacity [t/y] (Table 16). The actual tonnes handled in the reference year are calculated by adding the incoming waste tonnes declared by the facility.

Table 16: General information

Data requested	Detailed requests and calculations	Unit
Plant name Localization		
Site area		m^2
Treatment capacity		tonnes
Tonnes treated per year		tonnes/year
Expected lifespan		years
Plant type	○ Mobile ○ Fixed	

Section 2. Preliminary costs

These are the expenses incurred for acquiring the plant location [€], insurance [€], and end-of-life machinery [€] (Table 17). These expenses occur at the start of the facility activity or on a one-time basis (e.g., for machinery end-of-life). As a result, the yearly cost is estimated by dividing them by the projected lifespan of the plant.

Table 17: Preliminary costs

Data requested	Detailed requests and calculations	Unit
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

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) (see § 2.2.3) are the expected lifespan [y], the cost of purchasing [€], and the duration of usage during the year [h/y] (Table 18). 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 throughout the year.

Table 18: Machinery acquisition costs

Data requested	Detailed requests and calculations	Unit
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*	€

Section 4. Operative costs

The operating expenses of a waste treatment plant are the costs of machinery maintenance [€/y], yearly employee wages [€/y], security wages [€/y], and energy, fuel, and water consumption (Table 19). Furthermore, the CE certification level of the aggregates generated is required by EU Regulation 305/11 on building goods placed on the market and the current Legislative Decree 106/17 on construction products (including recycled ones). The survey questions the degree of CE certification (system 2+, which includes an initial examination of the recycling facility and continuous monitoring, evaluation, and verification) and the comparable yearly cost (€/y). The cost per tonne treated is calculated by dividing the yearly charge by the number of tonnes treated.

Table 19: Operative costs

Data requested	Detailed requests and calculations	Unit
Machine maintenance		€/year
Personnel wages		€/year
Security wages		€/year
CE certification	○ Level 2+ ○ Level 4	€/year
Consumption	Energy ○ Bill cost ○ *Total*	kWh €/kWh €
	Fuel ○ Bill cost ○ *Total*	Litres €/litre €
	Water ○ Bill cost ○ *Total*	Litres €/litre €

Section 5. Input flows

For each entering flow recognized by the EWC code, the incoming quantity [t] and the cost of access [€/t] (the so-called gate fee) are needed (Table 20). By multiplying the entering amount by the corresponding gate fee, the total income owing to incoming flows is computed.

Table 20: Input flows

Data requested	Detailed requests and calculations	Unit
Typology of waste	EWC code	-
Quantity treated		tonnes
Gate fee		€/t
Total revenue	*Quantity treated x gate fee*	€

Section 6. Output flows

This section includes all streams separated from inert mineral waste that cannot be processed at the plant and consequently have a different destination (Table 21), as well as the manufacturing and sale of RAs (Table 22). The type, end destination, amount [t], and landfill cost [€] or selling price (in the case of metal streams) are all provided for these outflows.

Table 21: Output flows (a)

Data requested	Detailed requests and calculations	Unit
Typology of waste	EWC code	-
Destiny	○ Landfill ○ Recycling	
Quantity	-	tonnes
Disposal cost/revenue		€/t

	Quantity x disposal cost/revenue ○ Landfill ○ Metal sale	€

The second part of the output flows section is dedicated to RAs products, which must 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 22: Output flows (b)

Data requested	Detailed requests and calculations	Unit
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	%

5.2.3 Case studies – Demolition

This section offers an overview of the specifics of the seven cases gathered.

Case 1

Case 1 refers to the selective demolition of a commercial building (built in 2004) of 550.000 m^3 located in Cinisello Balsamo (MI) (Table 23).

Table 23: Case 1 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Cinisello Barsamo (MI), Lombardy	Commercial masonry/concrete structure	2004	550.000 m^3	Selective	6500 hours

Case 2

Case 2 refers to the selective demolition of a commercial building of 385.000 m^3 located in Cassina de'Pecchi (MI) (Table 24).

Table 24: Case 2 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Cassina de' Pecchi (MI), Lombardy	Commercial, masonry/concrete structure	n.a.	385.000 m^3	Selective	25000 hours

Case 3

Case 3 refers to the selective demolition of a residential building (built in 1970) of 62.000 m^3 located in Ciserano (BG) (Table 25).

Table 25: Case 3 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Ciserano (BG), Lombardy	Residential, masonry/concrete structure	1970	62.000 m^3	Selective	2500 hours

Case 4

Case 4 refers to the selective demolition of a school building (built in 1960-70) of 18.800 m^3 located in Milano (MI) (Table 26).

Table 26: Case 4 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Milano (MI), Lombardy	School building, masonry/concrete structure	1960-70	18.800 m^3	Selective	2500 hours

Case 5

Case 5 refers to the selective demolition of a commercial building (built in 1960) of 36.155 m^3 located in Bergamo (BG) (Table 27).

Table 27: Case 5 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Bergamo (BG), Lombardy	Commercial, masonry/concrete structure	1960	36.155 m^3	Selective	470 hours

Case 6

Case 6 refers to the selective demolition of a commercial building (built in 1970) of 33.350 m^3 located in Pero (MI) (Table 28).

Table 28 : Case 6 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Pero (MI), Lombardy	Commercial, metal structure	1970	33.350 m^3	Selective	992 hours

Case 7

Case 7 refers to the selective demolition of a commercial building (built in 2002) of 80.000 m^3 located in Bergamo (BG) (Table 29).

Table 29: Case 7 - Specifics

Location	Typology of building	Year of construction	Volume (empty to full)	Demolition method	Demolition time-frame
Bergamo (BG), Lombardy	Commercial, metal structure	2002	80.000 m^3	Selective	400 hours

5.2.4 Case studies – Recycling plants

Both C&D recycling plant scenarios apply to mobile plants with varying yearly treatment capacities. Plant 2 processed little over 54,000 tons despite having a treatment capability of 240,000 tons per year (Table 30), whereas Plant 1 has nearly reached its full treatment capacity (Table 31).

Table 30: Plant 1 - Specifics

Location	Plant area	Treatment capacity	Treated tonnes 2019	Expected Lifespan	Typology
Merate (LC), Lombardy	13000 m2	160000 tonnes	121017,68 tonnes	50 years	Mobile Plant

Table 31: Plant 2 - Specifics

Location	Plant area	Treatment capacity	Treated tonnes 2019	Expected Lifespan	Typology
Montichiari (BS), Lombardy	25620 m2	240000 tonnes	54033,23 tonnes	10 years	Mobile Plant

5.2.5 Destiny of the waste flows

Following the economic inventory, the first evaluation that may be undertaken concerns the destiny of waste flows generated by demolition activities. The first five cases involved the selective demolition of concrete masonry buildings, which generated a wide range of debris with various final destinations. Figure 21 depicts the proportion of the destination of all waste flows leaving the demolition site in the first five examples. In the first three cases, more than 95% of the waste is reused on-site. In case four, 96% of the entire waste component is disposed of in a landfill, whereas 96% of the total production is recycled in case five.

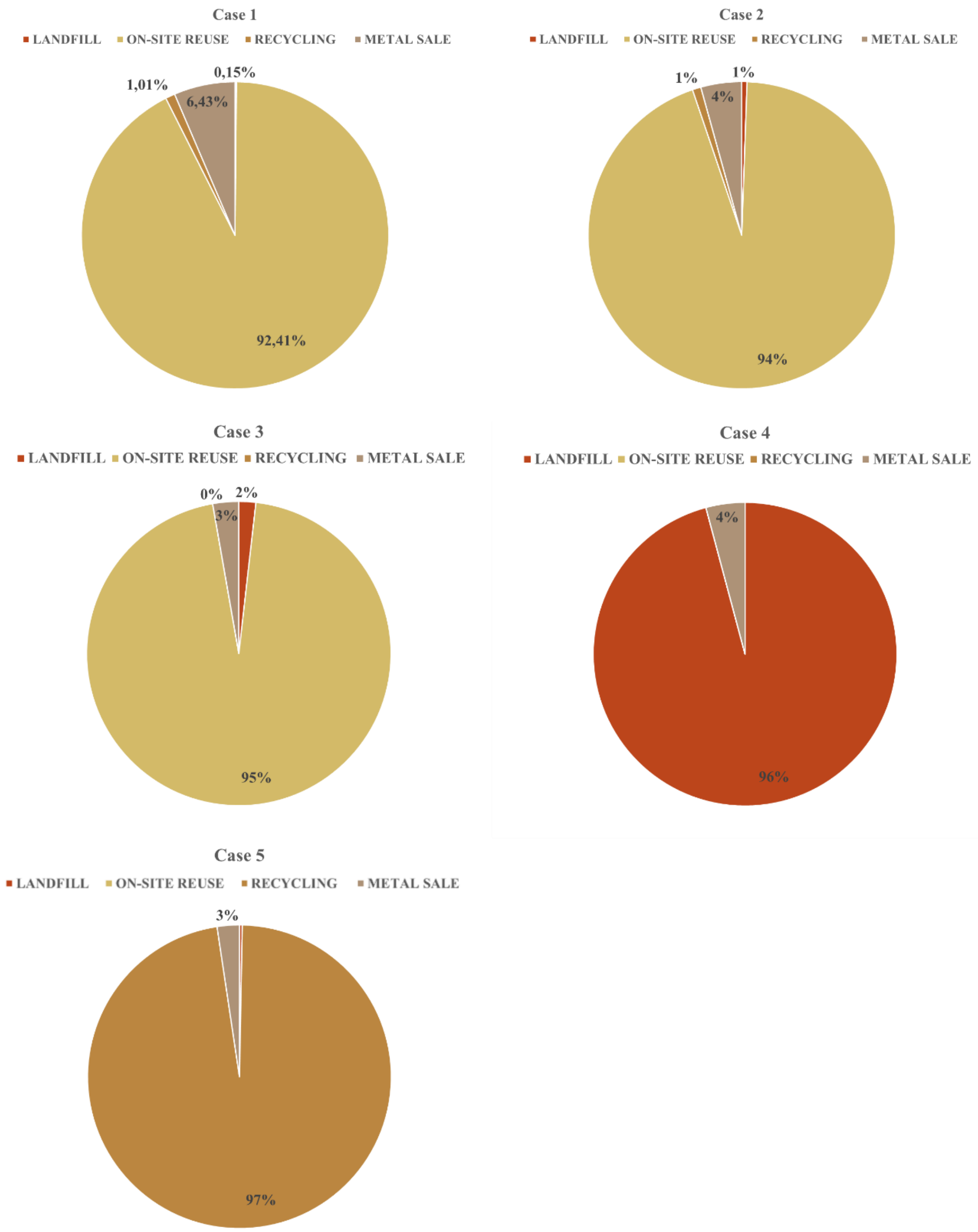


Figure 21: Destinies of the waste flows of case 1 to 5

Figure 22 shows that in the last two cases of selective demolition of metal structure buildings, 77% of the metal was sold, and the remaining debris was transported to a recycling plant.

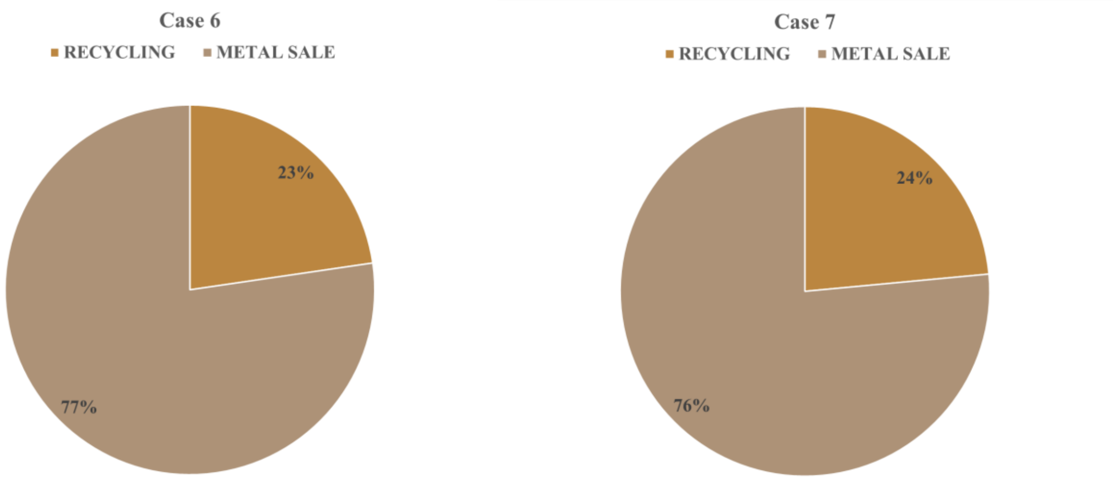


Figure 22: Destinies of the waste flows of case 6 and case 7

5.3 RESULTS

To calculate the final eLCC value, the LCC analyses applied throughout the demolition and recycling phases are combined. All values must be reported to the functional unit in the form of m^3 of demolished building. The values derived from the demolition survey questionnaire are reported in €/m^3 demolished, whereas it is necessary to normalize the recycling questionnaire' values expressed in €/t (euro per tonne treated in the plant). The result of the eLCC in average value is provided in the paragraph below (§ 5.3.2). Annex I show all of the eLCC values for each individual case.

5.3.1 Recycling plant costs

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 shown in Table 32, 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).

The calculation to report all the cost in €/m^3 demolished (FU) 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 in a demolished cubic meter [t/m^3] (data extracted from the demolition companies' questionnaire) and the obtained values are shown in table 33.

Table 32: 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 from output flows	***-2.88 €/t***
	Revenues from input flows	***-12.28 €/t***

* The value is insignificant.

Table 33: Specific recycling value reported to functional unit for each case

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Inert to recycling	0.0011 t/m3	0.0007 t/m3	0.00 t/m3	0.00 t/m3	0.242 t/m3	0.054 t/m3	0.056 t/m3
Recycling cost (see table 33)				3.21 €/t			
Value reported to FU	0.003 €/m3	0.002 €/m3	0.00 €/m3	0.00 €/m3	0.78 €/m3	0.17 €/m3	0.18 €/m3

5.3.2 Full chain costs

The results of the arithmetic mean for each cost item of the seven cases (see §§ A1.1- A1.7) are displayed in Table 34. 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 values in €/m^3 (Table 35) are determined by dividing each cost by the empty to full volume of the demolished structure. The highest costs, within the preliminary ones, are those borne for safety charges and removing hazardous materials from the building (mainly materials containing asbestos). Among all the machinery employed, the data show 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 gate fee of the recycling plant is excluded from the calculation to combine the two LCC analyses on demolition and recycling. The calculation excludes revenue from metal sales, which will be subject to a subsequent sensitivity analysis (see § 5.4). The average overall cost of the whole chain is 7.04 €/m^3.

Table 34: eLCC: average full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.06 €/m^3
	The setting of the demolition site	0.08 €/m^3
	Building reclamation	0.50 €/m^3
	Security wages	0.72 €/m^3
	Environmental due diligence	0.02 €/m^3
Machinery acquisition costs	Machinery acquisition	1.99 €/m^3
Operative costs	Machine maintenance	0.46 €/m^3
	Personnel wages	1.23 €/m^3
	Insurance	0.05 €/m^3
	Consumptions	0,42 €/m^3
Disposal and recycling costs	Landfill fee	0.52 €/m^3
	Transportation	0.25 €/m^3
	On-site reuse	0.50 €/m^3
	Recycling (excluding inert waste)	0.08 €/m^3
	Recycling inert waste*	0.16 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***7.04 €/m^3***

** Average value from table 32*

Figure 23 shows that operating costs (31%) and machinery acquisition costs (28%) weigh the most on the total eLCC value. Disposal costs demonstrate that landfill expenses much outweigh recycling fees, and the cost of on-site reusing is equivalent to a landfill fee.

However, because the recycling activity is done directly at the demolition site, it has the advantage of lowering transportation expenses.

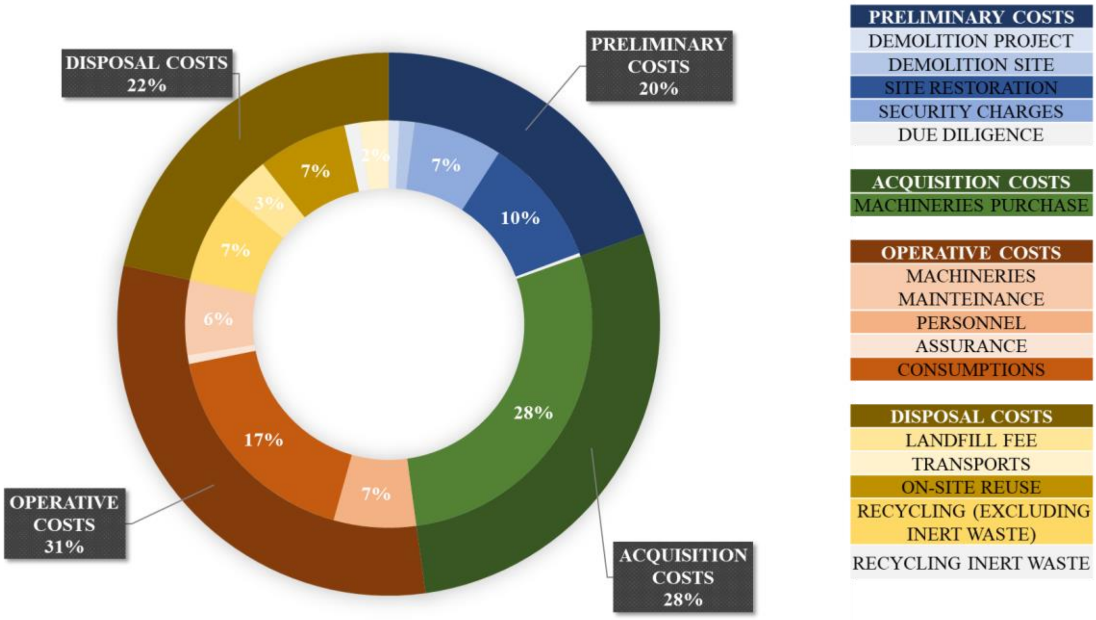


Figure 23: Percentage of contribution of the different cost items

5.4 SENSITIVITY ANALYSIS

Table 35a 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 is 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, cost items with a difference between maximum and minimum of more than 2.00 €/m^3 have been selected. 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 35a: eLCC - total range (min-max) and average value (wide range values are in italics)

	Cost item	a. Min	b. Max	c. 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

* Data obtained from the LCC on recycling plants

Table 36b: eLCC - total range (min-max) and average value (wide range values are in italics)

Scenarios	Brief description	Total eLCC value
Base-case	Average cost (Table 35a, column c.)	7.04 €/m^3
Best-case	Replacing the cost with the most significant variability margin with the minimum's values. (Table 35a, column a.)	3.13 €/m^3
Worst-case	Replacing the cost with the most significant variability margin with the maximum's values (Table 35a, column b.)	16.16 €/m^3

The starting scenario is the one with the average cost resulting in the value chain cost of 7.04 €/m^3. It is decided to evaluate the cost related to the best and worst scenarios. In the best-case scenario, the cost with the most significant variability margin has been replaced with the minimums defined in table 35a. The total cost of the supply chain in this way would be reduced by 55%, reaching the final cost of 3.13 €/m^3 (Table 35b). On the contrary, in the worst-case scenario, the five cost items are replaced with the maximum values, resulting in an increase of more than double of the cost up to 16.16 €/m^3 (Table 35b).

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. To test the cost variation caused by the addition of metal fluxes, the cases are divided into two macro-categories: buildings with a predominantly masonry/concrete structure (Case 1-5) and buildings with a predominantly metal structure (Case 6-7).

Table 37: Sensitivity analysis - metal fluxes contribution to eLCC

	Masonry / Concrete Buildings					**Metal Buildings**	
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Quantity of metal collected	0.01 t/m^3	0.01 t/m^3	0.01 t/m^3	0.02 t/m^3	0.01 t/m^3	0.18 t/m^3	0.18 t/m^3
Average selling price	-360 €/t (Among iron and steel, cables an aluminium price)						
Initial eLCC value*	4.61 €/m^3	11.37 €/m3	10.66 €/m3	12.50 €/m3	4.90 €/m3	2.30 €/m3	2.90 €/m3
Final eLCC value	1.68 €/m^3	9.48 €/m3	8.90 €/m3	8.39 €/m3	4.21 €/m3	-32.92 €/m3	-31.95 €/m3

*see Annex I

As can be seen from the table 36 and the figure 24, the two scenarios result in substantial differences. In masonry/concrete buildings on average 0.01 tonnes of metal waste is produced for m^3 demolished and sold at an average of 360 €/t. In these cases, by including metal scrap sales, the whole cost is reduced by more than 25% on average (Figure 24).

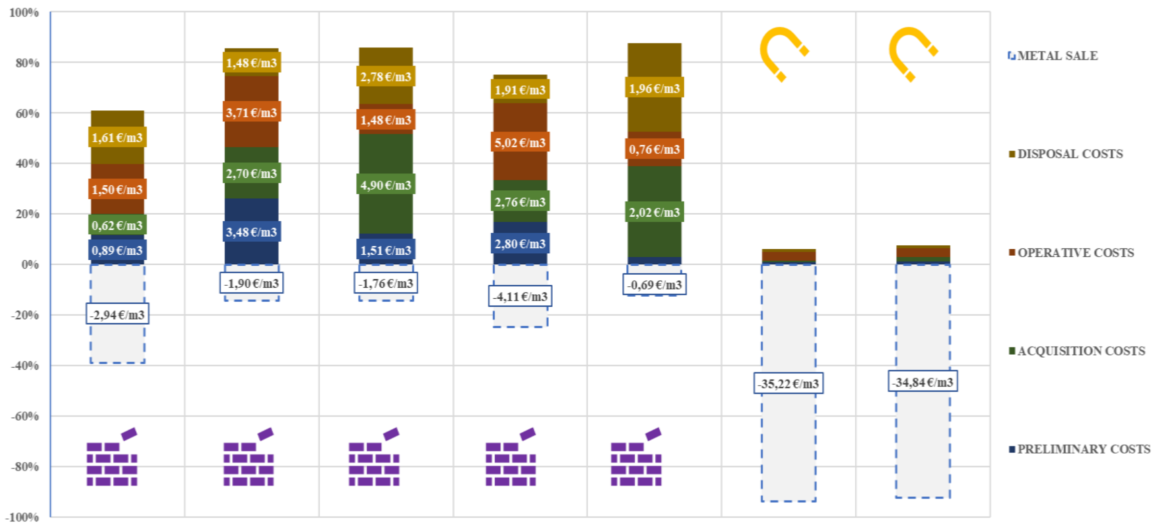


Figure 24: Sensitivity analysis - metal fluxes contribution to eLCC

Metal-structured building demolition, on the other hand, produced approximately 0.18 tonnes of metal waste for m^3 demolished. In these cases, and because the metal flows are significant, the revenues from their sale are sufficient to cover all demolition costs while also generating a profit (Table 37).

CHAPTER 6.

Life Cycle Assessment of the C&D waste management chain

This chapter retraces the use of LCA as the second step of the feLCC approach.

6.1 GOAL AND SCOPE

The LCA study is performed using the same assumptions and system boundaries as the eLCC discussed above to evaluate the environmental impacts of the entire C&D waste management chain and monetise the impact indicators to merge the eLCC study with the LCA subsequently. As for the eLCC, the functional unit chosen is the demolition of a cubic meter of a building (m^3). The system's boundaries, as previously stated (see § 5.1 - Figure 20), range from building demolition to the recycling or disposal of the C&D waste produced. The approach used to address cases of multi-functionality (the system produces new valuable materials while also managing waste) implies extending the system's boundaries, for which the LCA analysis also considers the avoidance of raw material production through the recovery and use of secondary resources. Concerning the processes inherent in the recovery of C&D and the avoided production of natural aggregates, data are taken from the work carried out by Rigamonti et al. (2017) for the Lombardy Region. In this work, the data is gathered from various sources: official statistical data (MUD, Provincial Quarry Statistics), data obtained through technical visits at some waste treatment and extraction sites, and surveys directed to the end users of the RAs (construction and road companies). The LCA analysis is performed using the SimaPro 9.3 software and the Ecoinvent 3.8 database. The inventory data is evaluated based on the Environmental Footprint 3.0 characterisation method. The method evaluates the system's environmental impacts through 16 impact categories, presented in the guide Recommendation for Life

Cycle Impact Assessment in the European context (EC – JRC, 2011) and summarised in Table 38.

Table 38: Impact categories, of the EF 3.0 characterisation method

Impact category	Acronym	Unit	Brief Description
Climate Change	CC	kg CO2 eq.	Indicator of potential global warming due to emissions of greenhouse gases to air.
Ozone depletion	OD	kg CFC-11 eq.	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer
Ionising radiation (IR)	IR	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides.
Photochemical ozone formation	POF	kg NMVOC eq.	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Particulate matter	PM	Disease inc.	Indicator of the potential incidence of disease due to particulate matter emissions.
Human toxicity, non-cancer effects	HTNC	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer related toxic substances.
Human toxicity, cancer effects	HTC	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer related toxic substances.
Acidification	A	Mol H+ eq.	Indicator of the potential acidification of soils and water

			due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication, freshwater	EF	kg P eq.	indicator of the enrichment of the fresh water ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds.
Eutrophication, marine	EM	kg N eq.	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.
Eutrophication, terrestrial	ET	Mol N eq.	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen containing compounds.
Ecotoxicity freshwater	ETF	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment.
Land use	LU	Pt	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Water use	WU	M3 deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors.
Resource use, fossil fuels	RUF	MJ	Indicator of the depletion of natural fossil fuel resources.
Resource use, minerals, and metals	RUM	kg Sb eq.	Indicator of the depletion of natural non-fossil resources.

6.2 LIFE CYCLE INVENTORY AND TRANSPOSITION ON SIMAPRO SOFTWARE

The inventory is implemented starting from the data gained by the eLCC surveys. The data gathered are the electricity, water and fuel consumptions, the typologies and relative quantities of waste produced and the final fate (i.e., recycled or disposed of on landfill).

Case 1

In Case 1 the demolition work involved the equipment of excavators (with sorting grapple, demolition shears, fixed pulveriser, hydraulic breaker and electro lifting magnet), mot-fog, forklift and trucks (Table 39), implying a total electricity, diesel and water consumption of 0.05 kWh/m^3 and 27 MJ/m^3, 0.002 kg/m^3 respectively. The outflows and the relative fate of the waste are shown in Table 40.

Table 39: Case 1 - Equipment usage

Equipment used	Hours of usage
Excavators	3100 hours
with sorting grapple	700 hours
with fixed pulveriser	1000 hours
with demolition shears	200 hours
with hydraulic breaker	1000 hours
with electro-lifting magnet	200 hours
Moto-fog	3000 hours
Forklift	400 hours
Trucks	700 hours

Table 40: Case 1 - Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6; §A2.10)	17 09 04	227.93 kg/m^3	On-site reuse	0
		0.04 kg/m^3	Landfill	8.5 km
Insulating materials (§A2.11)	17 06 04	1.09 kg/m^3	Storage + Landfill	30.6 km + 18.6 km (1)
Wood (§A2.5)	17 02 01	0.31 kg/m^3	Recycling	8.2 km (2)
Gypsum-based materials (§A2.4)	17 08 02	1.08kg/m^3	Recycling	73 km (3)
Iron and steel (§A2.2)	17 04 05	15.6 kg/m^3	Recycling	7.8 km (4)
Aluminium (§A2.1)	17 04 02	0.01 kg/m^3	Recycling	7.8 km (4)
Cables (§A2.3)	17 04 11	0.26 kg/m^3	Recycling	7.8 km (4)

1 Assumption: Nearest plant that accepts insulating materials is Gruppo ECOCHIMICA in Cantù (CO) + Nearest inert landfill is in Desio (MB) (where the company declared the mixed C&D conferment)
2 Assumption: Nearest Recycling plant is Cava Nord, Paderno Dugnano (MI)
3 Assumption: Ecolinea srl (from the paper: Giurato et al., 2018)
4 Assumption: Nearest plant for recycling and metals sale is Fer. bi. Metal in Monza (MB)

case 1

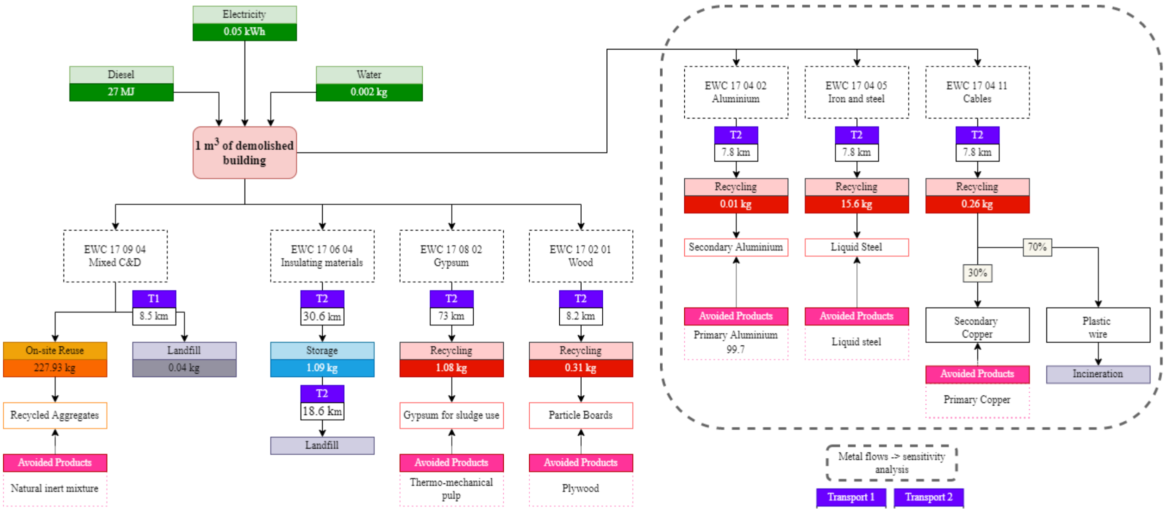


Figure 25: Case 1 - Mass balance

Figure 25 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

The Figure 26 depicts the transposition on SimaPro 9.3 software of the case 1 inventory. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

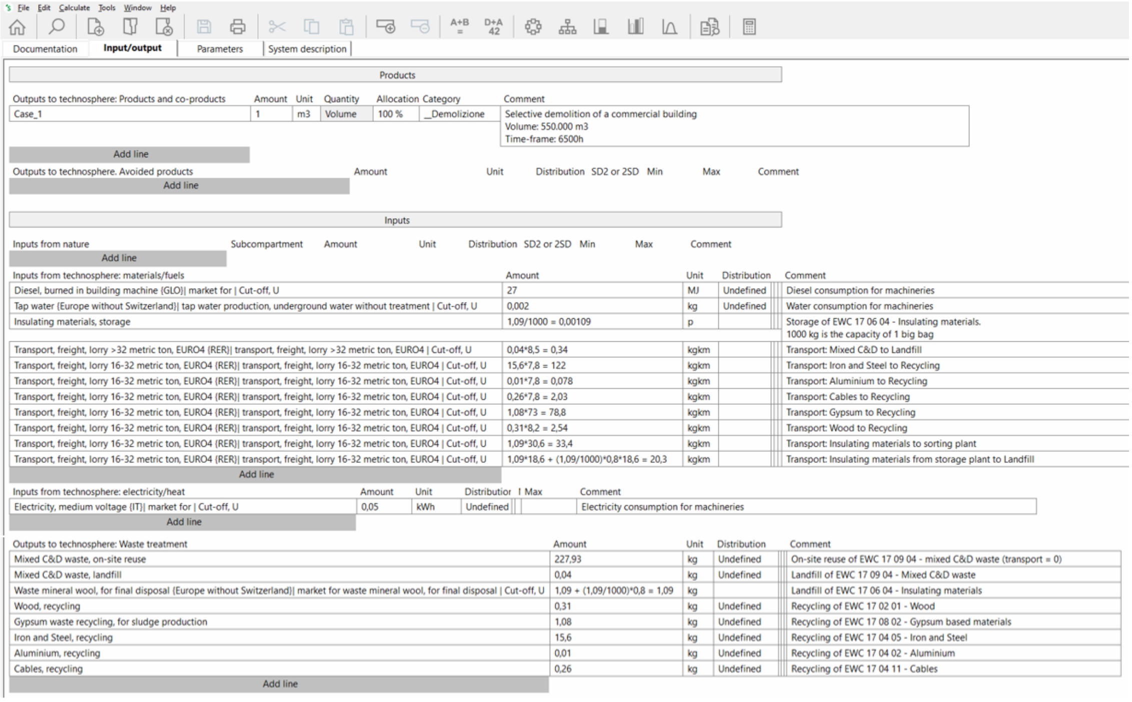


Figure 26: Case 1 – Main Process SimaPro 9.3

Case 2

The case 2 demolition work involved the equipment of excavators (with sorting grapple, demolition shears, fixed pulveriser, hydraulic breaker and electro lifting magnet), mot-fog, crusher and mobile screen and trucks (Table 41), implying a total electricity, diesel and water consumption of 0.06 kWh/m^3 and 19 MJ/m^3, 0.002 kg/m^3 respectively. The outflows and the relative fate of the waste are shown in Table 42.

Table 41: Case 2 - Equipment usage

Equipment used	Hours of usage
Excavators	10000 hours
with sorting grapple	1500 hours
with fixed pulveriser	2000 hours
with demolition shears	1500 hours
with hydraulic breaker	1000 hours
with electro lifting magnet	500 hours
Moto-fog	1800 hours
Crusher and mobile screen	400 hours
Trucks	2500 hours

Table 42: Case 2 - Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6; §A2.10)	17 09 04	210.26 kg/m^3	On-site reuse	0
		1.25 kg/m^3	Landfill	27.4 km
Insulating materials (§A2.11)	17 06 04	0.37 kg/m^3	Storage + Landfill	43.1 km + 18.6 km ([1])
Wood (§A2.5)	17 02 01	0.95 kg/m^3	Recycling	14.2 km ([2])
Gypsum-based materials (§A2.4)	17 08 02	0.69 kg/m^3	Recycling	70.3 km ([3])
Iron and steel (§A2.2)	17 04 05	9.11 kg/m^3	Recycling	10.9 km ([4])
Aluminium (§A2.1)	17 04 02	0.26 kg/m^3	Recycling	10.9 km ([4])

Cables (§A2.3)	17 04 11	0.2 kg/m^3	Recycling	10.9 km (4)

1 Assumption: Nearest plant that accepts insulating materials is Gruppo ECOCHIMICA in Cantù (CO) + Nearest inert landfill is in Desio (MB) (where the company declared the mixed C&D conferment)
2 Assumption: Nearest recycling plant is Eureko in Peschiera Borromeo (MI)
3 Assumption: Ecolinea srl (from the paper: Giurato et al., 2018)
4 Assumption: Nearest metals recycling plant and metals sale is Fer. bi. Metal in Monza

Figure 27 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

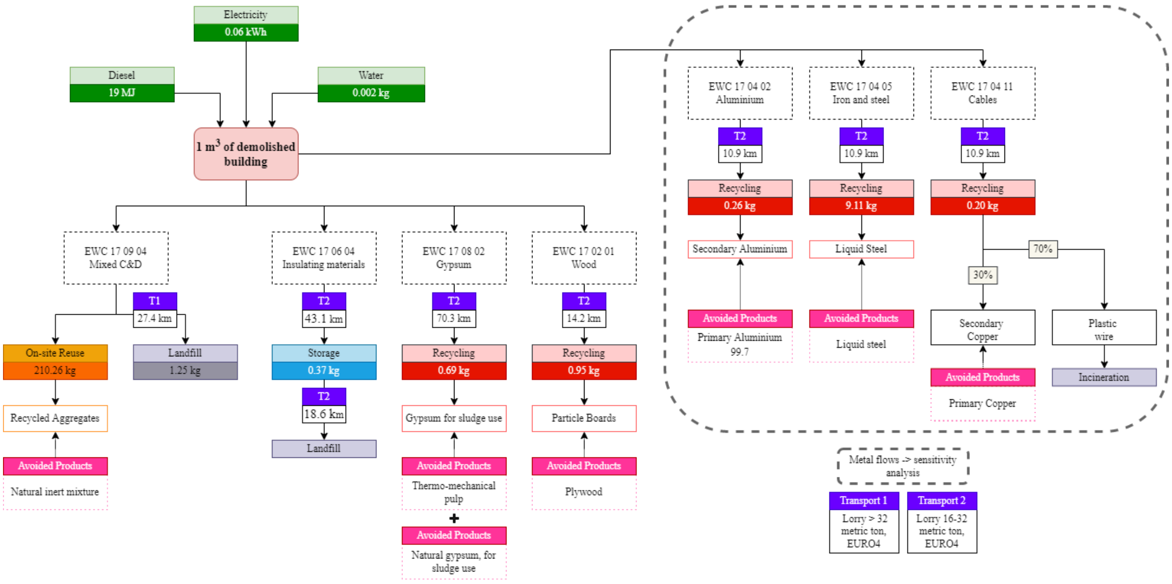


Figure 27: Case 2 - Mass Balance

Figure 28 depicts the transposition on SimaPro 9.3 software of the case 2 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

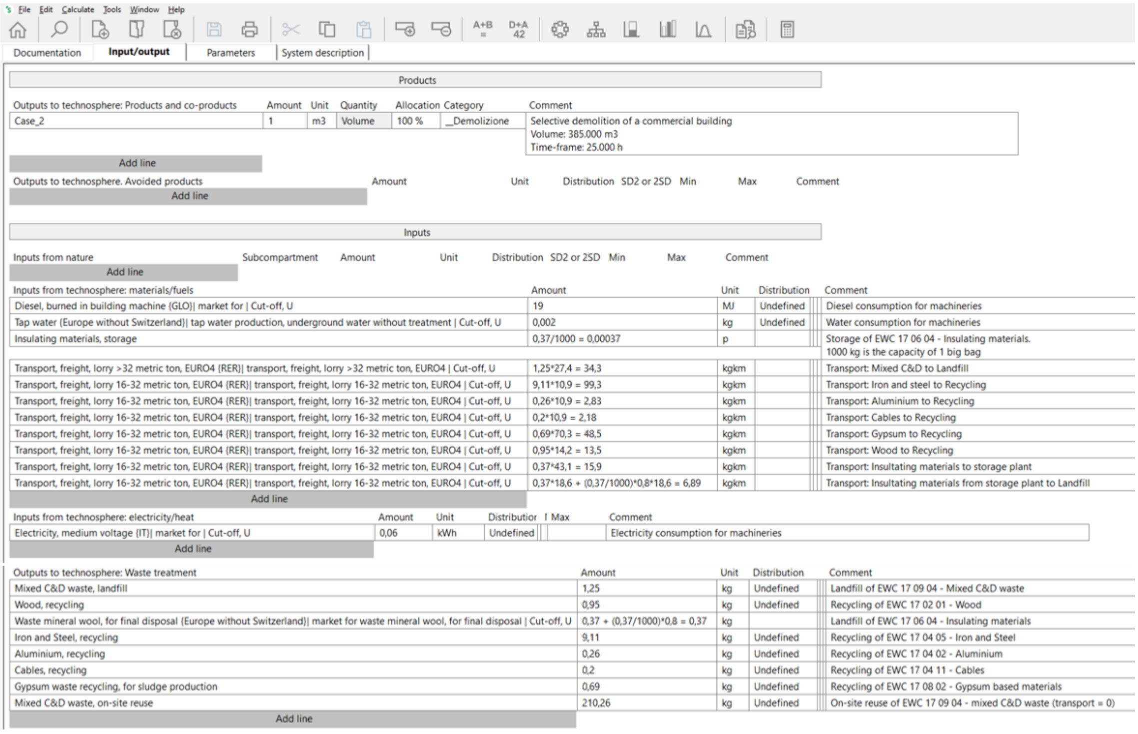


Figure 28: Case 2 – Main Process SimaPro 9.3

Case 3

The case 3 demolition work involved the equipment of excavators (with sorting grapple and fixed pulveriser), crane, crusher and mobile screen, electricity generator and trucks (Table 43), implying a total electricity, diesel, and water consumption of 0.29 kWh/m^3 and 38 MJ/m^3, 0.007 kg/m^3 respectively. The outflows and the relative fate of the waste are shown in Table 44.

Table 43: Case 3 - Equipment usage

Equipment used	Hours of usage
Excavators	2500 hours
with sorting grapple	273 hours
with fixed pulveriser	90 hours
Crane	290 hours
Crusher and mobile screen	316 hours
Electricity generator	177 hours
Trucks	210 hours

Table 44: Case 3 - Output flows of waste fractions (Ref. relative annex module (An))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6)	17 09 04	338.71 kg/m^3	On-site reuse	0
Insulating materials (§A2.11)	17 06 04	0.19 kg/m^3	Storage + Landfill	55.4 km + 18.6 km ([1])
Mixed Packaging (§A2.5)	15 01 06	5.08 kg/m^3	Landfill	23.5 km
Wood	17 02 01	1.29 kg/m^3	Landfill	17.2 km
Wood (§A2.5)	17 02 01	0.15 kg/m^3	Recycling	22.7 km
Iron and steel (§A2.2)	17 04 05	9.78 kg/m^3	Recycling	50 km

1 Assumption: Nearest plant that accept insulating materials is Gruppo ECOCHIMICA in Cantù (CO) + Nearest inert landfill is in Desio (MB) (where the company declared the mixed C&D conferment

Figure 29 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

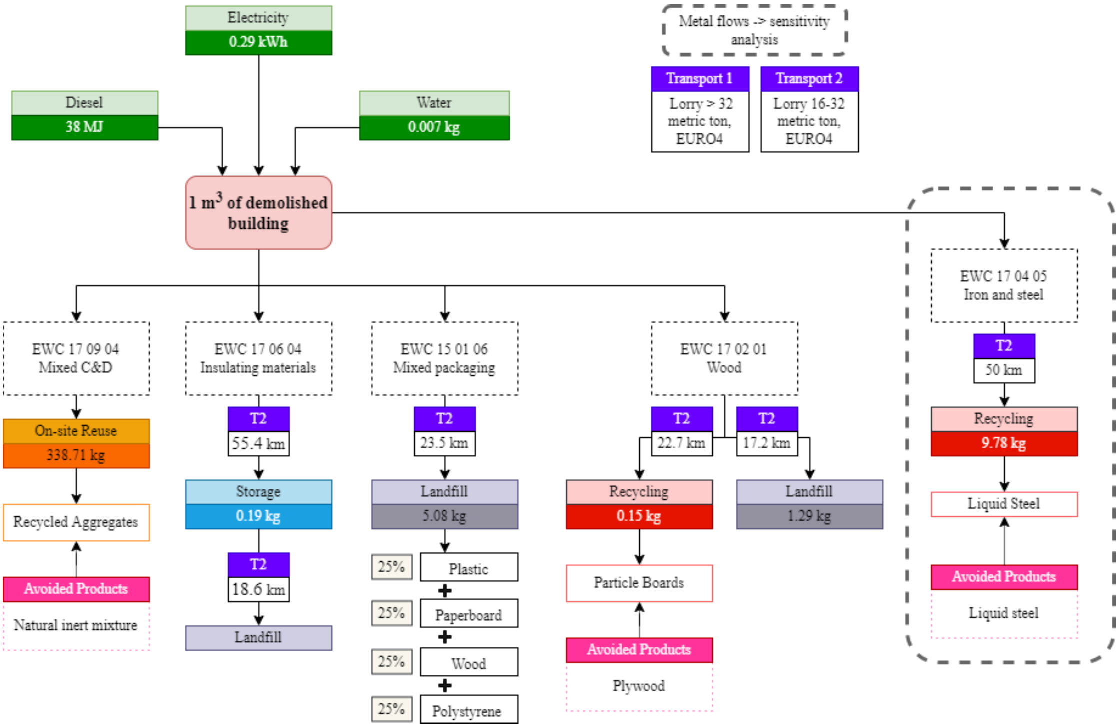


Figure 29: Case 3 - Mass Balance

Figure 30 depicts the transposition on SimaPro 9.3 software of the case 3 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

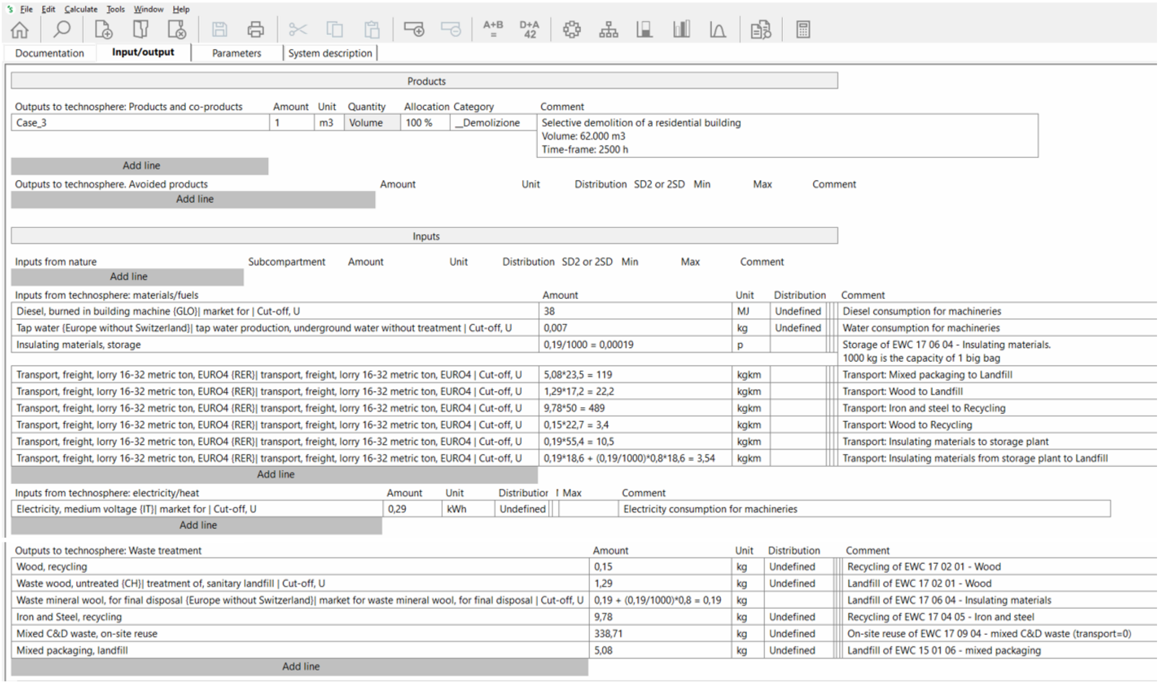


Figure 30: Case 3 – Main Process SimaPro 9.3

Case 4

The case 4 demolition work involved the equipment of excavators (with sorting grapple and fixed pulveriser), crane, moto-fog, electricity generator and trucks (Table 45), implying a total electricity, diesel, and water consumption of 0.80 kWh/m^3 and 3 MJ/m^3, 0.019 kg/m^3 respectively. The outflows and the relative fate of the waste are shown in Table 46.

Table 45: Case 4 - Equipment usage

Equipment used	Hours of usage
Excavators	330 hours
with sorting grapple	30 hours
with fixed pulverizer	107 hours
Crane	20 hours
Moto-fog	200 hours
Electricity generator	150 hours
Trucks	200 hours

Table 46: Case 4 - Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6)	17 09 04	420.21 kg/m^3	Landfill	33.8 km
Asbestos	17 06 05*	0.64 kg/m^3	Landfill	33.8 km
Insulating materials with asbestos	15 01 03*	0.85 kg/m^3	Landfill	33.8 km
Wood	17 02 01	0.43 kg/m^3	Landfill	46.6 km
Iron and steel (§A2.2)	17 04 05	17.02 kg/m^3	Recycling	70.2 km
Aluminium (§A2.1)	17 04 02	1.28 kg/m^3	Recycling	70.2 km

Figure 31 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

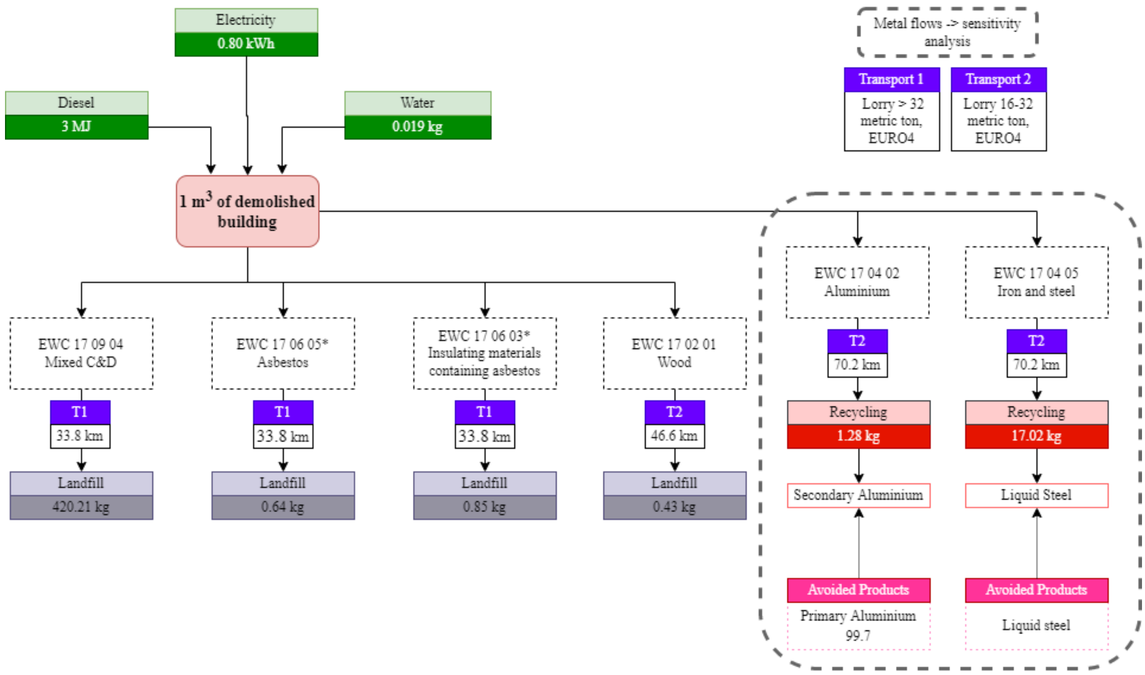


Figure 31: Case 4 - Mass Balance

Figure 32 depicts the transposition on SimaPro 9.3 software of the case 4 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

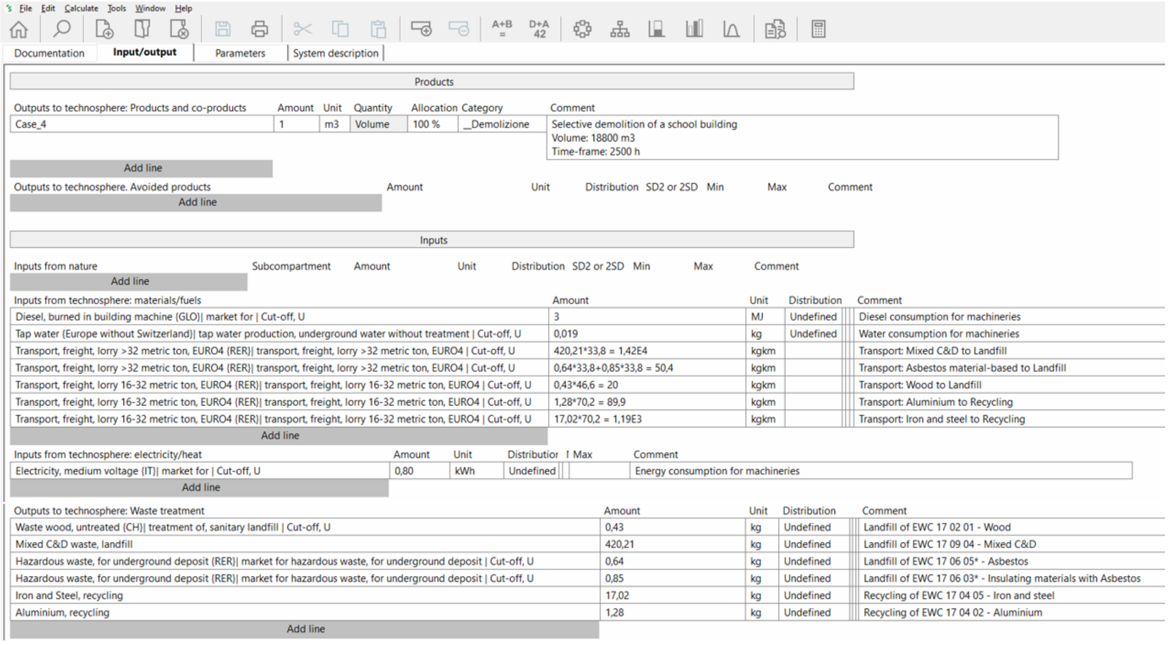


Figure 32: Case 4 – Main Process SimaPro 9.3

Case 5

The case 5 demolition work involved the equipment of excavators (with sorting grapple, fixed pulveriser, and demolition shears), moto-fog, crane, and trucks (Table 47), implying a total diesel, and water consumption of 0.01 kWh/m^3 and 21 MJ/m^3, respectively. Electricity consumption has not been declared. The outflows and the relative fate of the waste are shown in Table 47.

Table 47: Case 5 - Equipment usage

Equipment used	Hours of usage
Excavators	515 hours
with sorting grapple	233 hours
with fixed pulverizer	170.5 hours
with demolition shears	38 hours
Moto-fog	100 hours
Crane	5 hours
Trucks	270 hours

Table 48: Case 5 - Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6)	17 09 04	180.8 kg/m^3	Recycling	16.6 km ([1])
Cement (§A2.7)	17 01 01	60.99 kg/m^3	Recycling	16.6 km ([1])
Iron and Steel (§A2.2)	17 04 05	5.87 kg/m^3	Recycling	40.2 km ([2])
Bituminous materials	17 03 02	0.74 kg/m^3	Landfill	16.6 km ([1])

1 Assumption: nearest recycling plant is Pfc 2000 in Cologno al Serio (BG)
2 Assumption: Nearest metals recycling plant and metals sale is Fer. bi. Metal in Monza (MB)

Figure 33 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

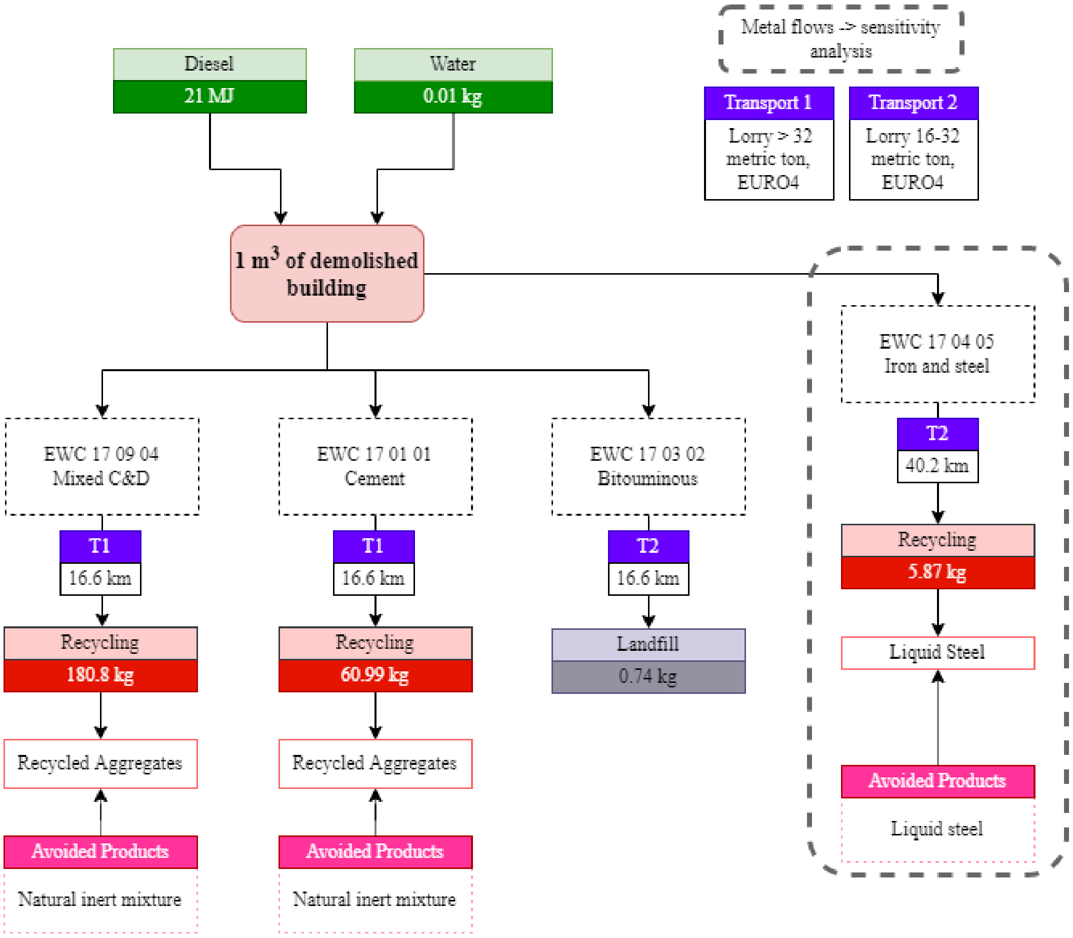


Figure 33: Case 5 - Mass balance

Figure 34 depicts the transposition on SimaPro 9.3 software of the case 5 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

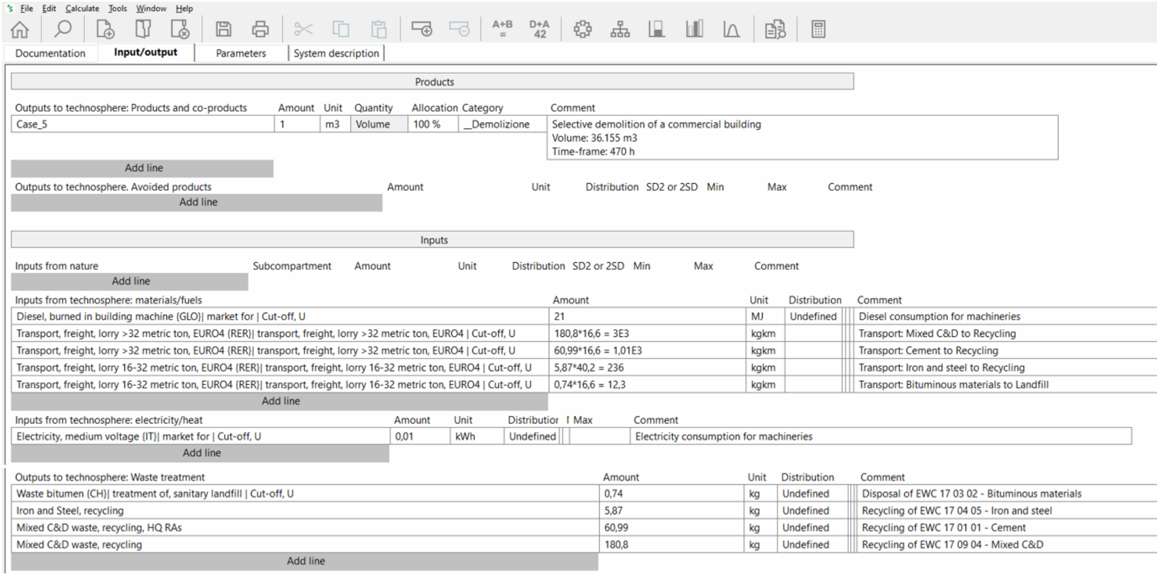


Figure 34: **Case 5 – Main Process SimaPro 9.3**

Case 6

The case 6 demolition work involved the equipment of excavators (with fixed pulveriser), scraper, crusher and mobile screen and trucks (Table 49), implying a total diesel consumption of 4 MJ/m^3. Electricity and water consumption have not been declared. The outflows and the relative fate of the waste are shown in Table 50.

Table 49: Case 5 -Equipment usage

Equipment used	Hours of usage
Excavators	200 hours
with fixed pulveriser	320 hours
Scraper	320 hours
Crusher and mobile screen	104 hours
Trucks	104 hours

Table 50: Case 5 -Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6)	17 09 04	53.63 kg/m^3	Recycling	13 km ([1])
Insulating materials (§A2.11)	17 06 04	0.36 kg/m^3	Storage + Landfill	41.8+18.6 km ([2])
Wood (§A2.5)	17 02 01	0.28 kg/m^3	Recycling	13 km ([1])
Iron and Steel (§A2.2)	17 04 05	185 kg/m^3	Recycling	58.7 km

1 Assumption: nearest recycling plant is MonvilBeton in Cascina Brodolini (MI)
2 Assumption: Nearest plant that accept insulating materials is Gruppo ECOCHIMICA in Cantù (CO) + Nearest inert landfill is in Desio (MB)

Figure 35 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

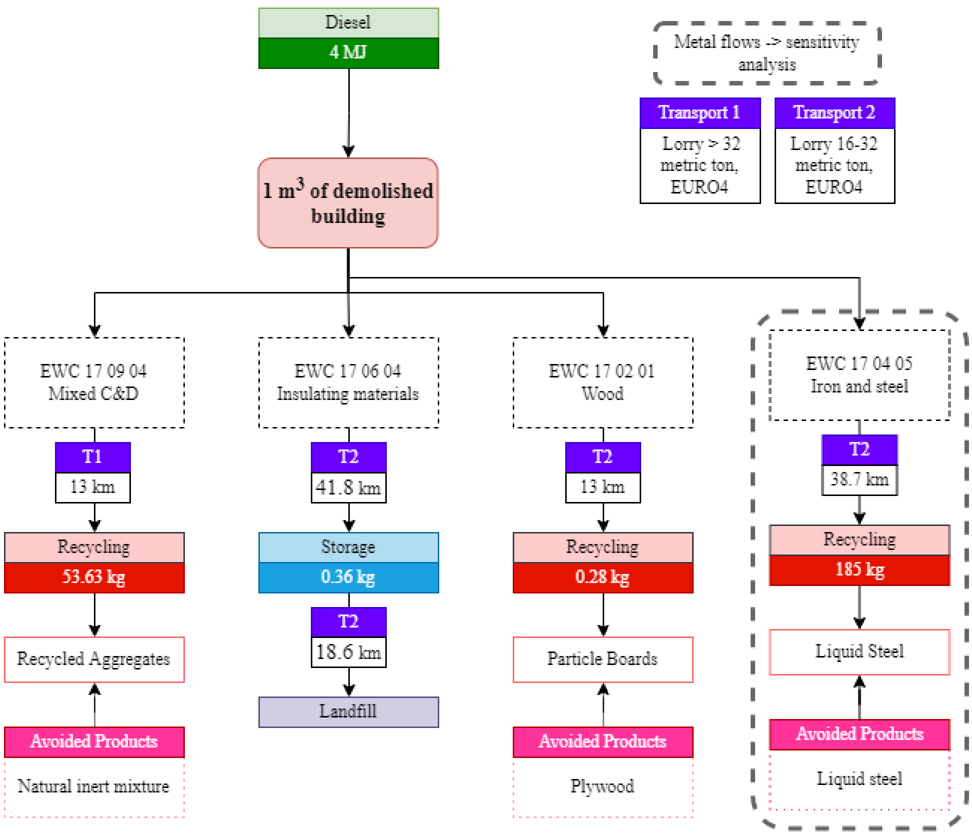


Figure 35: Case 6 - Mass Balance

Figure 36 depicts the transposition on SimaPro 9.3 software of the case 6 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

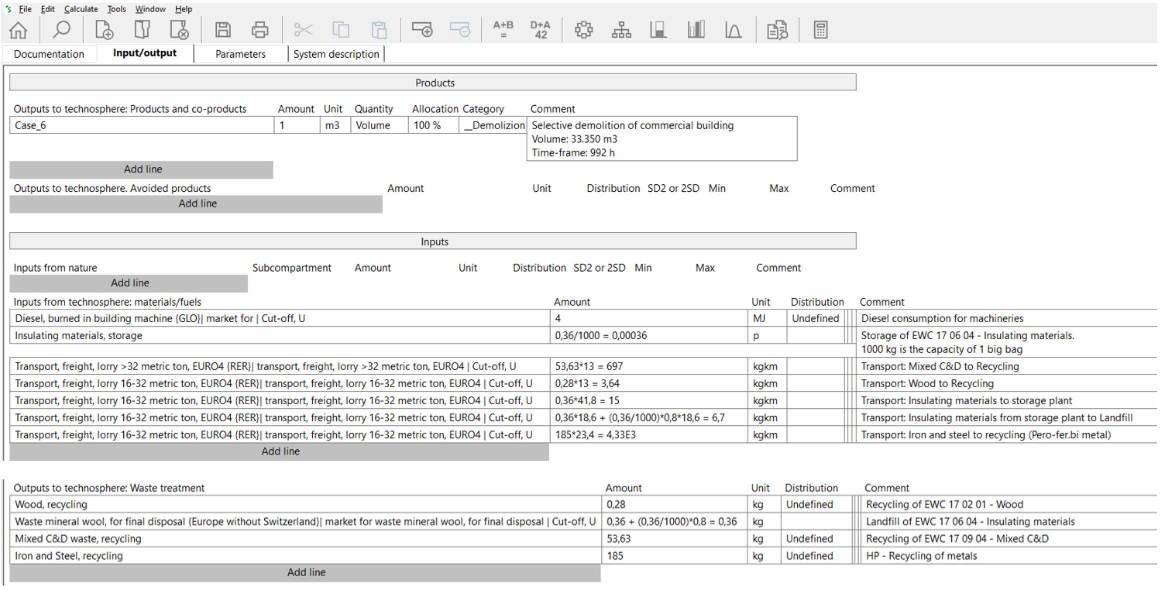


Figure 36: Case 6 – Main Process SimaPro 9.3

Case 7

The case 7 demolition work involved the equipment of excavators (with sorting grapple and fixed pulveriser) (Table 51), implying a total electricity, diesel, and water consumption of 11 MJ/m^3 and 0,001 kg/m^3 respectively. Electricity consumption has not been declared. The outflows and the relative fate of the waste are shown in Table 52.

Table 51: Case 7 - Equipment usage

Equipment used	Hours of usage
Excavators	1200 hours
with sorting grapple	500 hours
with fixed pulveriser	500 hours

Table 52: Case 7 - Output flows of waste fractions (Ref. relative annex module (A2.))

Waste fraction	EWC Code	Produced Quantity	Destiny	Transportation distance
Mixed C&D waste (§A2.6)	17 09 04	56.25 kg/m^3	Recycling	14.3 km ([1])
Iron and Steel (§A2.2)	17 04 05	183 kg/m^3	Recycling	38.7 km

1 Assumption: nearest recycling plant is Orobica inerti in Osio Sopra (BG)

Figure 37 depicts the mass balance of the system in the case study under examination. The section relating to metal fluxes inside the dashed line will be examined in the context of sensitivity analysis.

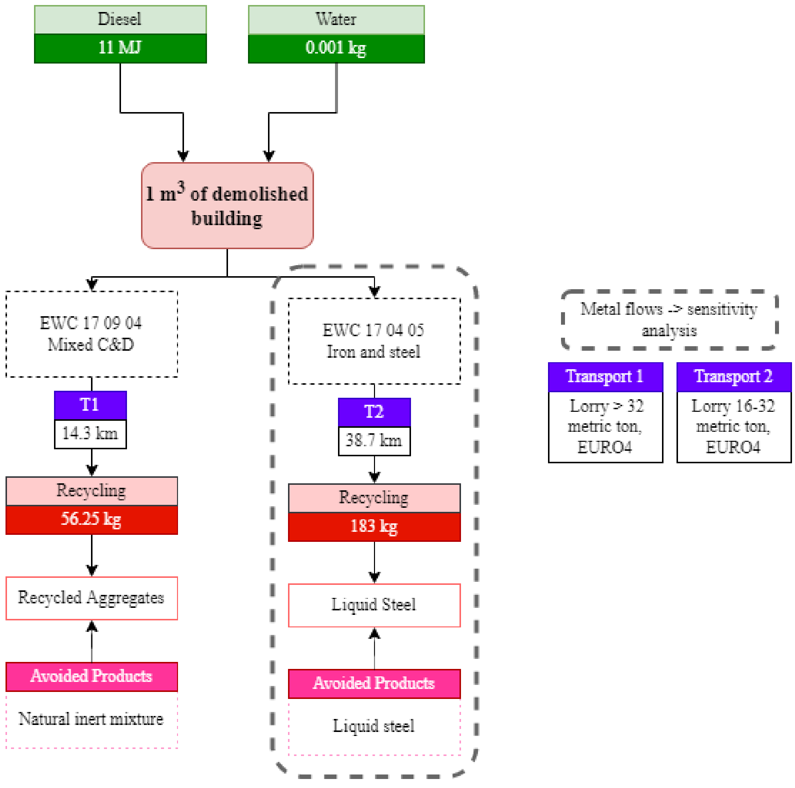


Figure 37: Case 7 - Mass Balance

Figure 38 depicts the transposition on SimaPro 9.3 software of the case 7 inventories. The procedure includes the use of diesel, water, and electricity, as well as the handling of demolition waste, including transportations. Annex II contains a report on the SimaPro modelling of all individual waste treatment processes.

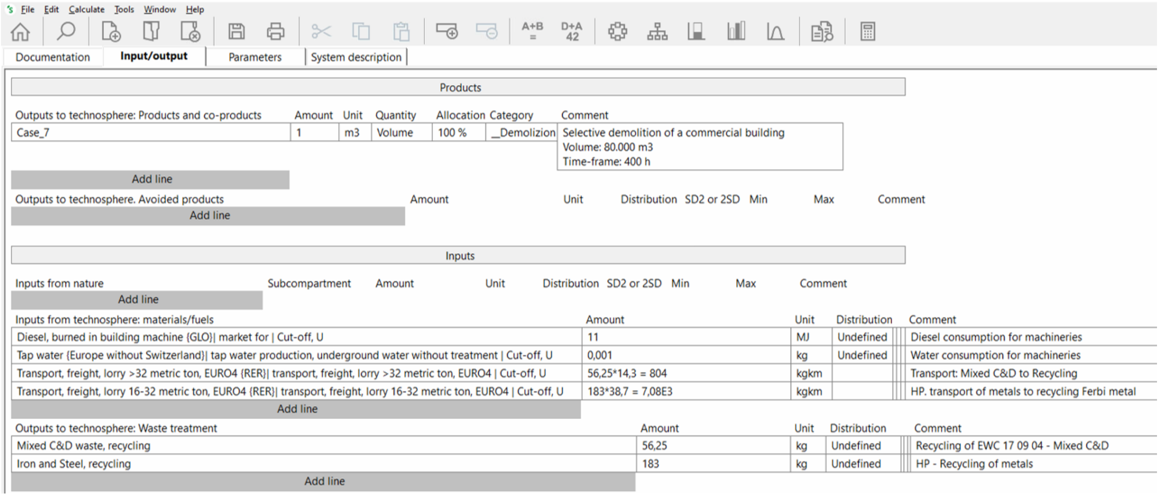


Figure 38: Case 7 – Main Process SimaPro 9.3

6.3LIFE CYCLE IMPACT ASSESSMENT

The inventory data are modelled in the SimaPro 9.3 program through the Ecoinvent 3.8 dataset and some ad hoc datasets and are evaluated using the EF 3.0 characterization method. In this study, sixteen effect categories are analysed for each case study. The analyses presented here excluded metal waste streams, object of a sensitivity study (see §6.4.2).

Case 1

Table 53 illustrates the impact assessment results of Case 1 in terms of the seven aggregate inputs: Consumption (diesel, water, and electricity), on-site reuse of mixed C&D waste, landfill of mixed C&D waste, storage and landfill of insulating materials, recycling of wood, recycling of gypsum and transportations to handling plants.

Table 53: Impact assessment results from the selective demolition of 1 m^3 of a commercial concrete/masonry building (Case 1)

Impact Categories	DEM	ORCD	LCD	SLI	RW	RG	T
CC	2.50E+00	-5.40E-01	3.06E-04	8.17E-03	-9.88E-03	3.59E+00	2.23E-02
OD	5.33E-07	-1.38E-07	1.13E-10	2.38E-09	-1.36E-09	6.57E-07	5.20E-09
IR	1.56E-01	-4.67E-02	3.86E-05	9.00E-04	-1.39E-02	4.40E-01	1.75E-03
POF	3.45E-02	-1.43E-03	2.49E-06	6.74E-05	-4.88E-04	2.39E-02	1.21E-04
PM	6.92E-07	-3.35E-08	4.36E-11	1.18E-09	-1.17E-08	4.18E-07	1.99E-09
HTNC	1.46E-08	-8.75E-09	3.35E-12	8.44E-11	2.16E-10	1.31E-08	2.78E-10
HTC	7.75E-10	9.54E-10	1.99E-13	3.42E-12	4.82E-10	4.59E-09	8.58E-12
A	2.59E-02	-1.63E-03	2.45E-06	6.39E-05	-3.30E-04	2.49E-02	1.13E-04
EF	8.15E-05	-3.54E-05	1.01E-07	1.11E-06	-1.55E-05	4.05E-04	1.45E-06
EM	1.14E-02	-3.63E-04	7.75E-07	2.07E-05	-1.65E-04	8.09E-03	3.89E-05
ET	1.25E-01	-3.95E-03	8.45E-06	2.25E-04	-1.78E-03	8.94E-02	4.25E-04
ETF	2.01E+01	-7.02E+00	5.48E-03	1.26E-01	-1.33E+00	2.01E+01	2.65E-01
LU	4.39E+00	-1.31E+01	2.15E-02	3.45E-01	-2.20E+01	3.68E+00	2.34E-01
WU	6.68E-02	-1.79E-02	4.29E-04	8.76E-03	-6.23E-02	1.70E+00	1.02E-03
RUF	3.44E+01	-8.96E+00	8.47E-03	2.32E-01	-2.53E-01	5.50E+01	3.40E-01
RUM	1.32E-06	-1.59E-06	1.26E-09	2.64E-08	1.57E-07	-9.62E-07	7.81E-08

DEM: Demolition (diesel, water, electricity consumptions); **ORCD**: On-site reuse of mixed C&D waste; **LCD**: Landfill of mixed C&D waste; **SLI**: Storage + Landfill of insulating materials; **RW**: Recycling of wood; **RG**: Recycling of gypsum; **T**: Transportation

The result of the contribution analysis of case 1 is shown in Figure 39.

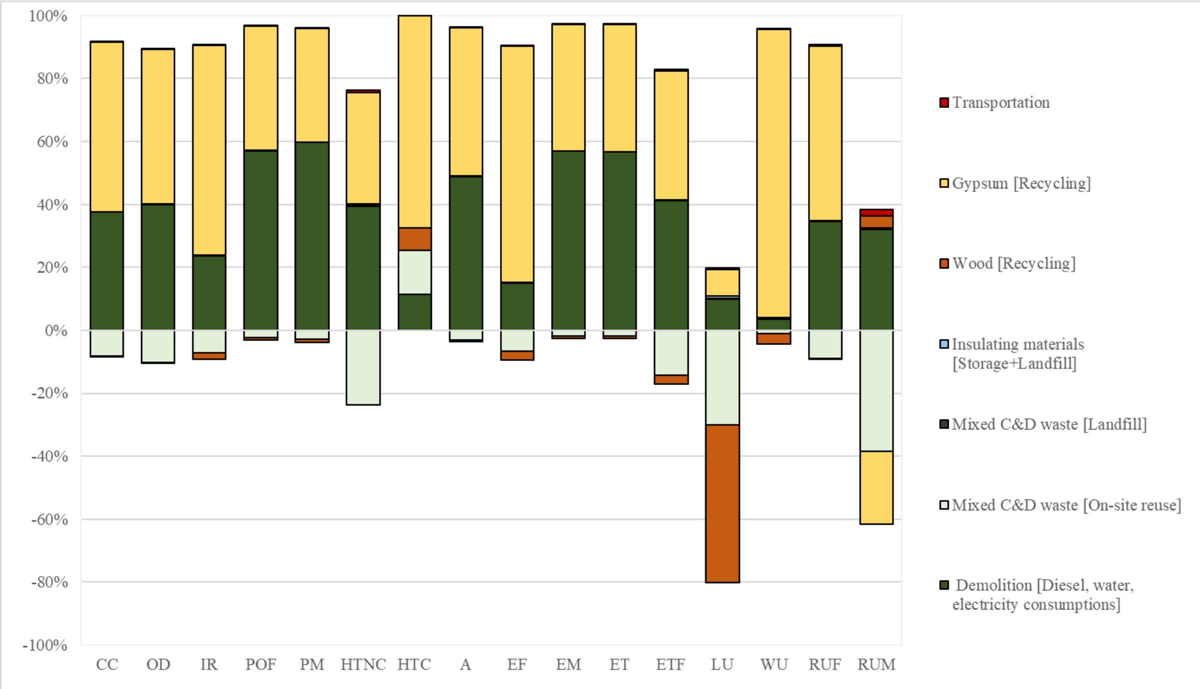


Figure 39: Contribution analysis for the selective demolition of 1 m3 of a commercial concrete/masonry building (Case 1)

The two main contributors of potential environmental impacts for most impact categories are the consumption of demolition machinery and the recycling of gypsum-based material (except for the minerals resources use (RUM) impact category). The system under study presents a primary benefit in most impacts categories from the on-site reuse of mixed C&D waste. The recycling of wood substantially benefits the category of land use (LU) but is an impact on human toxicity (NHTC and HTC) and mineral resource use (RUM). The other inputs are minimal contributors throughout all the impact categories.

Case 2

The outcome of the impact assessment for the second scenario indicates a situation comparable to the prior one. The seven aggregate inputs: Consumption (diesel, water, and electricity), on-site reuse of mixed C&D waste, landfill of mixed C&D waste, storage and landfill of insulating materials, recycling of wood, recycling of gypsum and transportations to handling plants gives the results on the 16 impact categories shows in table 54.

Table 54: Impact assessment results from the selective demolition of 1 m3 of a commercial concrete/masonry building (Case 2)

Impact Categories	DEM	ORCD	LCD	SLI	RW	RG	T
CC	1.77E+00	-4.98E-01	9.55E-03	2.77E-03	-3.03E-02	2.29E+00	1.82E-02
OD	3.77E-07	-1.27E-07	3.53E-09	8.09E-10	-4.17E-09	4.20E-07	4.26E-09
IR	1.11E-01	-4.31E-02	1.21E-03	3.06E-04	-4.25E-02	2.81E-01	1.43E-03
POF	2.43E-02	-1.32E-03	7.79E-05	2.29E-05	-1.50E-03	1.53E-02	9.95E-05
PM	4.87E-07	-3.09E-08	1.36E-09	4.00E-10	-3.59E-08	2.67E-07	1.71E-09
HTNC	1.03E-08	-8.07E-09	1.05E-10	2.87E-11	6.63E-10	8.39E-09	2.29E-10
HTC	5.48E-10	8.80E-10	6.20E-12	1.16E-12	1.48E-09	2.93E-09	6.85E-12
A	1.83E-02	-1.50E-03	7.67E-05	2.17E-05	-1.01E-03	1.59E-02	9.20E-05
EF	5.96E-05	-3.26E-05	3.15E-06	3.76E-07	-4.75E-05	2.59E-04	1.17E-06
EM	8.06E-03	-3.35E-04	2.42E-05	7.01E-06	-5.05E-04	5.17E-03	3.17E-05
ET	8.83E-02	-3.65E-03	2.64E-04	7.64E-05	-5.45E-03	5.71E-02	3.46E-04
ETF	1.43E+01	-6.47E+00	1.71E-01	4.28E-02	-4.08E+00	1.28E+01	2.17E-01
LU	3.12E+00	-1.21E+01	6.73E-01	1.17E-01	-6.75E+01	2.35E+00	2.13E-01
WU	5.37E-02	-1.65E-02	1.34E-02	2.98E-03	-1.91E-01	1.09E+00	8.55E-04
RUF	2.43E+01	-8.26E+00	2.65E-01	7.89E-02	-7.77E-01	3.51E+01	2.78E-01
RUM	9.51E-07	-1.47E-06	3.93E-08	8.95E-09	4.80E-07	-6.14E-07	6.00E-08

DEM: Demolition (diesel, water, electricity consumptions); **ORCD**: On-site reuse of mixed C&D waste; **LCD**: Landfill of mixed C&D waste; **SLI**: Storage + Landfill of insulating materials; **RW**: Recycling of wood; **RG**: Recycling of gypsum; **T**: Transportation

The result of the contribution analysis of Case 2 is shown in Figure 40.

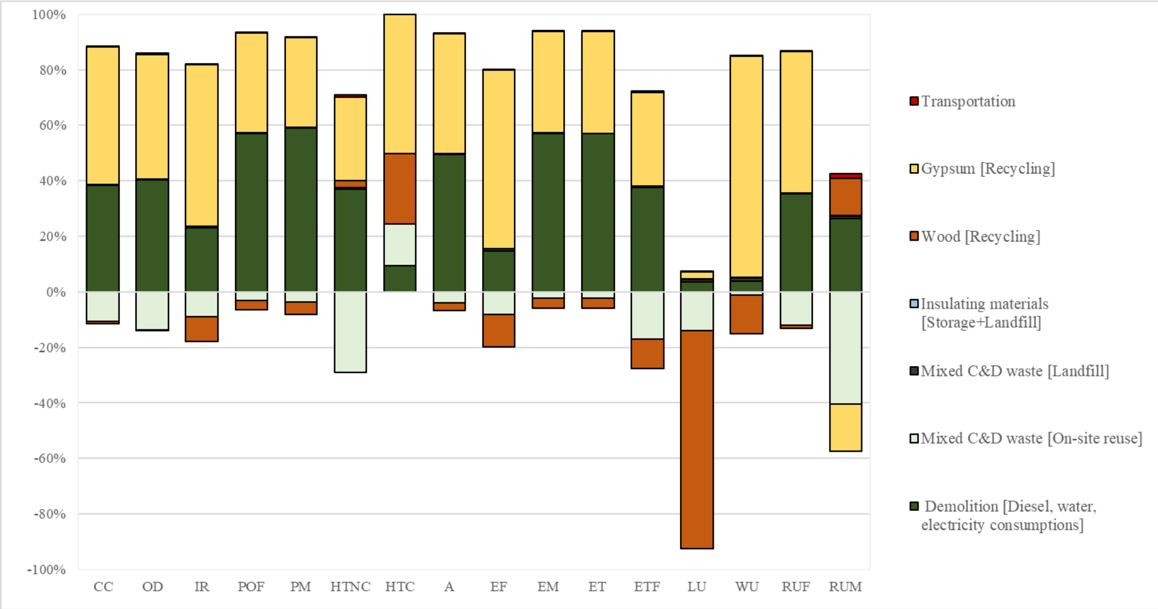


Figure 40: Contribution analysis for the selective demolition of 1 m3 of a commercial concrete/masonry building (Case 2)

For most of the impact categories, the two primary effect contributors are the consumption of fuel, water, and electricity for the employment of demolition machinery and the recycling of gypsum-based material, except for the RUM impact category indicates a benefit for gypsum recycling. The primary benefit in most impact categories comes from the on-site reuse of mixed C&D waste. Wood recycling helps the category of land use (LU) but has an impact on human toxicity (NHTC and HTC) and mineral resource consumption (RUM). The other inputs contribute relatively little to all the impact categories.

Case 3

Table 55 illustrates the impact assessment results of Case 3 in terms of the seven inputs: consumption (diesel, water, and electricity), on-site reuse of mixed C&D waste, landfill of mixed packaging waste, storage, and landfill of insulating materials, recycling al landfill of wood, and transportations to handling plants.

Table 55: Impact assessment results from the selective demolition of 1 m3 of a residential concrete/masonry building (Case 3)

Impact Categories	DEM	ORCD	LP	SLI	RW	LW	T
CC	3.61E+00	-8.02E-01	2.80E+00	1.42E-03	-4.78E-03	1.12E-01	2.62E-02
OD	7.63E-07	-2.05E-07	1.58E-08	4.16E-10	-6.58E-10	4.00E-09	6.11E-09
IR	2.32E-01	-6.94E-02	1.02E-02	1.57E-04	-6.71E-03	1.76E-03	2.05E-03
POF	4.87E-02	-2.12E-03	1.27E-03	1.17E-05	-2.36E-04	1.41E-04	1.43E-04
PM	9.75E-07	-4.98E-08	8.45E-09	2.06E-10	-5.67E-09	2.08E-09	2.34E-09
HTNC	2.10E-08	-1.30E-08	5.11E-09	1.47E-11	1.05E-10	2.66E-10	3.27E-10
HTC	1.11E-09	1.42E-09	4.68E-11	5.96E-13	2.33E-10	8.32E-12	1.01E-11
A	3.68E-02	-2.42E-03	5.30E-04	1.11E-05	-1.60E-04	9.39E-05	1.33E-04
EF	1.35E-04	-5.26E-05	4.94E-06	1.93E-07	-7.50E-06	1.87E-06	1.70E-06
EM	1.62E-02	-5.39E-04	6.39E-03	3.60E-06	-7.98E-05	4.81E-04	4.57E-05
ET	1.77E-01	-5.87E-03	1.68E-03	3.92E-05	-8.60E-04	3.87E-04	5.00E-04
ETF	2.92E+01	-1.04E+01	6.88E+00	2.20E-02	-6.44E-01	2.34E-01	3.12E-01
LU	6.41E+00	-1.95E+01	2.97E+00	6.02E-02	-1.07E+01	7.52E-01	2.75E-01
WU	1.53E-01	-2.66E-02	5.95E-03	1.53E-03	-3.01E-02	1.39E-03	1.20E-03
RUF	4.97E+01	-1.33E+01	1.19E+00	4.05E-02	-1.23E-01	2.89E-01	3.99E-01
RUM	2.05E-06	-2.36E-06	1.98E-07	4.59E-09	7.58E-08	3.66E-08	9.19E-08

DEM: Demolition (diesel, water, electricity consumptions); **ORCD**: On-site reuse of mixed C&D waste; **LP**: Landfill of mixed packaging waste; **SLI**: Storage + Landfill of insulating materials; **RW**: Recycling of wood; **LW**: Landfill of wood; **T**: Transportation

The result of the contribution analysis of case 3 is shown in Figure 41.

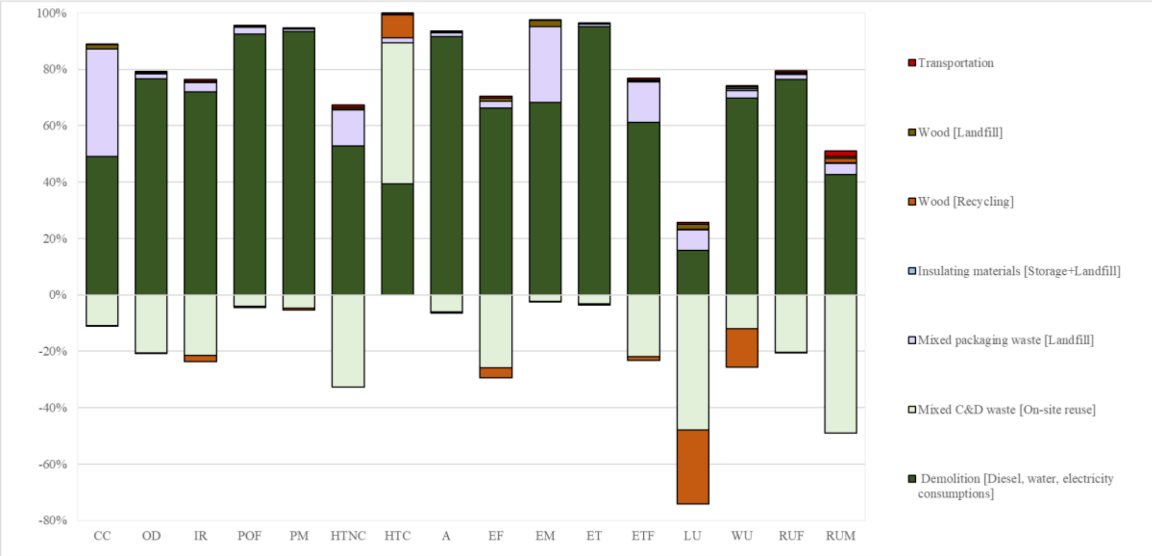


Figure 41: Contribution analysis for the selective demolition of 1 m3 of a residential concrete/masonry building (Case 3)

The diesel, water, and electricity consumption for the employment of demolition machinery and the disposal of mixed packaging waste in landfills are the two key contributors to the majority of the impact categories in Case 3. This scenario also identifies significant benefits for the on-site reuse of mixed C&D waste and wood recycling for the land use category (LU). The other inputs contribute relatively little to all of the impact categories.

Case 4

Table 56 illustrates the impact assessment results of Case 4 in terms of the five aggregate inputs: consumption (diesel, water, and electricity), disposal on landfill of mixed C&D waste, wood, and hazardous materials (e.g., asbestos), and transportations to handling plants.

Table 56: Impact assessment results from the selective demolition of 1 m3 of a concrete/masonry school building (Case 4)

Impact Categories	DEM	LCD	LW	LH	T
CC	6.00E-01	3.21E+00	3.73E-02	3.19E-01	1.29E+00
OD	1.03E-07	1.19E-06	1.33E-09	1.74E-08	3.09E-07
IR	6.15E-02	4.05E-01	5.87E-04	1.10E-02	1.02E-01
POF	4.53E-03	2.62E-02	4.69E-05	1.53E-03	7.33E-03
PM	8.24E-08	4.58E-07	6.94E-10	2.52E-08	1.55E-07
HTNC	3.45E-09	3.52E-08	8.88E-11	6.26E-09	1.73E-08
HTC	1.58E-10	2.09E-09	2.77E-12	1.61E-09	4.37E-10
A	4.34E-03	2.58E-02	3.13E-05	1.35E-03	6.54E-03
EF	8.23E-05	1.06E-03	6.25E-07	1.30E-04	8.07E-05
EM	1.49E-03	8.14E-03	1.60E-04	3.23E-04	2.24E-03
ET	1.64E-02	8.87E-02	1.29E-04	3.33E-03	2.45E-02
ETF	5.31E+00	5.76E+01	7.80E-02	8.29E+00	1.58E+01
LU	1.33E+00	2.26E+02	2.51E-01	6.64E+00	2.31E+01
WU	2.22E-01	4.51E+00	4.62E-04	7.95E-02	6.95E-02
RUF	8.68E+00	8.90E+01	9.63E-02	3.55E+00	2.02E+01
RUM	8.42E-07	1.32E-05	1.22E-08	6.21E-07	2.98E-06

DEM: Demolition (diesel, water, electricity consumptions); **LCD**: Landfill of mixed C&D waste; **LW**: Landfill of wood; **LH**: Landfill of hazardous materials; **T**: Transportation

The result of the contribution analysis of case 4 is shown in Figure 42.

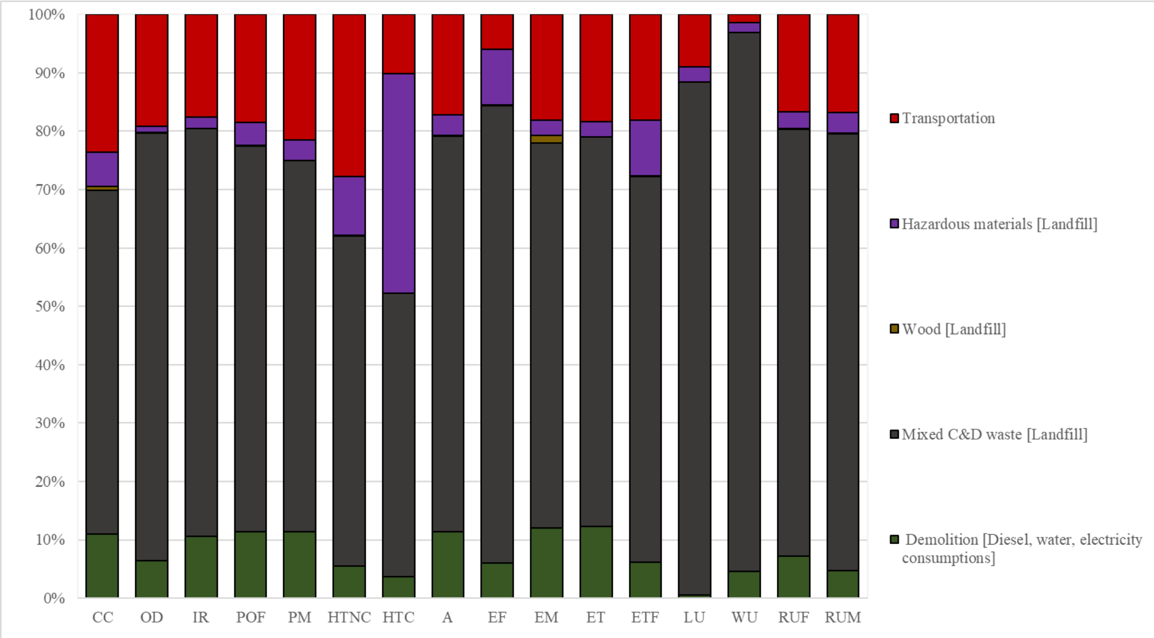


Figure 42: Contribution analysis for the selective demolition of 1 m3 of a concrete/masonry school building (Case 4)

In Case 4, all inputs had an impact on all categories examined. The landfill operations of C&D mixed waste cause approximately 60% of the total environmental impact. The transportation to dispose of the generated waste accounts for around 25% of the total. The hazardous waste dump operation has the most significant impact in terms of human toxicity and cancer effect (HTC). The impacts of diesel, water, and energy usage account for less than 10% of the overall impacts. The impact of wood landfills is a minimal factor across all impact categories.

Case 5

Table 57 illustrates the impact assessment results of Case 5 in terms of the five aggregate inputs: consumption (diesel and electricity), disposal on landfill of bituminous materials, recycling of mixed C&D waste and of the separated flow of pure cement and transportations to handling plants.

Table 57: Impact assessment results from the selective demolition of 1 m3 of a commercial concrete/masonry building (Case 5)

Impact Categories	DEM	LB	RCD	RC	T
CC	1.94E+00	1.09E-01	-5.00E-01	-1.27E-01	3.63E-01
OD	4.13E-07	2.29E-09	-6.65E-08	-3.33E-08	8.74E-08
IR	1.20E-01	1.08E-03	-6.51E-03	-8.46E-03	2.89E-02
POF	2.68E-02	9.11E-05	-1.64E-03	-9.48E-04	2.07E-03
PM	5.38E-07	1.24E-09	-2.56E-08	-2.06E-08	4.37E-08
HTNC	1.13E-08	6.12E-11	-1.08E-08	-1.75E-09	4.88E-09
HTC	6.00E-10	5.01E-12	3.38E-09	2.60E-10	1.23E-10
A	2.01E-02	1.05E-04	-1.53E-03	-7.37E-04	1.85E-03
EF	6.07E-05	5.30E-07	-1.40E-04	-2.15E-06	2.28E-05
EM	8.89E-03	1.30E-03	-2.65E-04	-2.95E-04	6.33E-04
ET	9.74E-02	2.26E-04	-2.87E-03	-3.23E-03	6.93E-03
ETF	1.55E+01	2.12E-01	-1.31E+01	-1.43E+00	4.46E+00
LU	3.38E+00	4.31E-01	-6.85E+00	-2.41E+00	6.52E+00
WU	4.41E-02	8.06E-04	-2.63E-02	9.46E-03	1.96E-02
RUF	2.65E+01	1.67E-01	-6.07E+00	-2.00E+00	5.70E+00
RUM	1.00E-06	2.21E-08	-6.51E-06	-2.61E-07	8.42E-07

DEM: Demolition (diesel, electricity consumptions); **LB**: Landfill of bituminous materials; **RCD**: Recycling of mixed C&D waste; **RC**: Recycling of cement; **T**: Transportation

The result of the contribution analysis of case 5 is shown in Figure 43.

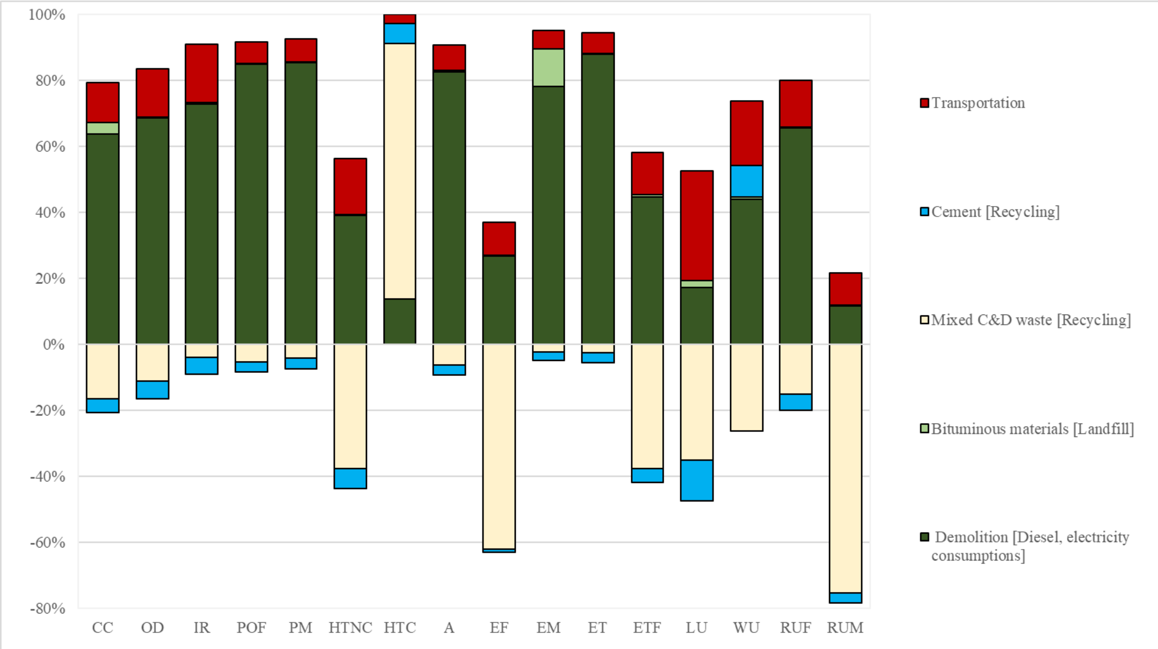


Figure 43: Contribution analysis for the selective demolition of 1 m3 of a commercial concrete/masonry building (Case 5)

In case 5, the impacts are caused mainly for diesel and electricity consumption and transportation to the handling plants. In this case, two benefits are found deriving from the recycling of the mixed fraction of C&D waste and cement recycling. The recycling of the mixed fraction of C&D appears to be much more beneficial than the single fraction of cement in all impact categories except human toxicity and cancer effects (HTC), in which it is much more impactful than the recycling of cement. The landfill operation of bituminous materials has a visible effect only on the marine eutrophication (EM) impact category.

Case 6

The impact assessment of the sixth case drawn upon the five aggregate inputs: diesel consumption, recycling of mixed C&D waste, storage and landfill of insulating materials, recycling of wood, and transportations to handling plants, gives the results on the 16 impact categories shows in table 58.

Table 58: Impact assessment results from the selective demolition of 1 m3 of a commercial metal building (Case 6)

Impact Categories	DEM	RCD	SLI	RW	T
CC	3.68E-01	-1.48E-01	2.70E-03	-8.92E-03	6.70E-02
OD	7.86E-08	-1.98E-08	7.88E-10	-1.23E-09	1.61E-08
IR	2.27E-02	-1.94E-03	2.97E-04	-1.25E-02	5.31E-03
POF	5.10E-03	-4.87E-04	2.23E-05	-4.41E-04	3.80E-04
PM	1.02E-07	-7.60E-09	3.89E-10	-1.06E-08	7.93E-09
HTNC	2.14E-09	-3.21E-09	2.79E-11	1.95E-10	8.95E-10
HTC	1.14E-10	1.00E-09	1.13E-12	4.35E-10	2.29E-11
A	3.82E-03	-4.56E-04	2.11E-05	-2.98E-04	3.40E-04
EF	1.14E-05	-4.16E-05	3.66E-07	-1.40E-05	4.21E-06
EM	1.69E-03	-7.87E-05	6.82E-06	-1.49E-04	1.17E-04
ET	1.85E-02	-8.54E-04	7.43E-05	-1.61E-03	1.28E-03
ETF	2.95E+00	-3.88E+00	4.17E-02	-1.20E+00	8.20E-01
LU	6.42E-01	-2.03E+00	1.14E-01	-1.99E+01	1.17E+00
WU	7.89E-03	-7.79E-03	2.89E-03	-5.62E-02	3.58E-03
RUF	5.05E+00	-1.80E+00	7.68E-02	-2.29E-01	1.05E+00
RUM	1.89E-07	-1.93E-06	8.70E-09	1.42E-07	1.60E-07

DEM: Demolition (Diesel consumptions); **RCD**: Recycling of mixed C&D waste; **SLI**: Storage + Landfill of Insulating materials; **RW**: Recycling of Wood; **T**: Transportation

The result of the contribution analysis of case 6 is shown in Figure 44.

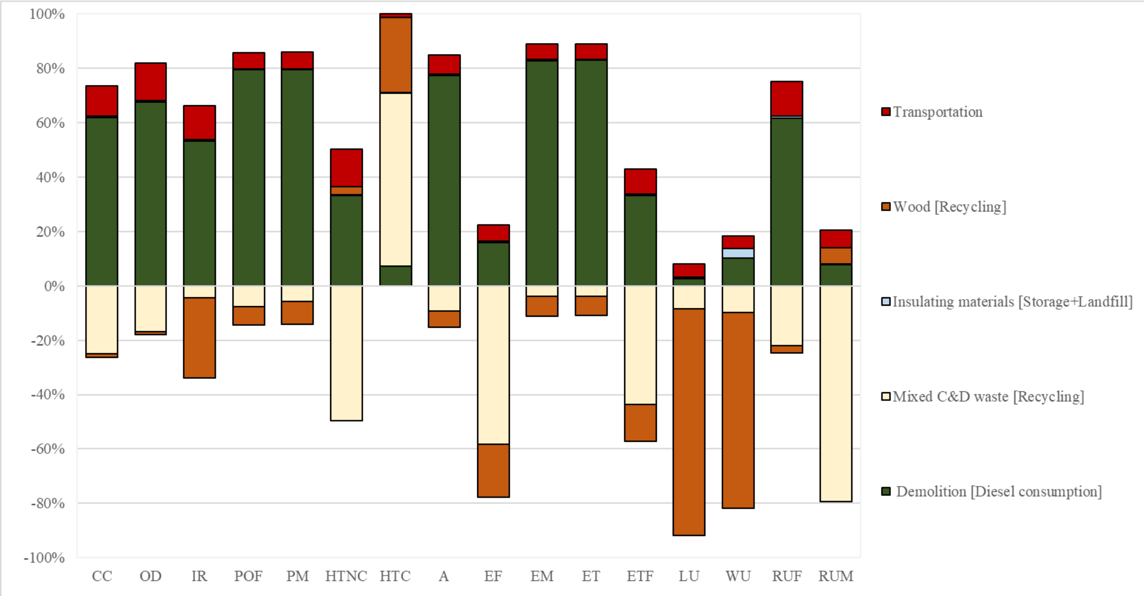


Figure 44: Contribution analysis for the selective demolition of 1 m3 of a commercial metal building (Case 6)

Also, in this case, the most impactful phase is given by demolition machinery (represented by diesel consumption). Recycling the C&D waste fraction and wood gives valuable benefits to the system for most of the impact categories, except for human toxicity, where they represent the major percentual of impact. Storage and landfilling of insulating material do not significantly impact all of the categories analysed.

Case 7

Finally, in case 7, the impact assessment of the sixth case is drawn upon only three aggregate inputs: diesel and water consumption, recycling of mixed C&D waste, and transportations to handling plant. The results on the 16 impact categories are shown in table 59.

Table 59: Impact assessment results from the selective demolition of 1 m3 of a commercial metal building (Case 7)

Impact Categories	DEM	RCD	T
CC	1.01E+00	-1.56E-01	7.24E-02
OD	2.16E-07	-2.07E-08	1.74E-08
IR	6.25E-02	-2.03E-03	5.75E-03
POF	1.40E-02	-5.11E-04	4.13E-04
PM	2.82E-07	-7.97E-09	8.72E-09
HTNC	5.89E-09	-3.37E-09	9.72E-10
HTC	3.14E-10	1.05E-09	2.46E-11
A	1.05E-02	-4.78E-04	3.68E-04
EF	3.13E-05	-4.36E-05	4.54E-06
EM	4.66E-03	-8.26E-05	1.26E-04
ET	5.10E-02	-8.96E-04	1.38E-03
ETF	8.12E+00	-4.07E+00	8.88E-01
LU	1.77E+00	-2.13E+00	1.30E+00
WU	2.18E-02	-8.18E-03	3.91E-03
RUF	1.39E+01	-1.89E+00	1.14E+00
RUM	5.20E-07	-2.02E-06	1.67E-07

DEM: Demolition (diesel, water consumptions); **RCD**: Recycling of mixed C&D waste; **SLI**: Storage + Landfill of insulating materials; **RW**: Recycling of wood; **T**: Transportation

The result of the contribution analysis of case 7 is shown in Figure 45.

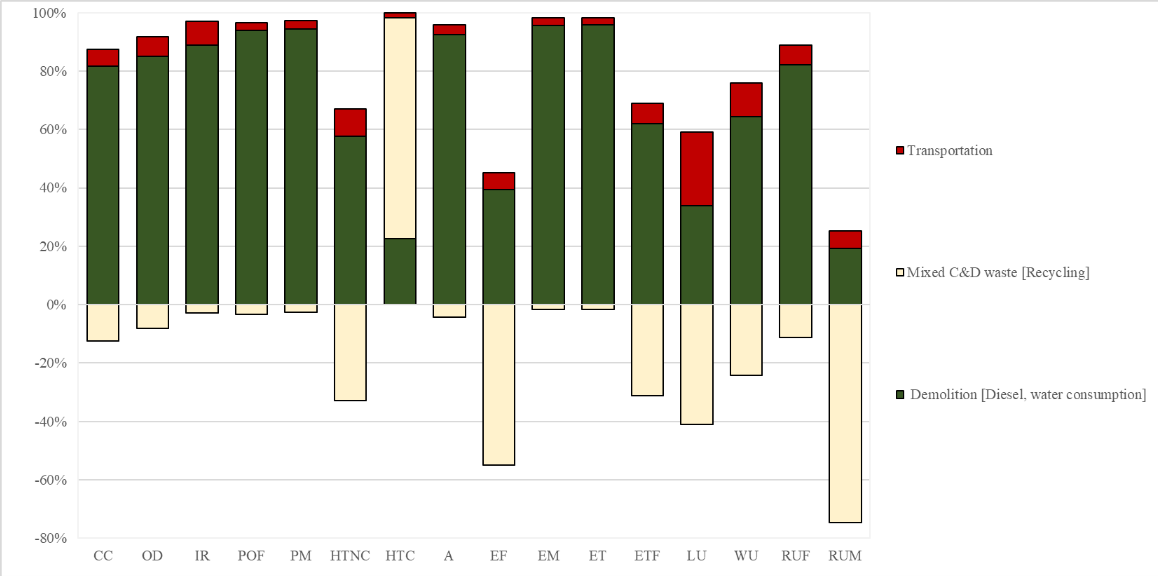


Figure 45: Contribution analysis for the selective demolition of 1 m3 of a commercial metal building (Case 7)

Also, in this case, the most impactful phase is given by demolition machinery (represented by diesel and water consumption). Transportation to the processing plants has a modest influence on the total. In this scenario, recycling the C&D waste component also contributes positively.

Comparison

By analysing the entire outcomes of the seven case studies, the most impactful scenario may be identified (Table 60).

Table 60: Impact assessment results (Comparison between the seven cases studies)

Impact Categorie s	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 7
CC	5.57E+00	3.57E+00	5.74E+00	5.45E+00	1.78E+00	2.80E-01	9.29E-01
OD	1.06E-06	6.74E-07	5.83E-07	1.62E-06	4.03E-07	7.45E-08	2.13E-07
IR	5.38E-01	3.10E-01	1.70E-01	5.81E-01	1.35E-01	1.39E-02	6.63E-02
POF	5.66E-02	3.69E-02	4.79E-02	3.96E-02	2.64E-02	4.58E-03	1.39E-02
PM	1.07E-06	6.90E-07	9.32E-07	7.21E-07	5.37E-07	9.25E-08	2.82E-07
HTNC	1.95E-08	1.16E-08	1.38E-08	6.22E-08	3.62E-09	4.54E-11	3.49E-09
HTC	6.81E-09	5.85E-09	2.83E-09	4.30E-09	4.37E-09	1.58E-09	1.39E-09
A	4.90E-02	3.19E-02	3.50E-02	3.80E-02	1.98E-02	3.43E-03	1.04E-02
EF	4.39E-04	2.43E-04	8.36E-05	1.35E-03	-5.83E-05	-3.96E-05	-7.77E-06
EM	1.91E-02	1.24E-02	2.25E-02	1.24E-02	1.03E-02	1.59E-03	4.70E-03
ET	2.10E-01	1.37E-01	1.73E-01	1.33E-01	9.85E-02	1.74E-02	5.15E-02
ETF	3.22E+01	1.70E+01	2.55E+01	8.70E+01	5.71E+00	-1.27E+00	4.94E+00
LU	-2.65E+01	-7.31E+01	-1.97E+01	2.58E+02	1.07E+00	-2.00E+01	9.37E-01
WU	1.70E+00	9.49E-01	1.07E-01	4.88E+00	4.78E-02	-4.96E-02	1.75E-02
RUF	8.07E+01	5.10E+01	3.82E+01	1.22E+02	2.44E+01	4.14E+00	1.31E+01
RUM	-9.68E-07	-5.41E-07	9.54E-08	1.77E-05	-4.90E-06	-1.43E-06	-1.34E-06

According to the graph in figure 46, the most impactful cases are the first five, characterized by a discrete subdivision of the outgoing flows that have been sent for recycling or on-site reuse.

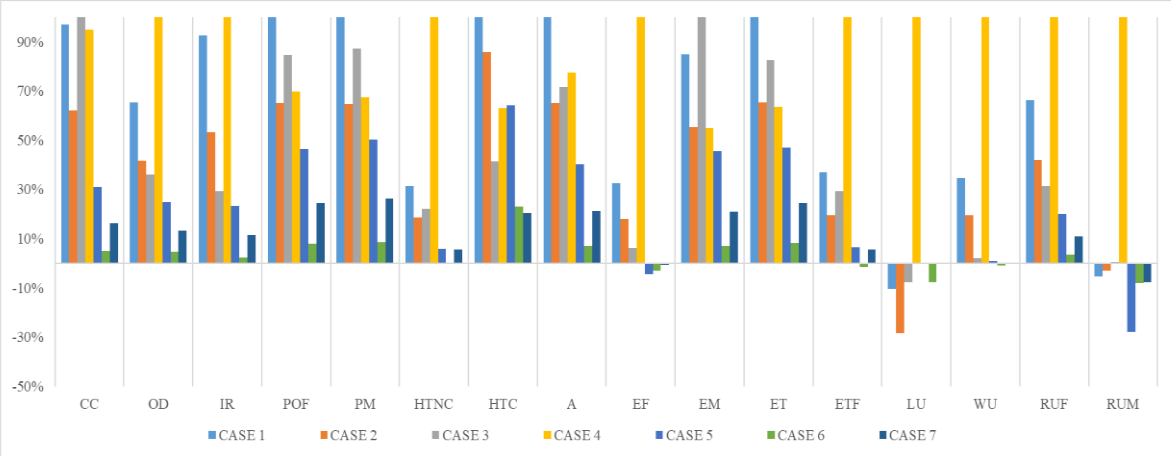


Figure 46: Comparison between the seven cases studies

When the consumption of the seven cases is compared in terms of kg of CO_2 equivalent emitted (Climate change impact category) (Figure 47), the consumption of the first cases is much higher, owing to the prolongation of the usage times of the machinery for sorting the material and thus the higher consumption of the latter.

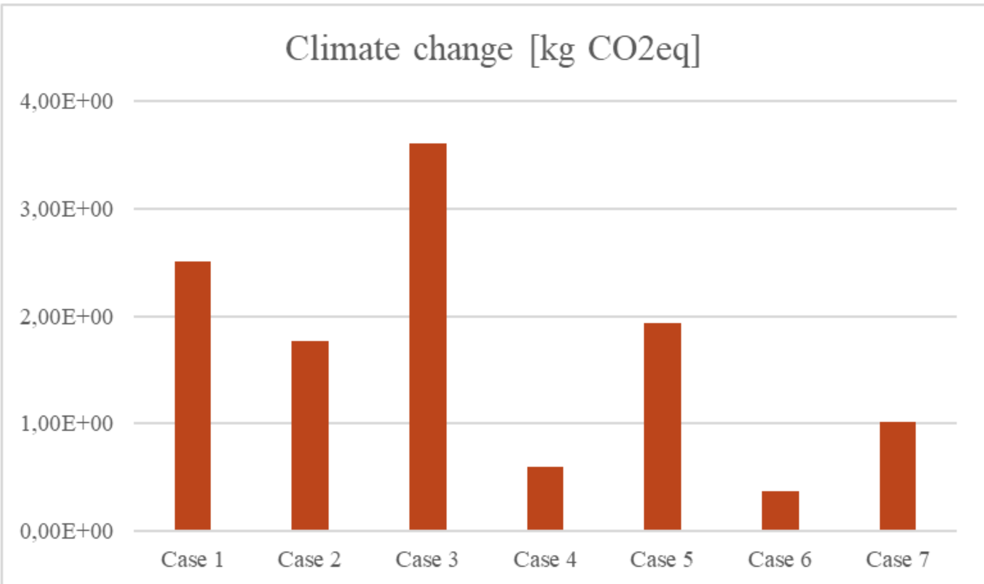


Figure 47: LCIA of Consumption comparison among the seven cases

As a result, as illustrated, the environmental impact decreases as less waste leaves the demolition site. It would be beneficial to divide only those flows that provide benefits for this purpose, like C&D waste streams, cement, and wood. For example, recycling gypsum, as demonstrated in cases 1 and 2, brings no benefits and significantly impacts the process.

6.4 SENSITIVITY ANALYSIS

As for the eLCC analysis, it is decided to exclude all metal waste streams to consider them in the context of a sensitivity analysis in paragraph 6.4.1. It is also thought to be worthwhile to analyse the workforce's environmental impact, as shown in paragraph 6.4.2.

6.4.1 The contribution of the metal flows

The contribution to environmental impacts varies according to the quantity of metal waste and the distances travelled to transfer for treatment. This contribution is shown in each case below.

Masonry/concrete buildings (Cases 1 to 5)

Table 61 depicts the base scenario and the scenario with the metal waste flows for Case 1 and Case 2.

Table 61: Impact assessment results – contribution of the metal flows (Case 1 and Case 2)

	Case 1		Case 2	
Impact Categories	**Base Scenario**	**Scenario with metal flows**	**Base Scenario**	**Scenario with metal flows**
CC	5.57E+00	-1.51E+01	3.57E+00	-1.20E+01
OD	1.06E-06	2.56E-07	6.74E-07	1.12E-07
IR	5.38E-01	1.26E+00	3.10E-01	5.08E-01
POF	5.66E-02	-5.08E-02	3.69E-02	-3.98E-02
PM	1.07E-06	-3.46E-07	6.90E-07	-3.46E-07
HTNC	1.95E-08	-9.10E-07	1.16E-08	-6.91E-07
HTC	6.81E-09	1.79E-07	5.85E-09	1.02E-07
A	4.90E-02	-6.63E-02	3.19E-02	-7.64E-02
EF	4.39E-04	-1.87E-02	2.43E-04	-1.49E-02
EM	1.91E-02	-8.94E-04	1.24E-02	-3.96E-03
ET	2.10E-01	-7.65E-03	1.37E-01	-3.83E-02
ETF	3.22E+01	-8.76E+02	1.70E+01	-6.13E+02
LU	-2.65E+01	-8.82E+01	-7.31E+01	-1.15E+02
WU	1.70E+00	-3.50E+02	9.49E-01	-2.69E+02
RUF	8.07E+01	-1.05E+02	5.10E+01	-9.34E+01
RUM	-9.68E-07	-3.39E-04	-5.41E-07	-1.93E-04

The metal waste flows in these two cases regard the aluminium, the iron and steel, and the cables to be sent to recycling (See § 6.2 - Figure 25-27). The new scenarios integrated their treatment operations and transportation to the facility. The graphs in Figure 48 shows that the input of metals offers considerable advantages to the system, even covering the impacts of demolition and other waste treatment. The only impact categories that have a pejorative result are human toxicity, cancer effects (HTC) and Ionising radiation (IR) caused by metal recycling processes.

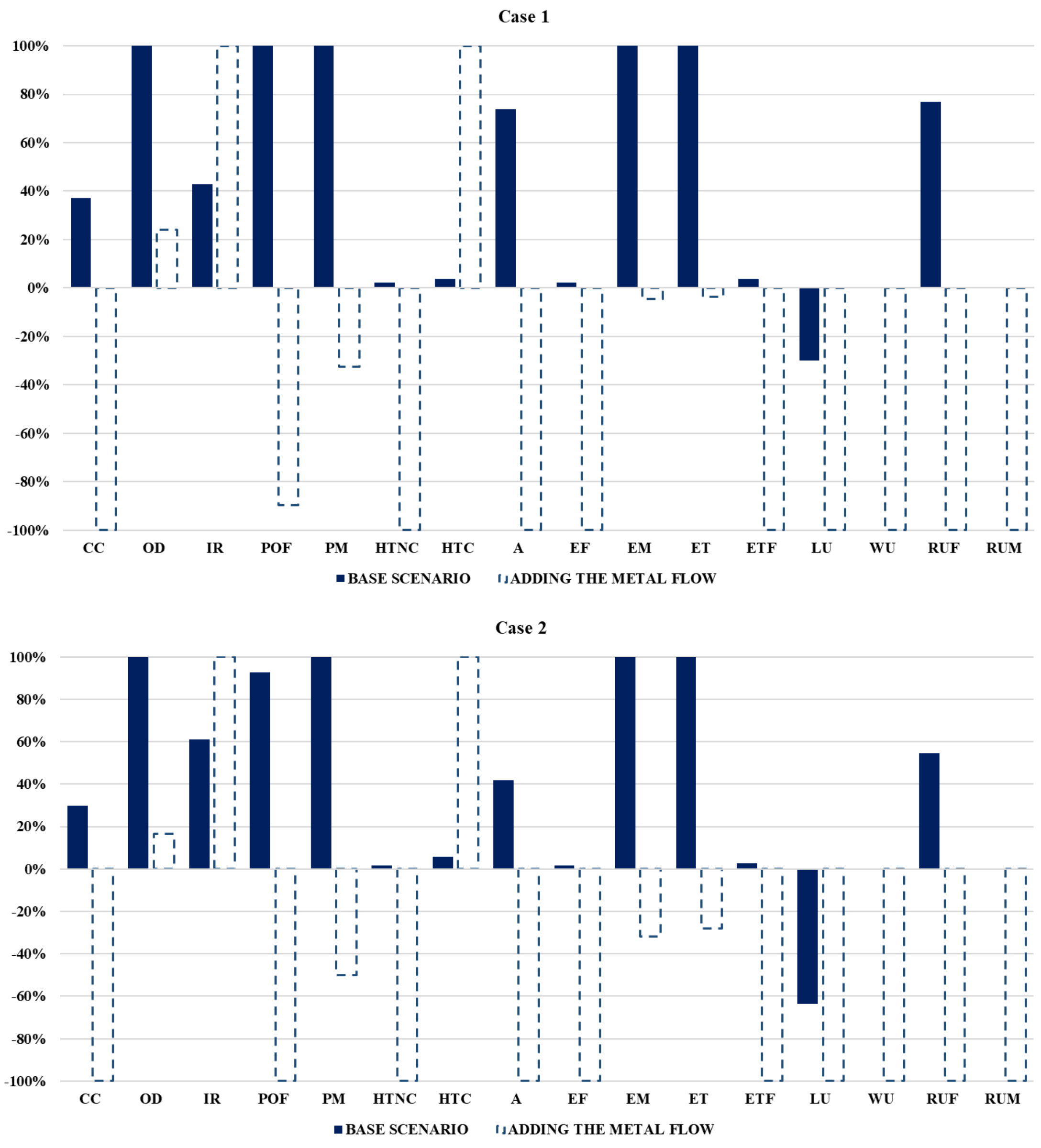


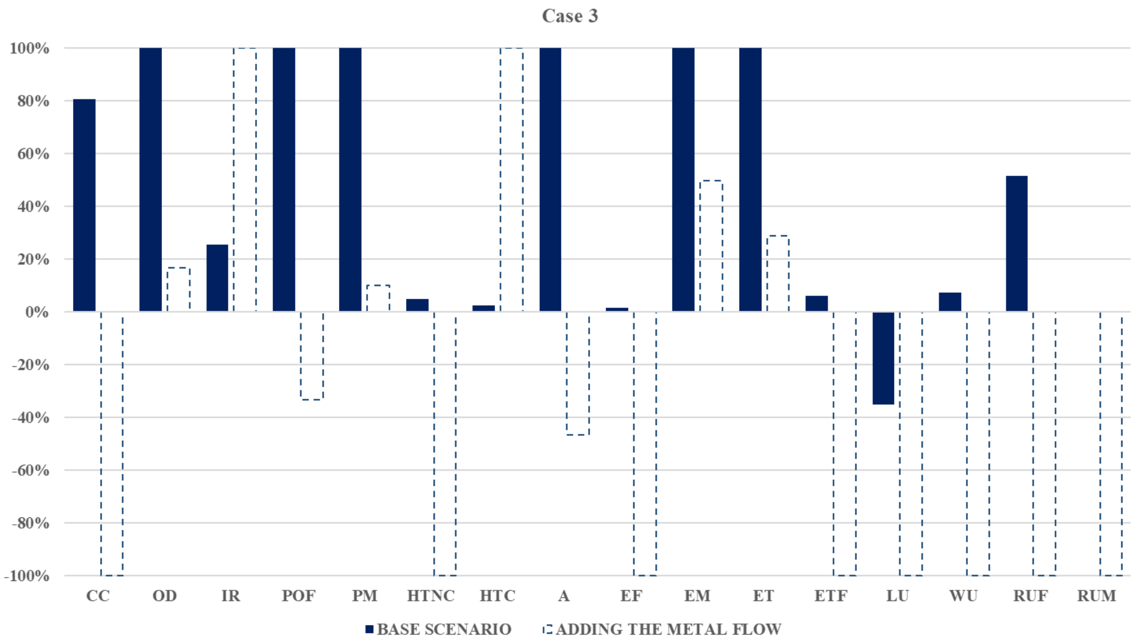
Figure 48: Base scenario vs. scenario with metal flows (Case 1 and Case 2)

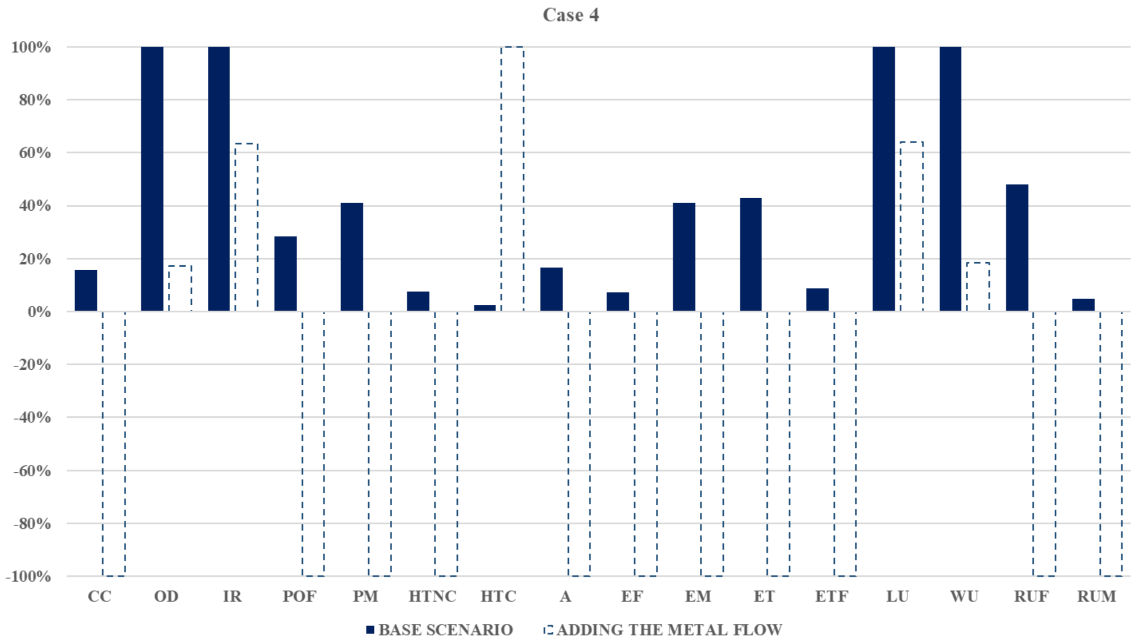
Table 62 depicts the base scenario and the scenario with the metal waste flows for Case 3, Case 4, and Case 5.

Table 62: Impact assessment results – contribution of the metal flows (Case 3, Case 4 and Case 5)

	Case 3		Case 4		Case 5	
Impact Categories	**Base Scenario**	**Scenario with metal flows**	**Base Scenario**	**Scenario with metal flows**	**Base Scenario**	**Scenario with metal flows**
CC	5.74E+00	-7.12E+00	5.45E+00	-3.50E+01	1.78E+00	-5.95E+00
OD	5.83E-07	9.74E-08	1.62E-06	2.78E-07	4.03E-07	1.09E-07
IR	1.70E-01	6.65E-01	5.81E-01	3.69E-01	1.35E-01	4.31E-01
POF	4.79E-02	-1.59E-02	3.96E-02	-1.39E-01	2.64E-02	-1.20E-02
PM	9.32E-07	9.41E-08	7.21E-07	-1.76E-06	5.37E-07	3.25E-08
HTNC	1.38E-08	-2.77E-07	6.22E-08	-8.17E-07	3.62E-09	-1.71E-07
HTC	2.83E-09	1.14E-07	4.30E-09	1.79E-07	4.37E-09	7.10E-08
A	3.50E-02	-1.63E-02	3.80E-02	-2.28E-01	1.98E-02	-1.11E-02
EF	8.36E-05	-5.45E-03	1.35E-03	-1.90E-02	-5.83E-05	-3.38E-03
EM	2.25E-02	1.12E-02	1.24E-02	-3.00E-02	1.03E-02	3.46E-03
ET	1.73E-01	5.00E-02	1.33E-01	-3.10E-01	9.85E-02	2.45E-02
ETF	2.55E+01	-4.15E+02	8.70E+01	-9.97E+02	5.71E+00	-2.59E+02
LU	-1.97E+01	-5.61E+01	2.58E+02	1.65E+02	1.07E+00	-2.09E+01
WU	1.07E-01	-1.46E+00	4.88E+00	8.98E-01	4.78E-02	-8.94E-01
RUF	3.82E+01	-7.40E+01	1.22E+02	-2.54E+02	2.44E+01	-4.31E+01
RUM	9.54E-08	-2.26E-04	1.77E-05	-3.72E-04	-4.90E-06	-1.41E-04

The metal waste flows in case 3 and case 5 regard the iron and steel waste fraction. In Case 4, other than Iron and Steel the aluminium fraction is also sorted. The new scenarios integrated their treatment operations and transportation to the facility. The graphs in figure 49 show that, also in these cases, the input of metals offers considerable advantages to the system, even covering the impacts of demolition and other waste treatment. Even in these cases, there are pejorative impacts caused by metal recycling processes in the impact categories of human toxicity, carcinogenic effects (HTC) and ionizing radiation (IR).





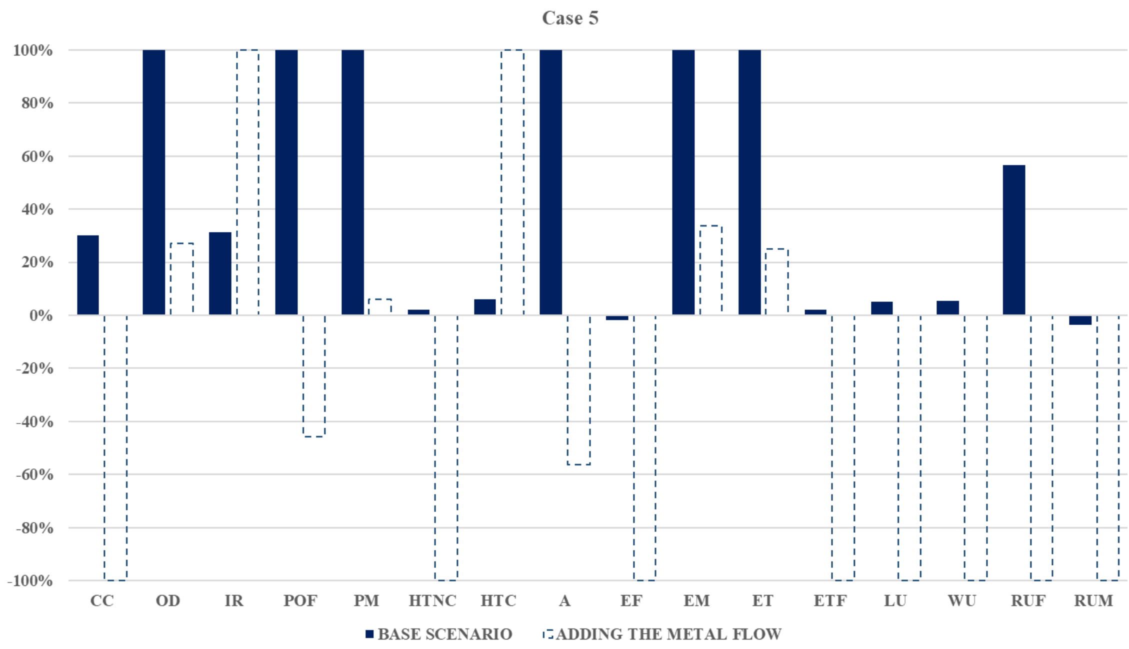


Figure 49: Base scenario vs. scenario with metal flows (Case 3, Case 4 and Case 5)

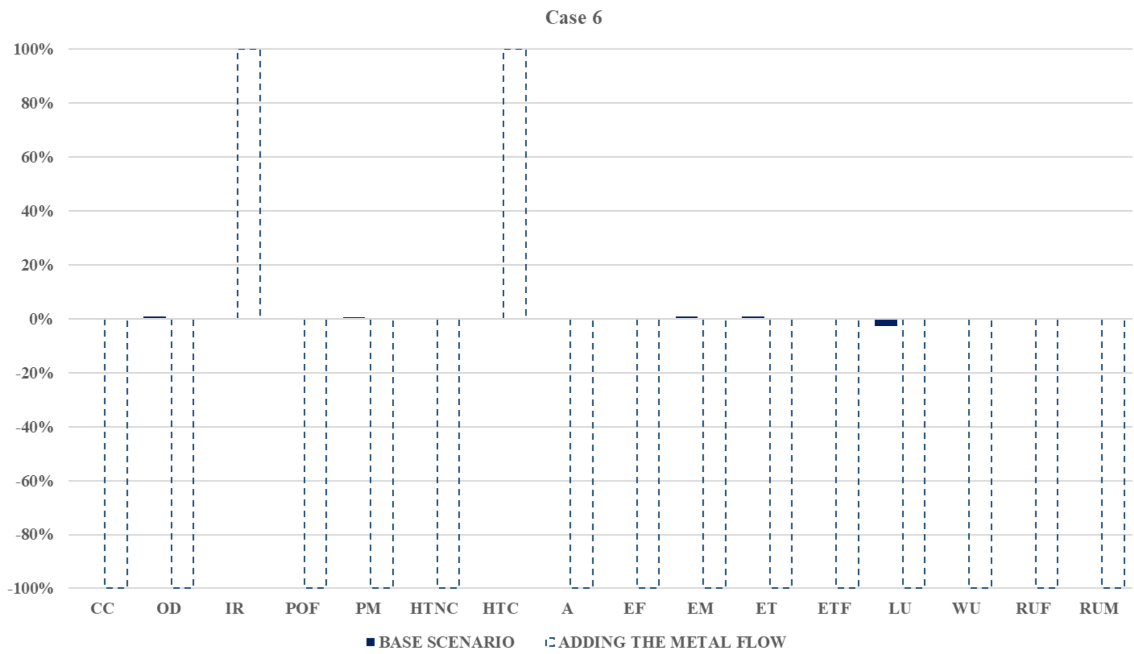
Metal buildings (Cases 6 and Case 7)

Cases 6-7, associated with the demolition of commercial buildings with metal structures, which previously revealed economic advantages in eLCC research with the inclusion of metal fluxes, also offer clear advantages in LCA. Table 63 shows the base scenario results and the results from the scenario with the metal waste flows for the last two cases.

Table 63: Impact assessment results – contribution of the metal flows (Case 6 and Case 7)

	Case 6		Case 7	
Impact Categories	**Base Scenario**	**Scenario with metal flows**	**Base Scenario**	**Scenario with metal flows**
CC	2.80E-01	-2.44E+02	9.29E-01	-2.40E+02
OD	7.45E-08	-9.33E-06	2.13E-07	-8.96E-06
IR	1.39E-02	9.31E+00	6.63E-02	9.30E+00
POF	4.58E-03	-1.21E+00	1.39E-02	-1.18E+00
PM	9.25E-08	-1.58E-05	2.82E-07	-1.54E-05
HTNC	4.54E-11	-5.51E-06	3.49E-09	-5.43E-06
HTC	1.58E-09	2.10E-06	1.39E-09	2.08E-06
A	3.43E-03	-9.72E-01	1.04E-02	-9.52E-01
EF	-3.96E-05	-1.05E-01	-7.77E-06	-1.04E-01
EM	1.59E-03	-2.14E-01	4.70E-03	-2.07E-01
ET	1.74E-02	-2.32E+00	5.15E-02	-2.26E+00
ETF	-1.27E+00	-8.35E+03	4.94E+00	-8.25E+03
LU	-2.00E+01	-7.19E+02	9.37E-01	-6.83E+02
WU	-4.96E-02	-2.98E+01	1.75E-02	-2.94E+01
RUF	4.14E+00	-2.13E+03	1.31E+01	-2.09E+03
RUM	-1.43E-06	-4.28E-03	-1.34E-06	-4.23E-03

Case 6 and Case 7 contribution analysis graphs (Figure 50) clearly indicate how the advantages of metal recycling have completely offset the effects of demolition and waste treatment.



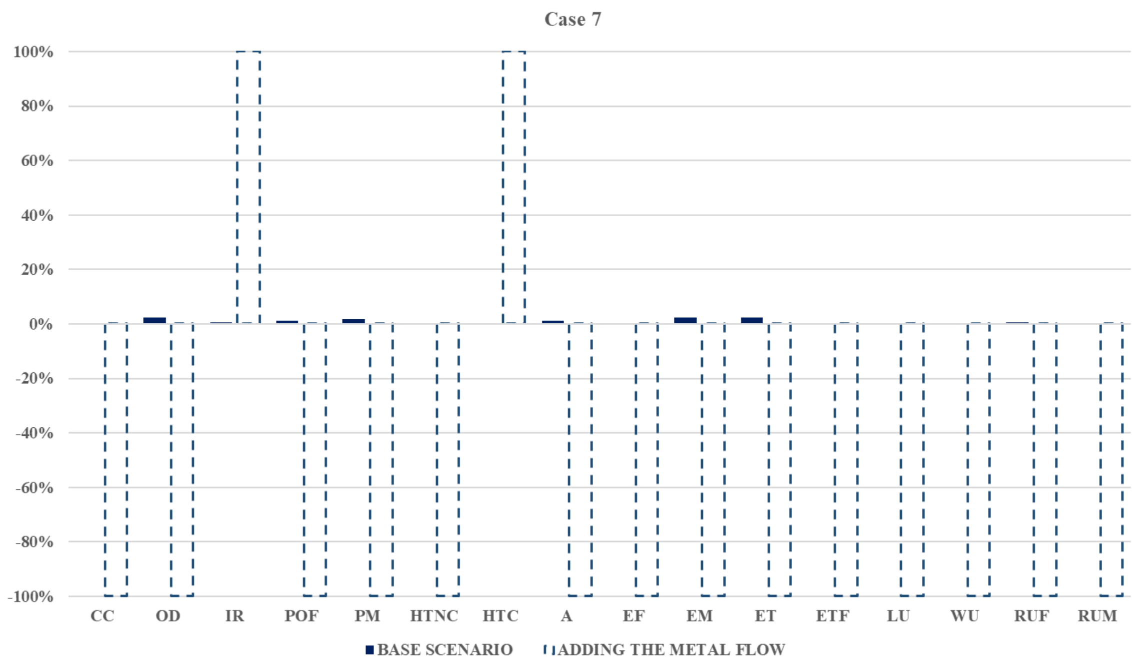


Figure 50: Base scenario vs. scenario with metal flows (Case 6 and Case 7)

Finally, the graph in Figure 51, which compares the sensitivity scenarios, demonstrates how the demolition of mostly metal structures gains the highest benefits from metal flow separation.

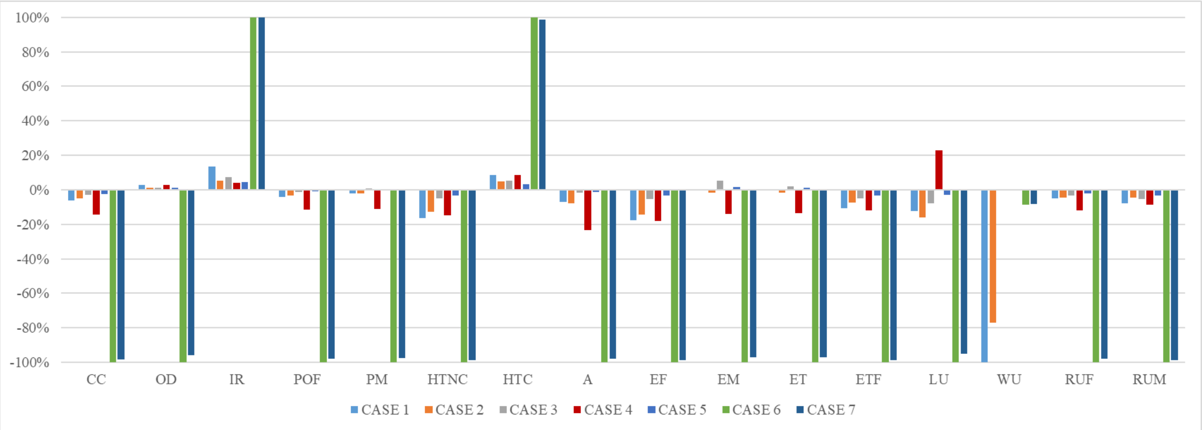


Figure 51: Comparison between the seven cases studies (sensitivity scenarios)

6.4.2 The contribution of the workforce

Another aspect that was thought worthwhile to investigate is the influence of the workforce on demolition operations. The research, conducted in collaboration with Sreepryia Venugopal, thesis student, aims to analyse the environmental impacts of the demolition workforce using the LCA (Venugopal, 2022). The key parameters responsible for the environmental impacts have been discovered in worker consumption during demolition activities. The inventory is developed using inputs from contributions (inputs) such as metabolic energy (in terms of food consumption), transportation (for the workers from-to the demolition site), toilet usage (paper, water, soap consumption), shelter (in terms of electricity consumption), and personal protection equipment (PPE) (production and disposal at end-of-life stage). Due to the fewer workers required to demolish metal buildings compared to concrete/masonry buildings selectively, two scenarios are investigated: one for masonry concrete buildings and one for metal buildings.

Masonry/concrete buildings

Table 65 illustrates the impact assessment results related to the workforce implied in the demolition of masonry/concrete buildings, for the five inputs: energy input, transportation, toilet usage, shelter, and PPE (Table 64).

Table 64: Inventory for the selective demolition of 1 m³ of masonry / concrete buildings

Input Flow	Quantity
Energy input	
Potatoes	0.259 g
Root vegetables	0.172 g
Leafy and fruit vegetables	0.951 g
Fruits	2.270 g
Milk, yogurt	1.277 g
Cheese	0.604 g
Pasta	1.520 g
Bread	1.092 g
Meat	0.786 g
Poultry	0.212 g
Fish	0.147 g
Eggs	0.111 g
Olive oil	0.216 g
Sugar and jam	0.205 g
Coffee	0.736 g
Tea	0.390 g
Fruit and vegetable juice	0.311 g

Carbonated drinks	0.628 g
Wine	1.549 g
Beer	0.517 g
Drinking water	0.015 kg
Transportation	
Transportation by car	1.179 km
Toilet usage	
Water	0.737 kg
Toilet paper	1.120 g
Hand tissue paper	0.655 g
Soap	0.511 g
Shelter	
Electricity	3.42 x 10^{-3} kWh
PPE	
Reflective safety jacket (Polyester)	0.091 g
Safety helmet (High density polyethylene)	0.013 g
Safety glass (Polycarbonate)	0.010 g
Face shield (Polycarbonate)	0.011 g
Hearing protection (Acrylonitrile Butadiene Styrene)	0.093 g
Safety boots (Polyurethane)	0.615 g
Fall protection device (Polyester)	0.063 g

Safety gloves (Polyvinyl chloride)	0.010 g
Respiratory protection (Thermoplastic elastomer- Plastic)	0.002

Table 65: Impact assessment results from the selective demolition of 1 m3 of masonry / concrete buildings

Impact Categories	Energy input	Transportation	Toilet usage	Shelters	PPE
CC	3.17E-02	2.13E-01	4.48E-03	1.38E-03	7.07E-03
OD	1.84E-09	3.71E-08	4.03E-10	1.88E-10	2.59E-09
IR	1.02E-03	4.30E-02	5.54E-04	1.90E-04	3.28E-04
POF	1.07E-04	7.63E-04	1.27E-05	2.99E-06	1.83E-05
PM	3.54E-09	1.52E-08	3.10E-10	2.41E-11	5.05E-10
HTNC	1.37E-09	1.94E-09	1.86E-10	7.88E-12	1.42E-10
HTC	5.83E-11	9.49E-11	7.20E-12	3.09E-13	6.97E-12
A	4.32E-04	9.09E-04	2.61E-05	6.30E-06	2.50E-05
EF	7.55E-06	2.89E-05	2.74E-06	3.15E-07	1.08E-06
EM	1.86E-04	2.82E-04	2.70E-05	9.60E-07	6.60E-06
ET	1.75E-03	3.09E-03	7.02E-05	1.07E-05	5.28E-05
ETF	2.45E+00	1.72E+00	5.99E-01	1.32E-02	2.31E-01
LU	5.46E+00	1.26E+00	1.00E-01	3.63E-03	1.17E-02
WU	7.76E-02	2.36E+01	6.56E-03	9.21E-04	4.00E-03
RUF	2.65E-01	3.31E+00	5.04E-02	2.09E-02	9.08E-02
RUM	2.01E-07	5.46E-07	3.01E-08	2.99E-09	2.55E-08

The results show that the major contributor to potential environmental impacts for most of the impact categories is the transportation of the workers from/to the demolition site. An exception can be seen for the land use (LU) category, where the main impact contributor is energy input which constitutes around 80% of all the impacts in that category. Also, for freshwater ecotoxicity (ETF), significant environmental impacts are caused by energy input of about 50%, followed by 35% from transportation. The water use impact category is affected substantially by transportation with negligible impact from other inputs. Toilet usage and personal safety devices contribute little to impact categories. However, its effects are the maximum for freshwater ecotoxicity (ETF) and ozone depletion (OD) categories by 10% and 6%, respectively. The shelter is a minor contributor throughout all the impact categories (Venugopal, 2022). The contribution of the workforce to demolition is shown in table 66 and figure 52.

Table 66: Impact assessment results of workforce + demolition phase for the selective demolition of 1 m3 of masonry/concrete building

Impact Categories	Demolition activity	Workforce
CC	2.08E+00	2.57E-01
OD	4.38E-07	4.21E-08
IR	1.36E-01	4.50E-02
POF	2.78E-02	9.04E-04
PM	5.55E-07	1.95E-08
HTNC	1.21E-08	3.65E-09
HTC	6.39E-10	1.68E-10
A	2.11E-02	1.40E-03
EF	8.38E-05	4.06E-05
EM	9.21E-03	5.03E-04
ET	1.01E-01	4.98E-03
ETF	1.69E+01	5.01E+00
LU	3.73E+00	6.84E+00
WU	1.08E-01	2.37E+01
RUF	2.87E+01	3.74E+00
RUM	1.23E-06	8.06E-07

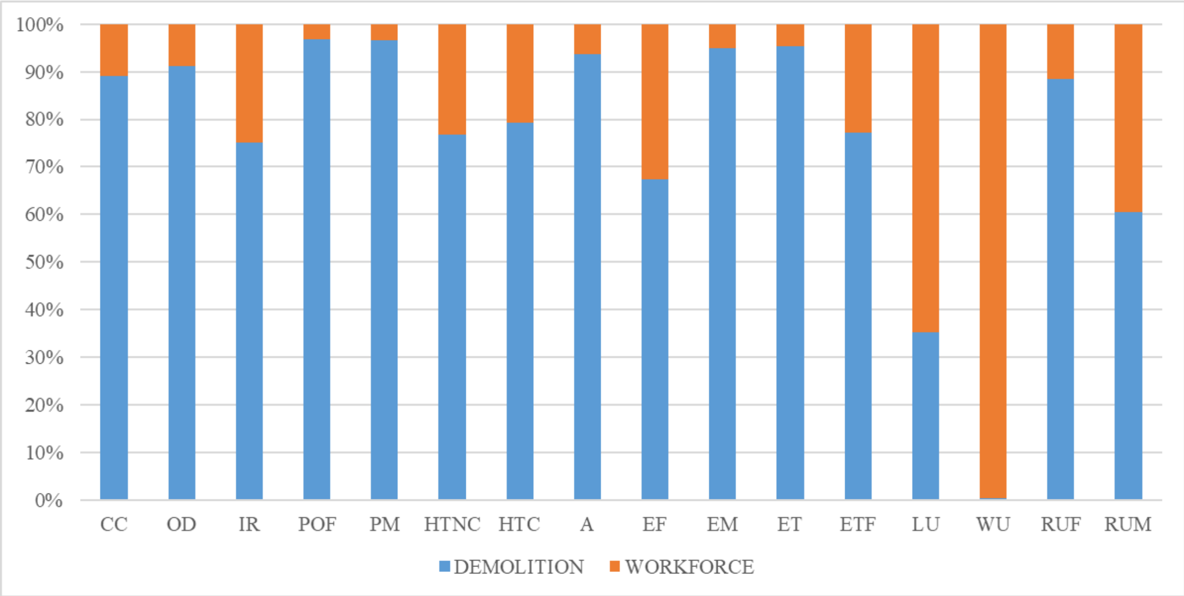


Figure 52: Contribution analysis for the selective demolition of concrete/masonry buildings

Overall, the workforce has the second highest impact (24%), after only the demolition site's diesel, water and electricity consumption (72%). The workforce provides more than half of the impacts in the land use (LU) and water usage (WU) categories. It contributes more than 10% to impact categories such as climate change (CC), ionising radiation (IR), human toxicity, non-cancer (HTNC), human toxicity, cancer (HTC), freshwater eutrophication (EF), freshwater ecotoxicity (ETF), resource usage, fossils (RUF), and minerals and metals (RUM).

Metal Buildings

Table 68 illustrates the impact assessment results related to the workforce implied in the demolition of metal buildings, in terms of the five inputs: energy input, transportation, toilet usage, shelter, and PPE (Table 67).

Table 67: Inventory for the selective demolition of 1 m^3 of metal buildings

Input Flow	Quantity
Energy input	
Potatoes	0.056 g
Root vegetables	0.037 g
Leafy and fruit vegetables	0.204 g
Fruits	0.487 g
Milk, yogurt	0.274 g
Cheese	0.130 g
Pasta	0.326 g
Bread	0.234 g
Meat	0.169 g
Poultry	0.045 g
Fish	0.031 g
Eggs	0.024 g
Olive oil	0.046 g
Sugar and jam	0.044 g
Coffee	0.158 g
Tea	0.084 g
Fruit and vegetable juice	0.067 g

Carbonated drinks	0.135 g
Wine	0.333 g
Beer	0.111 g
Drinking water	0.003 Kg
Transportation	
Transportation by car	0.326 km
Toilet usage	
Water	0.174 kg
Toilet paper	0.264 g
Hand tissue paper	0.154 g
Soap	0.121 g
Shelter	
Electricity	1.129×10^{-3} kWh
PPE	
Reflective safety jacket (Polyester)	0.018 g
Safety helmet (High density polyethylene)	0.003 g
Safety glass (Polycarbonate)	0.002 g
Face shield (Polycarbonate)	0.002 g
Hearing protection (Acrylonitrile Butadiene Styrene)	0.021 g
Safety boots (Polyurethane)	0.145 g
Fall protection device (Polyester)	0.010 g
Safety gloves (Polyvinyl chloride)	0.002 g

Respiratory protection (Thermoplastic elastomer- Plastic)	0.0005 g

Table 68: Impact assessment results from the selective demolition of 1 m3 of metal buildings

Impact Categories	Energy input	Transportation	Toilet usage	Shelters	PPE
CC	6.82E-03	5.88E-02	1.06E-03	4.57E-04	1.59E-03
OD	3.93E-10	1.03E-08	9.51E-11	6.22E-11	4.75E-10
IR	2.19E-04	1.19E-02	1.31E-04	6.27E-05	7.31E-05
POF	2.29E-05	2.11E-04	3.00E-06	9.88E-07	4.08E-06
PM	7.60E-10	4.19E-09	7.32E-11	7.94E-12	1.15E-10
HTNC	2.94E-10	5.37E-10	4.38E-11	2.60E-12	3.25E-11
HTC	1.25E-11	2.62E-11	1.70E-12	1.02E-13	1.60E-12
A	9.29E-05	2.51E-04	6.15E-06	2.08E-06	5.59E-06
EF	1.62E-06	7.99E-06	6.45E-07	1.04E-07	2.40E-07
EM	4.00E-05	7.79E-05	6.37E-06	3.17E-07	1.50E-06
ET	3.76E-04	8.55E-04	1.66E-05	3.53E-06	1.17E-05
ETF	5.27E-01	4.75E-01	1.41E-01	4.37E-03	5.31E-02
LU	1.17E+00	3.48E-01	2.37E-02	1.20E-03	2.51E-03
WU	1.67E-02	6.53E+00	1.54E-03	3.04E-04	9.17E-04
RUF	5.69E-02	9.16E-01	1.19E-02	6.91E-03	2.04E-02
RUM	4.32E-08	1.51E-07	7.10E-09	9.88E-10	5.41E-09

For metal buildings, a similar environmental impact trend is seen in the case of concrete/masonry buildings. Transportation is the main impact contributor in all the categories except land use (LU), for which energy input constitutes around 75% of all the impacts in that category. Also, for freshwater ecotoxicity (ETF), significant environmental impacts are caused by energy input which constitutes 45%, followed by 40% from transportation. The water use impact category is affected substantially by transportation with negligible impact from other inputs. Toilet usage and personal safety devices contribute little to impact categories. However, the toilet usage effects are the maximum for freshwater ecotoxicity by 10% approximately. At the same time, impacts from personal safety devices are maximum for ozone depletion (OD) and freshwater ecotoxicity (ETF) categories by 4% approximately. The shelter is a minor contributor throughout all the impact categories (Venugopal, 2022). The workforce's contribution to demolition is shown in table 69 and figure 53.

Table 69: Impact assessment results of workforce + demolition phase for the selective demolition of 1 m3 of metal building

Impact Categories	Demolition activity	Workforce
CC	6.90E-01	6.87E-02
OD	1.47E-07	1.13E-08
IR	4.26E-02	1.24E-02
POF	9.56E-03	2.42E-04
PM	1.92E-07	5.15E-09
HTNC	4.01E-09	9.10E-10
HTC	2.14E-10	4.22E-11
A	7.17E-03	3.58E-04
EF	2.14E-05	1.06E-05
EM	3.17E-03	1.26E-04
ET	3.48E-02	1.26E-03
ETF	5.53E+00	1.20E+00
LU	1.20E+00	1.55E+00
WU	1.48E-02	6.55E+00
RUF	9.46E+00	1.01E+00
RUM	3.55E-07	2.08E-07

Also, in this case, the workforce is overall the second leading impact contributor (22%), following diesel, water and electricity consumption (78%) in a demolition site. For impact categories such as water use (WU) and resource use, fossils (RUF), the workforce contributes to greater than 50% of impacts. On the other hand, its contribution is more than 10% of all the impacts for impact categories such as photochemical ozone formation (POF), human toxicity, cancer (HTC), acidification (A), marine eutrophication (EM), land use (LU) and resource use, minerals, and metals (RUM).

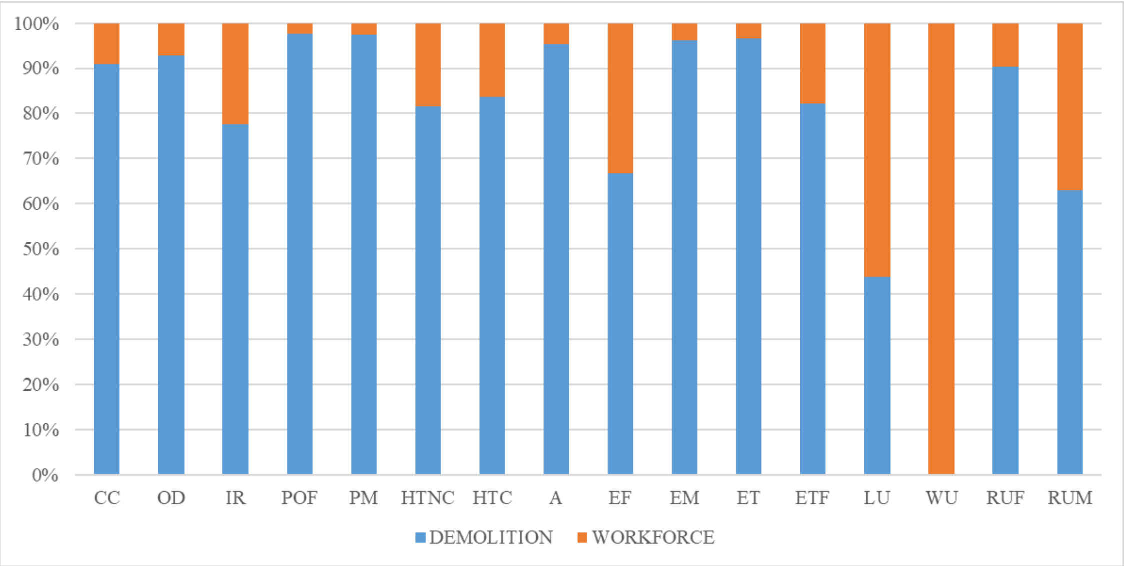


Figure 53: Contribution analysis of the factors that are responsible for the impacts in the selective demolition of metal buildings

CHAPTER 7.

ARCADIA Database

The first practical output of this PhD thesis work is the implementation of the ENEA-ARCADIA Italian Database with the datasets modelled on SimaPro software for the LCA of the selective demolition on the seven cases.

The Arcadia project "Life cycle approach in public contracts and the Italian LCA database for the efficient use of resources" (https://www.arcadia.enea.it/), developed and coordinated by ENEA - National Agency for New Technologies, Energy and Sustainable Economic Development, was launched in 2019 and will end in October 2023. Arcadia's main objective is to strengthen the skills of the Public Administrations to correctly integrate the LCT methodologies in the definition of tenders for public contracts aimed at the construction of infrastructures and public works and the implementation of green procurement through the development of two main actions: a preliminary analysis of the state of implementing approaches and methodologies for assessing environmental aspects, economic aspects and external costs of the life cycle related to public and green procurement (national and European); The creation of a national LCA database for 15 supply chains (so-called BDI-LCA).BDI-LCA represents a strategic tool to promote ecoinnovation and support circular economy actions along national production chains. The target audience of the Italian LCA database is:

- Public Administrations.
- Policy makers who, through LCA scenario studies based on national data, can acquire valuable information to support and elaborate public policies for the management and development of the territory.
- Companies and consultants who can use national data from the database to carry out LCA studies to improve the environmental impact of products and acquire environmental labels/certifications (e.g., EPD or Carbon Footprint).
- Research institutions/Universities for using the LCA methodology in research and development activities and the teaching field.

All the dataset created for the LCA analysis (see § 6.2) is uploaded through MEdit (Metadata Edit), which is a tool for developing the metadata in ILCD format (International Reference Life Cycle Data) and imported into the BDI-LCA of Arcadia.The metadata, shown in Annex III, is compiled for Case 1 and Case 7 as representative of the two cases of demolition of a masonry/concrete building and a metal building.

Figures 54 and 55 provide a list of all the datasets that have been turned into metadata and imported into BDI-LCA (see Annex III).

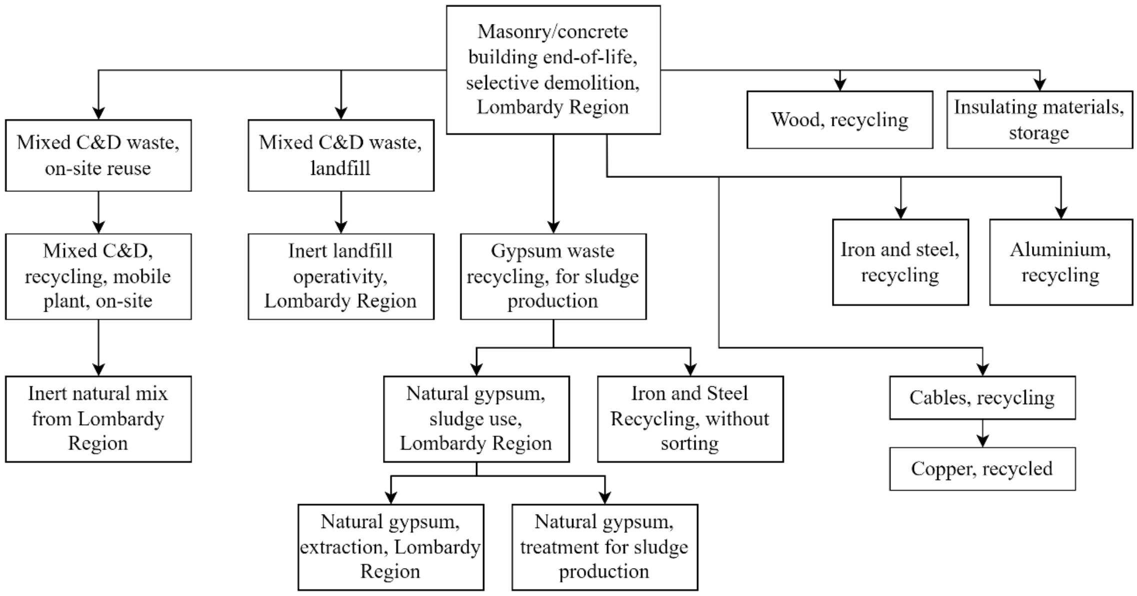


Figure 54: Datasets for the demolition of a masonry/concrete building imported on MeDit

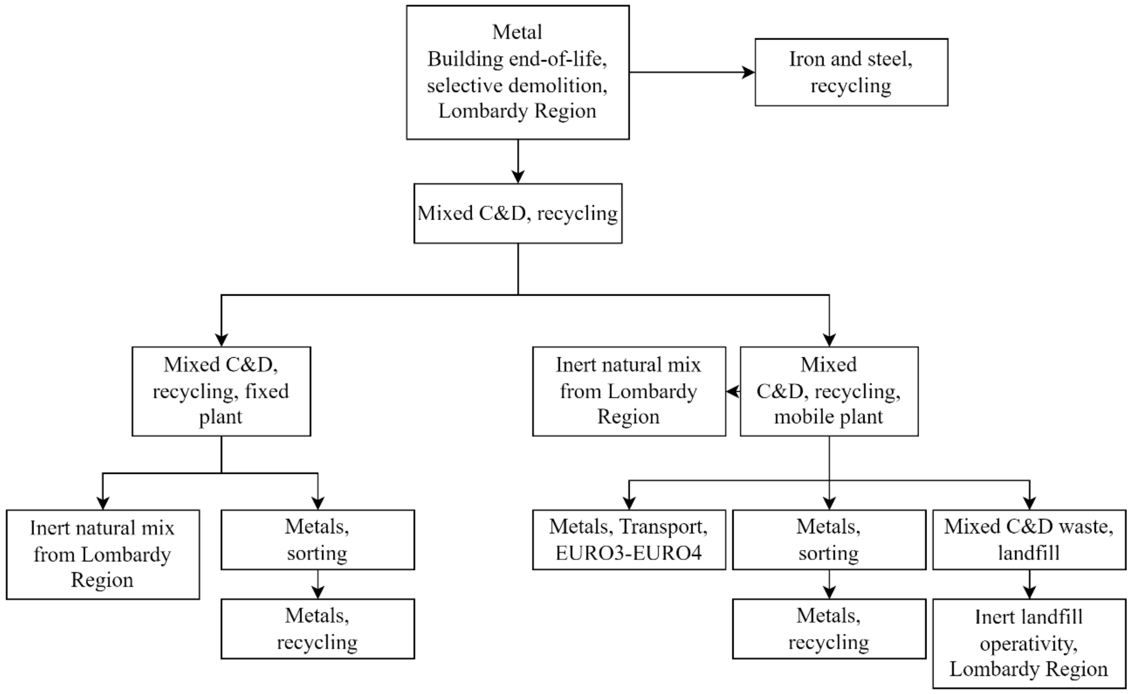


Figure 55: Datasets for the demolition of a metal building imported on MeDit

The BDI-LCA website may be accessed using the following link: https://bancadatiitalianalca.enea.it/Node/ . Figure 56 depicts the website interface, which provides all uploaded databases available for free download.

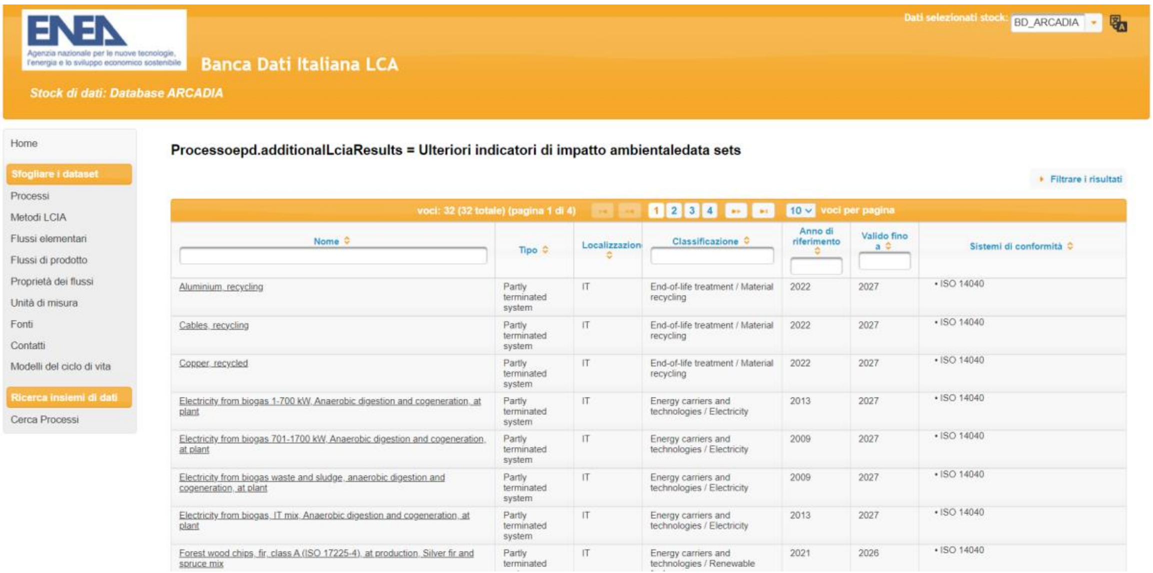


Figure 56: ARCADIA Database website interface

Figure 57 displays the appearance of the dataset on the webpage. The first part presents all the data entered in Annex III's metadata files.

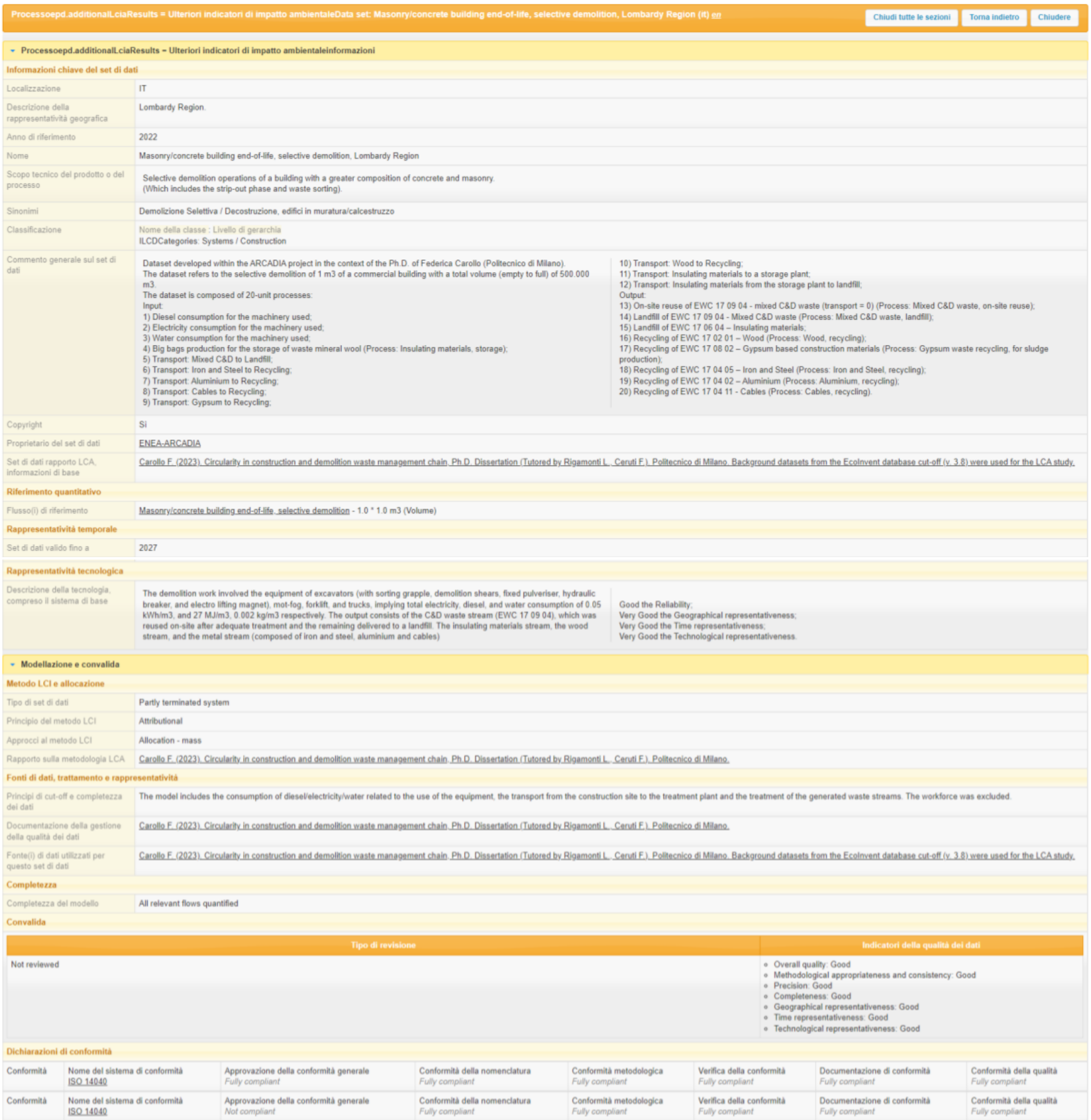


Figure 57: Dataset visualization on BDI-LCA website (part 1)

In the second part of the page (Figure 58), all the inputs and outputs of the process, referring to the functional unit, are indicated, along with the relative quantities and any notes.

Input e Output

Input

Tipo di flusso	Classificazione	Flusso	Localizzazione	Valore medio	Valore risultante
Product flow	Energy carriers and technologies / Mechanical energy	Diesel, burned in building machine {GLO}| market for | Cut-off, U	GLO	27.0 MJ	27.0 MJ
Commento generale	Diesel consumption for machineries				
Product flow	Materials production / water	Tap water {Europe without Switzerland}| tap water production, underground water without treatment | Cut-off, U	GLO	0.002 kg	0.002 kg
Commento generale	Water consumption for machineries				
Product flow	Systems / Other systems	Insulating materials, storage	GLO	0.00109 Item(s)	0.00109 Item(s)
Commento generale	[Amount=1,09/1000] Storage of EWC 17 06 04 - Insulating materials. 1000 kg is the capacity of 1 big bag				
Product flow	Transport services / Road	Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	GLO	3.4E-4 t*km	3.4E-4 t*km
Commento generale	[Amount=0,04*8,5] Transport: Mixed C&D to Landfill				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.122 t*km	0.122 t*km
Commento generale	[Amount=15,6*7,8] Transport: Iron and Steel to Recycling				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	7.8E-5 t*km	7.8E-5 t*km
Commento generale	[Amount=0,01*7,8] Transport: Aluminium to Recycling				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.00203 t*km	0.00203 t*km
Commento generale	[Amount=0,26*7,8] Transport: Cables to Recycling				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.0788 t*km	0.0788 t*km
Commento generale	[Amount=1,08*73] Transport: Gypsum to Recycling				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.00254 t*km	0.00254 t*km
Commento generale	[Amount=0,31*8,2] Transport: Wood to Recycling				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.0334 t*km	0.0334 t*km
Commento generale	[Amount=1,09*30,6] Transport: Insulating materials to storage plant				
Product flow	Transport services / Road	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	GLO	0.0203 t*km	0.0203 t*km
Commento generale	[Amount=1,09*18,6 + (1,09/1000)*0,8*18,6] Transport: Insulating materials from storage plant to Landfill				
Product flow	Energy carriers and technologies / Electricity	Electricity, medium voltage {IT}| market for | Cut-off, U	GLO	0.18 MJ	0.18 MJ
Commento generale	Electricity consumption for machineries				

Output

Tipo di flusso	Classificazione	Flusso	Localizzazione	Valore medio	Valore risultante
Product flow	Systems / Other systems	Masonry/concrete building end-of-life, selective demolition	GLO	1.0 m3	1.0 m3
Commento generale	Selective demolition of a commercial building Volume: 550.000 m3 Time-frame: 6500h				
Waste flow	End-of-life treatment / Other end-of-life services	Mixed C&D waste, on-site reuse	GLO	227.93 kg	227.93 kg
Commento generale	On-site reuse of EWC 17 09 04 - mixed C&D waste (transport = 0)				
Waste flow	End-of-life treatment / Landfilling	Mixed C&D waste, landfill	GLO	0.04 kg	0.04 kg
Commento generale	Landfill of EWC 17 09 04 - Mixed C&D waste				
Waste flow	End-of-life treatment / Other end-of-life services	Waste mineral wool, for final disposal {Europe without Switzerland}| market for waste mineral wool, for final disposal | Cut-off, U	GLO	1.09 kg	1.09 kg
Commento generale	[Amount=1,09 + (1,09/1000)*0,8] Landfill of EWC 17 06 04 - Insulating materials				
Waste flow	End-of-life treatment / Other end-of-life services	Wood, recycling	GLO	0.31 kg	0.31 kg
Commento generale	Recycling of EWC 17 02 01 - Wood				
Waste flow	End-of-life treatment / Other end-of-life services	Gypsum waste recycling, for sludge production	GLO	1.08 kg	1.08 kg
Commento generale	Recycling of EWC 17 08 02 - Gypsum based materials				
Waste flow	End-of-life treatment / Other end-of-life services	Iron and Steel, recycling	GLO	15.6 kg	15.6 kg
Commento generale	Recycling of EWC 17 04 05 - Iron and Steel				
Waste flow	End-of-life treatment / Other end-of-life services	Aluminium, recycling	GLO	0.01 kg	0.01 kg
Commento generale	Recycling of EWC 17 04 02 - Aluminium				
Waste flow	End-of-life treatment / Other end-of-life services	Cables, recycling	GLO	0.26 kg	0.26 kg
Commento generale	Recycling of EWC 17 04 11 - Cables				

Figure 58: Dataset visualization on BDI-LCA website (part 2)

CHAPTER 8.
Full-Environmental Life Cycle Costing

The last phase of the project entails monetizing the environmental impacts and merging these monetized impacts with the eLCC findings.

8.1 MONETISATION OF THE IMPACTS

Four monetisation models outlined previously (see § 3.3.1) are chosen in collaboration with thesis student Stefano Lasperini (Lasperini, 2021). In particular, the Stepwise and Environmental Prices models are chosen, as well as the set of weights proposed by the authors De Nocker and Debacker and that by Smith et al. The latter are chosen based on their compatibility with the EF 3.0 method's impact categories and the units of measurement of the corresponding indicators. Furthermore, these sets have been developed in the European context, and one of the goals is to provide support to development policies, resulting in a case study-appropriate result. The weighting factor values are taken from the study by Amadei et al. (2021), so that they are all consistently expressed in euros and refer to the average value of 2019, which is also the reference year for the eLCC costs.

8.1.1 Smith et al., 2020

Smith et al. (2020) presented a set of monetisation factors that lends itself well to application to indicators obtained using the EF 3.0 method. The only impact category that does not have a weighting component is eutrophication of the terrestrial environment. In Table 70 all the monetisation factors for each EF 3.0 impact category are presented.

Table 70: Smith et al., 2020 monetisation factors and UM comparison with EF3.0 characterisation method

EF 3.0 Impact Categories	UM	Monetisation Value	UM
CC	kg CO2 eq	1.04E-01	[€/kg CO2]
OD	kg CFC11 eq	3.20E+01	[€/kg CFC-11]
IR	kBq U-235 eq	1.22E-03	[€/kBq U235]
POF	kg NMVOC eq	1.21E+00	[€/kg NMVOC]
PM	disease inc.	7.98E+05	[€/i.m.]
HTNC	CTUh	1.66E+05	[€/CTUh]
HTC	CTUh	9.19E+05	[€/CTUh]
A	mol H+ eq	3.50E-01	[€/mol H+]
EF	kg P eq	1.95E+00	[€/kg P]
EM	kg N eq	3.27E+00	[€/kg N]
ET	mol N eq	-	-
ETF	CTUe	3.89E-05	[€/CTUe]
LU	Pt	1.78E-04	[€/pt]
WU	m3 depriv.	5.08E-03	[€/m3 acqua]
RUF	MJ	1.32E-03	[€/MJ]
RUM	kg Sb eq	1.67E+00	[€/kg Sb]

The monetised indicators are calculated by multiplying the monetization factors from table 70 by the environmental impacts from table 60 (see § 6.3). The calculation is performed exclusively using compatible factors (identical UM), and the resulting indications are shown in Table 71.

Table 71: Monetised indicators by applying the method Smith et al., 2020

Impact Categories	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 7
CC	0.58 €	0.37 €	0.60 €	0.57 €	0.19 €	0.03 €	0.10 €
OD	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
IR	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
POF	0.07 €	0.04 €	0.06 €	0.05 €	0.03 €	0.01 €	0.02 €
PM	0.85 €	0.55 €	0.74 €	0.58 €	0.43 €	0.07 €	0.23 €
HTNC	0.00 €	0.00 €	0.00 €	0.01 €	0.00 €	0.00 €	0.00 €
HTC	0.01 €	0.01 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
A	0.02 €	0.01 €	0.01 €	0.01 €	0.01 €	0.00 €	0.00 €
EF	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
EM	0.06 €	0.04 €	0.07 €	0.04 €	0.03 €	0.01 €	0.02 €
ET	-	-	-	-	-	-	-
ETF	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
LU	0.00 €	-0.01 €	0.00 €	0.05 €	0.00 €	0.00 €	0.00 €
WU	0.01 €	0.00 €	0.00 €	0.02 €	0.00 €	0.00 €	0.00 €
RUF	0.11 €	0.07 €	0.05 €	0.16 €	0.03 €	0.01 €	0.02 €
RUM	**0.00 €**	**0.00 €**	**0.00 €**	**0.00 €**	**0.00 €**	**0.00 €**	**0.00 €**

The only impact category that has not been calculated using this method is Terrestrial Eutrophication (TE).

8.1.2 De Nocker e DeBacker, 2018

Also, in the set of weights proposed by De Nocker and DeBacker, there is no weighting factor for the category of eutrophication of the terrestrial environment. However, in this case, the factors related to tropospheric ozone formation, particulate matter, acidification, freshwater eutrophication, seawater eutrophication and land use are available, but with different units of measure from those foreseen by the EF 3.0**.** Table 72 presents all the monetisation factors for each EF 3.0 impact category.

Table 72: De Nocker e Debacker, 2018 monetisation factors and UM comparison with EF3.0 characterisation method

EF 3.0 Impact Categories	UM	Monetisation Value	UM
CC	kg CO2 eq	5.92E-02	[€/kg CO2]
OD	kg CFC11 eq	5.20E+01	[€/kg CFC-11]
IR	kBq U-235 eq	1.03E-03	[€/kBq U235]
POF	kg NMVOC eq	5.08E-01	[€/kg etene]
PM	disease inc.	3.60E+01	[€/kg PM2.5]
HTNC	CTUh	1.53E+05	[€/CTUh]
HTC	CTUh	7.04E+05	[€/CTUh]
A	mol H+ eq	4.55E-01	[€/kg SO2]
EF	kg P eq	2.12E+01	[€/kg PO43-]
EM	kg N eq	2.12E+01	[€/kg PO43-]
ET	mol N eq	-	-
ETF	CTUe	3.92E-05	[€/CTUe]
LU	Pt	1.59E-06	[€/kg C deficit]
WU	m3 depriv.	7.09E-02	[€/m3 acqua]
RUF	MJ	6.88E-03	[€/MJ]
RUM	kg Sb eq	1.65E+00	[€/kg Sb]

The monetised indicators are calculated by multiplying the monetization factors from table 72 by the environmental impacts from table 60 (see § 6.3). The calculation is performed exclusively using compatible factors (identical UM), and the results are shown in Table 73.

Table 73: Monetised indicators by applying the method De Nocker e Debacker, 2018

Impact Categories	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 7
CC	0.33 €	0.21 €	0.34 €	0.32 €	0.11 €	0.02 €	0.05 €
OD	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
IR	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
POF	-	-	-	-	-	-	-
PM	-	-	-	-	-	-	-
HTNC	0.00 €	0.00 €	0.00 €	0.01 €	0.00 €	0.00 €	0.00 €
HTC	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
A	-	-	-	-	-	-	-
EF	-	-	-	-	-	-	-
EM	-	-	-	-	-	-	-
ET	-	-	-	-	-	-	-
ETF	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
LU	-	-	-	-	-	-	-
WU	0.12 €	0.07 €	0.01 €	0.35 €	0.00 €	0.00 €	0.00 €
RUF	0.56 €	0.35 €	0.26 €	0.84 €	0.17 €	0.03 €	0.09 €
RUM	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €

POF, PM, A, EF, EM, ET, and LU impact categories are not calculated.

8.1.3 Stepwise

For the Stepwise model, the factors for the impact categories water use and use of mineral and metal resources are not available. This model presents many weighting factors expressed in units of measurement different from those envisaged by EF 3.0. Therefore, it is possible to weigh only the indicators in the categories of climate change, stratospheric ozone reduction and use of fossil resources**.** Table 74 presents all the monetisation factors for each EF 3.0 impact category.

Table 74: Stepwise monetisation factors and UM comparison with EF3.0 characterisation method

EF 3.0 Impact Categories	UM	Monetisation Value	UM
CC	kg CO2 eq	1.11E-01	[€/kg CO2]
OD	kg CFC11 eq	1.34E+02	[€/kg CFC-11]
IR	kBq U-235 eq	2.68E-05	[€/Bq C14]
POF	kg NMVOC eq	4.95E-04	[€/m2*ppm*h]
PM	disease inc.	9.10E+01	[€/kg PM2.5]
HTNC	CTUh	3.62E-01	[€/kg C2H3Cl]
HTC	CTUh	3.62E-01	[€/kg C2H3Cl]
A	mol H+ eq	1.03E-02	[€/m2 UES]
EF	kg P eq	1.34E-01	[€/kg NO3]
EM	kg N eq	1.34E-01	[€/kg NO3]
ET	mol N eq	1.74E-02	[€/m2 UES]
ETF	CTUe	9.51E-06	[€/TEG]
LU	Pt	1.61E-01	[€/m2 arabile]
WU	m3 depriv.	-	-
RUF	MJ	5.40E-03	[€/MJ]
RUM	kg Sb eq	-	-

The monetised indicators are calculated by multiplying the monetization factors from table 74 by the environmental impacts from table 60 (see § 6.3). The calculation is performed exclusively using compatible factors (identical UM), and the resulting indications are shown in Table 75.

Table 75: Monetised indicators by applying the method Stepwise

Impact Categories	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 7
CC	0.62 €	0.40 €	0.64 €	0.61 €	0.20 €	0.03 €	0.10 €
OD	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
IR	-	-	-	-	-	-	-
POF	-	-	-	-	-	-	-
PM	-	-	-	-	-	-	-
HTNC	-	-	-	-	-	-	-
HTC	-	-	-	-	-	-	-
A	-	-	-	-	-	-	-
EF	-	-	-	-	-	-	-
EM	-	-	-	-	-	-	-
ET	-	-	-	-	-	-	-
ETF	-	-	-	-	-	-	-
LU	-	-	-	-	-	-	-
WU	-	-	-	-	-	-	-
RUF	0.44 €	0.28 €	0.21 €	0.66 €	0.13 €	0.02 €	0.07 €
RUM	**-**	**-**	**-**	**-**	**-**	**-**	**-**

This method is incompatible with most of the EF 3.0 characterization method's UMs. The only impact categories that have been calculated are CC, OD and RUF.

8.1.4 Environmental Prices

The factors related to the categories of climate change, stratospheric ozone depletion, ionizing radiation, tropospheric ozone formation, freshwater eutrophication, and water eutrophication are available and compatible in terms of units of measurement with the EF 3.0 for the Environmental Prices model. All of the monetisation factors for each EF 3.0 impact category are shown in Table 76.

Table 76: Environmental prices monetisation factors and UM comparison with EF3.0 characterisation method

EF 3.0 Impact Categories	UM	Monetisation Value	UM
CC	kg CO2 eq	5.97E-02	[€/kg CO2]
OD	kg CFC11 eq	3.20E+01	[€/kg CFC-11]
IR	kBq U-235 eq	4.86E-02	[€/kBq U235]
POF	kg NMVOC eq	1.21E+00	[€/kg NMVOC]
PM	disease inc.	4.31E+01	[€/kg PM10]
HTNC	CTUh	1.04E-01	[€/kg 1.4DB]
HTC	CTUh	1.04E-01	[€/kg 1.4DB]
A	mol H+ eq	5.24E+00	[€/kg SO2]
EF	kg P eq	1.96E+00	[€/kg P]
EM	kg N eq	3.28E+00	[€/kg N]
ET	mol N eq	-	-
ETF	CTUe	3.81E-02	[€/kg 1.4DB]
LU	Pt	8.91E-02	[€/m2 arabile]
WU	m3 depriv.	-	-
RUF	MJ	-	-
RUM	kg Sb eq	-	-

The monetised indicators are calculated by multiplying the monetization factors from table 76 by the environmental impacts from table 60 (see § 6.3). The calculation is performed exclusively using compatible factors (identical UM), and the resulting indications are shown in Table 77.

Table 77: Monetised indicators by applying the method Environmental prices

Impact Categories	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 7
CC	0.33 €	0.21 €	0.34 €	0.33 €	0.11 €	0.02 €	0.06 €
OD	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
IR	0.03 €	0.02 €	0.01 €	0.03 €	0.01 €	0.00 €	0.00 €
POF	0.07 €	0.04 €	0.06 €	0.05 €	0.03 €	0.01 €	0.02 €
PM	-	-	-	-	-	-	-
HTNC	-	-	-	-	-	-	-
HTC	-	-	-	-	-	-	-
A	-	-	-	-	-	-	-
EF	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
EM	0.06 €	0.04 €	0.07 €	0.04 €	0.03 €	0.01 €	0.02 €
ET	-	-	-	-	-	-	-
ETF	-	-	-	-	-	-	-
LU	-	-	-	-	-	-	-
WU	-	-	-	-	-	-	-
RUF	-	-	-	-	-	-	-
RUM	-	-	-	-	-	-	-

As a result, no model or generalised set of weights is better than another; instead, the decision must depend on the particular case study. Recent monetisation systems should be considered if the impact indicators are calculated using the EF 3.0 approach since their factors are consistent with the impact categories and related units of measurement of the characterisation method. Table 70 shows that the Smith et al. set of weights is the most appropriate since it contains the most compatible weighting factors.

8.2 feLCC RESULTS

As shown in Figure 59, the contribution of the monetised environmental impacts on the total economic value, given by the sum of the impacts themselves and the costs determined with the eLCC, varies between 2%-30% according to the case, the scenario, and the monetisation model.

Figure 59: Contribution of monetised impacts to the feLCC

For example, in the second, third and sixth cases, the contribution of the monetised impacts is not particularly relevant (between 5%-12%), and the weighting model does not significantly affect the result (similar percentages for the four monetisation methods). In the first case, however, the monetised impact component is significant (between 10%-25%), and the model type significantly influences the final result, the comparison between the various monetization approaches is problematic since the only equivalent impact category in all the approaches analysed is climate change (kg CO_2eq.).When the average value of the eLCC, 7.04 €/m^3, is compared to the average of all cases of the impact of monetised climate change (Figure 60), the result demonstrates that the contribution for the various approaches is equal for De Nocker and Debacker 2018 and Environmental prices, and little higher for the other two methods.

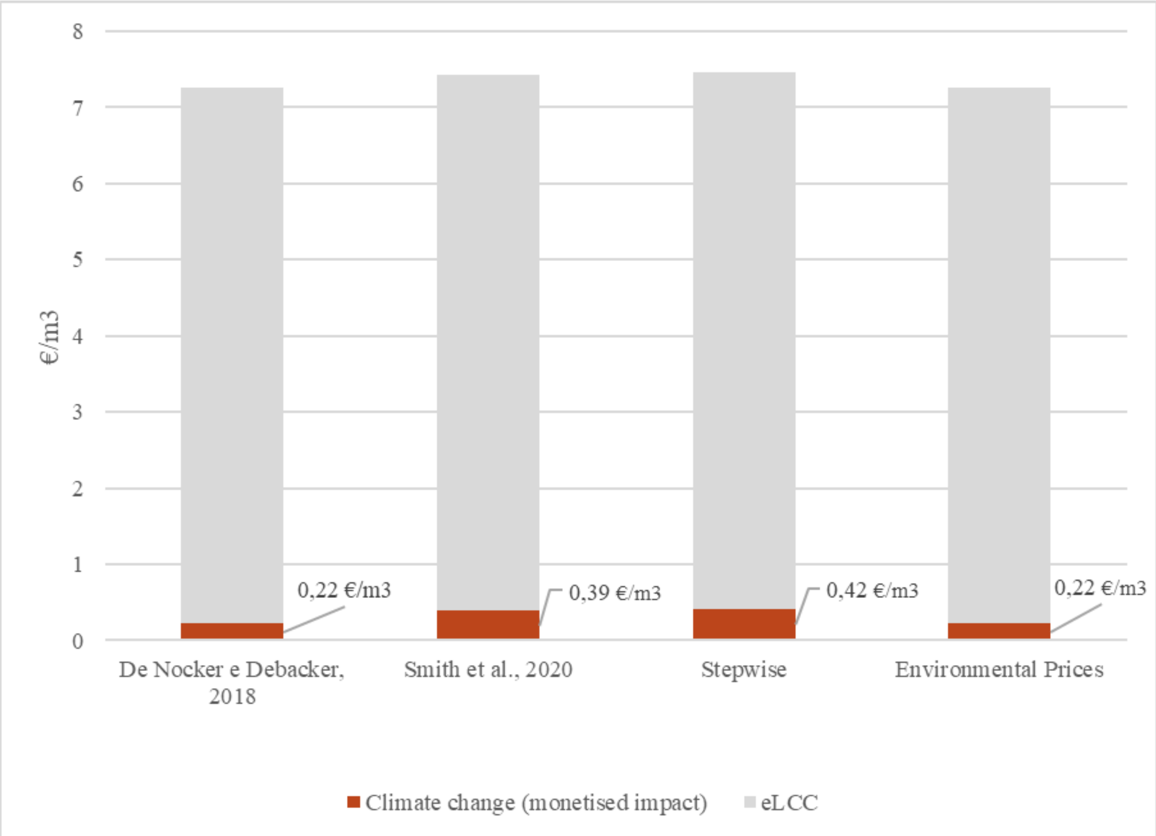


Figure 60: Comparison between monetisation methods for the climate change monetised impact

Considering an average between the four monetisation methods the feLCC result is of 7.35 €/m^3. As previously stated, it is difficult to say which model best represents the actual situation. Considering the uncertainty imposed by the monetization model chosen, it is acceptable to assume that more then one approaches should be examined to offer a range of variation within which is the value to add to the eLCC. A wide range of plausible alternative outcomes enables the uncertainty connected with them to be communicated plainly.

CHAPTER 9.

Incentive Mechanisms

Incentives are outlined as any measure used by policymakers to promote the circular economy (Katrakis et al. 2021). Incentives can be either temporary (like those used to encourage the development of new markets or to support first movers-companies that are the first to launch a new product, service, or technological advancement) or permanent (like those incorporated into laws, rules, and standards). As seen in Figure 61, they can be implemented by authorities using both financial and non-financial tools.

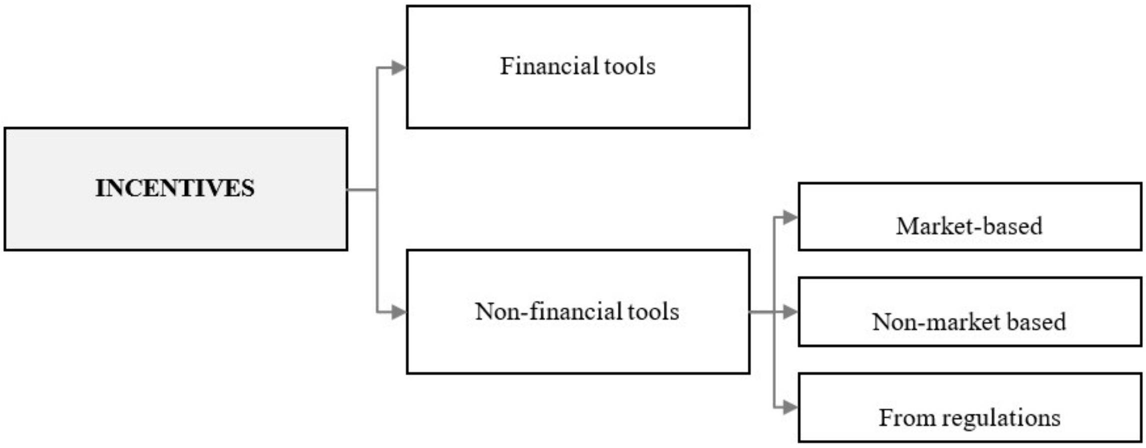


Figure 61: Types of incentives

This thesis project's goal is to provide incentives that encourage circularity in the building industry. As we will see in §9.1, the demolition industry in Lombardy is primarily composed of SMEs, making it necessary to go out and incentivise these enterprises. Nowadays, public works, granted through tenders, must meet the minimum environmental criteria (see §9.2), which are neither required nor verifiable for private construction. The incentive proposals for demolition companies and recycling plants, to be disbursed by the

Public Administrations, have been validated through the application to the cases previously provided and are described in paragraphs 9.3 and 9.4.

9.1 DEMOLITION SECTOR IN LOMBARDY REGION

Based on Recommendation 2003/361/EC of 6 May 2003 and the decree of the Minister of Economic Development of 18 April 2005, the enterprises are divided into micro, small, medium, and large:

- Micro-enterprises have fewer than ten employees and have an annual turnover or annual balance sheet total not exceeding €2 million.
- Small businesses have fewer than 50 employees and an annual turnover or annual balance sheet total that does not exceed €10 million.
- Medium enterprises have fewer than 250 employees and an annual turnover not exceeding €50 million or an annual balance sheet total not exceeding € 43 million.

Following the AIDA database (Analisi Informatizzata Delle imprese Italiane, https://www.bvdinfo.com/), it is feasible to locate the number and typologies of demolition enterprises in the Lombardy Region. The demolition or dismantling companies of buildings and other structures fall under the ATECO code 43.11.00 (ATECO classification). Considering the total annual turnover referring to the year 2020, among the 99 Lombard SMEs, 77 are micro-enterprises with a turnover of ≤ 50 million euros, 19 are small enterprises with a turnover of ≤ 10 million euros, and 3 are medium-sized enterprises with a turnover ≤ 50 million euros. At the same time, none exceeds € 50,000 in annual turnover. Thus, the need arises to direct the incentives to the SMEs for the execution of the selective demolition works.

9.2 PUBLIC WORKS: CAM EDILIZIA

Applying the minimum environmental criteria (CAM), which became effective in 2022, ensures selective demolition and the use of RAs for constructing public works entrusted through tenders (CAM Edilizia). The use of CAM is mandated by Article 34 of the new Code of Public Contracts (Legislative Decree 50/2016). The CAMs envisage both candidate selection reward criteria or subjective qualification requirements that must necessarily be possessed by economic operators to participate in tender procedures and technical specifications, i.e., the essential characteristics required for works, services, or supplies. Other than that, the CAM ordinance, also defines some awarding criterion for selective demolition, recovery, and recycling in Art. 2.6.2. As the previous mentioned article defines, to obtain the awarding, in the case of restructuring, maintenance, and demolition, the project requires that at least 70% of the non-hazardous waste generated on-site, excluding excavations, be sent to preparation operations for reuse, recycling, or other recovery operations, following the waste management hierarchy established by Art. 179 of Legislative Decree No. 152 of 3 April 2006. The CAM article also award the preliminary demolition study in which are calculated the percentage of waste that can be recycled or prepared for reuse. This estimate includes the following:

- Evaluation of the building’s characteristics.
- Identification and assessment of the risks associated with any hazardous waste and emissions that may occur during demolition.
- Estimation of the quantities of waste that will be produced, with a breakdown between the different fractions of material.

- Estimation of the percentage of waste to be sent to preparation for reuse and recycling, compared to the total waste produced, on a per-building basis. The following waste categories are identified by the project:

    a. waste divided into mono-material fractions (EWC codes 170101, 170102, 170103, 170201, 170202, 170203, 170401, 170402, 170403, 170404, 170405, 170406, 170504, 170402, 170403, 170404, 170405, 170406, 170504, 17076080, 17076080) to be started up for reuse operations, in the same construction site or, where this is not possible, employed in other construction sites.
    b. waste divided into mono-material fractions (EWC codes 170101, 170102, 170103, 170201, 170202, 170203, 170401, 170402, 170403, 170404, 170405, 170406, 170504, 170402, 170403, 170404, 170405, 170406, 170504, 17076080, 17076080) recovery.
    c. the mixed fractions of aggregates and waste (EER code 170107 and 170904) deriving from the demolition of works for which disassembly and selective demolition is not possible, which are sent to plants to produce RAs.

According to the CAM Art.4.3.1 - Methodologies for optimizing design solutions for sustainability (LCA and LCC), a rewarding score is attributed to the economic operator who presents an improvement project in terms of environmental and economic performance compared to the project placed at the bottom of the competition. An LCA study and an LCC study can both show improvement. The score is proportionate to the construction features evaluated (e.g., roofing, infill panels, attics) or to the project's environmental profile improvement.

9.3 PRIVATE WORKS: PROPOSAL FOR INCENTIVES

Based on the data, some incentive scenarios for selective demolition and recycled aggregates might be hypothesised. The cost items that might be subject to a reduction in the expense borne by demolition businesses or an increase in revenue for recycling facilities have been specified, along with the associated criteria that must be met to qualify for the incentive. The four actions underlying the identified scenarios are the demolition project, on-site reuse, the rate for recycling and the sale of the recycled aggregate (Table 78).

A discount of up to 15% on the design cost (the practical minimum value to appreciate a cost reduction) is supposed to be applied to the demolition project. The criterion to be respected to obtain the incentive is the preliminary quantification of the outgoing waste flows and the relevance to the voluntary practice UNI/PdR 75:2020, which defines an operating methodology for selective deconstruction which favours the recovery of waste deriving from construction and demolition (see § 2.1.2).

Depending on whether this is done or not, on-site reuse is the second item that qualifies for a discount of up to 15%. The discount, in this case, will take the form of tax relief on the costs of handling the inert waste.

The last incentive included in the demolition process is a 15% decrease in the fee for sending the mineral to recycling activities. This is valid if the waste streams are appropriately divided, that is, in a way that excludes the CER 17 09 04 streams from the outgoing waste and ensures that at least 70% of the outgoing streams are recycled. Furthermore, this will support increasing the landfill-related fee to disincentivize landfilling.

Instead, there is a need to encourage the sale of recycled aggregates focusing on the increase in demand which will determine an increase in the sale price. Demand will increase if the recycled aggregate is produced with good or excellent quality (as required by MATTM

Circular No. 5205, Circular UL/2005/5205). The incentive, therefore, consists of a 15% increase in the sale price if the aggregate is of medium quality (e.g., for road foundations) and 30% if it is of high quality (e.g., for foundations); there is no incentive if the aggregate is of low quality (e.g., for environmental restoration).

Table 78: Incentives proposal

Cost item	Criteria to be respected for obtaining the incentive	Amount of the incentive
Demolition project	Estimation of quantities and outgoing flows Application of UNI/PDR 75:2020	**- 15%** On the design cost
On-site reuse	Inert waste reused on-site	**- 15%** On the cost of treatment for reuse
Recycling fee	Correct division of flows (flow EWC 17 09 04 must not be present) 70% of the flows sent for recycling	**- 15%** On the recycling fee
Sale of recycled aggregates	For C2 use (Road substrates) For C3 – C6 use (Building foundations)	**+ 15%** **+ 30%** On the revenue from the sale of RAs

9.4 APPLICATION ON THE REAL STUDIES

The final step is to carry out a feasibility analysis on the application of the incentives described above to real case studies. The incentives in table 78 are applied with the aim of quantifying the cubic meters of building selectively demolished eligible for incentives.

Two incentive situations are taken into consideration:

Scenario 1: assumes that all cases under investigation will receive a 5% discount on project costs, on-site reuse treatment and recycling fees, and a 15% markup on recycled aggregates sales (for road substrates) (Table 79).

Table 79: Scenario 1 of incentives

Cost item	Amount of the incentive*
Demolition project	**- 5%** On the design cost
On-site reuse	**- 5%** On the cost of treatment for reuse
Recycling fee	**- 5%** On the recycling fee
Sale of recycled aggregates	**+ 15%** On the revenue from the sale of RAs

Scenario 2: assumes that all cases under investigation fully meet the criteria and obtain a 15% discount on project costs, treatment for in situ reuse and recycling fees, and a 30% mark-up on the price of recycled aggregates sold (for use in foundations) (Table 80).

Table 80: Scenario 2 of incentives

Cost item	Amount of the incentive*
Demolition project	**- 15%** On the design cost
On-site reuse	**- 15%** On the cost of treatment for reuse
Recycling fee	**- 15%** On the recycling fee
Sale of recycled aggregates	**+ 30%** On the revenue from the sale of RAs

The incentives are supposed to be payable by Public Administrations in the form of tax relief and/or non-repayable grants. Thanks to various interviews with employees of the Lombardy Region, it has been defined which available funds could be allocated for this purpose. Two funds have been identified which can be used to incentivize SMEs:

1. *Funds from excavation charges*

Monetary incentives deriving annually from the Region through excavation costs. The maximum availability is of € 1,078,000 per year.

2. *Funds from eco-tax*

Monetary incentives deriving from eco-tax revenues. They are supposed to be activated cyclically (every 7-10 years) compatibly with the strategic priorities of local administrations. The maximum availability is of € 2,000,000 per year.

Considering Scenario 1 (Table 79), the average reduction in supply chain costs would be -1.2%, which is equivalent to an average saving of 0.06 €/m^3 (Table 81).

Table 81: Reduction with scenario 1

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Base scenario [€/m^3]	4.61	11.37	10.66	12.50	4.90	2.30	2.90
Scenario 1 [€/m3]	4.54	11.31	10.59	12.50	4.76	2.26	2.86
Reduction percentage	**-1.6%**	**-0.5%**	**-0.6%**	**-0.0%**	**-2.9%**	**-1.7%**	**-1.4%**

Given access to the funds from excavation charges, the annual volume of building eligible for incentives would be 1,706,716 m^3. To make an estimation, based on the average volume of the seven case studies of 16,647 m^3, the number of demolitions eligible for incentives per year would be around 103 only in Lombardy Region. Every 7-10 years the eligible cubic meters can be increased with the help of eco-tax funds up to 48,731,649 m^3, or 293 selective demolitions.

Considering Scenario 2 (Table 80), the average reduction in supply chain costs would be -3.4%, which is equivalent to an average saving of 0.06 €/m^3 (Table 82).

Table 82: Cost reduction with scenario 2

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Base scenario [€/m^3]	4.61	11.37	10.66	12.50	4.90	2.30	2.90
Scenario 1 [€/m3]	4.39	11.19	10.46	12.49	4.53	2.20	2.79
Reduction percentage	**-4.8%**	**-1.6%**	**-1,6%**	**-0.1%**	**-7.5%**	**-4.3%**	**-3.8%**

Given access to the funds from excavation charges, the annual volume of building eligible for incentives would be 6.198.889 m^3. To make an estimation, based on the average volume of the seven case studies of 16.647 m^3, the number of demolitions eligible for incentives per year would be around 37 only in Lombardy Region. Every 7-10 years the eligible cubic meters can be increased with the help of eco-tax funds up to 17,699,612 m^3, or 106 selective demolitions.

CONCLUSION

Adopting the feLCC methodology made it was possible to investigate the environmental impacts and the internal and external costs of the entire C&D waste management chain. Nevertheless, more importantly, it allowed for identifying all the urgent issues with the management system under consideration. The improper sorting of waste flows at the demolition site is revealed to be one of the most significant critical issues. As stated in paragraph 2.1.2, proper selective demolition and waste sorting would result in distinct, homogeneous flows (e.g., concrete, bricks, and so on). According to the average result of the seven selective demolition cases, the mixed inert mineral waste stream makes up 83% of the production, with metals accounting for 15% and the remaining 2%. (Figure 62).

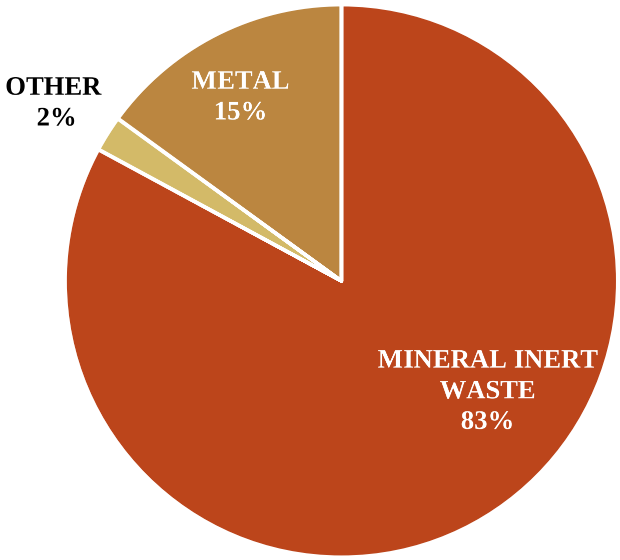


Figure 62: Average waste outcome (in percentage)

Table 83 illustrates the average percentage compositions of inert mineral waste, metals, and other materials. According to the average waste composition obtained, inert mineral waste is almost entirely composed of a mixed stream of C&D waste (EWC 17 09 04), with just 18 % referring to a distinct cement stream (EWC 17 01 01). Iron and steel (EWC 17 04 05) account for 98.8 % of the flux of metals, with aluminium (EWC 17 05 02) and cables accounting for the remainder (EWC 17 04 11). The “other” category, which constitutes a tiny fraction of the total, is mainly composed of mixed packaging (EWC 15 01 06) and hazardous materials (EWC 17 06 05* and 18 06 03*).

Table 83: Percentage composition of the categories of inert mineral, metallic and other waste

	Total mass fraction %	Materials division (EWC code)	Mass fraction %
Inert waste	83 %	170904 – Mixed C&D waste	82 %
		170802 – Gypsum materials	0.3%
		170101 – Cement	18 %
Metals	15%	170405 – Iron and steel	98.8 %
		170502 – Aluminium	0.8 %
		170411 – Cables	0.4 %
Other	2%	150106 – Mixed packaging	59.3 %
		170600 – Insulating materials	7.1 %
		170302 – Bituminous Materials	8.7 %
		170605* and 180603* - Hazardous materials (asbestos)	17.4 %
		170201 – Wood	7.6 %

The mixed C&D stream (EWC 17 09 04), which is discovered to be the major outgoing stream, is extremely heterogeneous and includes various types of substances. This makes it more complex and challenging to treat, which makes it difficult to obtain high-quality RAs for structural uses, which would have more demand on the market. 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 17 09 04). A possible solution for small to medium-sized 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 much personnel.

The eLCC study offered several obstacles in acquiring data suitable for the implementation of the economic inventory, owing to firms' unwillingness to share sensitive data such as their expenses or revenues. However, utilising the available data, it is possible to give an estimation of the costs in the Lombardy Region. According to the research, the average cost for demolition and C&D waste management is 7.04 €/m^3 of a demolished building. The findings show that operating costs and machinery acquisition costs weigh the most on the total eLCC value. Disposal costs demonstrate that landfill expenses much outweigh recycling fees, and the cost of on-site reusing is equivalent to a landfill fee. However, it has the advantage of zero transportation expenses. The sensitivity analysis revealed that the total cost is lowered when the earnings from the sale of metal waste cover the expenses of transporting the other flows to the recycling plant or landfill. It should be noted that the proper application of selective demolition requires more manual work and, therefore, a greater cost of security personnel and equipment use, therefore demolition with more accurate sorting of waste has higher costs than the scenario where the sorting is limited up to four separate waste flows (see Annex I). The study also identified a virtually untapped market for RAs since data from two cases of inert recycling facilities show that the revenue from the sale of RAs is -2.06 €/t, compared to the cost of manufacturing, which is 6.09 €/t. The plant revenues are almost exclusively generated from the payment for the supply of the waste to be treated.

With the support of the LCA study, it has been confirmed that when a more extensive breakdown of waste streams is accomplished, the outcome is opposite to the desired goal, i.e., increased environmental and economic impacts. When comparing the seven scenarios (see § 6.3), the environmental impacts of the first case is substantially higher, owing to the longer usage durations of the machinery for sorting the material and, therefore, the higher consumption of fuel and electricity. One alternative may be to separate just the streams where recycling or on-site reuse provides a substantial value to the system. In this context, the on-site reuse and recycling of mixed C&D, concrete, wood, and metal streams have yielded significant benefits (see § 6.3). Recycling and separation of other waste streams fail to offset the environmental impacts of machinery use, and in certain situations, such as the recycling of gypsum-based products, have an impact comparable to, if not higher than, demolition.

The monetisation of the impacts has revealed that the contribution of the monetised environmental impacts to the overall economic value varies depending on the case, scenario, and monetisation methodology. The choice of the monetisation model must depend on the case study (see § 8.1). However, with the feLCC, external costs have been shown to have between 2%-30% impact on total internal costs, depending the monetisation model.

The results above confirm the outcomes obtained from previous LCT studies on the C&D waste management chain, demonstrating that the studies are related even though the geographical context is different. Like the findings of Coelho & de Brito's (2010) study, it is shown that selective demolition is more expensive than traditional demolition techniques, with labour costs in the latter being about six times higher because of the longer time required to complete the operation and the limited use of mechanical equipment. It is also confirmed that the material input gate fee in recycling plants makes up the largest share (Coelho & 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. As on Rigamonti & Pantini, 2019 the environmental sustainability of selective demolition is proven heavily dependent on the characteristics of the building to be demolished as well as local markets for recycled materials, and alone cannot solve the chain issues because a good waste management system must follow it.

Based on the analysis a set of incentives for favouring correct selective demolition and RAs sale has been defined that can be directly used by public administrations in favour of SMEs in the execution of private works. The cost categories chosen to be subject to a decrease in demolition firms' expenses or an increase in income for recycling facilities, as well as the accompanying requirements that must be completed to qualify for the incentive are: the demolition project, on-site reuse, recycling rate, and sale of RAs. Finally, a feasibility analysis on the application of incentives is performed, which demonstrated the functionality of the application and the estimation of building volumes to be demolished eligible for the incentivisation.

This PhD thesis aims to create a foundation for implementing what has been described into concrete actions that will lead to the accomplishment of the circular economy in the construction sector. The limits of the research provided are connected to the difficulties in gathering sufficient and representative data, which may result in an incomplete study conclusion and increased difficulty in understanding the results. The study was also geographically restricted to the Lombardy Area, which may not be replicable in other Regions. As a result, one of the research's future directions is to expand the study to other Italian regions in order to gain an exhaustive case study of the current scenario and to ensure that incentive programs are aligned throughout Italy and among all public administrations.

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REFERENCES

Ahlroth S (2014) The use of valuation and weighting sets in environmental impact assessment. Resources, Conservation and Recycling 85.

Alberini A., Hunt A. & Markandya A. Willingness to Pay to Reduce Mortality Risks: Evidence from a Three-Country Contingent Valuation Study. Environ Resource Econ 33, 251–264 (2006).

Amadei A. M., De Laurentiis V. e Sala S. (2021) A review of monetary valuation in life cycle assessment: State of the art and future needs. Journal of Cleaner Production 329.

ANPAR (2022). Decreto End Of Waste rifiuti inerti – Addio Economia Circolare, Bloccata l'intera filiera del riciclo. Available at: http://anpar.org/decreto-end-of-waste-rifiuti-inerti-addio-economia-circolare-bloccata-lintera-filiera-del-riciclo/

Antonini E, Donati V (2004) Il mattone ritrovato - Manuale per la gestione dei rifiuti da costruzione e demolizione in Provincia di Bologna in applicazione dell'Accordo di Programma, Labanti e Nanni - Bologna

Arendt R, Bachmann TM, Motoshita M (2020) Comparison of Different Monetization Methods in LCA: A Review. Sustainability.

Aydenlou, R. M. (2020). Types of existing buildings: detailed introduction and seismic rehabilitation. Seismic Rehabilitation Methods for Existing Buildings, 193–553. doi:10.1016/b978-0-12-819959-6.00003-8

Bazzani G, Grillenzoni M, Malagoli C, Ragazzoni A, 1994. Valutazione delle risorse ambientali, Edagricole, Milano.

Borghi G, Pantini S, Rigamonti L (2018) Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). J Clean Prod 184:815–825. https://doi.org/10.1016/J.JCLEPRO.2018.02.287

Borghi, G, Pantini, S, Rigamonti, L, 2018. Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). J. Clean. Prod. 184, 815-825.

Butera, S, Christensen, TH, Astrup, TF, 2015. Life cycle assessment of construction and demolition waste management. Waste Manag. 44, 196-205.

Cárcel-Carrasco J, Peñalvo-Lòpez E, Pascual-Guillamón M, Salas-Vicente F (2021) An Overview about the Current Situation on C&D Waste Management in Italy: Achievements and Challenges. Build 11:284. https://doi.org/10.3390/BUILDINGS11070284

Carollo F, Rigamonti L (2019) L'end of waste: dalla culla alla crisi. Ingegneria dell'Ambiente Vol. 6 n. 4/2019. https://doi.org/10.32024/ida.v6i4.246

Circular 15/07/2005 No. 5205 of Ministry of the Environment: Indicazioni per l'operatività nel settore edile, stradale e ambientale, ai sensi del Decreto Ministeriale 8 maggio 2003, n. 203.

Coelho A, de Brito J (2011) Economic analysis of conventional versus selective demolition - A case study. Resour Conserv Recycl 55(3):382–392. https://doi.org/10.1016/J.RESCONREC.2010.11.003

Coelho A, de Brito J (2013) Economic viability analysis of a construction and demolition waste recycling plant in Portugal - part I: location, materials, technology and economic analysis. J Clean Prod 39:338–352. https://doi.org/10.1016/J.JCLEPRO.2012.08.024

Cutaia L, Altamura P, Ceruti F, Cellurale M, Corrado S, de Marco E, Luciano A, Klein A, Carollo F, Kisser J, Bertino G, Bukowski H, Sabbadin D (2022) A two-year stakeholder" consultation on the construction and infrastructure value chains. Output Paper of the activities coordinated by ENEA in 2020-2021. http://dx.doi.org/10.13140/RG.2.2.11001.13928

D.G.R.V. no. 1773, 2012 Modalità operative per la gestione dei rifiuti da attività di costruzione e demolizione

D.Lgs 16 June 2017, no. 106 - Adaptation of national legislation to the provisions of Regulation (EU) no. 305/2011, which establishes harmonised conditions for the marketing of construction products and which repeals Directive 89/106 / EEC

D.Lgs 18 April 2016, no. 50 - Code of public contracts

D.Lgs 18/04/2005 - Adeguamento alla disciplina comunitaria dei criteri di individuazione di piccole e medie imprese. (GU Serie Generale n.238 del 12-10-2005)

D.Lgs 23/06/2022 .Criteri ambientali minimi per l'affidamento del servizio di progettazione di interventi edilizi, per l'affidamento dei lavori per interventi edilizi e per l'affidamento congiunto di progettazione e lavori per interventi edilizi

D.Lgs 3 April 2006, no. 152 - Environmental regulations. Part Four - Rules on waste management and remediation of polluted sites. Title I - Waste management

D.Lgs. 03.04.2006 e s.m.i. n.152; L.R. 3/2000

D.Lgs. 27/09/2022, n. 152 - Regolamento che disciplina la cessazione della qualifica di rifiuto dei rifiuti inerti da costruzione e demolizione e di altri rifiuti inerti di origine minerale, ai sensi dell'articolo 184-ter, comma 2, del decreto legislativo 3 aprile 2006, n. 152. (22G00163)

Dahlbo H, Bachér J, Lähtinen K, Jouttijärvi T, Suoheimo P, Mattila T, Sironen S, Myllymaa T, Saramäki K (2015) Construction and demolition waste management - a holistic evaluation of environmental performance. J Clean Prod 107:333–341. https://doi.org/10.1016/J.JCLEPRO.2015.02.073

De Menna F, Loubiere M, Dietershagen J, Unger N, Vittuari M (2016) Methodology for evaluating LCC. Report number: Deliverable 5.2Affiliation: EU Resource Efficient Food and drink for the Entire Supply cHain REFRESH) Horizon 2020 Grant Agreement no. 641933.

Dhir RK, de Brito J, Silva R, Lye CQ (2019) Recycled Aggregate Concrete. Sustain Const Mat 365–418. https://doi.org/10.1016/B978-0-08-100985-7.00010-8

Di Giulio E, 1962. Enciclopedia degli idrocarburi volume IV / economia, politica, diritto degli idrocarburi. Treccani

Di Maria A, Eyckmans J, van Acker K (2018) Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policymaking. Waste Manag 75:3–21. https://doi.org/10.1016/J.WASMAN.2018.01.028

Directive 15 luglio 1975, n. 442. Direttiva n. 75/442/CEE del Consiglio relativa ai rifiuti.

Directive 2004/35/CE del Parlamento europeo e del Consiglio, del 21 aprile 2004, sulla responsabilità ambientale in materia di prevenzione e e riparazione del danno ambientale Gazzetta ufficiale n. L 143 del 30/04/2004 pag. 0056 – 0075

Directive 2008/98/CE of European Parliament and of the Council relating to waste and repealing certain Directives. Official Journal of the European Union L. 312/3 of 19/11/2008.

Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC

Directive 2014/25/EU of the European Parliament and of the Council of 26 February 2014 on procurement by entities operating in the water, energy, transport and postal services sectors and repealing Directive 2004/17/EC

DPR 26/08/1993, n. 412 (G. U. N.96 14/10/1993). Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, COMMA 4, DELLA LEGGE 9 GENNAIO 1991, N. 10.

Durao V, Silvestre J, Mateus R, De Brito J (2019) Economic valuation of life cycle environmental impacts of construction products - A critical analysis. IOP Conference Series: Earth and Environmental Science.

ECESP (2021) Circular Buildings and Infrastructure: State of play report ECESP Leadership group on building and infrastructure. https://circulareconomy.europa.eu/platform/sites/default/files/circular_buildings_and_infrastructure_brochure.pdf. Accessed 29 June 2022

EC-JRC (2011). Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors (International Reference Life Cycle Data System - ILCD handbook)

EEC, 1975, Council directive 75/442/EEC of 15 July 1975 on waste (OJ L 194, 25.7.1975, p.39-41), 75/442/EEC

Environmental LCC 2008. (eds) Hunkeler et al. Chapter 4. SETAC

European Parliament (2016) Legislative train: Strategy for secondary raw materials

Eurostat (2010) Guidance on classification of waste according to EWC-Stat categories. Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics

Eurostat, 2010. Guidance on classification of waste according to EWC-Stat categories. Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics

Ghufran M, Khan KIA, Ullah F, Nasir AR, Al Alahmadi AA, Alzaed AN, Alwetaishi M (2022) Circular Economy in the Construction Industry: A Step towards Sustainable Development. Buildings 2022, 12, 1004. https:// doi.org/10.3390/buildings12071004

Hoogmartens R, van Passel S, van Acker K, Dubois M (2014) Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ Impact Assess Rev 48:27–33. https://doi.org/10.1016/J.EIAR.2014.05.001

Hu M, Miranda-Xicotencat B, Ita-Nagy D, Prado V, Guinée J, van Roekel E, Huismans R, Rens F, Lotfi S, di Maio F (2017) Life cycle assessment and life cycle costing for demolition waste management | TU Delft Repositories. HISER International Conference 2017. https://repository.tudelft.nl/islandora/object/uuid:eb4f4f13-0750-4157-b6bf-c19e4486fa46?collection=research

Hunkeler D, Lichtenvort K, Rebitzer G (2008) Environmental life cycle costing. SETAC, Pensacola, FL (US) in collaboration with CRC Press, Boca Raton, FL, USA

ICESP (2020) Rapporto di filiera Rapporto di filiera sulla transizione verso l’economia circolare nel settore Costruzione&Demolizione e nel settore Agrifood. https://www.icesp.it/sites/default/files/DocsGdL/L%27economia%20circolare%20nelle%20filiere%20industriali%20i%20casi%20Costruzione%26Demolizione%20e%20Agrifood.pdf. Accessed 29 June 2022.

IEC 60300-3-3. Dependability management - Part 3-3: Application guide - Life cycle costing

Islam H, Jollands M, Setunge S (2015) Life cycle assessment and life cycle cost implication of residential buildings - A review. Renew Sustain Energy Rev 42:129–140. https://doi.org/10.1016/J.RSER.2014.10.006

ISPRA (2021) Special waste report 2021 edition. https://www.isprambiente.gov.it/files2021/pubblicazioni/rapporti/rapportorifiutispeciali_ed-2021_n-345_versionedati-di-sintesi.pdf. Accessed 29 June 2022

Jacob-Lopes E, Zepka LQ, Deprá MC (2021 Assistant'sss tools toward life cycle assessment. Sustain Metr Indic Environ Impact 77–90. https://doi.org/10.1016/B978-0-12-823411-2.00006-2

Katrakis E, Nacci G, Couder N, 2021. Incentives to boost circular economy: a guide for public authorities. European Commission

Kelly J, Hunter K (2009) Life cycle costing of sustainable design. London: RICS

Lasperini S (2021) Approcci, Metodi e modelli di monetizzazione degli impatti ambientali e il caso di studio di un LCA sui rifiuti da costruzione e demolizione. Master thesis on environmental engineering. Politecnico di Milano.

Mah CM, Fujiwara T, Ho CS (2018) Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. J Clean Prod 172:3415–3427. https://doi.org/10.1016/J.JCLEPRO.2017.11.200

Manewa A, Siriwardena M, Wijekoon C (2021) Life cycle costing in construction: Current trends and emerging directions. World Constr Symp 403–412. https://doi.org/10.31705/WCS.2021.35

Martinez-Sanchez V, Kromann MA, Astrup TF (2015) Life cycle costing of waste management systems: Overview, calculation principles and case studies. Waste Manag 36:343–355. https://doi.org/10.1016/J.WASMAN.2014.10.033

Mercante, IT, Bovea, MD, Ibánez-Forés, V, Arena, AP, 2012. Life cycle assessment of construction and demolition waste management system: a Spanish case study. Int J. Life Cycle Assess. 17, 232-241.

Mondini N (2019). Verso la decostruzione selettiva riduzione degli sprechi e recupero dei rifiuti inerti da costruzione e demolizione. ANPAR seminar. https://www.milomb.camcom.it/documents/10157/39983334/edilizia-pubblica-sostenibile-19-06-2019-intervento-mondini.pdf/fd9e6224-1b42-43ec-a533-314eca93e79e . Accessed 30 July 2022

Mordà N (2011). Demolizioni civili e industriali. EPC Editore

Pheng, L, Hou L (2019). The Economy and the Construction Industry: A Study at the Firm Level. 10.1007/978-981-13-5847-0_2.

Pizzol M., Laurent A., Sala S. et al. (2017) Normalisation and weighting in life cycle assessment: quo vadis? The International Journal of Life Cycle Assessment 22.

Polidoro D (2020) La due diligence ambientale – DDA. ZED PROGETTI. https://zedprogetti.it/wp-content/uploads/2020/02/DUE-DILIGENCE-AMBIENTALE.pdf. Accessed 29 June 2022

Rebitzer G, Hunkeler D (2003) Life cycle costing in LCM: ambitions, opportunities, and limitations. Int J Life Cycle Assess 8(5):253–256. https://doi.org/10.1007/BF02978913

Regulation (EU) n. 305/2011 of the European Parliament and of the Council of 9 March 2011 establishing harmonised conditions for the marketing of construction products and repealing Council Directive 89/106 / EEC

Rigamonti L, Pantini S, Borghi G (2017) Relazione FinaleValutazione con metodologia LCA (Life Cycle Assessment) dei flussi e del destino dei rifiuti da costruzione e demolizione. Report for Lombary Region

Rigamonti, L, Pantini, S, 2019. Is selective demolition always a sustainable choice?. Waste Manag. 103, 169-176.

Rosado, LP, Vitale, P, Penteado, CSG, Arena, U, 2019. Life cycle assessment of construction and demolition waste management in a large area of São Paulo State, Brazil. Waste Mangag. 85, 477-489.

Sherif YS, Kolarik WJ (1981) Life cycle costing: concept and practice. Int J Manag Sci 9:287–96

Swarr TE, Hunkeler D, Klöpffer W, Pesonen HL, Ciroth A, Brent AC, Pagan R (2011) Environmental life-cycle costing: A code of practice. Int J Life Cycle Assess 16(5):389–391. https://doi.org/10.1007/S11367-011-0287-5/

Toniolo S, Tosato RC, Gambaro F, Ren J (2020) Life cycle thinking tools: Life cycle assessment, life cycle costing and social life cycle assessment. Life Cycle Sustain Assess Decision-Making: Methodologies and Case Studies, 39–56. https://doi.org/10.1016/B978-0-12-818355-7.00003-8

UNI EN ISO 14001:2015. Environmental management systems - Requirements and guidance for use

UNI EN ISO 14040. Environmental management, Life cycle assessment, Principles and framework.

UNI EN ISO 15663:2021. Petroleum and natural gas industries - Life-cycle costing - Part 3: Implementation guidelines

UNI EN ISO 15686-5:2017. Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing

UNI/PdR 75:2020. Decostruzione selettiva - Metodologia per la decostruzione selettiva e il recupero dei rifiuti in un'ottica di economia circolare

Venugopal S (2022). Evaluation of the Environmental Impact associated with the Workforce in the Construction and Demolition Industry using Life Cycle Assessment. Master thesis in Environmental engineering. Politecnico di Milano

ANNEX I

Full chain costs of the single cases (1-7)

A1.1 Case 1

The total eLCC value for case 1 is of 4.61 €/m^3 (Table A1.1). Most of the cost is derived from disposal and recycling charges, of which the on-site reuse costs contribute for the 25% of the total cost. The costs borne for diesel, energy, and water use are the second largest contributors (Figure A1.1).

Table A1. 1: eLCC - Case 1 full chain costs

Section	**Cost item**	**Average cost per m^3 demolished**
Preliminary costs	Demolition project	0.04 €/m^3
	Setting of the demolition site	0.07 €/m^3
	Building reclamation	0.45 €/m^3
	Security wages	0.31 €/m^3
	Environmental due diligence	0.02 €/m^3
Machinery acquisition costs	Machinery acquisition	0.62 €/m^3
Operative costs	Machine maintenance	0.18 €/m^3
	Personnel wages	0.37 €/m^3
	Insurance	0.02 €/m^3
	Consumptions	0.93 €/m^3
Disposal and recycling costs	Landfill fee	0.09 €/m^3
	Transportation	0.05 €/m^3
	On-site reuse	1.14 €/m^3
	Recycling (excluding inert waste)	0.32 €/m^3
	Recycling inert waste	0.00 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***4.61 €/m^3***

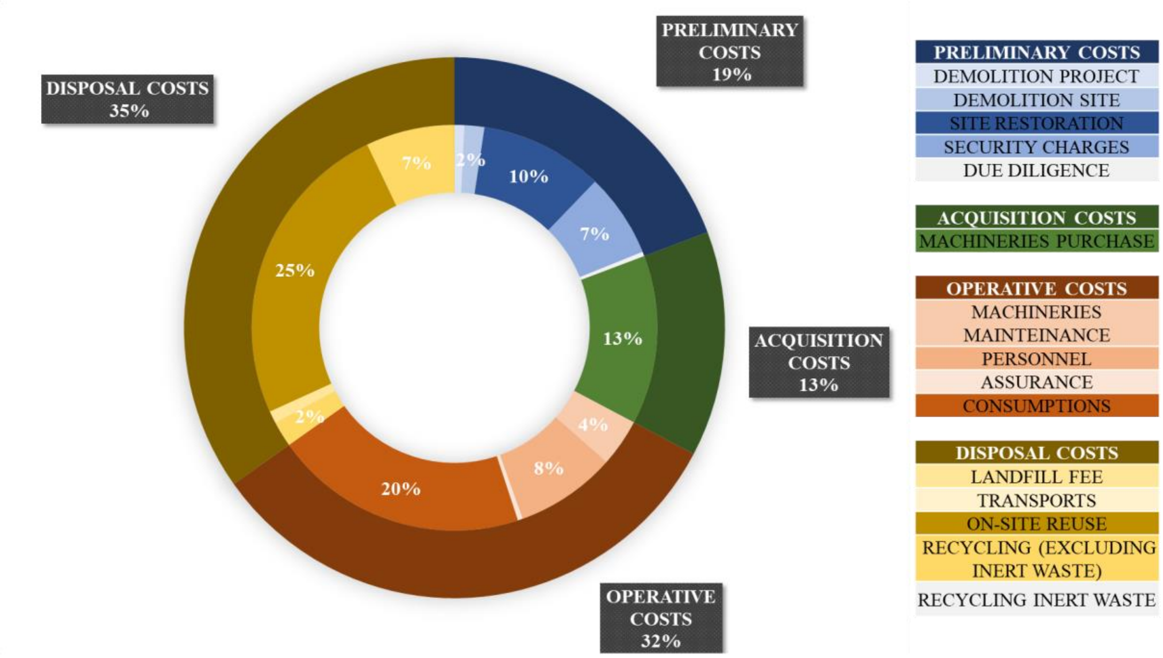


Figure A1. 1: Percentage of contribution of the different cost items – case 1

A1.2 Case 2

The total eLCC value for case 2 is of 11.37 €/m^3 (Table A1.2). Most of the cost is derived from preliminary and operative costs (31% and 33%). Building reclamation competes for the majority of the total preliminary costs (about 25% of total costs). The consumption of diesel, water and electricity cover the 18% of the total costs. The machineries acquisition costs compete for the 24% (Figure A1.2).

Table A1. 2: eLCC - Case 2 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.05 €/m^3
	Setting of the demolition site	0.21 €/m^3
	Building reclamation	2.86 €/m^3
	Security wages	0.34 €/m^3
	Environmental due diligence	0.02 €/m^3
Machinery acquisition costs	Machinery acquisition	2.70 €/m^3
Operative costs	Machine maintenance	0.96 €/m^3
	Personnel wages	2.03 €/m^3
	Insurance	0.05 €/m^3
	Consumptions	0.66 €/m^3
Disposal and recycling costs	Landfill fee	0.25 €/m^3
	Transportation	0.06 €/m^3
	On-site reuse	1.01 €/m^3
	Recycling (excluding inert waste)	0.16 €/m^3
	Recycling inert waste	0.00 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***11.37 €/m^3***

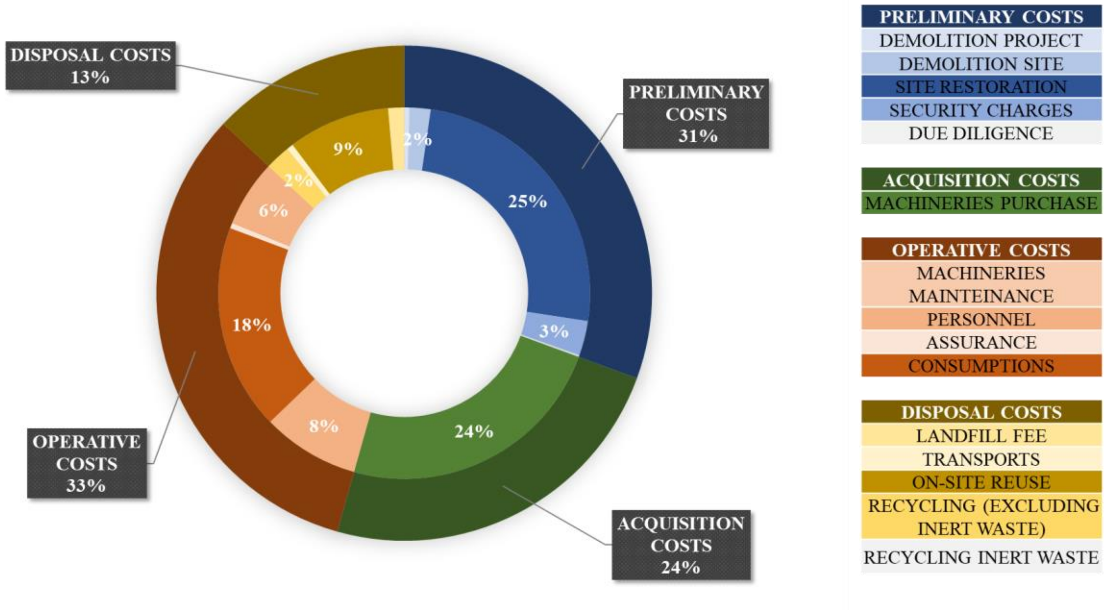


Figure A1. 2: Percentage of contribution of the different cost items – case 2

A1.3. Case 3

The total eLCC value for case 3 is of 10.66 €/m^3 (Table A1.3). Most of the cost is derived from the machineries acquisition costs, competing for the 46% of the total costs. In second place the disposal costs with on-site reuse as major contributor (Figure A1.3).

Table A1. 3: eLCC - Case 3 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.03 €/m^3
	Setting of the demolition site	0.03 €/m^3
	Building reclamation	0.02 €/m^3
	Security wages	1.42 €/m^3
	Environmental due diligence	0.00 €/m^3
Machinery acquisition costs	Machinery acquisition	4.90 €/m^3
Operative costs	Machine maintenance	0.40 €/m^3
	Personnel wages	1.00 €/m^3
	Insurance	0.03 €/m^3
	Consumptions	0.05 €/m^3
Disposal and recycling costs	Landfill fee	1.21 €/m^3
	Transportation	0.22€/m^3
	On-site reuse	1.35 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3
	Recycling inert waste	0.00 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***10.66 €/m^3***

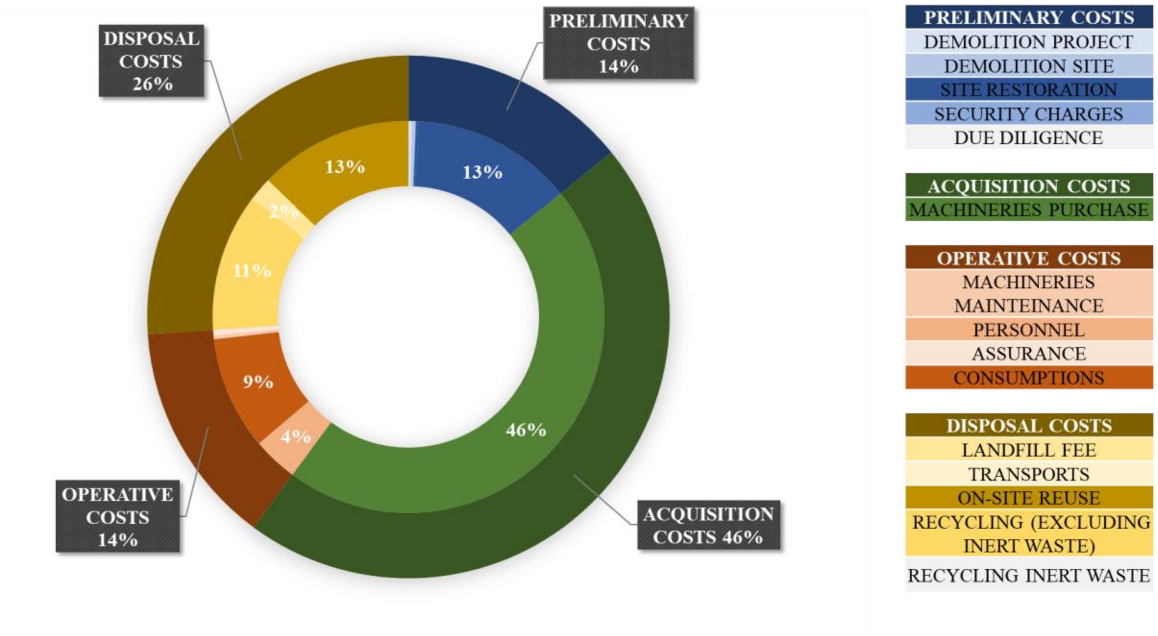


Figure A1. 3: Percentage of contribution of the different cost items – case 3

A1.4. Case 4

The total eLCC value for case 4 is of 12.50 €/m^3 (Table A1.4). The operative costs compete for the 40% of the total costs, directly followed by the machineries acquisition costs and the preliminary costs (22%). The 26% of the total is covered by the costs of diesel, water, and electricity consumptions (Figure A1.4).

Table A1. 4: eLCC - Case 4 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.11 €/m^3
	Setting of the demolition site	0.11 €/m^3
	Building reclamation	0.08 €/m^3
	Security wages	2.51 €/m^3
	Environmental due diligence	0.00 €/m^3
Machinery acquisition costs	Machinery acquisition	2.76 €/m^3
Operative costs	Machine maintenance	1.31 €/m^3
	Personnel wages	3.29 €/m^3
	Insurance	0.21 €/m^3
	Consumptions	0.21 €/m^3
Disposal and recycling costs	Landfill fee	1.90 €/m^3
	Transportation	0.01 €/m^3
	On-site reuse	0.00 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3
	Recycling inert waste	0.00 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***12.50 €/m^3***

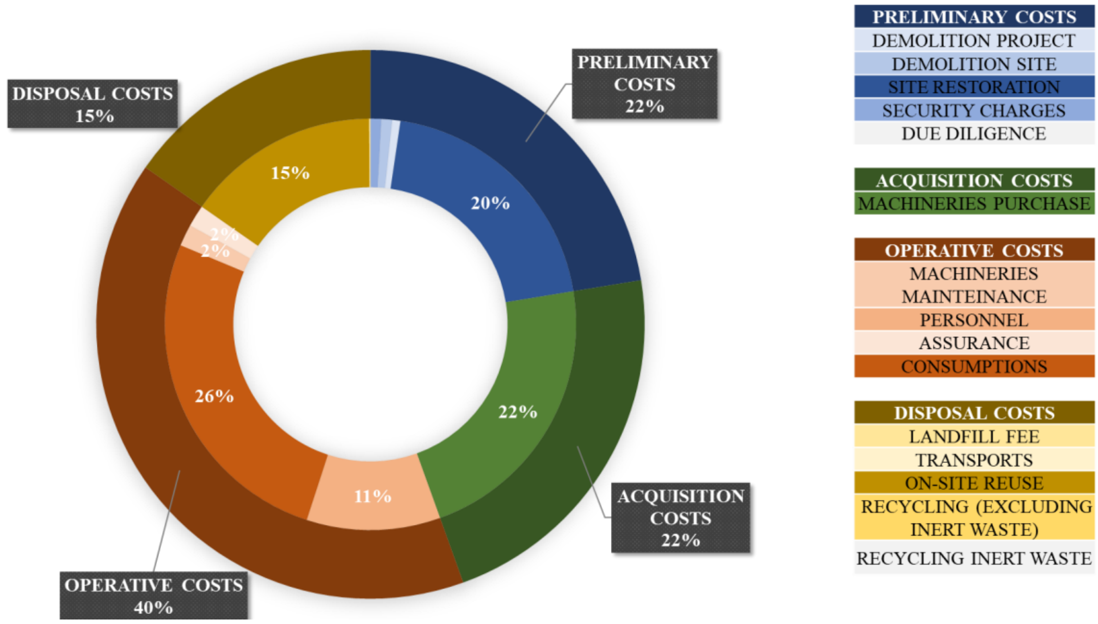


Figure A1. 4: Percentage of contribution of the different cost items – case 4

A1.5. Case 5

The total eLCC value for case 5 is of 4.90 €/m^3 (Table A1.5). In this case the main contributors are acquisition costs (41%) and disposal costs (40%) of which the transportation (Figure A1.5).

Table A1. 5: eLCC - Case 5 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.03 €/m^3
	Setting of the demolition site	0.00 €/m^3
	Building reclamation	0.00 €/m^3
	Security wages	0.14 €/m^3
	Environmental due diligence	0.00 €/m^3
Machinery acquisition costs	Machinery acquisition	2.02 €/m^3
Operative costs	Machine maintenance	0.00 €/m^3
	Personnel wages	0.14 €/m^3
	Insurance	0.00 €/m^3
	Consumptions	0.62 €/m^3
Disposal and recycling costs	Landfill fee	0.21 €/m^3
	Transportation	0.97 €/m^3
	On-site reuse	0.00 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3
	Recycling inert waste	0.78 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***4.90 €/m^3***

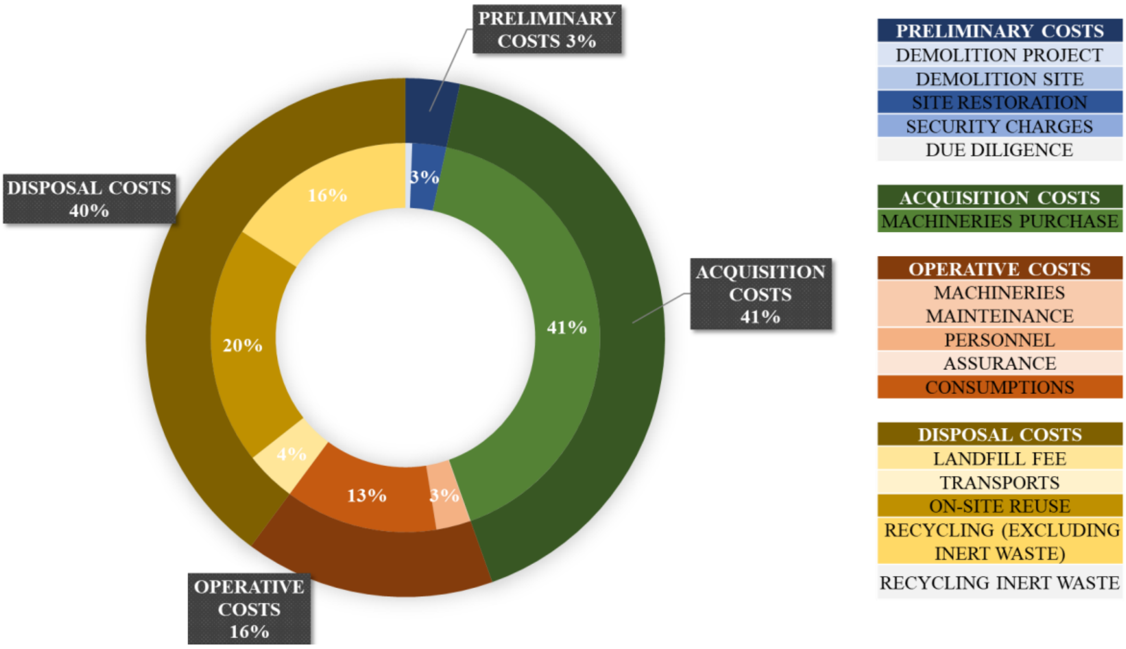


Figure A1. 5: Percentage of contribution of the different cost items – case 5

A1.6. Case 6

The total eLCC value for case 6 is of 2.30 €/m^3 (Table A1.6). Operative costs with the consumptions are the major contributor of the total costs (Figure A1.6).

Table A1. 6: eLCC - Case 6 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.04 €/m^3
	Setting of the demolition site	0.11 €/m^3
	Building reclamation	0.06 €/m^3
	Security wages	0.12 €/m^3
	Environmental due diligence	0.00 €/m^3
Machinery acquisition costs	Machinery acquisition	0.27 €/m^3
Operative costs	Machine maintenance	0.34 €/m^3
	Personnel wages	0.81 €/m^3
	Insurance	0.03 €/m^3
	Consumptions	0.11 €/m^3
Disposal and recycling costs	Landfill fee	0.00 €/m^3
	Transportation	0.13 €/m^3
	On-site reuse	0.00 €/m^3
	Recycling (excluding inert waste)	0.11 €/m^3
	Recycling inert waste	0.17 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***2.30 €/m^3***

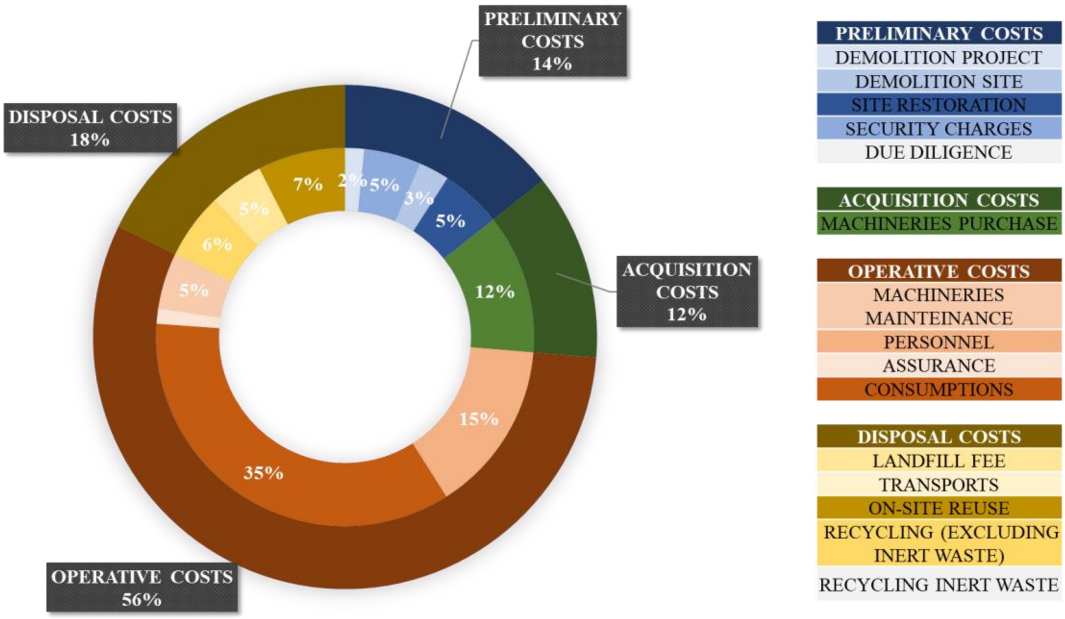


Figure A1. 6: Percentage of contribution of the different cost items – case 6

A1.7. Case 7

The total eLCC value for case 7 is of 2.90 €/m^3 (Table A1.7). Operative costs with the consumptions are the major contributor of the total costs, followed by the machinery acquisition costs which compete for the 16% of the total (Figure A1.7).

Table A1. 7: eLCC - Case 7 full chain costs

Section	Cost item	Average cost per m^3 demolished
Preliminary costs	Demolition project	0.13 €/m^3
	Setting of the demolition site	0.06 €/m^3
	Building reclamation	0.00 €/m^3
	Security wages	0.19 €/m^3
	Environmental due diligence	0.10 €/m^3
Machinery acquisition costs	Machinery acquisition	0.63 €/m^3
Operative costs	Machine maintenance	0.03 €/m^3
	Personnel wages	0.99 €/m^3
	Insurance	0.00 €/m^3
	Consumptions	0.32 €/m^3
Disposal and recycling costs	Landfill fee	0.00 €/m^3
	Transportation	0.28 €/m^3
	On-site reuse	0.00 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3
	Recycling inert waste	0.18 €/m^3
TOTAL	***eLCC (Demolition + Recycling)***	***2.90 €/m^3***

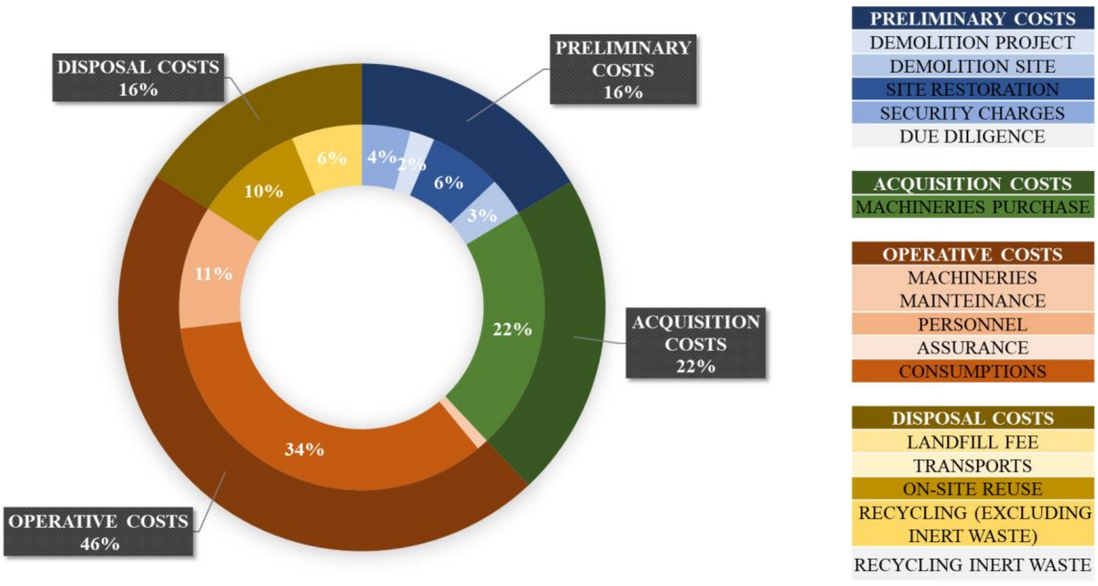


Figure A1. 7: Percentage of contribution of the different cost items – case 7

ANNEX II

SimaPro models of single datasets

A2.1 Recycling of aluminium

The *main process* contains the treatment of aluminium scraps and the avoided production of liquid aluminium (Figure A2.1).

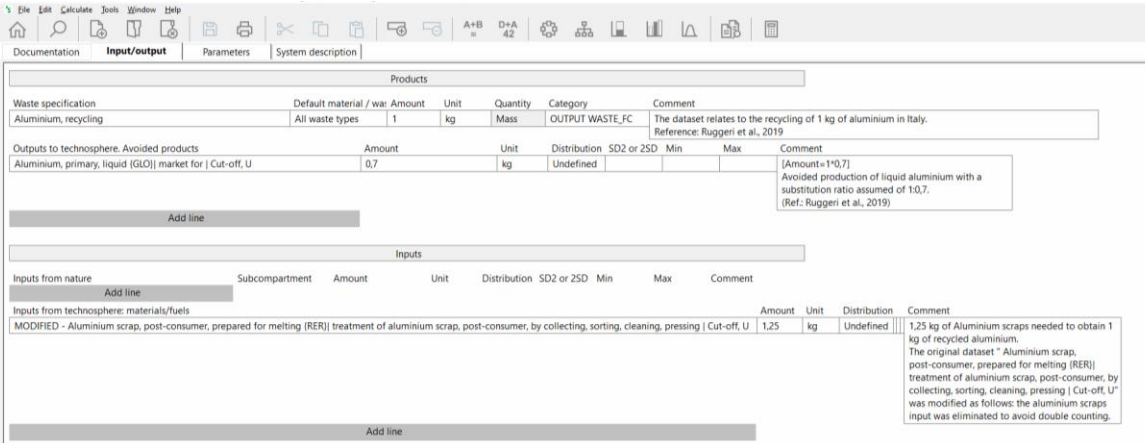


Figure A2. 1: Aluminium recycling - main process

The *avoided production* of liquid aluminium "Aluminium, primary, liquid {GLO}| market for | Cut-off, U" has a substitution ratio of the aluminium of 1:0.70 in mass (Ruggeri et al., 2019) (Table A2.1)

Table A2. 1: Substitution ratio of the different materials and secondary and substituted primary product (Ruggeri et al.,2019)

Material	Secondary product	Primary product	Substitution ratio
Aluminium	Aluminium scrap	Al 99.7	1:0.70 (in mass)

To obtain 1 kg of recycled aluminium is needed 1.25 Kg of Aluminium. The original Ecoinvent 3.8 treatment process "Aluminium scrap, post-consumer, prepared for melting {RER}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing | Cut-off, U" was modified deleting all the aluminium scraps input to avoid double counting.

Reference: Ruggeri, M., Pantini, S., & Rigamonti, L. (2019). Assessing the impact of selective demolition techniques on C&D waste management. IOP Conference Series: Earth and Environmental Science, 296(1), 012005. https://doi.org/10.1088/1755-1315/296/1/012005

A2.2 Recycling of Iron and steel

The *main process* contains the treatment of iron and steel scraps and the avoided production of liquid steel (Figure A2.2).

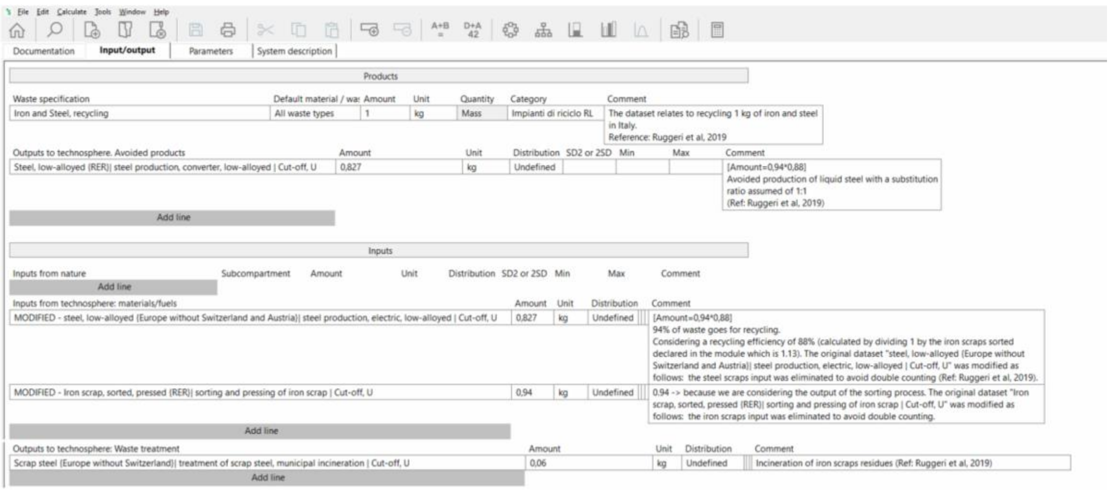


Figure A2. 2: Iron and steel recycling - main process

The *avoided production* of liquid steel "Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, U" has a substitution ratio of the steel of 1:1 in mass (Ruggeri et al., 2019) (Table A2.2)

Table A2. 2: Substitution ratio of the different materials and secondary and substituted primary product (Ruggeri et al.,2019)

Material	Secondary product	Primary product	Substitution ratio
Steel	Liquid steel	Liquid steel	1:1 (in mass)

The iron and steel scraps going for the:

- 94% to sorting: The original Ecoinvent 3.8 dataset "*Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U*" was modified by deleting all the iron scraps input to avoid double counting.
- 94% to treatment: It is considered a recycling was modified deleting all the aluminium scraps input to avoid double counting.efficiency of 88% (Calculated by dividing 1/1.13 (which is the original value of iron scrap inside the treatment module)) The original Ecoinvent 3.8 dataset "*Steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | Cut-off, U*" was modified by deleting all the steel scraps input to avoid double counting.
- 6% to incineration**:** It was used the Ecoinvent 3.8 dataset "*Scrap steel {Europe without Switzerland} | treatment of scrap steel, municipal incineration | Cut-off, U*"

Reference: Ruggeri, M., Pantini, S., & Rigamonti, L. (2019). Assessing the impact of selective demolition techniques on C&D waste management. *IOP Conference Series: Earth and Environmental Science*, *296*(1), 012005. https://doi.org/10.1088/1755-1315/296/1/012005

A2.3 Recycling of cables

The *main process* "Cables, recycling" is a modified Ecoinvent 3.8 process "*Used cable {GLO}| treatment of | Cut-off, U"* and contains the treatment of copper scraps and incineration of plastics (Figure A2.3). The electric cables are, indeed, subjected to shredding to optimize the subsequent mechanical separation of the copper from the rubber. Both fractions are then sent for recovery.

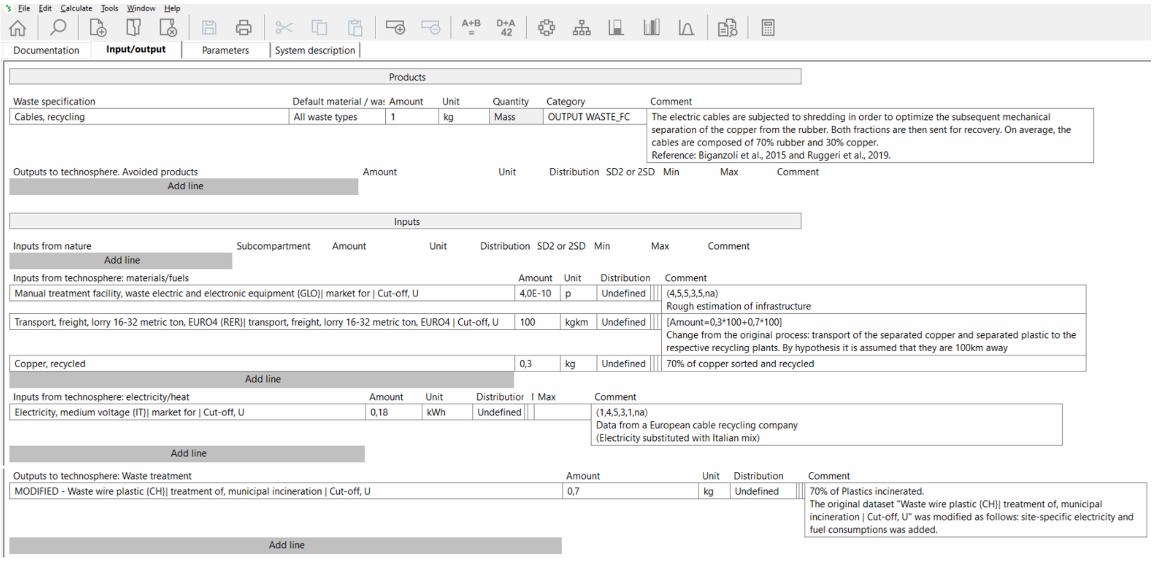


Figure A2. 3: Copper, recycling main process

On average, the cables are composed of 70% rubber and 30% copper (Source: Valcart: Lombard treatment plant).

- 70% of plastic goes to incineration: The original Ecoinvent 3.8 treatment process "*Waste wire plastic {CH}| treatment of, municipal incineration | Cut-off, U*" was modified introducing the modelling of avoided electrical and thermal energy, calculated from the PCI of rubber, equal to 25.95 MJ / kg (Source: Ecoinvent database) and the average energy efficiencies of Lombard incinerators (Figure A2.4).

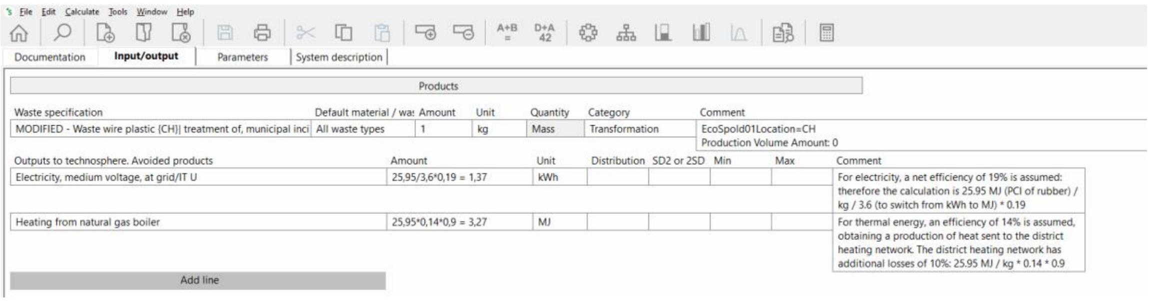


Figure A2. 4: Waste wire plastic landfill – modified module

- 30% of copper goes to recycling: The process "*Copper, recycled*" (Figure A2.5) contains the avoided production of primary copper "Cathode, copper, primary copper production/GLO U" with a substitution ratio of 1:1 and the copper treatment: 1.31 kg of copper waste is required to obtain 1 kg of recycled copper. The original Ecoinvent 3.8 dataset "*Copper, cathode {RER}| treatment of copper scrap by electrolytic refining | Cut-off, U*" was modified by deleting all the copper scraps input to avoid double counting.

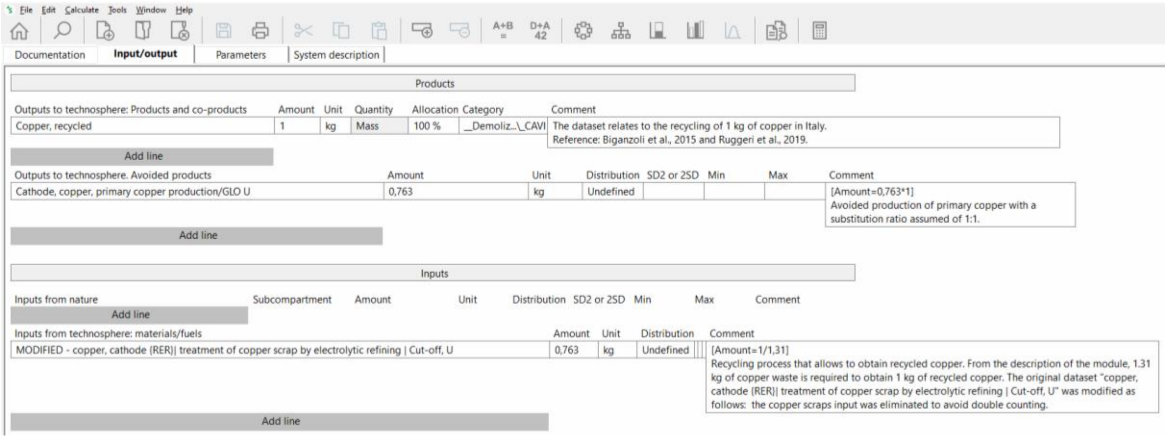


Figure A2. 5: Copper, recycled process

Reference: Ruggeri, M., Pantini, S., & Rigamonti, L. (2019). Assessing the impact of selective demolition techniques on C&D waste management. *IOP Conference Series: Earth and Environmental Science*, *296*(1), 012005.

Biganzoli, L., Falbo, A., Forte, F., Grosso, M., & Rigamonti, L. (2015). Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). Science of The Total Environment, 524–525, 361–375.

A2.4 Recycling of gypsum-based materials

The sole specialised plasterboard waste recovery facility functioning in the Lombardy area is a fixed type of unit that performs sequential grinding and screening operations (Giurato et al., 2018).

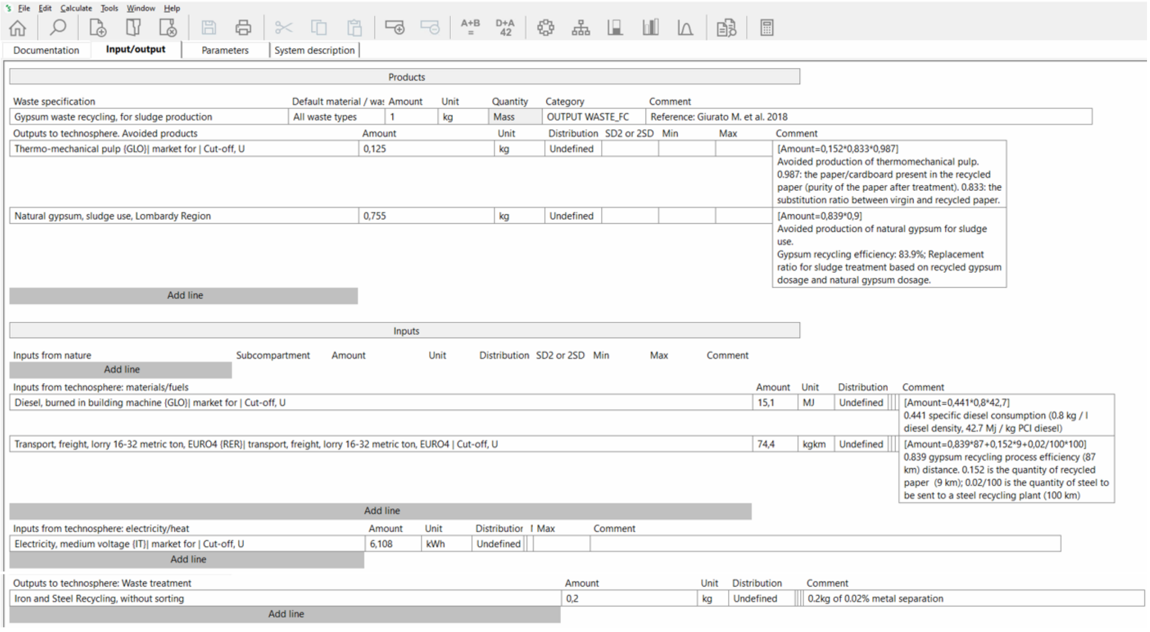


Figure A2. 6: Gypsum waste recycling main process

The *main process* on Figure A2.6 “*Gypsum waste recycling, for sludge production*” contains the overall mass balance of the plant that include:

- 83.9% powdered gypsum which is exclusively intended for use in the production of “gypsum of defecation” in place of natural gypsum. The substitution ratio is 1:0.9; The avoided production of natural gypsum “*Natural gypsum, sludge use, Lombardy Region*” (ad hoc process on Figure A2.7) include the process for natural gypsum extraction “*Natural gypsum, extraction, Lombardy Region*” (Figure A2.8) and the process for natural gypsum treatment “*Natural gypsum, treatment for sludge production*” (Figure A2.9).

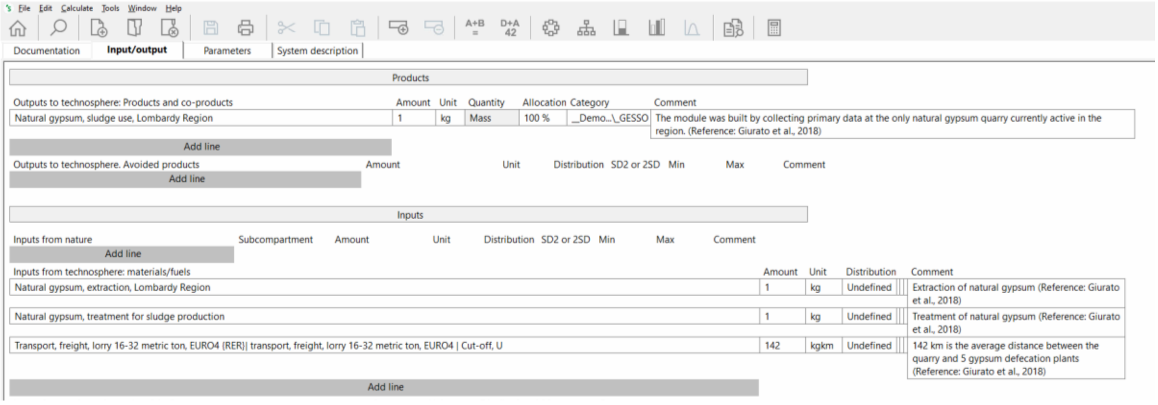


Figure A2. 7: Avoided production of natural gypsum

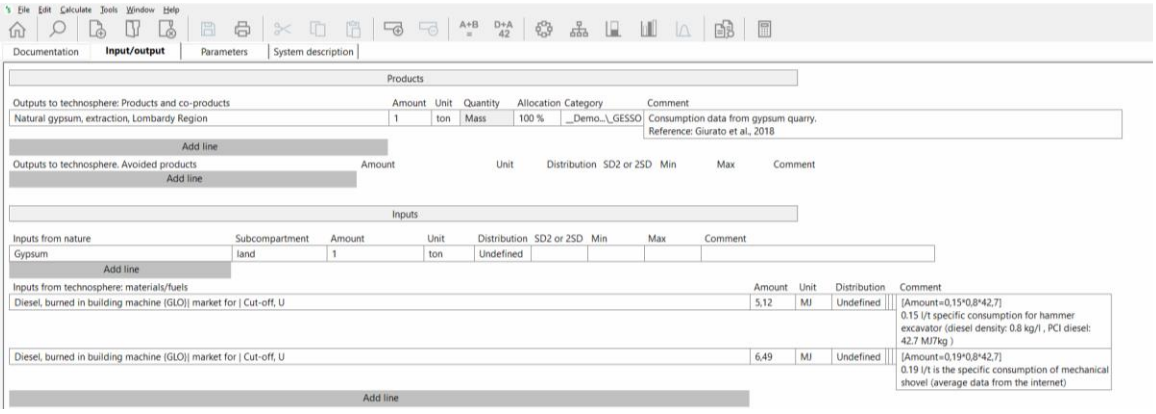


Figure A2. 8: Natural gypsum extraction - ad hoc process

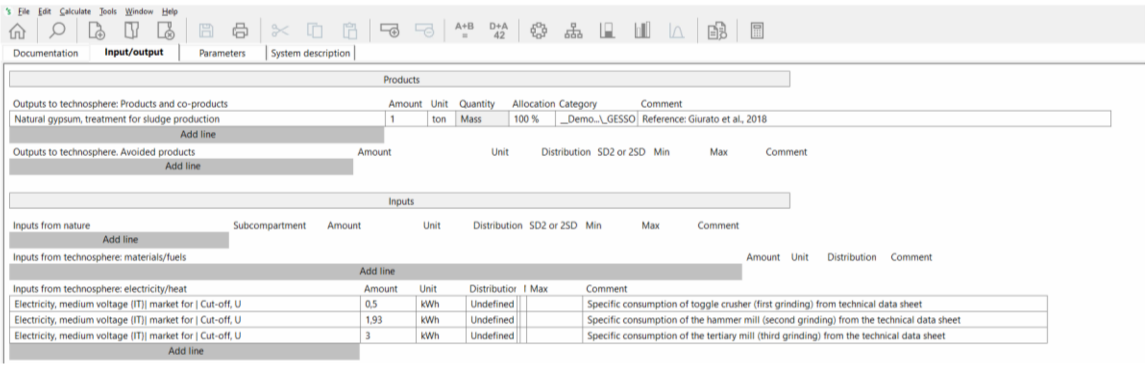


Figure A2. 9 Natura gypsum treatment - ad hoc process

- 15.2% cellulosic waste deriving from the separation of cardboard. The separated paper is sent to the nearest paper mill, where it will be used in place of thermomechanical virgin pulp, in dependent measure of the quality of the separated flow (98.7%) and on the substitution ratio (1: 0.833);

- 0.02% ferrous metals. The ferrous metals are sent directly to the steel mill, without any intermediate selection step, to produce secondary steel which will be used in place of primary steel. The process “*Iron and steel, without sorting*” is the same as the one show in § A2.2 but in this case 100% of iron scraps goes to treatment (Figure A2.10).
-

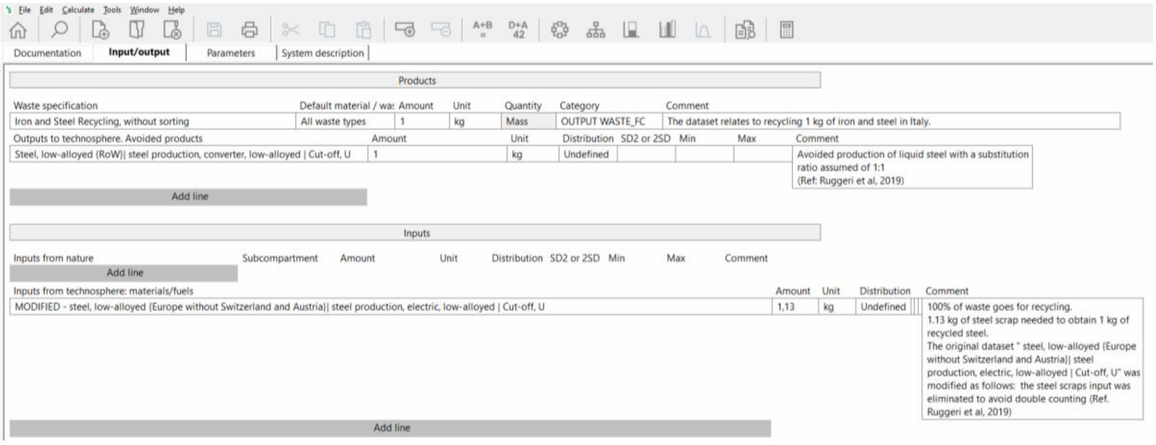


Figure A2. 10: Iron and steel recycling, without sorting

- 0.88% process losses (which are not modelled).

The treatment gives gypsum powder with a particle size distribution from 8 mm to 0.063 mm.

Reference: Giurato, M., Pantini, S., Rigamonti, L. (2018). Valutazione LCA del sistema di riciclo dei rifiuti a base di gesso in Regione Lombardia. Ingegneria Dell’Ambiente, 5(2). https://doi.org/10.32024/IDA.V5I2.146

A2.5 Recycling of wood

The *main process* contains the treatment of wood scraps and the avoided production of plywood (Figure A2.1).

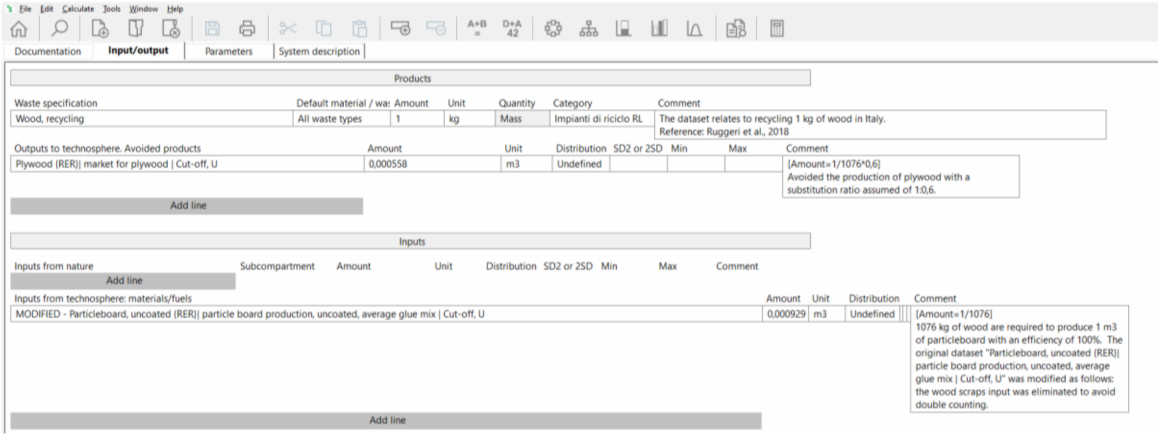


Figure A2. 11: Wood, recycling - main process

The *avoided production* of plywood “*Plywood {RER}| plywood production | Cut-off, U*” has a substitution ratio of the steel of 1:06 in volume (Ruggeri et al., 2019) (Table A2.3).

Table A2. 3: Substitution ratio of the different materials and secondary and substituted primary product (Ruggeri et al.,2019)

Material	Secondary product	Primary product	Substitution ratio
Wood	Particle board	Plywood	1:0.6 (in volume)

Considering a 100% treatment efficiency, 1076 kg of wood are required to produce 1m^3 of particleboard. The original Ecoinvent 3.8 dataset “*Particleboard, uncoated {RER}| particle board production, uncoated, average glue mix | Cut-off, U*” was modified by deleting all the wood chips input to avoid double counting.

Reference: Ruggeri, M., Pantini, S., & Rigamonti, L. (2019). Assessing the impact of selective demolition techniques on C&D waste management. *IOP Conference Series: Earth and Environmental Science*, *296*(1), 012005.

A2.6 Recycling of mixed C&D waste

For the recycling of mixed C&D waste (Figure A2.12) , it was supposed that the majority (86,1%) goes on a mobile recycling plant and the 13,9% goes to a fixed plant *(Borghi et al, 2018)*.

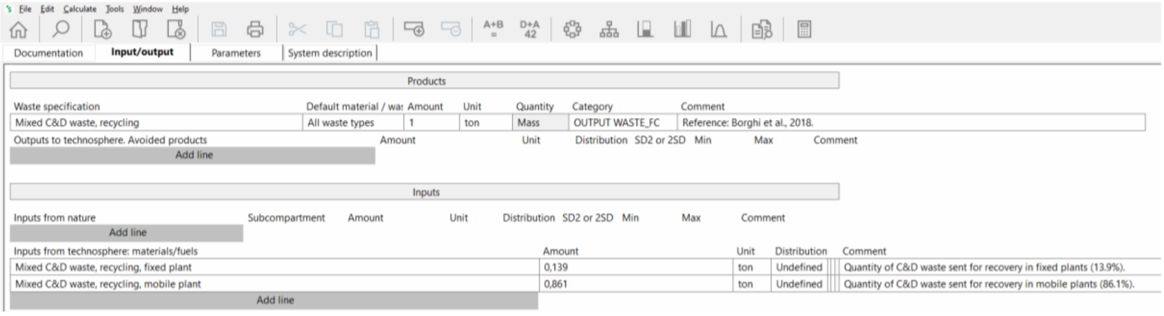


Figure A2. 12: Fixed C&D waste, recycling – main process

The process "*Mixed C&D waste, recycling, fixed plant*" process contains the avoided production of the natural aggregates considering two separate productions based on the quality (C1/C2 or C4 use), the plant consumptions, the transportations and the ferrous metals waste that goes for sorting (Figure A2.13).

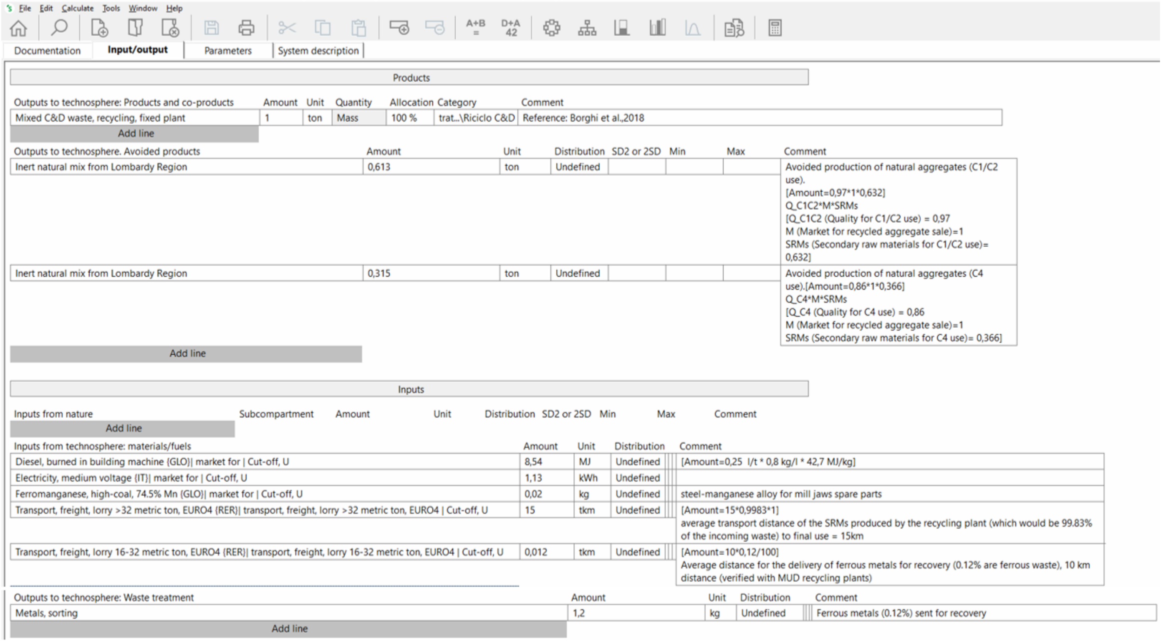


Figure A2. 13: Fixed plant C&D treatment process

The process "*Mixed C&D waste*, *recycling*, *mobile plant*" process contains the avoided production of the natural aggregates considering two separate productions based on the quality (C1/C2 or C4 use), the plant consumptions, the transportations and the ferrous metals waste that goes for sorting and the mixed C&D waste fraction that goes to landfill (Figure A2.14).

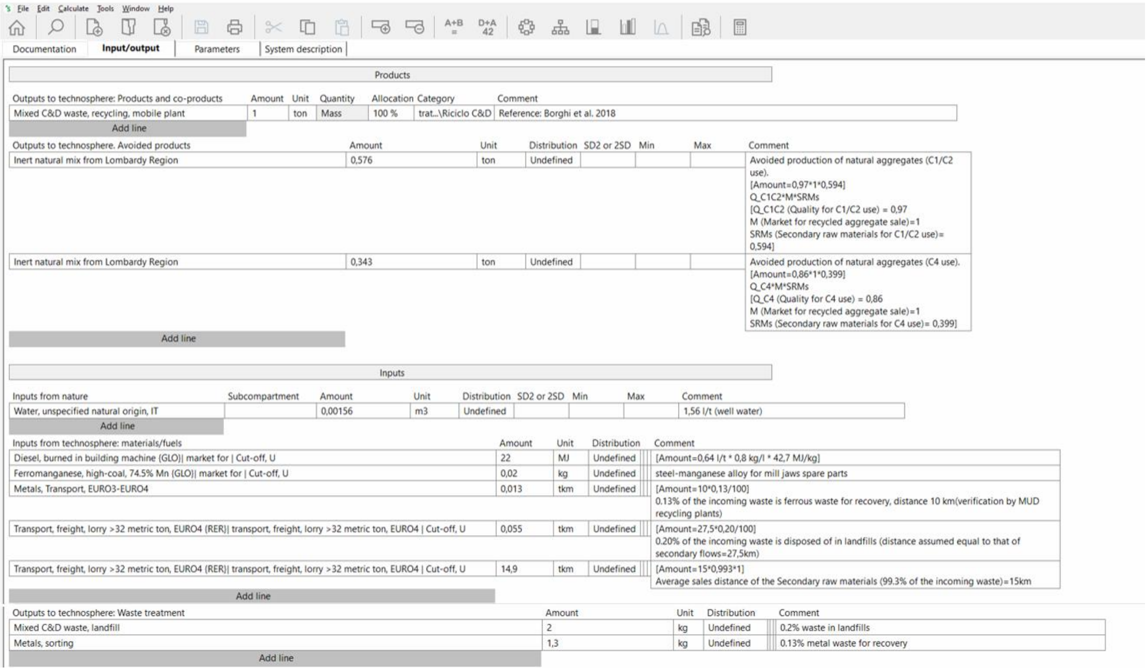


Figure A2. 14: Mobile plant C&D treatment process

The avoided production “*Inert natural mix from Lombardy Region*” refer to the extraction of a tonne of natural mixture from a sand and gravel quarry located in Lombardy Region (Rigamonti et al., 2017) (Figure A2.15).

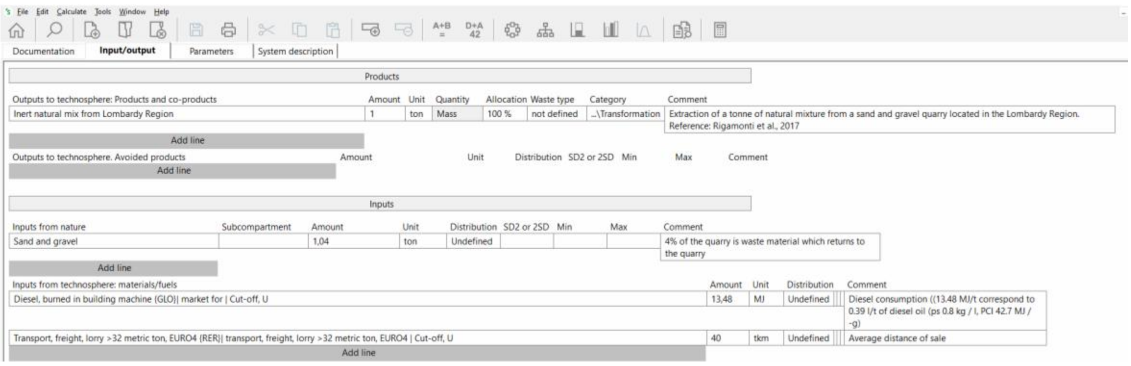
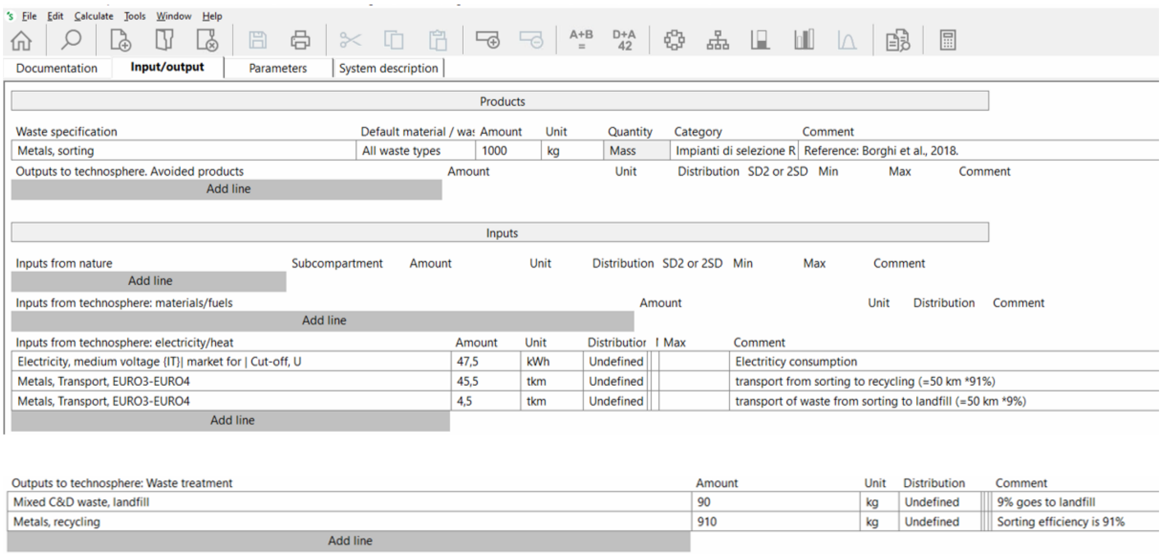


Figure A2. 15: Avoided production of natural aggregates

The metal sorting and transport processes are shown in Figures A2.16 – A2.17 – A2-18.


File Edit Calculate Tools Window Help
Documentation | Input/output | Parameters | System description

Products

Waste specification	Default material / wa:	Amount	Unit	Quantity	Category	Comment
Metals, sorting	All waste types	1000	kg	Mass	Impianti di selezione R	Reference: Borghi et al., 2018.

Outputs to technosphere. Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment
Add line

Inputs

Inputs from nature | Subcompartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment
Add line

Inputs from technosphere: materials/fuels | Amount | Unit | Distribution | Comment
Add line

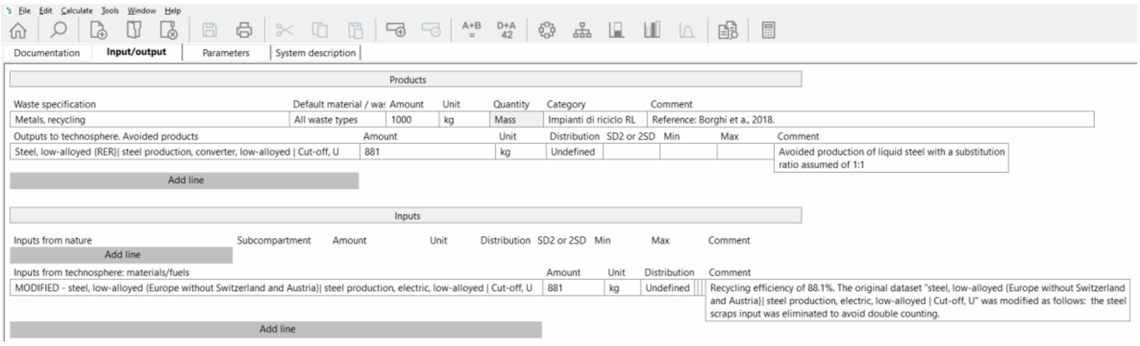
Inputs from technosphere: electricity/heat	Amount	Unit	Distributior	Max	Comment
Electricity, medium voltage {IT}| market for | Cut-off, U	47,5	kWh	Undefined		Electricity consumption
Metals, Transport, EURO3-EURO4	45,5	tkm	Undefined		transport from sorting to recycling (=50 km *91%)
Metals, Transport, EURO3-EURO4	4,5	tkm	Undefined		transport of waste from sorting to landfill (=50 km *9%)

Add line

Outputs to technosphere: Waste treatment	Amount	Unit	Distribution	Comment
Mixed C&D waste, landfill	90	kg	Undefined	9% goes to landfill
Metals, recycling	910	kg	Undefined	Sorting efficiency is 91%

Add line

Figure A2. 16: Metal, sorting process


File Edit Calculate Tools Window Help
Documentation | Input/output | Parameters | System description

Products

Waste specification	Default material / wa:	Amount	Unit	Quantity	Category	Comment
Metals, recycling	All waste types	1000	kg	Mass	Impianti di riciclo RL	Reference: Borghi et a., 2018.

Outputs to technosphere. Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, U	881	kg	Undefined				Avoided production of liquid steel with a substitution ratio assumed of 1:1

Add line

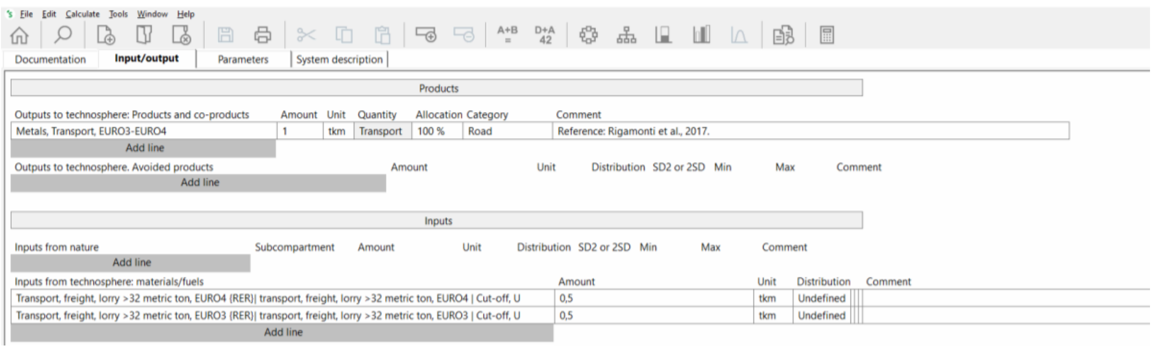
Inputs

Inputs from nature | Subcompartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment
Add line

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	Comment
MODIFIED - steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | Cut-off, U	881	kg	Undefined	Recycling efficiency of 88.1%. The original dataset "steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | Cut-off, U" was modified as follows: the steel scraps input was eliminated to avoid double counting.

Add line

Figure A2. 17: Metals, recycling process


File Edit Calculate Tools Window Help
Documentation | Input/output | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Category	Comment
Metals, Transport, EURO3-EURO4	1	tkm	Transport	100 %	Road	Reference: Rigamonti et al., 2017.

Add line

Outputs to technosphere. Avoided products | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment
Add line

Inputs

Inputs from nature | Subcompartment | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment
Add line

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	Comment
Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U	0,5	tkm	Undefined	
Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Cut-off, U	0,5	tkm	Undefined	

Add line

Figure A2. 18: Metals, transport process

Reference: Borghi, G., Pantini, S., & Rigamonti, L. (2017). Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). Journal of Cleaner Production, 184, 815–825. https://doi.org/10.1016/J.JCLEPRO.2018.02.287

A2.7 Recycling of cement

Also for the recycling of cement (Figure A2.19) , it was supposed that the majority (86,1%) goes on a mobile recycling plant and the 13,9% goes to a fixed plant (Rigamonti et al, 2017).

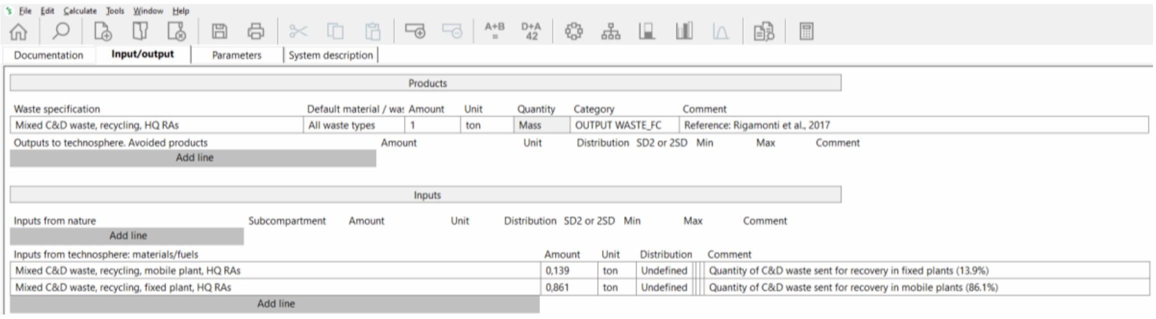


Figure A2. 19: Mixed C&D waste, recycling, HQ RAs - main process

For both processes (Figure A2.20 – A2.21) it is assumed that 100% of recycled aggregates (RAs) produced by the plants are of high quality (avoided product: sand and gravel). The substitution ratio used is 1:1. It is assumed that the pure concrete stream does not contain metals and other impurities to be sent to landfills (Rigamonti et al., 2017).

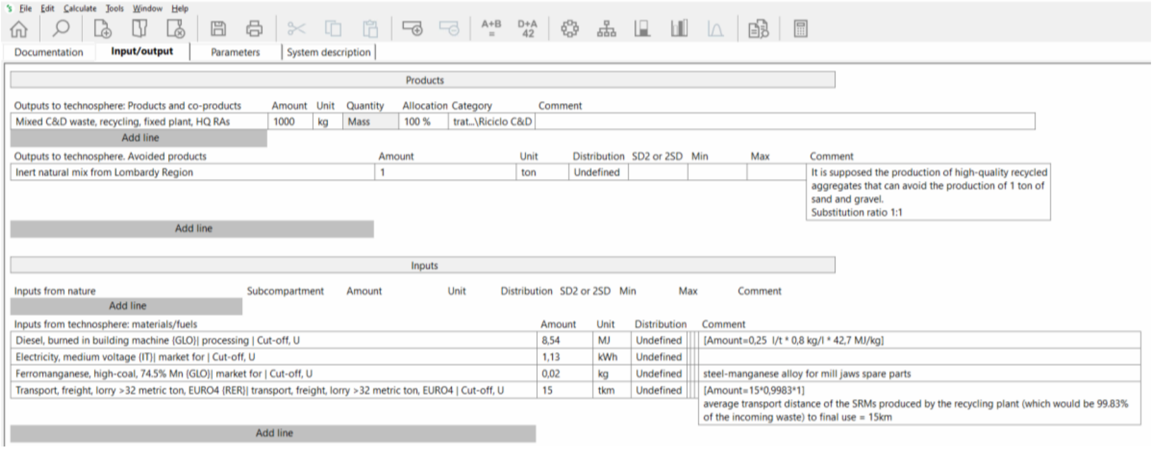


Figure A2. 20: Cement recycling - fixed plant

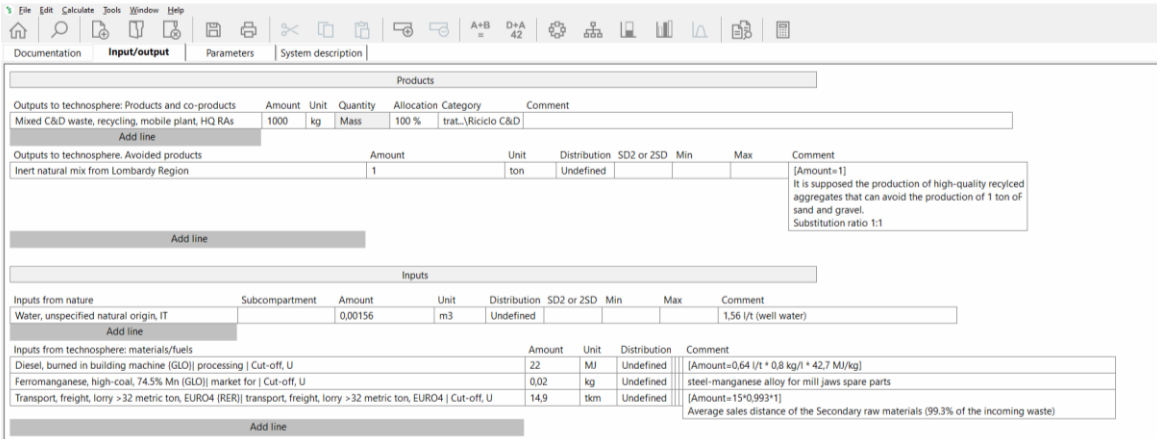


Figure A2. 21: Cement recycling - mobile plant

Reference: Rigamonti, I. L., Pantini, S., & Borghi, G., 2017. Relazione Finale Valutazione con metodologia LCA (Life Cycle Assessment) dei flussi e del destino dei rifiuti da costruzione e demolizione. Centro studi MatER Materia & Energia da Rifiuti per Regione Lombardia.

A2.8 On-site reuse of C&D waste

For the on-site reuse of mixed C&D waste, the use of a mobile plant was envisaged. The original reference module is "*Mixed C&D waste, recycling, mobile plant*" (see §A2.6), from which the value for metals treatment and inert landfills was excluded because these two waste streams are counted in the case study overall module (Figure A2.23).

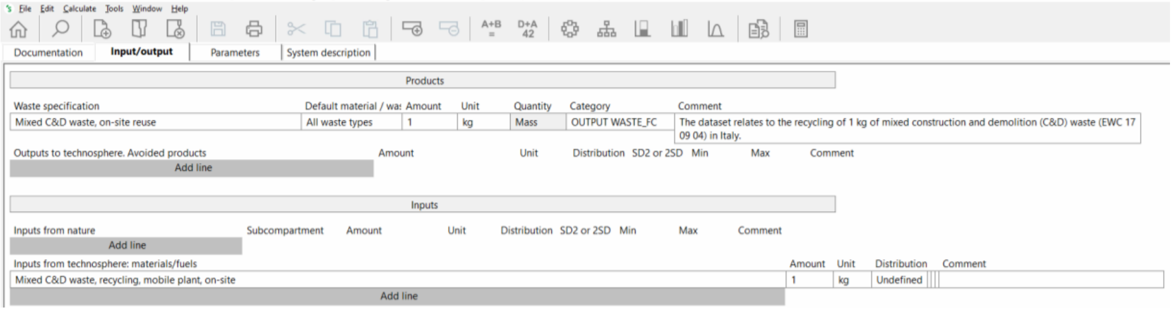


Figure A2. 22: mixed C&D waste, on-site reuse – main process

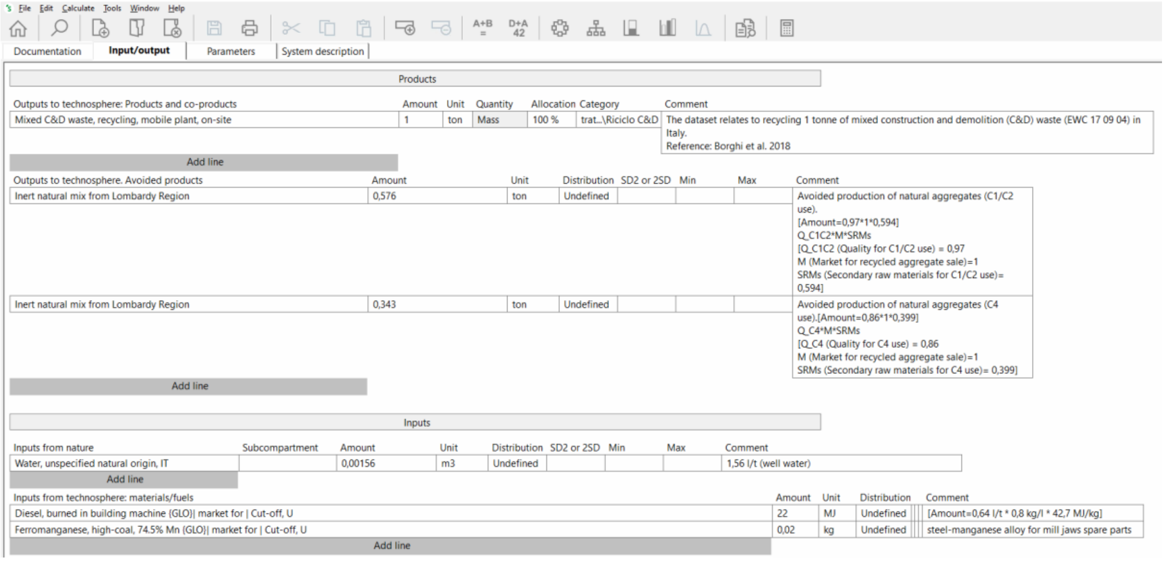


Figure A2. 23: mixed C&D waste, on-site reuse - mobile plant

Reference: Borghi, G., Pantini, S., & Rigamonti, L. (2018). Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). Journal of Cleaner Production, 184, 815–825. https://doi.org/10.1016/J.JCLEPRO.2018.02.287

A2.10 Landfill of C&D waste

The original Ecoinvent 3.3 dataset *"Inert waste {CH}| treatment of, sanitary landfill | Cut-off, U"* was modified to add some site-specific values concerning an Italian inert landfill.

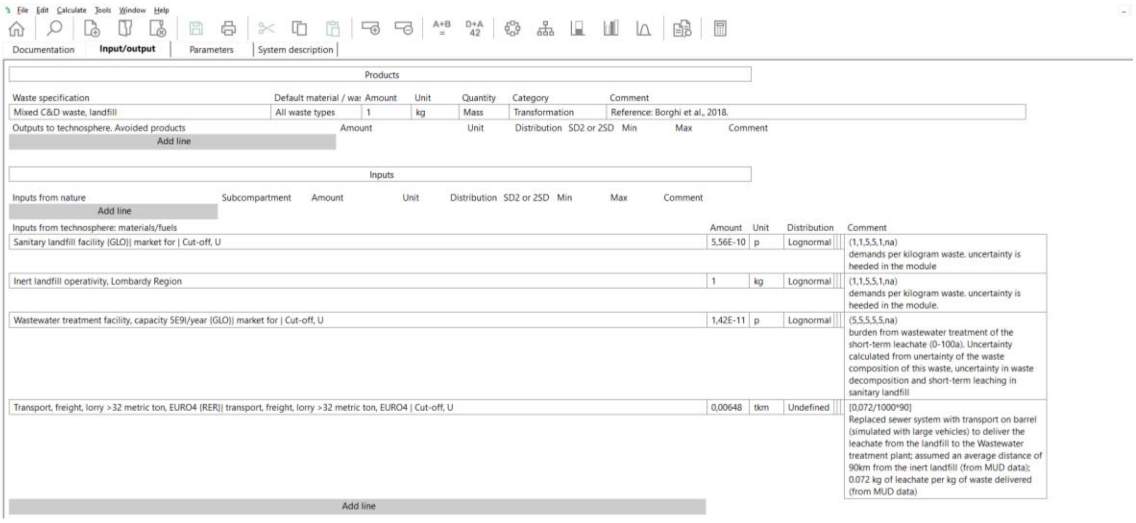


Figure A2. 24: Mixed C&D waste, landfill – main process

Figure A2.25 it is shown the site-specific values (Borghi et al., 2018 and Blengini, 2009) inserted in the C&D waste treatment main process in Figure A2.24.

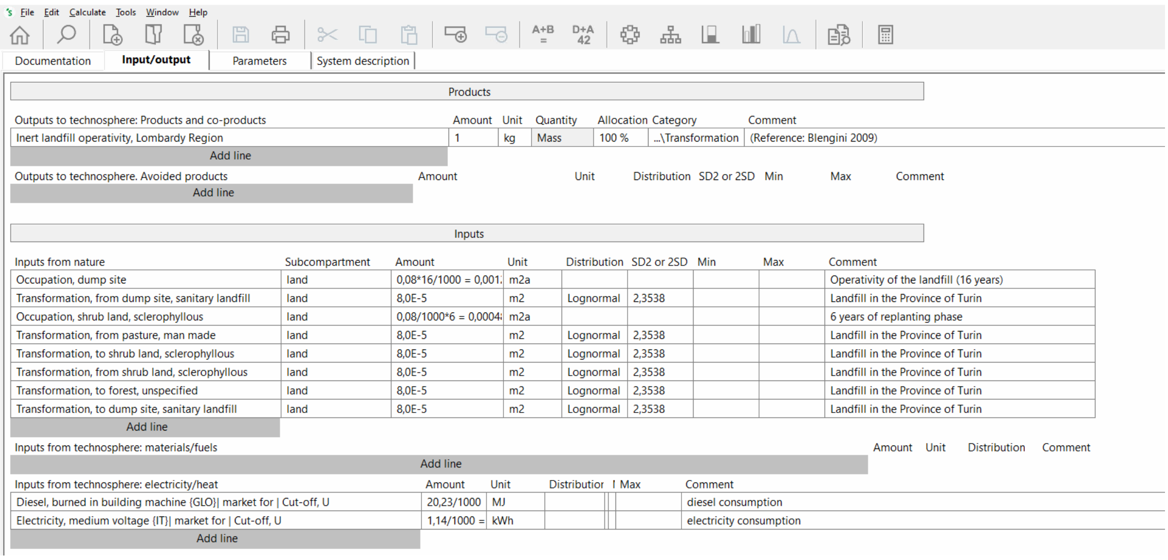


Figure A2. 25: Inert landfill specific values from Blengini, 2009

Reference: Borghi, G., Pantini, S., & Rigamonti, L. (2018). Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). Journal of Cleaner Production, 184, 815–825. https://doi.org/10.1016/J.JCLEPRO.2018.02.287

A2.5 Landfill of mixed packaging

The mixed packaging waste is assumed composed by equal part of plastic, paperboard, polystyrene, and wood packaging (Figure A2.26).

- 25% of Plastic packaging: Ecoinvent 3.8 process "*Waste plastic, mixture {CH}|treatment of, sanitary landfill | Cut-off,U*"
- 25% of paperboard packaging: Ecoinvent 3.8 process "*Waste paperboard {CH}|treatment of, sanitary landfill | Cut-off,U*"
- 25% of polystyrene packaging: Ecoinvent 3.8 process "*Waste polystyrene {CH}|treatment of, sanitary landfill | Cut-off,U*"
- 25% of wood packaging: Ecoinvent 3.8 process "*Waste wood, untreated {CH}|treatment of, sanitary landfill | Cut-off,U*"

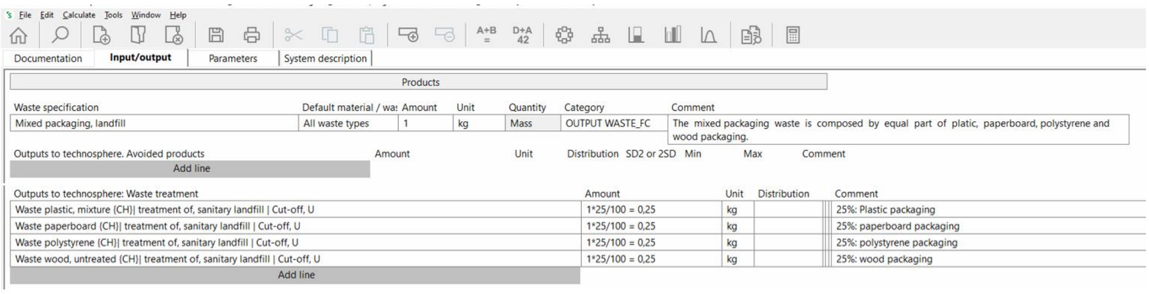


Figure A2. 26: Mixed packaging, landfill – main process

A2.11 Storage of Insulating materials

The simplest and cheapest solution currently available for the management of mineral wool waste is landfill disposal. Waste producers generally send them to specialize plants which pack the waste in big bags. The packaged materials are then sent to landfills equipped with a dedicated cell and disposed of. So mineral wool goes to a storage plant and then disposed of in a landfill (Policaro et al., 2020).

The main module, “Insulating materials, storage”, refer to the production of 1 piece of polystyrene big bag (Figure A2.27)

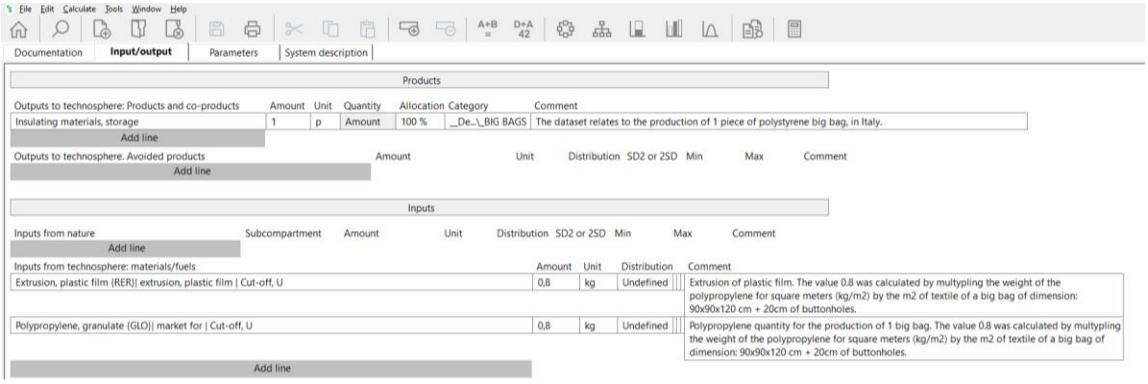


Figure A2. 27: Insulating materials, storage

The data on the weight of the polystyrene for 1 m^2 of fabric (140 gr/m^2) are obtained from the technical data sheet (TDS) in Figure A2.28 . The total area of the fabric was calculated knowing the size of the big bag B1 = 90cm x B2 = 90cm x H1 = 120cm + buttonholes L1 = 30 cm. The total quantity of polystyrene needed to produce a big bag is:

Fabric = 5.4 m^2 (0.9 m · 1.20 m · 4 + 0.9 m · 0.3 m · 4) · 140gr/m^2 = 756 gr = 0.8 kg.

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Scheda Tecnica
BIG BAG - CONTENITORE FLESSIBILE
ELC 000004

Contenitore in tela polipropilene ricavato da tela piana con quattro bretelle di sollevamento cucite esternamente lungo il corpo saccone. Fondo chiuso e chiusura superiore a caramella.

PESO FINALE : kg 1,32 circa

PORTATA DEL SACCONE (swl) : 1000 kg

FATTORE DI SICUREZZA (sf) : 5:1

CORPO SACCONE : confezionato con tela di polipropilene peso 140 gr/m2.
100% polipropilene vergine, colore bianco.

TENACITÀ : in ordito non inferiore a 1350 n/50 mm
in trama non inferiore a 1230 n/50 mm
relativo allungamento 17.5%

TRATTAMENTO ANTI U.V. : la tela polipropilene mantiene piu' del 50% di resistenza residuale dopo un'esposizione di 200 ore ai raggi ultravioletti.

BRETELLE DI SOLLEVAMENTO: n. 4 in tessuto di polipropilene , 100%polipropilene vergine, colore bianco. cucite sul corpo del saccone con doppia cucitura, larghezza 50mm,peso 50 grammi al ml. carico di rottura di ogni bretella kg 1.500. anello bretelle 30 cms.
Ogni bretella e' cucita lungo corpo del saccone ; 75 cms e' la misura del lembo lungo con ritorno di 40 cms,

CHIUSURA SUPERIORE A CARAMELLA: confezionata in tessuto polipropilene , 100% polipropilene vergine, tessuto 70 gr/m2, colore bianco. Altezza 80 cms; 2 stringhe per la chiusura di 60 cms fissate all'altezza di 65 cms.

CUCITURE: tutte le cuciture del corpo saccone e della valvola di scarico sono doppie, cucitura herackle con cucitura di sicurezza (a catenella). il filo usato e' in polipropilene 6000 denari a due capi il cui sviluppo e' di 1500 metri lineari al kg. Colore blu o nero.

Figure A2. 28: TDS of big bags

Reference: Policaro, P., Carollo, F., & Rigamonti, L. (2020). Analisi qualitativa e quantitativa della gestione dei rifiuti di lana di roccia. *Ingegneria Dell'Ambiente*, *7*(4). https://doi.org/10.32024/IDA.V7I4.280

ANNEX III

Metadata sheets for BDI-LCA ARCADIA Project

The metadata is compiled for Case 1 and Case 7 as representative of the two cases of demolition of a masonry/concrete building and a metal building. Figures A3.1 and A3.2 provide a list of all the datasets that have been turned into metadata and imported into BDI-LCA. For the metadata sheets, please contact: federicacarla.carollo@polimi.it.

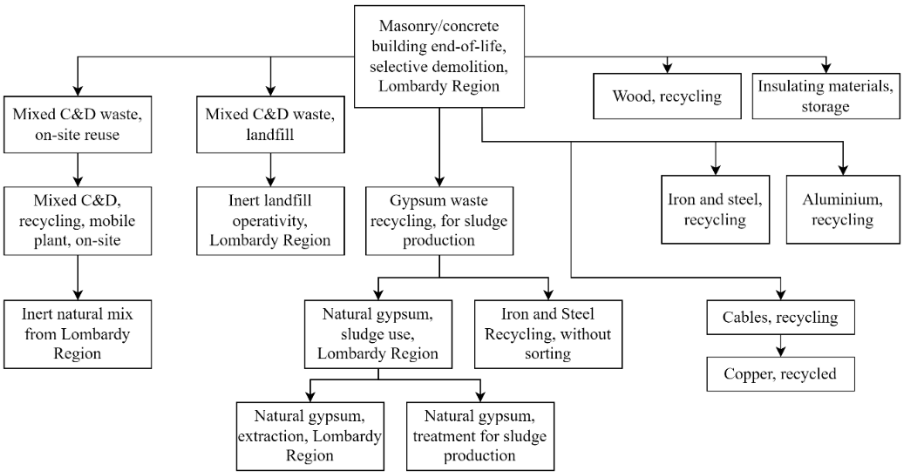

Figure A3.1: Datasets for the demolition of a masonry/concrete building imported on MeDit

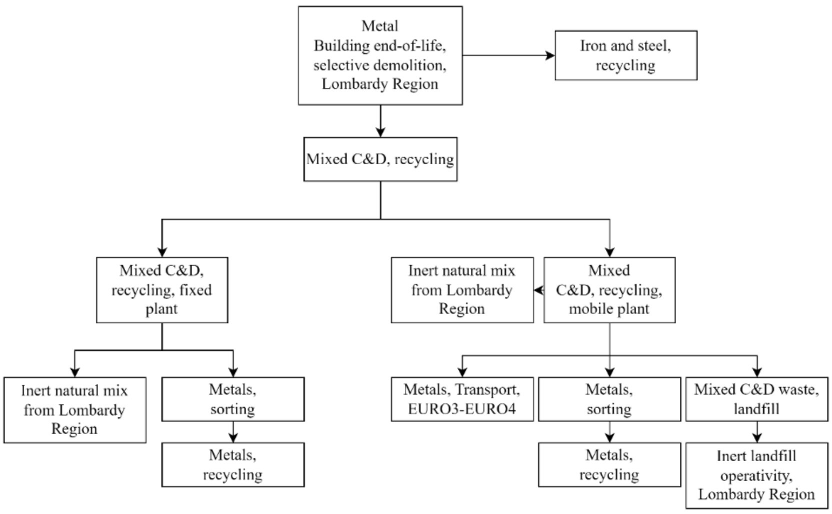

Figure A3.2: Datasets for the demolition of a metal building imported on MeDit