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Life cycle assessment of construction and demolition waste management systems: a Spanish case study

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Abstract
Purpose The aim of this study is to develop and analyse a life cycle inventory of construction and demolition waste (C&DW) management systems based on primary data collected directly from Spanish enterprises involved in the life cycle of this type of waste material. Special emphasis is placed on assessing the environmental profile of inert waste sorting and treatment (IWST) facilities.
Methods Taking the management of 1 t of C&DW as the functional unit, this study describes the boundaries of the C&DW management system and the scope of the research, which includes all stages from the temporary storage of waste in containers to its recovery or disposal on landfills. Primary data were collected directly from some Spanish enterprises involved in the life cycle of C&DW management: two firms that manufacture containers and bags, two companies responsible for the temporary storage of waste and transporting it, five firms devoted to sorting and treating the waste and two enterprises that operate inert landfills. Special attention was given to the IWST facilities, whose inventory data were related to four phases: pre-treatment and the primary, secondary and tertiary sectors. Finally, indicators were obtained for different impact categories.
Results The environmental profiles of IWST facilities for mixed C&DW show that the greatest environmental impacts are produced in primary and tertiary sectors. From the life cycle analysis of C&DW management, it can be seen that transport, sorting and disposal make a net contribution to the environmental impact. Savings are due to the recycling of plastics, metals, aggregates and wood for all the impact assessment categories, except global warming in the case of wood and cardboard.
Conclusions Impact of IWST can be reduced by selective collection at source, since it avoids the separation of light fractions at plants. Life cycle assessment of C&DW shows that transportation stage plays a decisive role and recycling is not always beneficial.

Keywords Construction and demolition waste · C&DW · Inert waste sorting and treatment plant · IWST · Life cycle inventory · LCI · Waste management system

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1 Introduction

In recent years, within the field of solid waste management, there has been an increasing development of tools for supporting decision-making with regard to regional and national planning in different countries. Internationally, the alternative ways of solid waste management follow a general hierarchical order (waste hierarchy), i.e. prevention, preparing for re-use, recycling, other types of recovery (e.g. energy recovery) and disposal (Directive 2008/98/EC 2008). Yet, this order of priorities does not ensure the minimisation of environmental impacts of waste management systems or the optimal combination of possible alternatives. To address this issue, European Commission Communication (COM 666 2005) recommended that life cycle assessment (LCA) methodology (ISO 14040–44 2006a, b) should be used jointly with the waste hierarchy.

Application of LCA methodology to the environmental assessment of municipal waste management systems is a practice that has started to be applied in several European countries in recent years, as shown in the studies by Bovea and Powell (2006) and Bovea et al. (2010) in Spain, Buttol et al. (2007) and Cherubini et al. (2009) in Italy, Khoo (2009) in Singapore, Kim and Kim (2010) in Korea, Niskanen et al. (2009) in Finland, Stenmarck et al. (2009) in Chile or Tunesi (2011) in England, among others.

This fact is also confirmed by the amount of specific software that has been developed in recent years to allow the application of LCA methodology to environmental assessment of waste management systems. Examples of such applications include IWM-2 (McDougall et al. 2004), IWMMM (Cirko et al. 2000), WARM (EPA 2006), LCA-IWM (den Boer et al. 2007), WISARD (The Ecobilan Group 1999) or EASEWASTE (Kirkeby et al. 2005), among others.

Nevertheless, for other waste streams, such as industrial waste (Tarantini et al. 2009) and more especially construction and demolition waste (C&DW), research is still just beginning and so far conducted studies are not comparable with those reported in the field of municipal solid waste. This is why no life cycle inventory (LCI) databases that characterise the waste being examined in this paper (i.e. C&DW) have been developed.

Some applications of the LCA methodology to C&DW management have been reported in the literature. Blengini (2009), for instance, conducted a study of the application of LCA methodology to the demolition of a building in Italy and analysed different scenarios for the end-of-life management of C&DW. The author used both his own data collected during the demolition and others from Idemat (2001) and ETH-ESU 96 (1996) databases. Ortiz et al. (2010) compared three C&DW management scenarios for a new building in Catalonia, Spain, taking as functional unit the average waste generated per square metre of the building. The management scenarios (landfilling, recycling and incineration) were analysed using LCI data from the Ecoinvent database (SCLCI 2008). Another study (Blengini and Garbarino 2010) analysed the benefits of recycling inert fraction in Turin, Italy, using the local management system data. The article reports data from mobile, semi-mobile and stationary crushing plants operating in the Torino Province. Sorting of the C&DW were included in the third type of plants. A consumption of 0.68 l of diesel and 3.6 MJ of electricity was assumed per tonne of C&DW treated by fixed inert waste sorting and treatment plant (IWST).

With regard to the LCI databases and LCA software, it is important to note that some of them include inventories for different kinds of construction materials and several alternative methods of end-of-life disposal. Ecoinvent V2.01 (SCLCI 2008) includes three possible alternative ways of treating construction materials in Switzerland: direct recycling, (partial) recycling after sorting and direct final disposal without recycling (landfilling or incineration), and it does not take into account the burdens that are avoided by recycling. The LCI proposed for these alternatives contains generic data based on Swiss facilities. In the case of IWST, fuel and electrical power consumption data used were 0.10 l and 13.32 MJ per tonne of C&DW treated, respectively. The latest version of WARM (EPA 2010) includes nine greenhouse gas emission factors for the end of life of six construction and demolition materials, i.e. asphalt concrete, asphalt shingle, plaster, fibreglass insulation, vinyl flooring and wood flooring. However, this software only calculates energy consumptions and CO_2 emission factors and was specifically designed for application to case studies from USA and Canada.

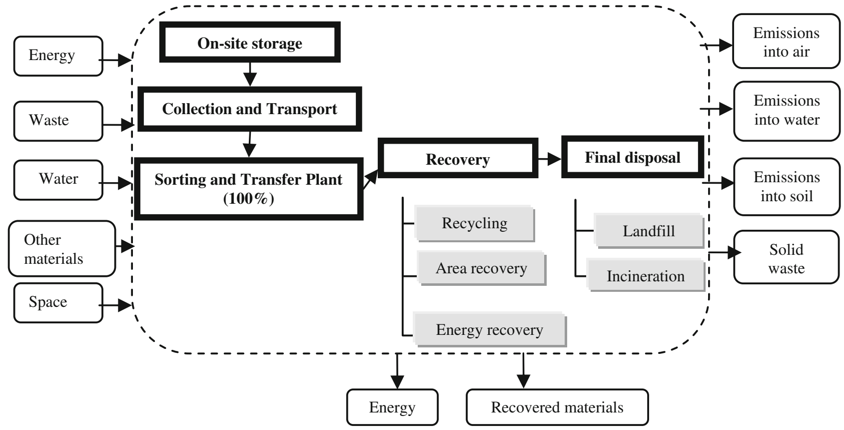
Against this background, it can be seen that there is a need for further work in the application of LCA methodology to the assessment of C&DW management systems. It is therefore essential to have access to high-quality inventory data referred specifically to C&DW management systems and adapted to the relevant geographic area, because the quality of the results of an LCA study largely depends on the quality of the inventory data used in it. The aim of this paper is therefore to present and analyse an inventory that includes the processes and materials involved in the Spanish C&DW management system. This LCI was developed from primary or field data gathered directly from enterprises involved in this kind of waste management and dedicated to manufacturing containers and bags, transporting C&DW, inert waste sorting, C&DW transfer and treatment, recycling materials and landfilling inert waste. The LCI was then used to carry out a detailed analysis of both IWST facilities and the whole management system, from the environmental point of view, as well as to identify the unit processes that make the greatest contribution to the impact and certain aspects that could be improved.

2 Description of the process of C&DW management in Spain

The general life cycle of a C&DW management system is made up of the stages shown in Fig. 1. The stages of the system under study are the following:

- *On-site storage.* As C&DW is generated, it is stored in containers on site or loaded directly onto lorries in case of demolitions. It is usually stored without making any distinction between different materials and will therefore need to be separated later into fractions.

Fig. 1 System boundaries of the C&DW management for the LCI. Inputs and outputs



- *Collection and transport.* The containers and bags are collected on site regularly and are taken to plants where the waste is sorted into different fractions.
- *Classification and transfer.* In this stage, the mixed waste is taken to IWST plants, where it is separated into the fractions that can be recovered. Although different plants have different levels of technology, in this case study, they were classified into two types, depending on their production capacity and the type of input waste:

– Type I. These plants process mixed C&DW belonging to category 17 according to the European Waste Catalogue (Commission Decision 2000/532/EC 2000). They have a treatment capacity of 500–650 t/day and an installed power of 150–160 kW. For fractions that are separated at plant, such as paper and cardboard, plastics, wood, and ferrous and non-ferrous metals, these facilities serve as transfer plants, which send this waste to enterprises that are responsible for recycling it. In these plants, sorted inert fraction is transformed into recycled aggregate, as it will be explained in the next stage of valorisation.

– Type II. These are larger facilities with two lines. The first one processes mixed C&DW with a production capacity of 3,000–4,500 t/day. The second one handles concrete waste, separately and independently from the mixed one. This second line, with a capacity of 2,500 t/day, produces secondary aggregate with better quality and more uniform composition.

- *Valorisation.* Valorisation process depends on the fraction that is separated in sorting plants. Inert fraction, after being crushed and sieved, yields recycled aggregates of different grain sizes. This process is carried out in IWST plants using mobile crushing machines, in type I plants, or stationary machines, in type II. Valorisation of remaining fractions takes place in specific recycling facilities for each recovered material (paper/cardboard, plastic, wood and ferrous and non-ferrous metal). As a result, recycled material that is a substitute of virgin material is obtained. Other possible means of valorisation, such as the recovery of energy and areas of land, are not taken into account in this work.
- *Final disposal*. This stage includes the disposal of reject material by sending it to a landfill. Since incineration is not a common practice in Spain, it is not considered as an option here.

3 Aim and scope of the study

The aim of this study is twofold: (a) to draw up an LCI of C&DW management in Spain based on primary data

Table 1 Composition of the C&DW

Waste fraction	Percentage % Type I	Percentage % Type II
Inert	82.000	83.218
Plastics	0.500	0.003
Wood	1.500	0.618
Metals	0.700	0.044
Paper/cardboard	0.300	0.023
Reject materials	15.000	16.094

Table 2 Electric mix in Spain (REE 2010)

Generation rate	Percentage (%)
Hard coal	8.74
Oil	3.25
Natural gas	23.27
Hydropower	12.85
Nuclear	20.95
Photovoltaic	2.46
Wind power	14.53
Combined cycle plant	13.95

Table 3 Containers used in handling C&DW

Type of container	Volume (m^3)	Material process	Weight (kg)
Metallic 1	5	S275JR steel Plate. Welded	650
Metallic 2	8	S275JR steel Plate. Welded	800
Metallic 3	16	S275JR steel Plate. Welded	1,000
Sacks	1	PP fibres Extrusion	5.49

collected directly from some Spanish enterprises involved in its management and valorisation and (b) to analyse their environmental profile in order to identify the stages of the life cycle of C&DW management with the greatest environmental impact, as well as the sub-processes and causes that explain why this is so. The study covers all the stages of the life cycle of C&DW, from the on-site generation of the waste to its transformation into recycled material or its disposal on a landfill. Special attention is given to offering details of both the way sorting and the recycling plants work. Data come from three facilities type I and two facilities type II, of them with less than 8 years old and located in Spain. To achieve the aims of the study, the functional unit was defined as the management of 1 t of C&DW, with the composition of the output of the sorting plants analysed here. This composition is shown in Table 1.

The scope of the study covers all the environmental burdens due to the manufacture and use of bags and containers for the temporary storage of C&DW, together with the generation and consumption of electrical energy and fuel in each sub-stage. Likewise, the burden avoided by recycled materials is also included. The environmental burdens due to capital goods such as the infrastructure of the recycling plants, buildings, machinery and lorries, and their maintenance are not taken into account.

4 Inventory of each management stage

The LCI was performed following all the steps stated in ISO 14040–44 standard, as well as the formats and recommendations detailed in ISO/TS 14048 (2002) and ISO/TR 14049 (2000) standards. The inventory data were collected directly from Spanish enterprises involved in the life cycle of the C&DW management namely: two firms that manufacture containers and bags, two companies responsible for temporary storage of waste and transporting it, five firms devoted to sorting and treating C&DW and two enterprises that operate inert landfills. Firms provided annual data on inputs (waste, water, electricity and fuel) and outputs (emissions into the air and water, and solid waste) for the period 2008–2009. These data were related to the functional unit and, in the case of the sorting and treatment plants, to each sub-process by applying the following

Table 4 Calculation of fuel consumption in transporting C&DW

Section	Type of C&DW	Density (t/m^3)	Capacity (m^3)	Load (t)	Mean consumption (kg diesel/t km)	Distance for the case study (km)	
						Type I plant	Type II plant
Site—sorting plant or site—landfill[a]	Mixed and reject	0.98	5	4.9	0.039	15	15
			8	7.8	0.030		
			12	11.8	0.021		
			20	18[b]	0.018		
	Inert	1.2	5	6	0.032	15	15
			8	9.6	0.025		
			12	14	0.019		
			20	18[b]	0.016		
	Concrete	1.5	8	12	0.023	15	15
			12	18	0.016		
			25	25[b]	0.014		
Sorting plant–recycling facility	Paper	0.07	20	1.4	0.123	130	12
	Plastic	0.06	20	1.2	0.143	122	
	Wood	0.20	20	4	0.048	20	
	Metal	0.33	20	6.6	0.026	76	
	Metal	0.33	5	1.65	0.104	76	
Sorting plant–Landfill	Reject	1	8	8	0.030	25	1

[a] Distances collected for site–landfill section have not been modelled in this study

[b] Load limit

criteria: electricity consumption depending on the installed power in each sector, since the machines operate similar time periods and the system is continuous; fuel consumption depending on the power of mobile machinery and on the flow of material treated in each sector; water consumed in processes carried out to mitigate the amount of dust generated, based on data supplied by companies; and solid waste according to the reject fraction declared by the enterprises.

Inventory data were modelled using the SimaPro 7.3 (2011) software application, taking Ecoinvent (SCLCI 2008) database as a reference to configure the inventory of minority materials, fuel and electricity. These secondary data were adjusted to the case study by adapting both the electric mix, as shown in Table 2 (REE 2010), and the distances and means of transport to the case of Spain.

The following points detail inventory data taken into account for each stage of the life cycle shown in Fig. 1.

- *On-site storage.* Three different types of metallic containers and one kind of bag for the temporary on-site storage of C&DW were taken into account. The inventory data considered can be seen in Table 3.
- *Transport.* Transport stage is where the C&DW is transferred: at this stage, it may either be mixed (i.e. just as it is collected from site) or separated into fractions. Fuel consumptions are based on the capacity of containers and the density of transported materials, as shown in Table 4. Transport distances can vary according to the location of plants or treatment facilities. Distances assumed in the case study are those reported in the last column of Table 4.
- *Inert waste sorting and treatment plants.* Figure 2 shows a general diagram of the operations and processes carried out in types I and II plants, including operations related to both the classification and transfer

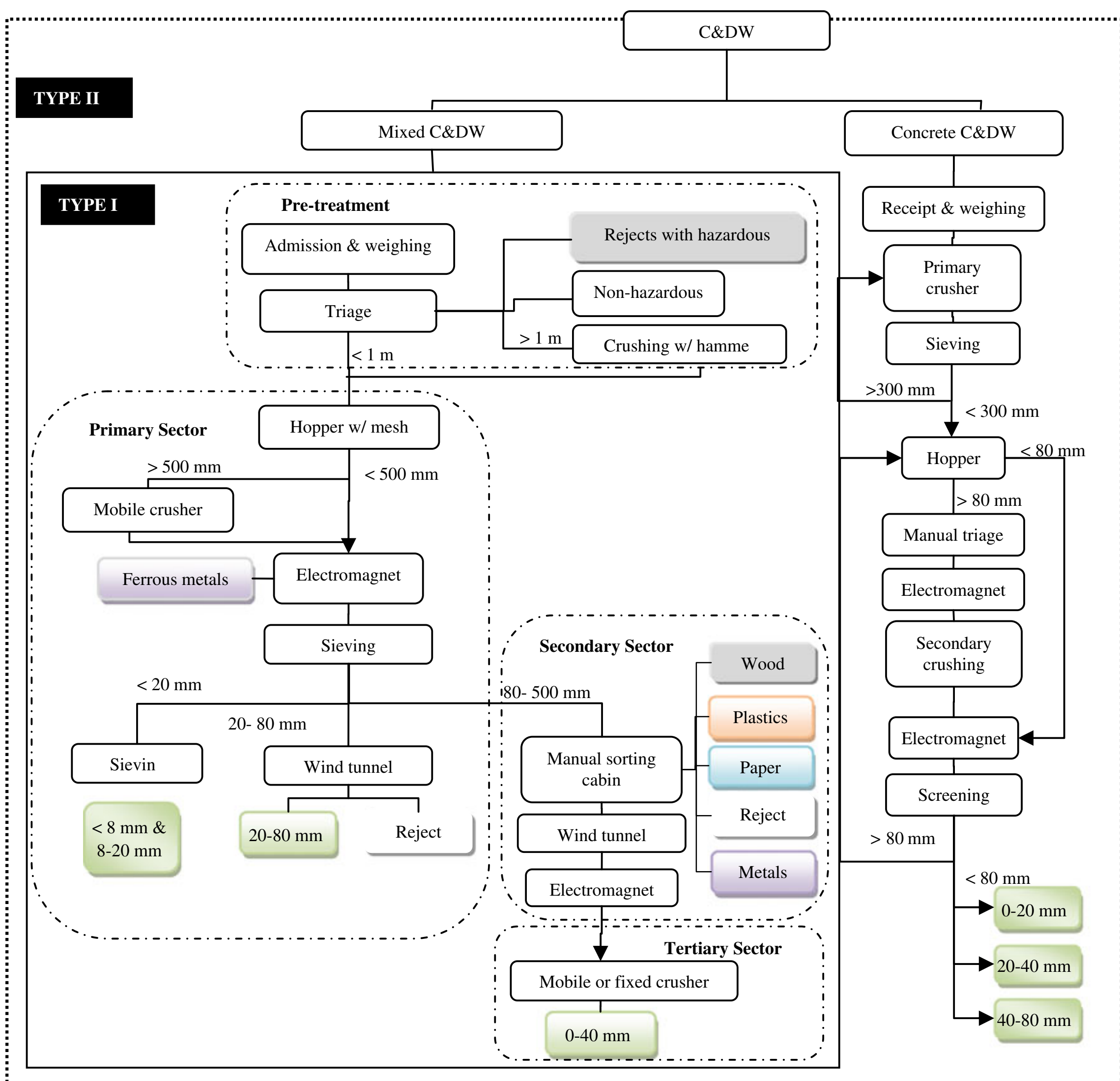


Fig. 2 Flow chart and system boundaries for types I and II plants

Table 5 Energy and materials input in the stage involving the sorting and recycling of inert materials (data per 1 t of treated C&DW)

Type of plants	Process	Diesel fuel (l/t)	Electrical energy (kWh/t)	Water (l/t)
I	Pre-treatment	0.06	–	n/a
	Primary sector	0.28	1.44	n/a
	Secondary sector	–	0.62	n/a
	Tertiary sector	0.28	–	n/a
	Total	0.62	2.06	1.00
II	Mixed C&DW plant			
	Pre-treatment	0.05	0.02	n/a
	Primary sector	0.19	0.12	n/a
	Secondary sector	–	0.06	n/a
	Tertiary sector	0.19	0.24	n/a
	Total	0.43	0.44	1.00
	Concrete C&DW plant	1.02	2.59	1.00

n/a Not allocated

and the treatment of the inert fraction. Each sub-process involves the following operations:

– *Pre-treatment.* The process begins on a weighbridge, which records the weight of the lorry and its load on arrival. Then, the material is subjected to a preliminary visual inspection in order to determine whether the C&DW is mostly made up of inert material or mixed C&DW. The density of the material defines the quality of the waste and therefore the tariff charged for its treatment. In the first case, inert waste with a diameter up to 1 m goes on to the next process or primary sector. In the second case, mixed waste is cleaned by hand with the help of a backhoe or grapple to remove large-sized materials such as iron, plastics and wood, which can damage the sorting circuit or reduce the quality of the recovered material. Reject materials are stockpiled to be recovered later by another management facility or sent to a landfill, and account for 14–20% by weight of all the material received.
– *Primary sector: fixed treatment line.* In this process, the material goes into the mechanical sorting circuit through a hopper, which has a capacity of 16–20 m^3 by means of a loader shovel or by loading it directly from the lorry. This process begins with a sieve, which has holes of different sizes, depending on the plant, between 300 and 500 mm. The largest C&DW is crushed and then sieved. A variation of the sieves is the trommel, which is a round perforated cylinder that classifies C&DW by size, with a limit of 80 mm. The waste up to 80 mm passes below an electromagnet, and is then taken on a conveyor belt to a dual sieve. Three different-sized fractions are obtained there: 0–20 mm, which is directly set aside for sale, although it sometimes undergoes further separation at 0–6 and 6–20 mm; 20–80 mm, which is sold after all lightweight material has been removed in a wind tunnel (drum separator); and 80–500 mm, which undergoes a new process in the secondary sector.
– *Secondary sector.* This process includes a second electromagnet, a cabin for manual sorting (triage) of unwanted materials and a separation equipment of lightweight materials. Different operations can be used to clean lightweight material, with variants that use air or water. In the first case, it is possible to use a windshifter, a drum separator or just a blower with a centrifugal fan and a cage for catching the lightweight

Table 6 Secondary materials obtained in recycling and avoided products

Recovered material	Avoided product	Substitution ratio
Paper and core board	Sulphate pulp and core board	1: 0.83
Recycled aggregates	Gravel unspecified, at mine	1:1
Metals[a]	Pig iron	1:1
Wood	Wood chips softwood	1:1
Plastic	Polyethylene, HDPE, granulate (40%), polyvinylchloride (15%), polyethylene terephthalate (40%)	1: 0.81

[a] Assumed ferro metal, since ferro metal represents 96%

Table 7 Phases and impacts included in the C&DW management system

Phase of the C&DW management system	Impacts considered	Environmental burden avoided
On-site pre-collection	Manufacture and use of containers.	
Transport to sorting plant	Fuel consumption by C&DW transport.	
Operation of the sorting plant	Water, fuel and electrical power consumed by the operation of the plant.	
Recycling of recovered fractions	Transporting C&DW to recycling plants. Manufacture and use of containers. Recycling of fractions.	Production of virgin raw material of each fraction.
Landfill	Transport to inert landfill. Manufacture and use of containers. Fuel consumption due to management of landfill	

material. In the second case, the material goes into a hydraulic separator, which consists of a vat filled with water at constant level, where the lower density material remains on the surface and is drawn towards a set of brushes that lift it out and send it towards the lightweight materials container. Water used in these processes runs through closed circuits in order to keep consumption to a minimum.

– *Tertiary sector.* The clean C&DW with a size between 80 and 500 mm is either crushed in a stationary or mobile facility, which results in a secondary aggregate with a grain size of 0–40 mm (wet mix macadam) or sold, depending on the demand.

In type II plants, there is also an independent line for concrete waste with a similar process, although it does not include cleaning with air or water. Most facilities have systems aimed exclusively at dust removal which work either automatically or manually, with sensors that release a curtain of water while lorries that transport the C&DW are being unloaded. Additionally, sprayers are often used to moisten the waste before it goes into the cleaning circuit. They are also equipped with bag filters that retain the particulate matter generated during the processes of sieving and cleaning by air.

About 35 million tonnes of waste are produced every year in Spain, with an average annual growing rate of 8.7% in the analysed period (2001–2005) (Marm 2008). The average production of RCD per inhabitant per year, according to 2005 data, can be estimated at 790 kg. Since most of these wastes are currently disposed of in landfills, the Spanish government is planning to implement programmes aimed at the recycling or reusing 40% of the total waste generated.

The inventory data taken into account for sorting, transfer and treatment of the inert fraction were gathered from five Spanish enterprises with an overall production capacity of 1,446,000 t of C&DW per year. Three of these enterprises are type I and the other two are type II. These facilities need a supply of electrical power, fossil fuels and water to work. This inventory data, set out in Table 5, were also collected from these five plants and related to each sector by applying the criteria detailed earlier.

- *Recycling recovered fractions.* Plants described in Section 3 separate fractions that can be recovered from mixed C&DW. Inert fraction is recovered at the plant itself as recycled aggregate. The rest of the fractions are stockpiled and later sent to recycling plants that are specialised in each fraction (plastics, wood, metals, and paper and cardboard). The inventory data used in this process, shown in Table 6, take into account the burdens (consumptions) due to recycling and the avoided burdens due to the savings resulting from the replacement of virgin raw material with secondary materials obtained from recovered fractions, bearing in mind the substitution ratios (Rigamonti et al. 2009). In all cases, data taken into account were obtained from Ecoinvent (SCLCI 2008) database after adapting them to the case study. The LCI data considered for the avoided materials has also been modelled according to the recommendations given by Ecoinvent (SCLCI 2008). Table 6 shows both secondary materials obtained following the process of recycling and avoided products.
- *Disposal.* The phase of C&DW disposal includes dumping the rejected materials from the treatment plant into an inert landfill. The composition of this rejected fraction complies with the criteria established by the

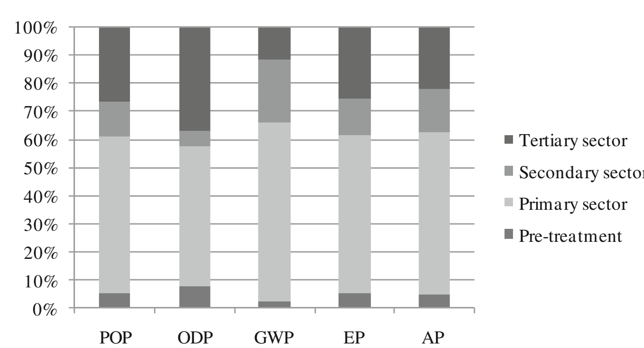


Fig. 3 Environmental profile of type I plants–mixed C&DW

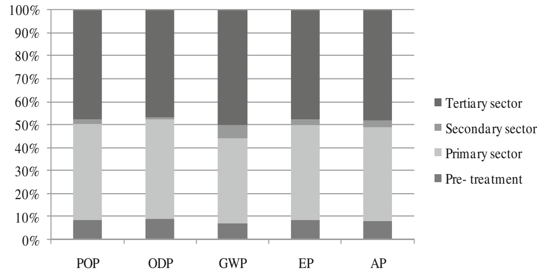


Fig. 4 Environmental profile of type II plants–mixed C&DW

Council Decision 2003/33/EC. Fuel consumption data were declared by the two enterprises that operate inert landfills; these range from 0.11 to 0.28 kg of diesel per tonne of C&DW managed at the landfill.

5 Assessment of the impacts of the life cycle of the C&DW management system

Assessment of the impact was performed following the mandatory elements set out in the ISO 14040–44 (2006a, b) standard. By applying the characterisation factors proposed by CML (Guinée 2002) to the selected impact categories, the following environmental indicators were obtained: global warming (GWP, in kilogrammes CO_2 equivalent), ozone layer depletion (ODP, in kilogrammes CFC-11 equivalent), photochemical oxidation (POP, in kilogrammes C_2H_4 equivalent), acidification (AP, in kilogrammes SO_2 equivalent) and eutrophication (EP, in kilogrammes PO_4^{3-} equivalent). Table 7 shows the phases that the life cycle of the management of C&DW was divided into, as well as the impacts and avoided burdens considered in each of them, in order to display the results.

The environmental profiles were obtained by taking the management of 1 t of C&DW with the composition given in Table 1 as the functional unit. These profiles, shown in Figs. 3 and 4, include the contribution of each sub-process of the IWST plants for mixed C&DW, with a distinction being made between types I and II treatment plants (not include products avoided). It can be seen that the greatest environmental impacts of these plants are produced in primary and tertiary sectors for the five indicators selected. In the case of enterprises type I, the contribution that each sub-process makes to each environmental indicator is ranging from 50% to 64% for the primary sector and from 12% to 37% for the tertiary sector, depending on the indicator. In the case of enterprises type II, the environmental profile shows a similar distribution of the environmental burden, with percentages ranging from 36% to 40% for the primary sector and from 46% to 50% for the tertiary sector. Figure 5 compares the environmental impact of types I and II plants for mixed C&DW and concrete C&DW. Environmental loads were calculated based on total consumption of fuel and electricity per tonne of C&DW treated. This figure also shows that plants that process concrete C&DW have higher environmental impact than mixed C&DW plants, due to the power required for grinding it.

The analysis of the operations that take place at each stage of the life cycle (Figs. 6 and 7) reveals that, for all impact categories, transport, sorting and landfilling make a net contribution to the environmental impact due to the

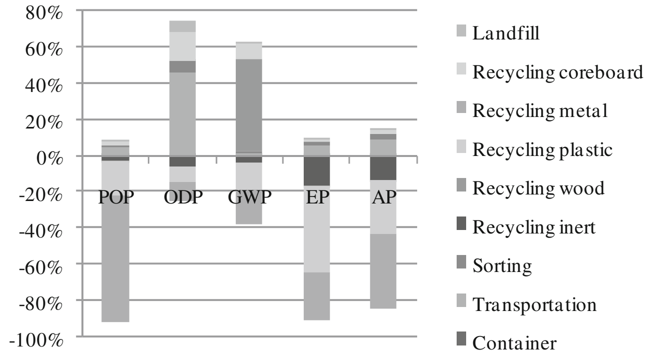


Fig. 6 Environmental impacts of the management system of type I–mixed C&DW plants

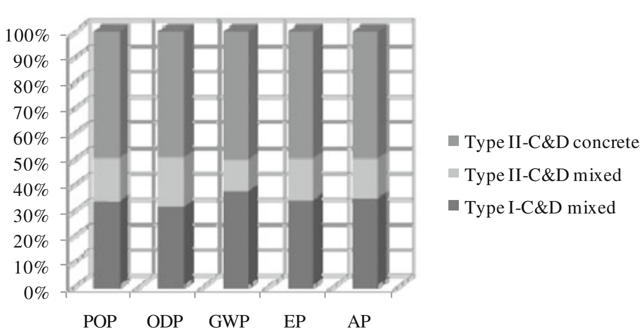


Fig. 5 Comparison of the environmental profiles of types I and II plants

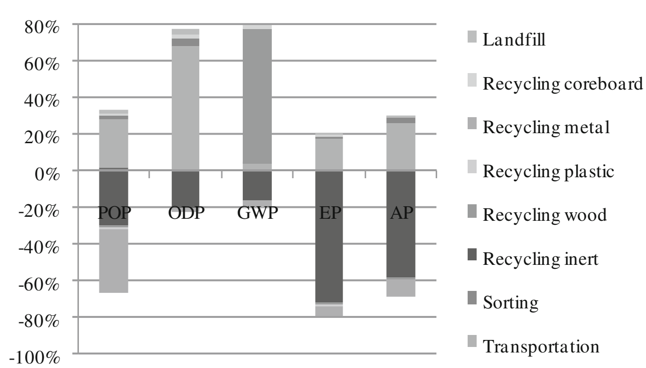


Fig. 7 Environmental impacts of the management system of type II–mixed C&DW plants

consumption of fuels and energy. Furthermore, it should be noted that the net contribution of the containers is lower than 1% of the global impact for all impact categories.

Savings are due to the recycling of plastics, metals, aggregates, cardboard and wood for all the impact assessment categories, except for GWP for wood and cardboard. The latter is explained by the CO_2 credit given to the production of natural wood. Actually, the GWP emissions for recycled wood and cardboard products are bigger than those of the corresponding virgin products, since last ones provide a physical storage of carbon that was previously in the atmosphere as a greenhouse gas (Zabalsa Bribián et al. 2011; Blengini and Di Carlo 2010; Sathre and O'Connor 2010).The consideration of avoided burdens are highly significant in the environmental profile of C&DW management system for POP, AP and EP indicators that overcome the environmental impacts in a ratio between 6:1 and 10:1. For the GWP and ODP indicators, the prejudicial impacts dominate the environmental profile in a ratio of 1:2/3 and 3:1, but always appears a benefit due to recycling.

6 Conclusions

Primary data collected from five Spanish sorting plants were used to analyse their environmental profile and obtain a detailed view of their operational phases. The opportunities to reduce the impact of sorting are associated with eliminating some of the processes performed in the secondary sector and part of the primary sector devoted to separate the lightweight fraction, which only accounts for 3% of C&DW by weight. This requires adopting selective collection at source in civil construction and demolition works since it can be expected to increase the performance of the plant and decrease both the percentage of rejects and the number of pre-treatment operations. Furthermore, primary sector involves part of the process of crushing inert material which makes a significant contribution to the environmental impact (up to 28%) as part of the cleaning operations. For this reason, the primary sector makes a higher contribution to the environmental impact than the secondary sector, as can be seen from Figs. 3 and 4. Taking the GWP as an example, Fig. 3 shows that the contribution made by the secondary sector is 22% of the total environmental burden, whereas for the primary sector is 63%. As far as tertiary sector is concerned, impacts decreases as a result of the use that is given to the secondary aggregate and the grain sizes required.

One point to note is that there are some differences between types I and II plants as regards to the contribution that each phase makes to each indicator. Moreover, the magnitude of environmental impact evaluated using different indicators varies according to the plant capacity, assuming that higher production capacities require lower consumption of energy per tonne of C&DW treated.

With respect to the assessment of the whole life cycle of the C&DW, it can be seen from Figs. 6 and 7 that transportation is the step that makes the greatest contribution to the environmental impacts and that recycling is not always beneficial. In the case of wood and cardboard, there are many other end-of-life alternatives, such as burning, controlled incineration, landfilling with methane capture, etc. Their advantages and disadvantages have been extensively treated in the scientific literature (Lippke et al. 2010; Pingoud et al. 2010; Salazar and Meil 2009). The inventory drawn up can be used as the basis for planning the management of C&DW on other sites, after adapting it to the local conditions of the region where it has to be applied.

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References

Blengini GA (2009) Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 44:319–330

Blengini GA, Di Carlo T (2010) The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energ Buildings 42:869–880

Blengini GA, Garbarino E (2010) Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J Cleaner Prod 18:1021–1030

Bovea MD, Powell JC (2006) Alternative scenarios to meet the demands of sustainable waste management. J Environ Manage 79:115–132

Bovea MD, Ibáñez Forés V, Gallardo A, Colomer Mendoza FJ (2010) Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Manage 30:2383–2395

Buttol P, Masoni P, Bonoli A, Goldoni S, Belladonna V, Cavazzuti C (2007) LCA of integrated MSW management systems: case study of the Bologna District. Waste Manage 27:1059–1070

Cherubini F, Bargigli S, Ulgiati S (2009) Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration. Energy 34:2116–2123

Cirko C, Edgecombe FH, Gagnon M, Perry G, Haight ME, Jackson D, Love G, Kelleher M, Massicotte S, Schubert J, South G, Veiga P (2000) EPIC/CSR Integrated Solid Waste Management Tools: Project Report. University of Waterloo, Canada

COM 666 (2005) Commission of the European Communities. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Taking sustainable use of resources forward: a thematic strategy on the prevention and recycling of waste. 666 final. Brussel, BE: http://eur-lex.europa.eu/LexUriServ/LexUriServdo?uri=COM:2005:666:FIN:EN:PDF . Accessed 10 February 2011

Commission Decision 2000/532/EC (2000) of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1 (a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) de la Directive 91/689/EEC on hazardous wastes. Oficial Journal CE L 22606.09.2000

Council Decision 2003/33/EC of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of Annex to Directive 1999/31/EC. Oficial Journal CE L 11 of 16.01.2003

Council Directive 91/689/EEC on hazardous waste Directive 2008/98/EC (2008) of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

Den Boer E, den Boer J, Jager J (2007) LCA-IWM: a decision support tool for sustainability assessment of waste management systems. Waste Manage 27(8):1032–1045

EPA. Environmental Protection Agency (2006) Solid waste management and greenhouse gases. A Life Cycle Assessment of Emissions and Sinks

EPA. Environmental Protection Agency (2010) US Environmental Protection Agency. WARM Waste Reduction Model. https://www.epa.gov/warm. Accessed 24 January 2011

ETH-ESU 96 (1996) Okoinventare von Energiesystemen. ESU Group, ETH Technical University of Zurich

Guinée JB (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Kluwer Academic Publisher, Dordrecht, The Netherlands

Idemat (2001) Idemat Material Database. Delft University of Technology, The Netherlands

ISO 14040 (2006a) Environmental management. Life Cycle Assessment. Principles and Framework. European Committee for Standardization (CEN)

ISO 14044 (2006b) Environmental management. Life Cycle Assessment. Requirements and guidelines. European Committee for Standardization (CEN)

ISO/TR 14049 (2000) Environmental management—life cycle assessment—examples of application of ISO 14041 to goal and scope definition and inventory analysis. European Committee for Standardization (CEN)

ISO/TS 14048 (2002) Environmental management. Life Cycle Assessment. Data documentation format. European Committee for Standardization (CEN)

Khoo H (2009) Food waste conversion options in Singapore: environmental impacts based on an LCA perspective. Sci Total Environ 15:1367–1373

Kim M, Kim J (2010) Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Sci Total Environ 408:3998–4006

Kirkeby JT, Hansen TL, Birgisdóttir H, Bhander GS, Hauschild MZ, Christensen TH (2005) Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Manage Res 24:3–15

Lippke B, Wilson J, Meil J, Taylor A (2010) Characterizing the importance of carbon store in wood products. Wood Fiber Sci 42 (CORRIM Special Issue):5–14

MARM (Ministerio de Medio Ambiente y Medio Rural y Marino) (2008) Plan Nacional de Residuos de Construcción y Demolición de España 2008–2015. Texto aprobado por Acuerdo de Consejo de Ministros de 26-12-2008.Boletin Oficial del Estado Nº 49 del 26-02-2009, Sección I, pp 19893–20016

McDougall F, White P, Franke M, Hindle P (2004) Integrated solid waste management: a life cycle inventory. Oxford, UK

Niskanen A, Manfredi S, Christensen T, Anderson R (2009) Environmental assessment of Ämmässuo Landfill (Finland) by means of LCA-modelling. Waste Manage Res 27:542–550

Ortiz O, Pasqualino JC, Castells F (2010) Environmental performance of construction waste: comparing three scenarios from a case study in Catalonia, Spain. Waste Manage 30(4):646–654

Pingoud K, Pohjola J, Valsta L (2010) Assessing the integrated climatic impacts of forestry and wood products. Silva Fenn 44 (1):155–175

REE (2010) Red Eléctrica de España, El sistema eléctrico español (in Spanish)

Rigamonti L, Grosso M, Sunseri MC (2009) Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. Int J Life Cycle Assess 14:411–419

Salazar J, Meil J (2009) Prospect for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J Cleaner Prod 17(17):1563–1571

Sathre R, O'Connor J (2010) A synthesis of research on wood products and greenhouse gas impacts. Vancouver, Canada

SCLCI (Swiss Centre for life cycle inventories) (2008). Centre, ecoinvent database v2.0, <http://www.ecoinvent.org>

SIMAPRO 7.3 (2011) Pré Consultants BV, Amersfoort, The Netherlands

Stenmarck A, Oddou M, Sundqvist J (2009) Using LCA-tool WAMPS in waste management planning. II Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica. Pucón, Chile

Tarantini M, Loprieno AD, Cucchi E, Frenquellucci F (2009) Life cycle assessment of waste management systems in Italian industrial areas: case study of 1st Macrolotto of Prato. Energy 34:613–622

The Ecobilan Group (1999) Waste integrated systems assessment for recovery and disposal. Reference Guide. Ecobilan

Tunesi S (2011) LCA of local strategies for energy recovery from waste in England, applied to a large municipal flow. Waste Manage 31(3):561–571

Zabalsa Bribián I, Valero Capilla A, Aranda Usón A (2011) Life cycle assessment of buildings materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46:1133–1140