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Economic viability analysis of a construction and demolition waste recycling plant in Portugal – part I: location, materials, technology and economic analysis

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ABSTRACT

The few construction and demolition waste (CDW) recycling plants that there are in Portugal separate the materials and then crush and sieve them prior to final delivery. These plants have limited overall capacity and the quality of the output material is not good enough for higher grade applications such as concrete and brick production. This study aims to better understand the economic implications of implementing and operating a large-scale high-end CDW recycling plant to serve a densely populated urban area in Portugal (Lisbon and its outskirts). This first part deals with the location of the plant, its design and the material entering and leaving it. There follows an economic analysis which leads to the sensitivity analysis presented in part two, which provides important conclusions for the economic viability of full-scale CDW recycling plants. The methodology used can be applied to other locations and resulted, within the regional data frame of the Lisbon Metropolitan area, on a return of the investment period of around 2 years, considering a plant capacity of 350 tonne/h, the collection of 21.8 million €/year in gate fees and the need to pay around €11.9 million €/year in running costs. Hence, there is a high profit potential in this venture, even though considering the high initial investment needs. Moreover, the venture seems economically viable even in the absence of specific regulatory government policy intervention for recycling CDW, which may indicate a clear alignment between economic viability and environmental benefits, arising from this CDW recycling plant operation.

1. Introduction

In Portugal most CDW is sent to landfill. According to (Pereira, 2002), around 76% of all CDW is landfilled, 11% is reused and 4% is incinerated, which leaves around 9% that is actually recycled. Although a few valuable initiatives have been prompted in several locations, especially near urban centres (Coelho and de Brito, 2007), the present reality is clear: the amount of CDW recycled/reused in Portugal is small compared with other countries such as UK – 52%, The Netherlands – 92%, Belgium – 89%, Austria – 48%, Denmark – 81% (Symonds Group Ltd, 1999). Indeed, the amount of CDW reused/recycled in Portugal is still far short of the European Community's (EC) commitment, which states that at least 70% of all CDW must be prepared for reuse and recycling by 2020 (Official Journal of the European Union, 2008/98/CE). Moreover, the quality of recycled products from installed CDW recycling plants is still poor, which limits possible applications and turns the process into one of down-cycling rather than an actual recycling activity (Coelho and de Brito, 2007). This quality has been observed in several plants (e.g. Ecolabor (2011), Trianovo (2011), Algarvio (2009)), and in the latter case the output material was found unfit even for use as road sub-bases. This is because of the presence of lightweight contaminants, even in amounts of less than 1%, lack of proper granular calibration, and no separation beyond medium grain size by manual and magnetic processes.

Higher grade uses of recycled CDW, which are at least as good as the products from which the waste derives, have been cited as an important factor for closed construction cycles (Weihong, 2004; Mulder et al., 2007; Weil et al., 2006), acknowledging as a fact that landfill is to be avoided as a general principle (Dewulf et al., 2009; Castells et al., 2008, 2010). The possible and actual uses of recycled construction materials have been the centre of much research in the past few years. For instance, concrete aggregate has been extracted from many different concrete structures and recycled to produce new concrete, with good technical and cost outcomes (Tam, 2008; Oikonomou, 2005; Kou et al., 2004; Buyle-Bodin et al., 2003; Richardson, 2010; Grübl et al., 1999). Red brick aggregate has not only been used to make new bricks (Reis, 2007), it has also proved successful as ingredient of mortar (Silva et al., 2007; Silva, 2006). Timber from construction and non-construction sources has been recycled for some years in Portugal, as confirmed by academic studies

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and industry practices (Pico, 2008; Ranita et al., 2005). Construction flat glass also has possible recycling routes in Portugal since the final product is suitable for flat glass manufacture (among other uses) (Vidrologic, 2011). High-grade plastic recycling (mainly PVC) has been investigated and found to be technically viable in both chemical and mechanical processes (Kreißig et al., 2003; Tucker et al., 1999), although it is less economically feasible, on the whole. However, Portugal has several companies operating in the area of lower grade applications of recycled PVC products and the reintroduction of other plastics into production processes. They mainly produce plastic aggregate for Portuguese plastics producers and for customers in Spain and France (Sousa, 2008). Some regional companies also use post-consumer waste plastic directly in covering elements (such as plastic wood boards) and outdoor furniture (public benches, fences and walkways). The recycling of bituminous mix, mainly from road demolition, has been thoroughly studied (Ainchil and Burgueño, 2004; Baptista, 2006) but seldom applied in Portugal (Baptista, 2006), even though specific legislation has been recently been promulgated (LNEC, 2006). Even though insulation waste is still traditionally landfilled, some is now being recycled, in new polyurethane insulation boards (pressed polyurethane aggregate) and lightweight polystyrene concrete (Wolff, 2008). These applications represent the present and potential recycling paths of material leaving CDW recycling plants (more details in §3). For a deeper analysis of construction waste recycling viable technology (Tam and Tam, 2006) is a solid reference.

In economic terms, there are several studies on CDW recycling plants (Nunes et al., 2007; Zhao et al., 2010; Peng et al., 1997) (Duran et al., 2006), and CDW recycling management programs in general have also been analysed (Kartam et al., 2004). Moreover, commercial CDW recycling plants of considerable size and complexity are already operating in the Netherlands and Germany, which proves that CDW recycling is a profitable business there. But economic viability is a highly regional variable, dependent on many physical, economic and social factors. Thus, different results have been reported, from no viability (for private investors) (Nunes et al., 2007; Peng et al., 1997) to conditional viability (Zhao et al., 2010) and to high economic viability (Duran et al., 2006). All these studies highlight the importance of key success factors, such as: taxing virgin aggregates; taxing recyclable materials that are landfilled (or even introducing a landfill ban); subsidising CDW recycling businesses; implementing standards for recycled materials, and promoting their introduction in the market, perhaps by lowering taxes on construction products with recycled content. Although all these market manoeuvre options are relevant, and for many regions, critical, the present analysis was conducted in a purely open market fashion, which means no government policy intervention for recycling CDW.

One of these studies (Zhao et al., 2010), concerning the Chongqing case, in China, is of particular relevance. In this work, a direct economic comparison was made between the implementation of fixed recycling CDW plant facilities, mobile processing stations and an equivalent (mobile) case in the Netherlands. It is concluded that, for fixed facilities, and for the regional constraints in place at that moment (year 2010), economic viability is only achieved if the installed equipment is not purchased new and enough economies of scale are attainable (from which a 240,000 tonne/year capacity fixed model facility was considered). In this viable scenario, a global cost of 1.04 €/tonne is incurred, for an average income of 2.1 €/tonne of processed CDW. This situation, however, is highly dependent on the expected demand for recycled construction materials, mainly concrete and ceramic aggregates, even though its estimation has resulted in high enough local potential quantities.

Another important case refers to the Irish situation (Duran et al., 2006). In this study three CDW recycling plants are proposed, one in Dublin, another in Limerick and the last a mobile station. This work's major conclusion is that economic viability, for any of these three options, is highly probable, as long as dumping costs (including transport) are higher than CDW recycling plant's tipping fee, and the cost per tonne of using virgin aggregate exceeds that of using recycled aggregates. In any of these scenarios, economic viability is significant, with potential benefits rising up to 24–62 times those of incurred costs, over 5 years of operation (given the study's assumptions, e.g. 99% of the incoming waste at the facilities gate is actually recycled). These results are valid for a pure open market industrial operation, which means absence of any taxation on virgin aggregate or subsidies to the use of recycled ones. Also in this study, economies of scale are highlighted, given the consequence of running down unit processing costs and implying enhanced capacity to process CDW and thus serve a higher quota of the population.

Other studies also explore the economic dimension in waste management systems, as is the case of waste minimization (Begum et al., 2006), where clear economic viability was found. In Wang et al. (2004), the economic viability is also confirmed for the CDW processor, although in this case very much linked with supplying waste wood for waste-to-energy installations. More generally, regional CDW networks have also been analysed, demonstrating, among other aspects, that disposal taxes are a cost-effective lever to increase total recycling (Hiete et al., 2011). Following this trend, but approaching the problem (of CDW regional management) from a different angle, expert-knowledge scenario analysis was applied to a Swiss region (Canton of Zurich; Spoerri et al., 2009), concluding that communication of recycled mineral construction materials properties and the establishment of quality standards is of primordial importance, along with public demonstration projects using those materials in massive quantities. This, as a consequence, might also spur technological development in CDW recycling (as, for instance, in designing and installing a level 3 fully equipped CDW recycling facility as discussed in the present paper), leading to reductions in costs of CDW processing and/or the ability to enhance their physical properties.

2. Recycling plant technology

The CDW recycling plant considered in this study can be labelled Level 3, as suggested in Symonds Group Ltd (1999). This is a highly mechanized facility, capable of receiving a complete mixture of CDW and separating all the main valuable/marketable constituents and rejecting only hazardous materials and wet sludge carrying ultra-fine mixed particles. A general flow diagram is presented in Fig. 1, based on (Weihong, 2004). Each piece of equipment was characterized according to its power, initial cost, maintenance cost, average service life, plus environmental factors such as intrinsic primary energy and carbon (which are relevant for other parts of the overall study). All the equipment for each function was commercially available and designed to cope with the amount of material to be processed. Several items of the same equipment were needed to meet the mass flow of certain steps. However, because the CDW facility studied has been generalised to accommodate a range of possible equipment, data were obtained from suppliers for each process machine, and a simple average was considered for each of the main features relevant to this study whenever more than one data entry was obtained (Table 1). More functional details are given in Table 2.

3. Input/output material estimation and location of the recycling plant

3.1. Input material

The plant was pre-set for two basic operation modes: when CDW is completely mixed, and when separate mineral aggregate

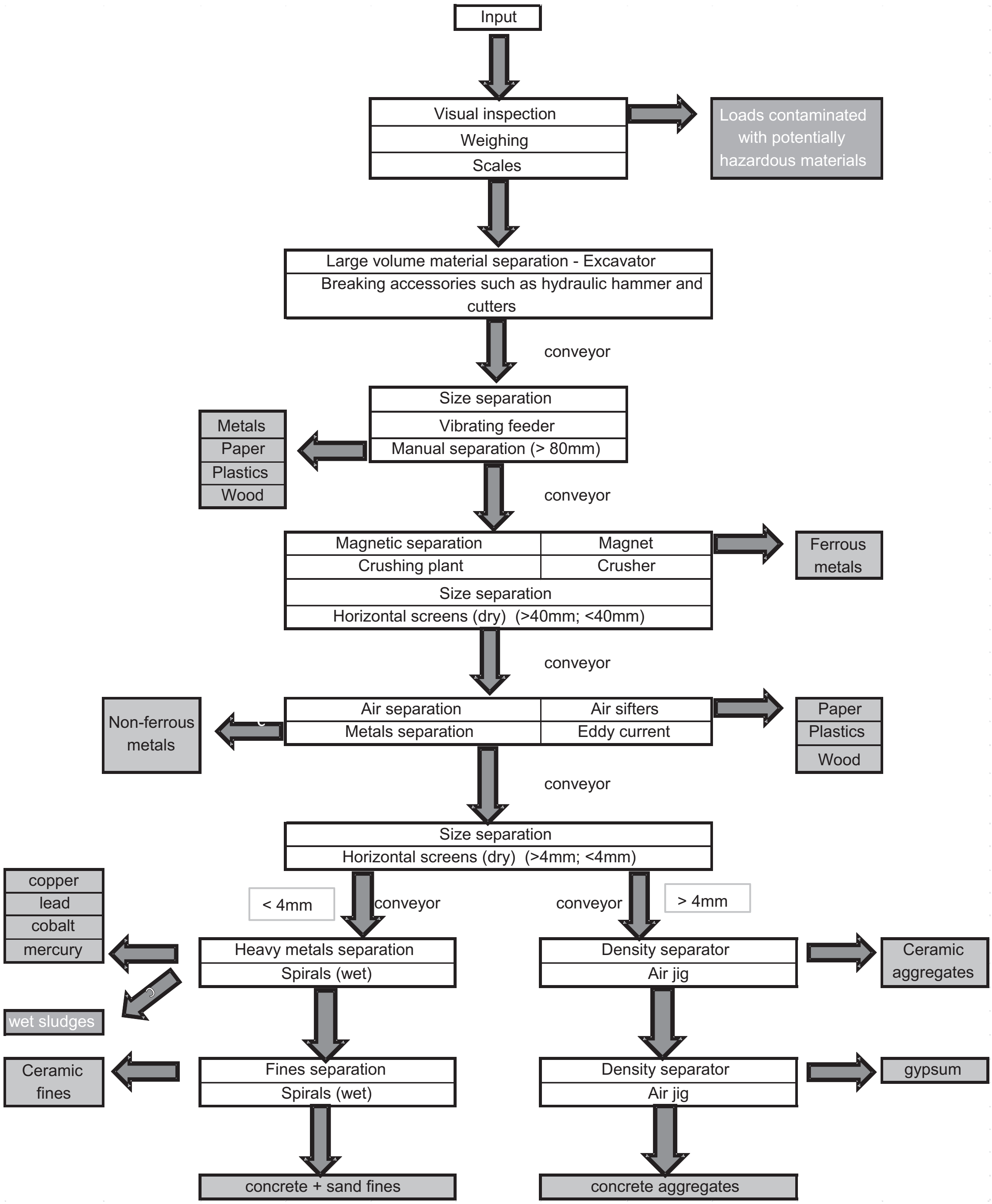

Fig. 1. General layout sequence for the CDW recycling plan.

(ceramic, concrete, rock) is a separate input. As a default state, 30% of all CDW input was considered to be separate, while the rest is mixed CDW; this is equivalent to 30% of the operating hours being in a simplified mode and 70% in the full mode. This simplified mode of operation, although taking place within the same fully equipped facility, will only use the process machines it requires: excavator, vibrating feeder, magnet, crusher, #1 horizontal screens, #2 horizontal screens, air jigs (only one process step – ceramics separation) and spirals (only one process step – separating fine ceramics from fine concrete particles). This means that all other machines or sections can be bypassed or switched off, cutting down on energy consumption, machine operation and human labour working time and therefore reducing costs.

Total CDW input material was calculated using a generation rate determined in an earlier part of the study, 416 kg/person-year, applied to Portugal as a whole (Coelho and de Brito, 2011a). This figure was obtained using data from building plans archives, field data from an experienced selective demolition contractor and literature sources. Since the plant under analysis is in the Lisbon metropolitan area, then a first approximation average CDW generation rate was calculated considering its resident population (INE, 2010a), which gave a 350 tonne/h average input flow, assuming

Table 1
Main attributes of equipment considered for the 350 tonne/h CDW recycling facility.

Equipment (each unit)	Capacity, tonne/h	Power, kW	Initial cost, €	Maintenance cost, €/year	Average service life, years	Number of items needed in the 350 tonne/h facility
Scales	–	0.05	19,170	134	30	1
Excavator	–	90	135,000	4486	20	1
Vibrating feeder	335	16.2	114,000	1117	8	1
Magnet	350	6.5	47,522	257	15	1
Manual separation cabinet	62	0.28	7250	50.8	30	1
Crusher	238	110	130,000	1183	10	1
Horizontal screen #1	300	18.5	82,325	1037	6	1
Air sifter	100	6.3	100,000	3888	20	3
Eddy current generator	350	16.4	98,114	257	15	1
Horizontal screen #2	300	22.3	82,325	1037	6	1
Air jig	30	127	688,333	8165	20	6
Spirals	40	27.0	50,194	651	15	7
Conveyors 5 m	300	5.4	34,417	446	20	2
Conveyors 10 m	300	10.8	68,833	892	20	3
Conveyors 15 m	300	16.3	103,250	1338	20	1

The manual separation cabinet capacity was calculated assuming that each worker can process 50 tonnes of material during an 8 h shift (Mimoso, 2011).
The average service lives were set according to: scales (arbitrary, given the fact that the equipment has no moving parts); excavator, conveyors, air sifter (Changbum et al., 2010); vibrating feeders, crusher, horizontal screens (Leitão, 2011); magnet and eddy current generator (Morgan, 2010); manual separation cabinet (arbitrary, given the fact that the facility has no moving parts); air jig (Horn, 2010); spirals (Turunen, 2011).
For conveyors and for simplicity's sake, a capacity of 300 tonne/h was considered for all items, although the capacity actually needed will diminish as processing reaches its final stages. Conveyor lengths were assigned summarily, without strict determination of distances between processing machines.

300 (Duran et al., 2006) 8 h working days (Zhao et al., 2010) per year.

3.2. Output material

For a CDW recycling business to operate successfully the recycled products must be marketable, which means there must be enough regional demand. All the demands for the output material were calculated before the envisaged CDW recycling plant's overall design was characterized. The regional potential CDW waste generation was calculated for each relevant material, as described below. These figures were then compared with the estimated demand to assess the potential marketability of these material flows.

Table 2
Functional details of chosen equipment.

Equipment	Average weight, kg	Description
Scales	9000	Weighing of loaded trucks at the plant's entrance; located at floor level, transmit all relevant data to central command - date, time of arrival, load weight, origin, empty truck weight
Excavator	18,000	After visual inspection of the waste, the excavator, perhaps assisted by a wheel loader and equipped with a hydraulic hammer or cutters, is used to break up large chunks of concrete, rock, masonry or commingled metals
Vibrating feeder	4500	First feeding of material, from excavator, yielding two main aggregate sizes: <80 mm and >80 mm
Magnet	4460	Working through the <80 mm aggregate size, this cross-belt electro-magnet will separate around 70% of all ferrous metals[a]
Manual separation	–	Alongside the ferrous metal magnet, a human operated cabin will separate around 30% in weight of all metals, paper and cardboard, plastics and wood from the >80 mm material
Crusher	17,000	This jaw crusher, calibrated to reduce all material flow down to 40 mm, works in a loop with the #1 horizontal screens, to separate out all particles larger than 40 mm
#1 horizontal screens	5660	In a double deck configuration, this 300 tonne/h elliptical motion vibrating unit will divide the incoming waste flow into <40 mm and >40 mm sizes
Air sifters	1190	These ventilators will blow air through the 40 mm or less particle-size waste flow in three different locations (one specifically calibrated blower to separate each contaminant), so as to extract light materials, especially paper and cardboard, plastics and wood[b]
Eddy current separator	2400	Right after the air sifters comes the non-ferrous metal separation section, where a magnetic rotor with alternating polarity, driven by the conveyor belt carrying the waste flow, will create eddy currents in the non-ferrous metal particles[c] and repel them from the conveyor. For calculation purposes, 70% separation is considered, with 30% of non-ferrous particles being too small to be projected far enough away from the conveyor belt surface
#2 horizontal screens	7340	Now in a 4-deck configuration; this vibrating motion machine will separate the waste flow into four grain sizes: <4 mm, 4–8 mm, 8–16 mm, 16–32 mm and 32–40 mm
Air jigs	40,000	Operating only with the >4 mm grain size flow and in absolutely dry conditions, these machines separate, in two consecutive steps, ceramics and gypsum materials from the concrete aggregate which is collected at the bottom end of this section; operating with a constant, pulsating air flow, separation operates as long as there is a palpable density difference (within the machine's precision range) between materials
Spirals	1030	For the <4 mm grain size, a wet separation method is necessary, since dry jigging techniques are less efficient or useless (Weihong, 2004). Spirals function entirely passively with their shape and positioning, as heavier particles will tend to flow closer to the centre while lighter ones closer to the outer walls. However, power is required to pump material back to its upper side, as more than one passage might be required to fully separate incoming flow. Spirals will separate heavy metals[d] and fine ceramic from fine concrete particles, in two steps. As it is a wet process, spirals will generate a certain amount of wet sludge (estimated at below 4% of total CDW weight entering the facility) that must be disposed of.

[a] A certain amount of ferrous metal items will naturally remain undetected due to their small size, but considered residual.
[b] This section will separate the rest of the contaminants that could not be separated by hand.
[c] For example, aluminium, brass, stainless steel.
[d] For example, lead, cadmium, and nickel.

Based on statistical data on finished buildings and registered demolitions (INE, 2009a) and resident population (INE, 2010a), partial CDW generation values were determined for the Lisbon Metropolitan Area and Setúbal Peninsula (which is a single statistical region as defined in national statistics (INE, 2011)). A proportional distribution was then calculated taking the initial generation number of 416 kg/person-year, resulting in Table 3. This calculation yielded 173 kg/person-year and 292 kg/person-year for these two areas, respectively. These figures are considerably lower than the initial global average of 416 kg/person-year, which is essentially because that figure is a projection of future CDW generation at national level and does not take present particular regional conditions into account. The 416 kg/person-year figure was maintained as an upper limit for the facility's capacity, since today's regional CDW generation will tend to rise in the next few years (Coelho and de Brito, 2011a). In any case, a sensitivity analysis has been performed for CDW input flow at the plant gate and is presented in part II of this paper.

The CDW generation figures for the Lisbon Metropolitan Area and Setúbal Peninsula were used for a distribution estimate and are the average derived CDW flow percentages previously calculated for demolition, retrofitting and new construction (Coelho and de Brito, 2010a,b), as seen in Table 4. This was done to establish the availability of waste materials at the plant gate; on the demand side, estimates were calculated per material flow, as detailed below.

3.2.1. Concrete aggregates

With information from the ready-mixed industry association in Portugal (APEB, 2011; Pato, 2011), which accounts for 80% of all ready-mixed concrete produced in the country, a global amount of around 1,640,000 tonnes per year of concrete aggregate was estimated as a potential need from the concrete industry. This figure takes into account a share of 35% of cement use in ready-mixed concrete production (with the rest attributed directly to contractors, the pre-fabrication industry and direct sale of bagged cement), average densities of 1870 kg/m^3 and 2400 kg/m^3 for the aggregates and hardened concrete, respectively, and an average use of 20% of recycled aggregates in new (structural) concrete produced (Gonçalves, 2007). This last figure is very conservative, however, as proof of acceptable (structural) concrete performance has been shown for concrete containing higher recycled aggregate percentages (Kou et al., 2004; Richardson, 2010; Gonçalves, 2007; de Brito, 2002; de Brito et al., 2004; Zaharieva et al., 2003; Gomes, 2007). Recycled concrete aggregates can also be used in road bases and sub-bases, with demand estimated at 83,000 tonnes per year. This figure was derived from average road base and sub-base volumes (from the Portuguese road construction standard), considering a 1950 kg/m^3 average aggregate mass density and a 44% void factor (Illston and Domone, 2001).

3.2.2. Ceramic masonry

Recycled ceramic masonry aggregates can be used to fill in foundation pit and slab bases, as well as to make cement. For the former, the total construction needs of new buildings were estimated. From statistical data for housing units per floor, rooms per house, average living area and total number of housing and services buildings finished in each year (INE, 2009b), a yearly average gross foundation area was determined (around 1,290,000 m^2), which resulted in a yearly projection (year 2009) of 439,000 tonnes of aggregate fill needed to level out this estimated foundation area. This figure takes an arbitrary average fill thickness of 30 cm, which is conservative as far as normal foundation base thickness is concerned. In cement production, it was assumed that 1% of the total regional cement produced would be made from recycled mixed

Table 3
Sub-region CDW generation estimation.

Region	Sub-region	Finished buildings and demolitions	Resident population	Finished buildings and demolitions, per resident, number/person (/1000)	CDW generation, tonne/year
		Year 2006	Year 2008		
North	Minho-Lima	1709	250,951	6.81	166,956
	Cávado	2005	412,791	4.86	195,873
	Ave	2307	524,589	4.40	225,376
	Metropolitan Porto	2137	1,283,446	1.67	208,768
	Tâmega	2940	560,782	5.24	287,215
	Entre Douro e Vouga	1035	288,401	3.59	101,111
	Douro	1401	210,019	6.67	136,867
	Alto Trás-os-Montes	1127	214,460	5.26	110,099
Centre	Baixo Vouga	2135	400,423	5.33	208,573
	Baixo Mondego	1631	330,494	4.94	159,336
	Pinhal Litoral	1334	268,140	4.98	130,321
	Pinhal Interior Norte	1029	137,341	7.49	100,525
	Dão-Lafões	2289	291,185	7.86	223,617
	Pinhal Interior Sul	403	40,407	9.97	39,370
	Serra da Estrela	195	47,415	4.11	19,050
	Beira Interior Norte	784	109,051	7.19	76,591
	Beira Interior Sul	608	73,138	8.31	59,397
	Cova da Beira	350	90,701	3.86	34,192
	Oeste	1693	363,930	4.65	165,393
	Médio Tejo	1134	231,059	4.91	110,783
Lisbon	Metropolitan Lisboa	3589	2,029,458	1.77	350,617
	Setúbal Peninsula	2365	789,975	2.99	231,042
Alentejo	Alentejo Litoral	556	95,524	5.82	54,317
	Alto Alentejo	915	116,744	7.84	89,388
	Alentejo Central	915	168,979	5.41	89,388
	Baixo Alentejo	813	126,234	6.44	79,424
	Lezíria do Tejo	1693	249,588	6.78	165,393
Algarve	Algarve	3128	430,084	7.27	305,581
Islands	Açores	1712	244,780	6.99	167,249
	Madeira	1365	247,161	5.52	133,350
		Total	Total	Global proportional average	Total
		45,297	10,627,250	4.26	4,425,157

Table 4
Estimation of CDW quantities, per waste flow, for the Metropolitan Lisbon and Setúbal Peninsula areas.

Input CDW characterization	%	Estimated quantities for the Metropolitan Lisbon and Setúbal Peninsula, tonne/year
Concrete	11.6	67,393
Ceramic masonry	8.06	46,895
Tiles, shingle and other ceramic covering materials	0.37	2127
Mixed or separated concrete, bricks, tiles, shingle and other ceramic materials	53.5	311,412
Wood	3.25	18,886
Glass	0.08	479
Plastic	0.10	594
Paper and cardboard	0.60	3464
Tar and tar products	0.07	420
Bituminous mix containing tar	0.00	0.26
Bituminous mix without tar	13.4	78133
Aluminium	0.01	52.2
Lead	0.02	123
Iron and steel	0.47	2709
Mixed metals	1.72	9995
Uncontaminated soil and rock	–	–
Contaminated soil and rocks	0.00	0.93
Uncontaminated insulating materials	0.03	203
Insulation materials containing hazardous substances	0.03	201
Asbestos contaminated materials	0.01	46.4
Uncontaminated gypsum materials	4.50	26,173
CDW contaminated with hazardous substances	0.36	2067
Mixed municipal solid waste equivalent materials	0.43	2498
Other waste	1.34	7786

Uncontaminated soil and rock were excluded because they need not be considered a CDW flow, given their unprocessed form and easy reusability (Coelho and de Brito, 2010a,b).

ceramic aggregates, resulting in an extra 26,500 tonnes per year demand for this material.

3.2.3. Wood

Three possible markets were found for wood based waste flow routing: particleboard and wood-chip panels, animal bedding and mulches. For the first market, 30% in weight of recycled wood particles/chips was considered included in each panel (Ranita et al., 2005), with an average density of 600 kg/m^3. From the annual wood particle/chip panel production in Portugal (INE, 2007a), predicted demand was estimated at 55,800 tonnes per year for the selected region. For the animal bedding market, a figure of 22.5 kg/animal-month was considered (Pereira, 2005), which results in an annual demand for wood particle/chip of 8120 tonnes, assuming around 30,100 animals raised annually in the region (INE, 2007b). As for mulches, a potential yearly demand of 28,300 tonnes was estimated, considering around 710,000 tonnes each year for organic waste treatment in Portugal (INE, 2010b), with incorporation of 15% recycled wood particle/chip in compost mulches (Mota, 2002).

3.2.4. Glass

Although glass aggregate has several uses, to make new glass (window glass, glass containers and glass bricks), inclusion in road sub-bases and cement production additive, the potential demand for new glass production is large enough to absorb all glass output generated by the CDW recycling facility. This demand has been estimated at around 224,000 tonnes each year, considering a regional yearly production of glass containers equivalent to 272,000 tonnes of glass (based on a national production of 1,000,000 tonnes per year (Soares, 2007)), discounting the quantity of already recycled glass products, which in Portugal is 17% of all discarded glass (INE, 2010b).

3.2.5. Plastics

Until 2005, the Portuguese plastic manufacturing industry only used a very limited amount of recycled plastics, with only 1.8% of the total weight of all plastics produced being recycled plastic (Texugo de Sousa, 2008). This is not linked to any technical problems of incorporating larger amounts of recycled plastics, so it was assumed that the industry can currently absorb at least 20% of plastic waste. With this percentage the industry would absorb around 104,000 tonnes annually nationwide, which would be roughly 28,000 tonnes every year in regional terms. This figure refers to a regional industry domain to which the CDW facility's secondary plastic output could be delivered, assuming it is located in central Portugal (corresponding to 27% of all plastic products suppliers operating in mainland Portugal (APIP, 2011)).

3.2.6. Paper and cardboard

Paper and cardboard material produced by recycling can be used to manufacture new products, insulation materials (for buildings), billboards and plasterboards. There are very few suppliers of recycled cellulose for installation purposes in Portugal, however (only one was found in the whole country) and no plasterboards or cellulose-based furniture panels are made using recycled content, so demand for those purposes is very small or non-existent. Nevertheless, the demand for post-consumer paper and cardboard can be significant, given the rise in paper and cardboard recycling rate in Portugal (19 kg/person in 2009, corresponding to 25.4% of all paper products produced (INE, 2010b)), up to 45%, near the world average (Escandolhero, 2000). This potential rise in paper and cardboard recycling could increase secondary paper and cardboard use by up to 156,000 tonnes per year nationally, which would be equivalent regionally to 41,500 tonnes a year.

3.2.7. Bituminous mix without tar

Bituminous mix material from recycled sources can easily be incorporated into new road wearing layers (Ainchil and Burgueño, 2004). Given the standard dimensions for wearing layers in modern roads (on average 13-m wide and 0.1-m deep) and considering an average density of 1950 kg/m^3, given regional road renovation and new construction needs of 272 km (2008 data) and 25 km (2009 data), based on (INE, 2008) and (Coelho and de Brito, 2010a,b), 83,000 tonnes of secondary bituminous mix aggregate could be absorbed each year by the road construction/rehabilitation industry in the region.

3.2.8. Aluminium

There is plenty of potential regional demand for secondary aluminium. Of all the aluminium produced in Portugal (60,000 tonnes per year (Eurostat, 2009)), a recycled content of 65% can be assumed, from national industry examples (Figueiredo and Partidário, 2007). Applying this number nationally, 39,000 tonnes of secondary aluminium are used per year; assuming the possibility of the recycled aluminium content in industry processes rising to nearly 100%, which is feasible, an extra 21,000 tonnes per year of recycled aluminium could potentially be absorbed. Regionally, considering the main aluminium processing facilities in the area, 8000 tonnes per year is a possible estimation for the regional demand for secondary aluminium.

3.2.9. Iron and steel

In all, Portugal's annual output of iron and steel is around 1,800,000 tonnes (Eurostat, 2009). Source separation and municipal solid waste (MSW) incineration plants account for 27,700 tonnes per year of secondary iron and steel (Magrinho et al., 2006). CDW iron and steel content may increase to 9200 tonnes per year, if entirely source separated and sent directly to iron and steel recyclers. Assuming a possible rise in recycled iron and steel content in production of up to 50% (European average; Commission of the European Communities, 2005), a potential recycled input of 882,000 tonnes yearly could be used in industrial processes nationally, which could be translated into 234,000 tonnes per year, at regional level.

3.2.10. Uncontaminated insulating materials

Traditionally, insulation materials taken from demolition sites are sent to landfill (mainly due to occasional hazardous content and difficulty in source separation). However, separated insulation materials are recyclable, in particular polystyrene, polyurethane and rock wool, which can be used to produce new insulation materials (Hart, 2007) and as aggregates in lightweight concrete and mortar (Ainchil and Burgueño, 2004; Siqueira et al., 2004). Around 45,400 and 25,000 tonnes, respectively, of polystyrene and polyurethane are produced in Portugal each year (INE, 2007a). Nationally produced rock wool has a smaller market share than polystyrene and polyurethane, but around 6300 tons are still produced annually (QMP, 2009). If 1% of the total production is reintroduced into the industrial processes, the nationwide demand will be around 7100 tonnes per year (a national figure is used here, instead of a regional estimation, as only one operating recycling facility was found in Portugal for polystyrene, another for polyurethane and none for rock wool). Potential demand for lightweight recycled aggregates in concrete and mortar is far greater. Considering a 70% market share of expanded clay aggregate in

Table 5
Recycled material estimated demand in Lisbon (statistical region).

Original raw material / product	Uses for waste-sourced materials	Recycled material estimated demand in Lisbon (statistical region), tonne/year	Possible recyclers/ producers/final users	CDW recycling facility output less than potential market demand in Lisbon (statistical region)?
Concrete	Concrete coarse aggregates	1,638,709	Ready-mixed concrete suppliers, contractors	Yes
	Road bases	82,946	Contractors (road construction)	
	Road sub-bases			
	Concrete fine aggregates	0[a]	–	
	General fills	[c]	Contractors (in general)	
Mixed or separated concrete, bricks, tiles, shingle and other uncontaminated ceramic materials	Mortar fine aggregates	0[a]	–	Yes
	General fills (including non-structural concrete)	439,161	Contractors (in general)	
	Cement production	26,504	Any cement producer	
Wood	Wood particle and fibreboards	55,783	Waste management firms	Yes
	Animal bedding	8124		
	Mulches	28,272		
	Incineration	[c]	–	
Glass	Glass aggregate for producing flat glass, bottles, tiles	223,797	Waste management firms	Yes
	Road sub-bases	[c]		
	Cement filler	[c]		
Plastic	Pipes, cables, window frames, shades production	28 244	Waste management firms (only separation)	Yes
	Floor and walls coverings		Waste management firms (only separation), recycled content material suppliers	
	Urban furniture, components for plastic wood			
	Lightweight composite soils		Waste management firms (only separation)	
	Other non-construction products (shoe soles, packages, toys, etc.)			
	Incineration	[c]		
Paper and cardboard	New paper and cardboard products	41 500	Paper producers/manufacturers	Yes
	Cellulose-based insulation products	0[b]	-	
	Display boards, billboards	[c]	Paper producers/manufacturers	
	Furniture and covering boards	0[c]	–	
	Incineration	[c]	–	
Bituminous mix without tar	Road wearing layers	732,024	Contractors (road construction)	Yes
Aluminium	New aluminium products	7939	Aluminium producers	Yes
Iron and steel	New iron and steel products	233,983	Iron and steel producers	Yes
Uncontaminated insulating materials	New insulation material products	705	Insulation materials producers	Yes
	Aggregates for lightweight concrete and mortar	3411	Ready-mixed concrete suppliers, contractors	Yes
Uncontaminated gypsum materials	New gypsum-based materials production	88,442	Mortar and plasterboard producers, dry construction gypsum suppliers	Yes
	Secondary input material for cement production	13,076	Any cement producer	
	Soil improvement	[c]	Farmers	

[a] Portuguese legislation does not allow recycled concrete fines to be included in new concrete production (Gonçalves, 2007), although it has been proven successful (Evangelista, 2007).

[b] No cellulose-based insulation material producers were found in Portugal; (c) No paper and cardboard-based furniture and covering boards were found in Portugal.

[c] Given the relatively large potential market demand estimates for the material's application in other end-uses, the quantification of possible material incorporation in this lower grade end-use was considered unnecessary (although it may not amount to zero).

Fig. 2. Straight line connection between the CDW recycling facility location and rough geometrical centres of Lisbon statistical region municipalities.

concrete and mortars (Silva, 2007) and an annual production of 600,000 tonnes of these aggregates for this specific end-use (Castro et al., 2004), a further share of 257,000 tonnes per year of other lightweight aggregates is used. If 5% of this share is supplied from secondary sourced insulation materials, a yearly amount of 3400 tonnes per year is required to meet this need, in regional terms.

3.2.11. Uncontaminated gypsum materials

No plasterboard recycling facilities were found in Portugal. However, waste-sourced gypsum may be used in stucco or plaster production, either in prefabricated products or for mixing on site (Ribeiro, 2006), and as a secondary component in cement production (John and Cincotto, 2003). For the first end-use, a possible incorporation of 5% of recycled gypsum in plasters mixed on site was determined. Considering a grand total of 1.5×10^{12} m^2 of plastered surface in Europe (Brodkom, 2000) and an average 1 mm finish surface covering, around 1500 million tons of gypsum-based mortars are used annually in Europe. Scaling down to Portugal, the figure would be 31.8 million tonnes. If prefabricated ready-mixed gypsum-based mortars, which account for approximately 22% of total national production (Paulo, 2006), are excluded the figure would be about 24.8 million tons. Taking an average gypsum content of 26.8% of all stucco or plaster applied (the rest being lime and sand) we get an annual demand of 6.7 million tonnes for gypsum for mixed on site for plaster and stucco in Portugal. Scaling down to this study's region and considering a 5% incorporation of recycled gypsum, a total potential demand of 88,400 tonnes per year is possible for this material. As for the introduction of waste-sourced gypsum materials in cement fabrication, a 4% mass addition of gypsum was considered (Ribeiro, 2006), for a total regional cement production of 3.3 million tonnes per year. This results in a yearly amount of 131,000 tonnes of gypsum needed for clinker production in the region; if 10% of that gypsum comes from waste sources (such as the CDW recycling plant), 13,000 tonnes per year is the estimated demand for this waste flow.

These estimations are compiled in Table 5, where the CDW recycling facility output capacities are established. There are therefore, as these results apparently confirm, fair chances that there will be sufficient demand in the regional market for all the output material leaving the CDW recycling plant.

3.3. Location of the recycling plant

The CDW recycling plant was sited in direct relation to each regional municipality's CDW generation, with a view to minimizing the overall average transport distance to the recycling plant. CDW generation was therefore estimated for each municipality within the Lisbon Metropolitan Area and Setúbal Peninsula using the same statistical parameters as in §3.2. Knowing the approximate geometrical configuration of the region (Fig. 2), several trials were undertaken, locating the recycling plant in seven central

Table 6
Sub-regional CDW generation rates.

Sub-region	Municipality	Finished buildings and demolitions	Resident population	Finished buildings and demolitions, per resident, number/person (/1000)	CDW generation, tonne/year
		Year 2006	Year 2008		
Metropolitan Lisbon	Amadora	83	172,110	0.48	8108
	Cascais	949	188,244	5.04	92,710
	Lisboa	279	489,562	0.57	27,256
	Loures	296	195,035	1.52	28,917
	Mafra	726	70,867	10.24	70,924
	Odivelas	256	153,584	1.67	25,009
	Oeiras	128	172,021	0.74	12,505
	Sintra	668	445,872	1.50	65,258
	Vila Franca de Xira	204	142,163	1.43	19,929
Setúbal Peninsula	Alcochete	174	17,464	9.96	16,998
	Almada	305	166,103	1.84	29,796
	Barreiro	136	77,893	1.75	13,286
	Moita	125	71,596	1.75	12,212
	Montijo	180	41,432	4.34	17,585
	Palmela	431	62,820	6.86	42,105
	Seixal	379	175,837	2.16	37,025
	Sesimbra	233	52,371	4.45	22,762
	Setúbal	402	124,459	3.23	39,272
		Total	Total		Total
		5954	2,819,433		581,659

municipalities (Fig. 2 shows the final location in Amadora), calculating for each the average transportation distance from all other regional municipalities, in proportion to their annual CDW generation. Table 6 lists these sub-regional CDW generation rate estimates, which are based on municipal statistical information (INE, 2009a) and Table 3. As the final location could not be chosen directly and immediately from the given data, a few tests were performed, considering a different plant location for each test; then the total amount of transported tons-km per year was calculated and the smallest result chosen (Table 7), which resulted in Amadora. Location is an important factor in cost, since it represents almost 70% of all annual operation costs for the 350 tonne/h facility (transportation costs are associated with having to send rejected material to suitable landfills). However, given the simplifications implicit here (e.g.: straight line connection between municipalities, calculating CDW generation rates indirectly through statistical information on finished buildings and demolitions for each municipality), the distances calculated must be seen as preliminary and may not necessarily give an accurate final optimum location of the CDW recycling plant.

4. Economic viability approach

4.1. Introduction

Based on simple cost–benefit analysis, the various costs – initial, operating, maintenance, labour and transportation – were listed for each process step, following a detailed flow chart derived by expanding the one presented in Fig. 1. The initial (new equipment purchase), operating, maintenance and all estimated labour costs were quantified for each piece of equipment. This was done following extensive market research on actual equipment suppliers, whenever possible collecting information from more than one (supplier) for a particular item. This also included gathering information on maintenance costs. Operating costs were determined based on the energy consumed by the equipment, which largely depends on its rated power and the fuel used (electricity or diesel). Labour costs include management, local supervision, equipment operators (in this case only the excavator) and non-specialized workers (for the manual separation), assuming current local market costs. Setup costs (engineering design and planning) were also considered on a simplified basis, as a given percentage of the initial equipment purchase cost, as well as land acquisition and further administrative costs such as permits and taxes. Waste transportation and disposal costs were included, using a fixed distance to landfill and an average cost for potentially hazardous waste. Finally, insurance, legal fees, marketing and credit cost (assuming an 80% credit funded venture) were also added into the operating cost. Total running costs for a 60-year period are summarized in Table 8, divided into eight main categories.

Benefits were measured in the shape of collection fees and sale of materials to downstream waste managers and recyclers. Sale revenue considers current average market prices in Portugal, whenever possible by listing values given by several companies, or from published sources otherwise.

All these cost and benefit items were accounted for on a yearly basis, taking into account inflation and money value update, for 60 years (although not updating for future fluctuations of the inflation and money value update rates). The resulting break-even period was calculated by simply identifying the year when the balance sheet becomes positive. As noted above, all the major CDW recycling plant life-cycle costs are taken into account except for dismantling at the end-of-life, which have been excluded because it cannot be known what will actually happen to a yet-to-be-erected CDW recycling facility in 60 years' time.

4.2. Fixed costs

Fixed costs were here taken as the costs incurred in choosing and procuring the appropriate machines and apparatus to install the CDW recycling facility. Table 9 shows these fixed initial costs, an essential investment in physical infrastructure. But after several years of operation machines reach the end of their service life and have to be replaced (Table 10). This entails fixed replacement costs within the 60 years of operation considered, approximately following the service life established for each piece of equipment. However, other fixed initial costs are incurred prior to equipment installation, including engineering design/planning, real estate purchase, licences and taxes. Engineering design was taken to be 5% of all physical equipment installed, including support structures, foundations and other basic infrastructure, whose construction in turn amounts to some 35% of all direct fixed equipment costs (Leitão, 2011). Real estate purchase cost was estimated at local marketplace prices, resulting in an average of 156 €/m^2 for industrial applications (from a six sample average). Considering an area of 27,500 m^2 to install the CDW recycling facility (Pereira et al., 2004), this represents an upfront cost of almost €4,280,000. These other fixed initial costs are summarized in Table 13.

4.3. Operating costs

These are all the costs inherent to the facility's day-to-day functioning, including all those mentioned in §4.1 but excluding fixed costs. A brief explanation of each operating cost is as follows.

4.3.1. Energy costs

Apart from the excavator, which uses diesel, all machines run on electricity. Energy cost for the excavator was determined by considering an 8 h/day, 300 days/year operating period and 90 kW average rated power (from excavator suppliers). Using an approximate diesel unit cost of €0.114/kWh (based on DGGE (2010)),

Table 7
Total annual transportation distance from regional sources to the CDW recycling plant.

Facility location - Municipality	Weighted average distance to the facility, km	Weight × transported kilometres, tonne-km/year
Barreiro	26.0	15,105,149
Moita	26.2	15,254,654
Seixal	24.9	14,486,853
Almada	22.8	13,282,747
Oeiras	21.8	12,683,639
Amadora	21.0	12,228,378
Odivelas	21.4	12,440,676

Table 8
60 year period total costs, divided into main categories.

	Cost, €	Percentage of total cost
Equipment fixed cost	12,900,861	3.09
Transportation	36,545,568	8.75
Facility construction	2,780,439	0.67
Real estate purchase and other initial costs	4,697,770	1.13
Energy, maintenance and labour	16,842,651	4.03
Other operational costs	9,175,084	2.20
Rejected materials dumping or delivery	332,182,738	79.56
Interest	2,387,827	0.57
Total cost	417,512,937	100

Table 9
Cost and benefit list (€/year) for a 350 tonne/h CDW recycling facility.

Summary of the detailed process – simplified and full operation modes.				Costs–Benefits						
				Fixed costs, €	Operational costs, €/year				Materials, €/year	
Process step, No.	Description	Related equipment	Quantity	Initial	Energy	Maintenance	Labour	Transport	Source	Cost/benefit
1	Weighing station	Scales	1	19,170	7	192	48,000		Input	−21,826,669
2.1	Visual inspection						28,800	844,432	Rejected	7,321,021
2.2	Loading for manual separation section	Excavator	1	135,000	24,524	6408	23,040			
		Conveyor belt #1	1	68,833	1546	1274				
3	Aggregate size separation (< 80 mm; > 80 mm)	Vibrating feeder	1	114,000	2311	1596				
		Conveyer belt #2	1	68,833	1546	1274				
3.1	Manual separation section	Conveyer belt #3	1	103,250	2319	1912				
		Hand separation cabin	1	7250	28	51	142,848		Metals	−1,852,421
									Paper and cardboard	−18,383
									Plastics	−5044
									Wood	−90,211
3.2	Crushing section	Jaw crusher	1	130,000	15,695	1690				
4	Ferrous metals separation	Magnet	1	47,522	927	367			Ferrous metals	−679,049
5	Aggregate size separation (> 4 mm; < 40 mm)	Vibrating screens #1	1	82,325	2640	1482				
		Conveyor belt #4	1	34,417	773	637				
6	Air separation section	Air sifters	3	300,000	1873	3888			Paper and cardboard	−42,894
									Plastics	−11,768
									Wood	−210,492
7	Non-ferrous metals separation	Eddy current generator	1	98,114	1638	257			Non-ferrous metals	−20,160
		Conveyor belt #5	1	34,417	773	637				
8	Aggregate size separation (<4 mm; 4–8 mm; 8–16 mm; 16–32 mm; 32–40 mm)	Vibrating screens #2	1	82,325	3187	1482				
9.1.1	Density separation section	Dry density separators #1	4	2,753,333	72,310	46,656			Ceramic aggregates (coarse)	0
		Conveyor belt #6	1	68,833	1546	1274				
9.1.2		Dry density separators #2	3	1,376,667	25,309	16,330			Gypsum	474,591
									Concrete aggregates (coarse)	−223,123
9.2.1	Density and friction separation section	Spirals #1	4	150,583	8090	1952		286,117	Heavy metals	−10,550
									Sludge (solids)	2,480,562
		Conveyor belt #7	1	68,833	1546	1274				
9.2.2		Spirals #2	4	200,777	15,409	3717			Concrete aggregates (fines)	−290,706
									Ceramic aggregates (fines)	0
Total				5,944,483	183,995	94,349	242,688	1,130,548		−15,005,295

Table 10
Service life of equipment (years until replacement).

Equipment	Years until replacement	Observations/notes
Scales	30	No moving parts
Excavator	20	Ahn et al. (2010)
Conveyor belts	20	
Vibrating feeder	8	Leitão (2011)
Hand separation cabin	30	No moving parts
Jaw crusher	10	Leitão (2011)
Magnet	15	Morgan (2010)
Vibrating screens	6	Leitão (2011)
Air sifters	20	Ahn et al. (2010)
Eddy current generator	15	Morgan (2010)
Dry density separators	20	Horn (2010)
Spirals	15	Turunen (2011)

Table 12
Human labour local prices (from specialized demolition contractor).

Human labour specialization	€/h
Non-specialized worker	6
Health and safety officer	9.6
Equipment operator	9.6
Local supervisor	12
Engineer	18
Assistant manager	20
Office/clerical worker	12

yearly energy costs for the excavator will be around €17,200. As for electrical equipment, the jaw crusher, for example, with an (electrical) 110 kW power rating for this use and output (250 tonne/h), operating over the same period and for roughly the same hours, will cost about €11,000/year in electricity consumption (considering an average unit electricity cost of €0.0595/kWh for a high voltage, long duration contract (ERSE, 2011)). All other equipment electricity costs were calculated in a similar way.

4.3.2. Maintenance costs

Although maintenance is the smallest equipment operating cost item (around 6%), it cannot be ignored. Data were collected on each piece of equipment in order to estimate maintenance costs, as presented in Table 11. Maintenance includes repairs, part replacement, cleaning and lubrication.

4.3.3. Labour costs

Manpower is needed in the CDW recycling facility for the following tasks: operations management (assistant manager), local supervisor, excavator operator and hand separation (non-specialized workers). The same working period mentioned above was assumed, and local labour prices were used for the different specializations (Table 12). The number of non-specialized workers needed for the hand separation section was calculated on a basis of 4 workers per 200 tonne of processed waste per day (Mimoso, 2011), which, scaled up to the present CDW facility (500 tonne/day), gives 10 workers. This amounts to €100,000/year for labour.

4.3.4. Rejected material costs (dumping fees)

Hazardous and untreatable (or not treatable with the facility's technology) materials are rejected at the visual inspection and spiral separator stages, which entails waste disposal costs. Materials can be rejected at the inspection stage if they contain tar, asbestos, municipal solid waste or other potentially hazardous materials, which can be spotted visually. At the spiral stage, sludge that may contain hazardous materials must be sent for disposal or further treatment. Although some of these materials may be treated in other specialized facilities, they were considered to be dumped in controlled conditions, as far as this study is concerned. An average dump fee was used, based on prices some waste operators and contractors are already paying at the moment to get their rejected materials landfilled, which gave €114/ton (from prices ranging from €90 to €150/tonne).

4.3.5. Transportation costs

Transportation costs are essentially incurred by sending rejected material away from the CDW recycling facility in the stages described earlier. Transportation costs naturally depend on the amount of material and the average distance to their destination (final or temporary). 42 km were considered as the average distance to a possible landfill location or treatment plant (Lourenço, 2007), incurring in a €2.95/km direct transportation cost (Coelho and de Brito, 2011b). A standard lorry of 19.3 m^3 was assumed for all transport purposes, which converts into around 4560 journeys per year, considering the need to transport an average of 51.4 tonne/h of rejected materials (from both rejection stages). This is around 383,000 km travelled per year, costing about €1,131,500. Transportation costs are the main operating cost and account for almost 70% of all yearly equipment operating costs (though only about 9% of the total 60 year costs).

4.3.6. Credit costs

Initial and operational investment in an industrial venture of this magnitude involves large funds, which most likely are not immediately available to the owner. Consequently, credit will be required, which was considered to represent 80% of all the initial fixed and operational costs (not including transportation). Annual

Table 11
Collected data for maintenance cost estimates.

Equipment	Data information	Observations/notes
Scales	1% of the initial purchase, yearly	Considering no moving parts
Excavator	€6408/year	Based on Caterpillar data
Conveyor belts	1.9% of the initial purchase, yearly	The same percentage calculated for the dry density separators
Vibrating feeder	1.4% of the initial purchase, yearly	Leitão (2011)
Hand separation cabin	not considered	No moving parts and not subject to heavy loads
Jaw crusher	1.3% of the initial purchase, yearly	Leitão (2011)
Magnet	€367/year	Morgan (2010)
Vibrating screens	1.8% of the initial purchase, yearly	Leitão (2011)
Air sifters	1.9% of the initial purchase, yearly	The same percentage calculated for the dry density separators
Eddy current generator	€367/year	Morgan (2010)
Dry density separator	€0.2/ton (per machine)	Horn (2010); it can be affected by a 90% factor because maintenance teams work on the whole set of machines on each visit
Spirals	1.9% of the initial purchase, yearly	The same percentage calculated for the dry density separators. Although spirals themselves have no moving parts, the pumping section will need regular maintenance, as will other mechanical–electrical machines

Table 13
Other fixed and operational costs.

Other fixed initial costs	€
Engineering design and planning	391,800
Land acquisition	4,278,970
Authorizations	27,000
Taxes	
Other operating costs	€/year
Insurance	58,095
Administration – legal advice	144,000
Administration – accounting	
Marketing	90,800

interest rate on the credit is assumed to be 1.52% (Bank of Portugal, 2010), and inflation and discount rates were considered at 2.4% ((Bank of Portugal, 2006) – projection to 2008) and 4.9% respectively (here the German rate is assumed by default, for public or private investments alike). In these circumstances and for the initial credit required, interest for the first year will be €154,000. Credit was assumed to be paid back over 30 years.

4.3.7. Other operating costs

The CDW recycling plant cannot function unless other operating costs are considered, such as insurance, administrative office costs, legal advice and accounting services, and commercial/marketing expenses (output materials). Insurance was considered to be 1% of all fixed assets (Zhao et al., 2010), administrative tasks were assumed to occupy a 5-person team and commercial/marketing activities by a 2-person team, with transportation needs covered by two company cars. These costs are presented in Table 13.

4.4. Benefits

Economic benefits from the CDW recycling facility derive essentially from material input gate fees and output material commercialization. Gate fees were calculated as an average of several recycling companies rated charges, all operating within the regional boundaries considered in this study. For mixed CDW, these companies gate fees range from €20 to €75/tonne, with an average of €48.2/tonne. A different average value was assumed for source-separated aggregates, since marketplace figures (also regional) range from €0 to €15/tonne, which translates into a €7.8/tonne average. With a 70/30% material distribution at the facility's gate (as described in §3), which leads to an average input of 250 tonne/h flux of mixed CDW and 105 tonne/h of separated aggregate, around €21,827,000 can be collected annually. Output material sale benefits will depend on the type of material, its quality (i.e. purity) and output quantities. Unit mass prices are listed in Table 14, and are mostly based on a regional market survey. Total benefits per material flow per year can be found in Table 9.

4.5. Life-cycle cost analysis

All costs and benefits were summed up on a yearly basis, taking into account present values for future investments, which correspond to any expenditure or benefit in future years, during the CDW recycling facility's operating period. This discount is established through expression (1):

$$V_{cp} = V\left[\frac{\left(1+\frac{i}{100}\right)}{\left(1+\frac{a}{100}\right)}\right]^{A} \quad (1)$$

where V_{cp} is the present value of a future transaction, V is this transaction's value (cost or benefit), i is the inflation rate, a is the money value update rate and A is the year for which the calculation is performed (where 0 is the initial investment year).

Assuming a 60 year facility operation life, and besides the inclusion of costs related to equipment replacement, based upon each machine's expected service life, a thorough infrastructure overhaul is accounted for after 40 years of operation, amounting, as in the year of the initial investment, to 35% of all direct fixed (installed) equipment costs.

5. Results and discussion

The approach described in §4 yielded an economic cost–benefit balance chart, which is plotted and presented in Fig. 3. The chart shows the return on investment period, which is around 2 years. This looks like a particularly attractive business, which makes one wonder why it has not been yet implemented in this region or in other parts of the country. In comparative terms, some national legislation documents state a return on investment period of 8 years as a reference for economic viability. This relates to the implementation of energy efficiency measures in buildings (RSECE, 2006). In view of this comparison, the return on investment period calculated for the CDW recycling plant is quite short. However, the scale of this facility must be considered. It would have a 350 tonne/h installed capacity for CDW input and be able, assuming an average market gate fee (€48.2/tonne for mixed and €7.8/tonne for separated CDW), to collect around 21.8 million € in the first year of operation alone. With an overall cost over the first year of operation of about €14 million, and even considering annual running costs of €11.9 million, gate fees and revenue from separated materials' sales quickly supersede total accumulated costs. This presumes ideal operating conditions: a constant 350 tonne/h material input, with gate fee rates remaining at the calculated average and output materials sale prices being as high as those estimated. These conditions can and probably will vary in the near future, if/when the facility is installed, and so a sensitivity analysis was performed

Table 14
Primary recycled output material regional average sale prices.

Output material	€/ton	Observations/notes
Mixed metals	−678	Averaged sale price of iron, steel, aluminium and copper, ranging from −€60 to −€1500/tonne
Paper and cardboard	−25	Price quoted by a large contractor operating in the region
Plastics	−40	Value provided by a recycling operator operating in the region (year 2001)
Wood	−22.5	Cutileiro (2011)
Iron and steel	−105	Average sale price of iron and steel, ranging from −€60 to −€150/tonne
Gypsum	63	A cost for the facility. Average delivery value of gypsum, ranging from €35 to €90/tonne
Concrete – coarse aggregates	−2.75	Considered 50% of the present sale price of natural stone aggregates (ranging from −€5.25 to −€5.75/tonne)
Concrete – fine aggregates	−2.75	(Kartam et al., 2004)
Heavy metals	−50	Considering that heavy metals can be sold to battery manufacturers (at €50/tonne, current price quoted by a large contractor operating in the region)
Ceramics – coarse aggregates	0	Mimoso (2011)
Ceramics – fine aggregates	0	

Negative values represent benefits.

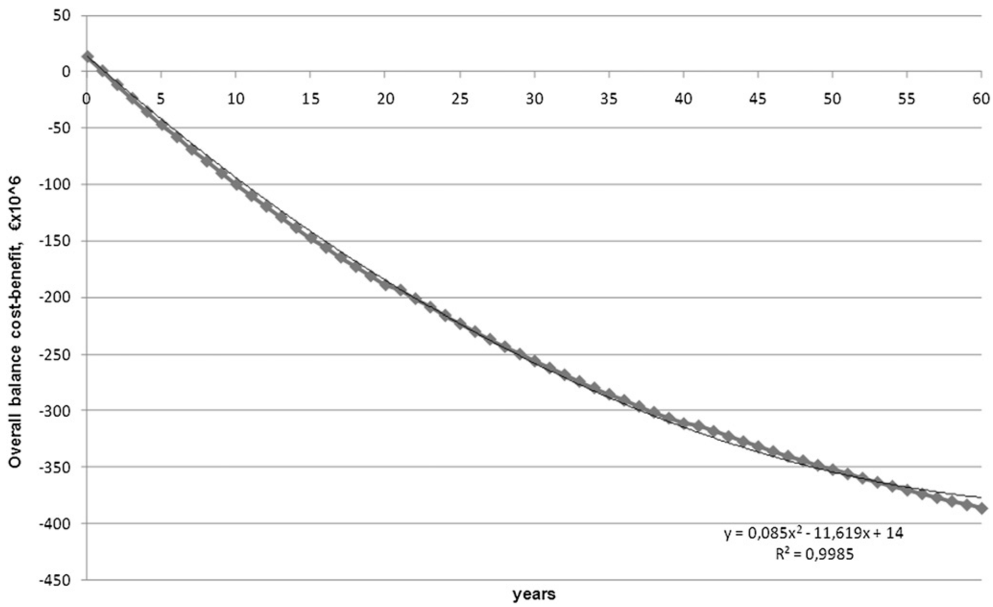

Fig. 3. CDW recycling plant overall cost–benefit balance – Base scenario – 350 tonne/h material flow capacity.

on their impact on the return on investment period (part II of this paper). Moreover, there are several factors that could discourage potential investors: the high initial investment, the inherent technical complexity of the installation and the need for costly investment in physical assets. Most of these assets have no use other than the one for which they are designed, meaning that conversion of the recycling plant for another use would be complex, lengthy and expensive.

Fig. 3 also shows a quadratic variation of the overall economic balance over the operating period. This quadratic approximation is a very good fit with the calculated data and derives essentially from expression (1). The correspondence is not perfect only because several instances of equipment replacement are necessary over the life-cycle, which introduces discrete costs at different moments in time. However, and despite these peak cost events, the economic overall balance has quite a steady, smooth progression. At today's prices, this economic model presents overall benefits for the entire 60 year period of almost €817 million, solely from gate fees and output material sales; only €418 million are attributed to costs in the same period, which offers the owner a €386 million surplus. It should be noted that material input gate fee represents 86% of all benefits, which makes this a potentially critical issue as far as revenue is concerned. Costs are somewhat more evenly distributed – energy operation, maintenance, labour, transportation, credit, material rejection – but still there are two major costs, which actually can be seen as one: rejected material (in two different steps), or dumping fees, which account for 80% of all costs over the 60 year operating period (Table 8). It naturally follows that variations in dumping fees have the potential to affect the profitability of the facility, and this is examined further in part II of this paper.

6. Conclusions

A relatively detailed study was undertaken on the initial and operating parameters of setting up a large-scale Level 3 (as described in §2) CDW recycling facility, to be installed in the Lisbon Metropolitan area. Initial and operating costs were considered, including the setup costs of real estate purchase and engineering design costs, as well as life-cycle maintenance/replacement costs. The large initial investment and capital intensive operation meant that a loan was considered as a starting point, i.e. the assignment of 80% of the first year's total costs to credit (excluding transportation), to be paid back in 30 years. A market survey was undertaken in order to find out the potential market absorption capacity for the output materials produced by the recycling facility, a necessary condition to justify the investment since a considerable part of the facility's income is attributed to the sale of output materials. The facility is intended to be a material processing industry, not a storehouse for the reject materials from other processes, and so a steady flow of input and output material is inherent to its operation. Although end-of-life costs could have been included in the analysis, uncertainty as to what that end-of-life will actually consist of led to the decision to exclude them.

The following conclusions can be drawn:

- Investment in a large-scale high-level CDW recycling facility is a multi-million euro enterprise, but has a high profit potential, even in the absence of specific regulatory measures which could help CDW material recycling or penalize dumping recyclable CDW in landfills;
- For a 350 tonne/h facility, average gate fees of €48/tonne for mixed and €8/tonne for separated input materials, the need to spend around 1.13 million euros a year on rejected material transportation and another 10.3 million euros a year to dump it in landfills (or onward transport for further treatment), a 2-year return on investment period is possible, under the conditions stated in this study (other CDW recycling plant economic viability studies in Portugal have also been encouraging, as in (Pereira et al., 2004))
- As far as benefits are concerned, the material input gate fee is the largest share, providing around 86% of all benefits;
- In terms of costs, dumping fees represent about 80% of total yearly costs, which puts into perspective the need to minimize non-treated material and the real weight of all other costs in the cost–benefit sheet balance.

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