Accepted Manuscript

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PII: S0959-6526(19)32331-5

DOI: <https://doi.org/10.1016/j.jclepro.2019.06.354>

Reference: JCLP 17523

To appear in: *Journal of Cleaner Production*

Received Date: 28 February 2019

Revised Date: 14 June 2019

Accepted Date: 30 June 2019

Please cite this article as: Galán B, Viguri JR, Cifrian E, Dosal E, Andres A, Influence of input streams on the construction and demolition waste (CDW) recycling performance of basic and advanced treatment plants, *Journal of Cleaner Production* (2019), doi: <https://doi.org/10.1016/j.jclepro.2019.06.354>.

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Methodology for selection of the best CDW management alternative

1. Composition and Destination of CDW:

- a. Characterization of CDW streams
- b. Definition of mixing grade and segregation level of waste streams
- c. Management option for each waste stream in function of the value, recycling potential, available recycling route, etc.

2. Selection of CDW recycling plant in function of technology and sorting processes:

- a. Basic plant
- b. Advanced plants

3. Definition of quality and destination of the final products from CDW recycling plan:

- a. Flows quantification
- b. Type of aggregate obtained

4. Definition of evaluation criteria:

- Recycling percentage
- Resource recovery percentage
- Global Warming Potential

Evaluation Criteria and
Aggregates standards **OK**

**Prioritized
options**

ACCEPTED

INFLUENCE OF INPUT STREAMS ON THE CONSTRUCTION AND DEMOLITION WASTE (CDW) RECYCLING PERFORMANCE OF BASIC AND ADVANCED TREATMENT PLANTS

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Keywords (max. 6) CDW, segregation, heterogeneity, recycling, treatment plants, performance criteria.

HIGHLIGHTS

- The methodology contributes to the classification of CDW management alternatives
- Segregation and heterogeneity rates create scenarios to quantify recycling streams
- Validation of the methodology through a case-study located in the north of Spain
- Recommendations to improve CDW recycling percentages are proposed
- Advanced plant at low segregation levels achieves 78% recycling without backfilling

ABSTRACT

The most common method of handling construction and demolition waste (CDW) is recycling; this produces recycled aggregates that can replace natural aggregates in various applications while offering social, economic, and environmental benefits. However, from technological, environmental, and management perspectives, CDW recycling faces complicated issues that require resolution. This study proposes a methodology for investigating the influence of segregation and heterogeneity of the inlet CDW stream, and the technological level of the recycling facilities, on the quantity and composition of aggregated product streams. Four different scenarios with the combination of two different segregation levels and two homogeneity grades of CDW were developed; two recycling plants of different technological levels, basic and advanced, were used to treat the CDW in these scenarios. The two segregation levels represent the actual situation and the future situation in Spain; the two homogeneity levels represent the mixing of different types of waste due to the contamination

of the fractions. The results obtained indicate that under low segregation levels, basic recycling plants can reach the minimum target of non-hazardous CDW resource recovery set at 70% before 2021 by the European Union, as backfilling is permitted. However, high segregation levels and advanced CDW recycling plants are required if backfilling is excluded since the recycling percentage is much lower than the resource recovery percentage.

1. Introduction.

The construction industry is one of the largest and most active sectors in Europe. It consumes more raw materials and energy than any other economic activity and generates construction and demolition waste (CDW) accounting for 25–30 % of all waste generated in the EU (Di Maria et al., 2018; European Commission, 2018a). In addition to CDW prevention research (Ajayi et al., 2017), extensive research on the factors and relationships that influence the sustainability of CDW management have been published. Waste treatment methods, sustainability impact (e.g., carbon footprint), technical properties of recycled products, waste management approach (e.g., life cycle assessment), quantification of waste generation, and newly emerging technologies (e.g., building information modeling) are identified as main clusters related to the common objective of better CDW management (Jin et al, 2019).

Other aspects of CDW are also covered in the current literature. Madi and Srour, 2019, proposed a GIS-based plan to recycled CDW from man-made and natural disasters to minimize environmental damage. Gálvez-Martos et al., 2018 showed the two main areas of heterogeneity among European countries: treatment of waste and development of markets for secondary materials, and linked the best practices for the management of CDW across the entire construction value chain. De Azevedo et al, 2018 analysed the sustainability of incorporating industrial waste into construction material.

Among possible solutions to waste minimization, CDW recycling has been commonly advised in line of the principle of circular economy (Ghisellini et al., 2018). Depending on the nature of the CDW, 50-95% can be recycled to provide concomitant social, economic and environmental benefits (Zhang et al., 2018). In general, the proximity of recycling plants to building sites and recovered products market are key factor for promoting environmental benefit (Suárez Silgado et al., 2018). However, a detailed analysis of the social, environmental, and economic aspects, as well as the complicated issues from the engineering, technological, management and policy perspectives is required since scientific studies also shows the complexity and drawbacks of the recycling process (Jin et al., 2019).

This study is focused on three different aspects: *European regulations, dismantling process* and *type of recycling plant*, which provide very different scenarios on the CDW sustainability. In addition, any methodology related to CDW management implies an adequate definition of the regional situation under study.

European Union Regulation

The minimum target of non-hazardous CDW recycling was set at 70% before 2021 by the EU. In 2016, the EU member states recovered around 90% of overall CDW including backfilling. However, some countries (Malta, Spain, Slovakia, Cyprus and Poland) achieved high percentage in downcycling processes (backfilling), whereas upcycling remained at a low percentage (Deloitte, 2017; Ferriz-Papi and Thomas, 2017; European Commission, 2018b).

Although a common model for calculation method across European member states exists, the definition of the EU recovery target for CDW is very susceptible to varying interpretations and consideration of *waste* and *waste recovery* by each country. Therefore, it is difficult to compare values between different countries with accuracy, or even within a country (Arm et al., 2017; Rodríguez-Robles et al., 2015).

The EU policy has contributed to significant reduction of the amount of CDW that is transferred landfill, although most of the effort has been put in downcycling practices. Sensitising and circulating among stakeholders the application of tools such as: *End of waste (EoW) status*; *Construction Products Regulation (CPR)*; and *Environmental Product Declaration (EPD)*, is imperative. Therefore, better knowledge of the local CDW recovery/recycling capacity can aid in the achievement of this objective.

Dismantling process: deconstruction and demolition

A significant area of research in the field of CDW has dealt with the management of deconstruction and demolition processes since dismantling resources and the level of sorting affect the quality of salvaged materials and available treatments (Aidonis, 2019). From an environmental standpoint, there are clear benefits of using *selective demolition or deconstruction* considering that reused and recycling materials account for 85% of a building's total weight. *Conventional demolition* leads to highly mixed materials that can be hauled to landfills (Estanqueiro et al., 2018; Di Maria et al., 2018; Tatiya et al., 2018; Chen et al., 2019). There is a last resort of dismantling: selective deconstruction at early stages, followed by demolition of the remaining parts of the structure. The final decision depends on two critical factors: total process cost and total process time.

Management practice: CDW recycling facilities

The performance of CDW management systems has been extensively studied (Bovea and Powell, 2016; Gálvez-Martos et al., 2018; Zhang et al., 2018). CDW recycling facilities are capable of treating waste regardless of its composition; however, highly mixed CDW requires more complicated separation techniques. The technology on which the CDW recycling plants is based is one of the decisive factors that affect the quality of the recycled products and together with the demolition approach, determines its viability. The aggregates from the recycling process have been extensively studied for application in various fields (Al-Azzawi and Shalal, 2019; Santos et al., 2019; Zhang et al., 2018; Deloitte, 2017; Silva et al., 2014; Behera et al., 2014).

Most of the current CDW recycling plants are based on automated crushing mobile machinery consisting of wheel loaders, vibration feeders, crushing machines, magnetic separators, and winnower machines, along with various screens and conveyor belts. For high-grade applications, more rigorous separation and sorting techniques are required. The challenge lies in finding the right combination of sorting during demolition, inexpensive separation techniques, and further advanced automated sorting techniques.

Regional characteristics

Regional particularities are a significant aspect of CDW management since the composition of CDW, type of recycling plants, or recycling rates is highly influenced by the region, and occasionally, specifically by the districts in the region (Pacheco-Torgal et al., 2013). In previous studies by our research group, economic, environmental, and social criteria were employed to obtain the optimal location of CDW storage and recycling facilities at a regional level, considering counties with heterogeneous economic activities and population density (Dosal et al., 2013; Galan et al., 2013).

In the literature, there are some gaps in relation to the real performance of CDW management (Di Maria et al., 2018; Jin et al., 2019). The present work takes a step towards bridging the gap and reports a simplified methodology that allows the quantification of the combined influence of the segregation and heterogeneity of the inlet CDW stream with the technological level of the recycling facilities on the quantity and composition of aggregated product streams. The analysis of the results will facilitate the classification of the actual management strategy and prediction of improved future options. The applicability of the proposed methodology is

illustrated using real data obtained from a case study of CDW management at the Regional level, in Cantabria (Northern Spain).

2. Methodology

The methodology for classification of the CDW management scenarios includes four steps, as illustrated in Figure 1.

2.1. Composition and destination of CDW

In general, CDW typically consists of stony fraction (concrete, ceramics, mortar and aggregates), metals (steel, iron, copper and aluminum), non-stony fraction (plastics, wood, paper, organic materials and glass) and, occasionally, hazardous wastes as lubricants, oils and materials containing asbestos and heavy metals (Rodríguez-Robles et al., 2015). Although each country presents specificities that need to be considered; in general, the southern European countries generate very high percentage of petrous components (Rodríguez-Robles et al., 2015; Santos et al., 2017).

If appropriate selective demolition is carried out, each component of the construction waste can be obtained without mixing and can be sold or recycled depending on its economic value. If the traditional demolition method is performed, three types of mixed streams appear normally: mixed petrous, mixed metals, and in the worst case, mixed CDW. Table 1 shows the components, streams, and destinations considered in this study. It is observed that the mixed metal stream is dispatched to a metal or waste manager to be sold, while mixed petrous and mixed CDW are recycled. At present, mixed metals are easily recycled owing to their high economic value. The mixed petrous fraction can be recycled to different types of products. Mixed CDW has relatively few recycling options since some components such as gypsum, plastics, metals, and mortar decrease the mechanical properties of the final products (Zhang et al., 2018).

The first variable considered in this study is the percentage of source segregation associated with the grade of selective demolition. Importantly, demolition practices rely on clients and prime contractors, and if the latter do not ensure that the CDW is sorted and dispatched correctly, new disorganisation could emerge. Consequently, another question needs to be addressed: the level of heterogeneity owing to contamination with other fractions due to the inadequate organisation, training, and sensitisation of the workers, among others. Therefore, two variables are established in this study to analyse the influence of the inlet streams: (i) the source segregation grade and (ii) heterogeneity grade of groups of wastes due to mixing.

2.2. CDW Recycling Plants

The selection of the CDW recycling plant (operational units and configuration of the plant) affects the quantity and quality of the recycled aggregates materials and, thus, the recycling rates. The configuration of the recycling facilities depends on technological, legal, and economic factors (Pacheco-Torgal et al., 2013), and varies considerably amongst countries and amongst regions of the same country (Oliveira-Neto et al., 2017). Pacheco-Torgal et al, 2013 identified different technological levels for CDW plants ranging from a simple mobile crusher and sieving plant to more complex machinery for sorting/sieving (Symonds Group, 1999). Recently, Oliveira-Neto et al, 2017 presented a current classification, adapted to the economy and objectives of the EU member states, that considers three types of sorting in plants: *current advanced process* (based on four steps: crush, sieve, magnetic and trommel), *advanced process* (that adds air density separation), and *advanced sorting process* (that adds infrared sorting).

The viability of the CDW plants, in addition to the technological level, is significantly limited by the inter-regional differences in deposit fees, the existence of illegal dumps, absence of legislation on the use of recycled aggregates, and market of the recycled aggregates.

2.3. Quality and destination of the final products from CDW recycling plants

To evaluate the best CDW recycling technological alternative at different waste segregation and/or mixing levels, a realistic quantification of recycling products is necessary. In this work, mass flow analysis (MFA) is used, wherein once the potential inflows to a plant have been determined, a mass balance approach is applied to determine the composition and quantity of the outlet streams. MFA has been widely used for CDW to complement decision-making related to the production and usage of recycled aggregates (Zhang et al., 2018).

Several classifications appear in the literature on recycled aggregates from CDW processing. Considering the composition, in general, recycled aggregates can be divided into three or four main categories: recycled concrete aggregate (RCA), recycled masonry aggregate (RMA), and mixed recycled aggregate (MRA) (Cantero et al, 2018). There is a fourth category considered by some authors: construction and demolition recycled aggregates, which differ from the previous in the high level of contaminants, such as asphalt, glass, plastics, and wood (Pedro et al., 2018).

The recycled aggregates also differ in particle size distribution: coarse, fines, and all-in-one. In general, the incorporation of coarse recycled aggregates in concrete has already been

accepted, although with restrictions, set by the construction industry. In fact, full substitution is allowed in some countries in particular situations. The use of fine recycled aggregates (FRA) is most limited even though this fraction represents about half of the total CDW weight (Ulsen et al., 2013). FRA can be incorporated between 20% and 50% for various applications (Muñoz-Ruiperez et al., 2016); however, they are firmly excluded from concrete and mortar productions by almost all existing standards and regulations.

CDW aggregates are being considered as possible candidates for the development of EoW criteria at the European level for increasing the recovery of resource. If this becomes a reality, construction products will be regulated by CPR as far as the functional criteria and CE are concerned (Velzeboer and Van Zomeren, 2017).

2.4. Definition of evaluation criteria

The technological criteria are necessary to compare the different technological alternatives that fulfil the main objective of the CDW recycling plants: obtaining valuable products. Generally, recovery is divided into three sub-categories: preparation for reuse, recycling, and other recovery. The differentiation between the terms, recovery and recycling, is relevant in relation to 'backfilling' materials. One of the most critical aspects of the EU waste framework directive is the inclusion of backfilling in the recycling percentage, considering that backfilling is a waste substituent to other materials (Giorgi et al, 2018); for example, in the UK, in 2014, backfilling accounted for 75% of the recovery, whereas 25% was recycled.

Two technical criteria are used in this work to compare the CDW management alternatives: (i) the recovery rate, as the ratio CDW prepared for reuse, recycled, or subject to material recovery, including backfilling operations, divided by inlet CDW; (ii) recycling rate, as an indicator similar to recovery rate but excluding backfilling. Backfilling is lower in the waste hierarchy than recycling is. However, currently, no harmonised definition of the application of backfilling in the waste framework directive exists; therefore, the defining line between recycling and backfilling differs among member states.

In terms of global warming potential, the most environmentally friendly method of treating CDW is recycling compared with incineration and landfill disposal (Rangel et al., 2019); however, the operation of CDW recycling facilities presents three main potential environmental impacts: energy, noise, and particles generation. Furthermore, even though most of the energy consumption and CO₂ emissions of a building occurs throughout its lifetime, 7–14% originates from the production of materials (Atmaca and Atmaca, 2016).

Emissions from the combustion of fossil fuels and energy consumption at the recycling plant have been selected in this work as environmental criteria. Coelho and de Brito, 2013b and Azúa et al., 2019 also used CO₂ emissions as a basic indicator to assess the contribution of CDW recycling system to the greenhouse effect, and particularly, to compare the characteristics of different systems. Emissions are reported as tCO₂e/year using the appropriate emission factors (EF) associated with CO₂ (Cifrian et al., 2012).

The proposed methodology would require revisiting the second step of Figure 1 (CDW recycling plants) if the aggregates obtained do not reach the required standard of quality, or the technological level of the recycling facilities does not allow the achievement of the required levels of any evaluation criterion.

The criteria discussed in this paper (recycling percentage, resource recovery percentage and global warming potential) are generic suggestions that must be adapted to consider the specificities of the area under study along with project-specific costs, scheduling constraints, and relevant social and stakeholder considerations.

This four-step methodology is a general procedure that can be applied at multiple locations; however, local circumstances including the scale and the surroundings of the project drastically influence the results of CDW management; therefore, it is crucial to acknowledge this diversity.

3. Case study: Santander county

As a case study, the general methodology developed in this paper is applied in the county of Cantabria, a Spanish region located in the North of the Iberian Peninsula with 581,413 inhabitants (2017), 45% of which live in Santander (capital of Cantabria) county (~1,000 inhabitants/km²). In this work, this highly populated county is studied since the low population density areas of Cantabria with the low generation of CDW, low occupancy, and high transportation distances require different analyses due to the important effects of these factors at the environmental and economic level.

Figure 2 summarises the experimental application of the proposed methodology in the case under study.

3.1. Composition and destination of CDW

During the Spanish construction boom from 2000–2008, between 120,000–190,000 tonnes/year of CDW were generated in Cantabria (CFP, 2015; Dosal, 2015). From 2009 to date,

reductions of up to 90,000–110,000 tonnes of CDW have been recorded. For the case study, Santander county, it is estimated that 50,000 tonnes of CDW are generated annually; this value fits the CDW generation ratios in $\text{kg.inhabt}^{-1}.\text{year}^{-1}$ from Santos et al., 2017.

Proper segregation at a demolition site is the main condition that must be satisfied to ensure the best recyclability of the CDW; however, at present, Cantabria records low percentage of source segregation (15%), which leads to highly mixed waste. Hypothetical and future situations, where the regional government promotes segregation at the source, would significantly improve the segregation outline, around 85%.

Table 3 shows the distribution of the waste quantities generated in two main scenarios considering the segregation levels applied in Cantabria, at present (15%) and in the future (85%). In each of these scenarios, two additional versions are defined, as explained in Table 2. The petrous fraction can be mixed with the same type of waste, as in mixed petrous (MP), or it can be mixed with other types of waste, as in mixed CDW (MCDW). The non-petrous fraction contains metals and can be mixed with other metals (MM) or mixed CDW (MCDW). Based on the previous data obtained in the region under study (Dosal, 2015), proportions of 20% and 80% are considered for the mixed streams (MP or MCDW)-in the petrous part, and proportions of 30% and 70% of mixed metal or mixed CDW in the non-petrous parts (Table 3).

3.2. Set up of the two types of recycling plant

The high CDW values in Cantabria at the end of the 2000s led to the opening of three treatment plants between 2010 and 2011 with a global capacity of more than 430,000 tonnes/year; two of these recycling plants are located at the Santander county (area under study). As is the case with most of the Spanish CDW plants, the activities of these facilities are based on relatively simple sorting methods-(Rodríguez-Robles et al., 2015).

Regarding the management of CDW in the Santander county, the current situation and future forecasts necessitate the adaption of the number and characteristics of the CDW treatment plants to the realistic amount of waste generated, as well as to the future recycling targets for CDW. Consequently, two types of recycling plants have been considered in this study: *basic* recycling plant (Fig. 3) and *advanced* recycling plant (Fig. 4). The basic plant is similar to the industrial recycling plant in Cantabria and it is one step simpler than the simplest in Oliveira-Neto et al., 2017. The advanced recycling plant is similar to the medium of Oliveira-Neto et al., 2017 and can also be labelled as Level III in Symonds Group Ltd. (1999) (Coelho and De Brito, 2013a; Pacheco-Torgal et al., 2013).

The capacity of the plant under study is 60,000 tonnes/year considering a 20% security factor. Oliveira-Neto et al., 2017 adopted a production level of 100,000 tonnes/year as a small capacity for the recycling plant and indicated that this small capacity is the most common in Europe, currently. The capacity of the plant under study is lower than this value; however, it is adapted to the specificity of Cantabria.

Basic CDW recycling plant

Figure 3 shows the process flow diagram of this recycling facility. An initial classification is made at the discharge area, diverting contraries, large materials, and reinforced concrete. Large materials are destined to crushing, and once the sizes are adequate, they are merged with the rest of the input. The crushing unit (~~jaw crusher~~) is only used for large materials. In fact, the presence of large amounts of iron inside the panels in reinforced concrete impedes the use of this machinery for crushing because the rubber conveyors could be easily damaged. Consequently, this recycling plant treats reinforced concrete manually, being unable to recover all the materials contained (steel and concrete). After the first size separation, a magnetic separation is applied to recover ferrous metals, and the separation of fines and all-in-one is developed by a rotating screen. In the coarse fraction, more classification steps are applied to divert low-density materials, using an air sifter and a hand sorting cabinet. In this recycling facility, mixed and segregated waste are not treated in batches.

Advanced CDW recycling plant

For this recycling facility (Fig. 4), the process consists of two previous steps for sorting large contraries, to crush the waste stream before subsequent treatment. Once the stream is crushed, a more specific classification is used to separate metals; eventually, this stream is separated into two fractions: fines and all-in-one, and coarse. On the one hand, the fines and all-in-one fraction is cleaned in spirals in a wet classification to produce high-quality products, although a sludge output that should be properly treated is generated. On the other hand, the coarse fraction is treated with wind sifting and two steps of wet classification, to remove contraries from recycled aggregates. In fact, in these wet classification steps, the ceramic coarse fraction can be separated from concrete; finally, concrete is treated under specific conditions to eliminate gypsum and affording two different recycled aggregates: concrete and ceramic. Furthermore, this type of plant is based on the scheduling of different batches, with segregated materials treated separately from mixed ones, leading to different types and qualities of recycled aggregates.

3.3.- Quality and destination of the final products from CDW recycling plants

Mixed recycled aggregates are obtained from the basic recycling plant, while recycled concrete aggregate with high-added value and recycled ceramic aggregate are obtained from the advance recycling plant (Table 5).

Based on data from Coelho and de Brito (2013a) and the real data from CDW recycling facilities in Cantabria, the particle size distribution obtained in the recycling plants consists of 43% coarse aggregates and 57% fines fraction with the all-in-one fraction included in the latter. To distinguish between fines and all-in-one, data from the study developed by Dosho, (2007) is used in this work, in which the fine fraction is formed by 60% fines and 40% all-in-one.

In addition to the aggregates, the comparison in Tables 4 and 5 indicates that two more output streams are generated in the advanced plant compared with the case in the basic recycling facility: sludge, and gypsum & light material streams are produced due to wet classification mainly. The separation of these two types of stream improves the quality of the recycled aggregates produced, allowing them to be used in upgrade applications. In fact, for low segregation scenarios (scenario 1A and 1B) more than 3,000 tonnes/year of gypsum & light materials, and sludge are separated in the advanced plant.

In Table 4, it is observed that the total quantity of recycled aggregates (sum of coarse, fine, and all-in-one) is around 35,500 tonnes/year in all scenarios and represents around 74% of the total streams in the recycling plant. Furthermore, the differences between the coarse, fine, and all-in-one aggregates are lower than 2%. Clearly, in the basic plant, neither the source segregation nor heterogeneity influences the recycled aggregates due to the contamination of the mixture. The final destination of fines and all-in-one fractions is downcycling, e.g. as filling materials in road construction. While road construction activities are expected to remain stable in the near future, the amount of recycled aggregates from CDW is expected to increase constantly (Di Maria et al., 2018).

Ceramic aggregates and concrete aggregates are differentiated in the advanced plants (Table 5); furthermore, differences in particle size distributions and three grades are considered. The different grades of the aggregates are because the segregated, petrous, and CDW streams are treated separately; therefore, high grade originates from segregated streams, medium grade from petrous streams, and low grade, from mixed streams.

3.4. Application of evaluation criteria

Tables 4 and 5 show the recycling rates (%) where downcycling is not included and resource recovery rates (%) where backfilling is included. Large differences between both rates are observed in the basic plant (Table 4) and small differences are observed in the advanced plant (Table 5). In the basic plant, less than 50% of the recycling goal is achieved, although 87% of the resource recovery rates are obtained. Furthermore, it is clearly observed that the basic plant is not influenced by the source segregation percentage or contaminant levels. For the advanced plant, high recycling and recovery percentages are obtained for 3 out of the 4 scenarios that fulfil the EU target, even with the exclusion of downcycling. Downcycling of low-grade fines and all-in-one ceramic aggregates leads to the lowest recycling ratio and resource recovery in scenario 1-B. The difference between the recycling percentages in scenarios 1-A and 2 is low; this indicates that even at low segregation levels, a high percentage of recycling can be achieved if efforts are made to avoid the contamination of petrous waste with other CDW.

In this work, the CO₂ emissions from the energy consumption (diesel oil and electricity) of the recycling plants are considered as environmental criteria to compare both types of plants. Notably, fuel consumption produces emissions *in situ*, while electric energy consumption produces remote emissions. First, CO₂ emissions of fuel consumption are calculated using the CO₂ emission factors for diesel consumption included in the Spanish emissions inventory for 2012 (Magrama, 2014). This inventory proposed a low calorific value (LCV) of 42.4 GJ/tonne for gasoil, considering an average density of 850 kg/m³ for diesel, and an emission factor of 73 tCO₂e/TJ. In addition, the emissions derived from electric energy consumption are calculated considering demand coverage, which is the source of this energy (including nuclear, coal, and wind energies). Data regarding the demand coverage in Spain are periodically published by the sole transmission agent and operator of the Spanish electricity system REE, 2014). Emission factors derived from kWh consumed are calculated annually by the *Spanish observatory of electricity (2014)*, and for CO₂, the value is 0.273 kg/kWh. From the estimated emissions derived from energetic consumption (Table 6), it can be observed that the advanced plant generates around 10% tonnes more CO₂ than the basic plants does, due to the higher number of equipment involved in the process. Furthermore, both facilities are mainly influenced by the segregation level, but not by the heterogeneity levels.

The authors published a research (Dosal, 2015) about location of CDW recycling and storage facilities in Cantabria considering environmental and economic objective functions. From this study, values around 30–50 tCO₂e /year can be estimated for the transportation of 50,000

tonnes/year CDW in the case under study (Santander county), which is lower than the emissions due to recycling processes; noteworthy, this area is highly populated.

4. Discussion

There are numerous differences related to the CDW generation and treatment due to variations in amount and type of CDW generated, level of source segregation, data collection method, available CDW management infrastructures, standards and specifications for the use of recycled aggregates, etc. Similarly, there are important differences in the global socio-political and economic framework, such as the legislation on waste management, level of environmental protection, waste prevention programs and actions, policies related to recovery targets, and implementation of EoW, among others (Deloitte, 2017). Moreover, the targets and recommendations for CDW management need to be applied at the national, regional, and local level despite the differences between the levels; therefore, any methodology that considers the regional and local realities in coherent decision making, is essential (Bilsen et al., 2018).

The methodology described in this paper, based on four steps, can be applied to compare the CDW management options considering a wide range of situations of CDW generation, destination, treatment, and market of final products in different geographical areas. However, the proposed approach is not meant to be rigid or prescriptive, but to be a flexible methodology, in which the adaptation of its steps to the peculiarities of the case under study is crucial.

Selective dismantling of buildings and waste segregation minimize CDW and increase the acceptability of recycled aggregates, thereby making it easier to reuse and recycle; in the same way, CDW processing and recycling techniques with high performance can produce high-quality aggregates (Gálvez-Martos, et al, 2018; Ajayi et al, 2017).

The definition of several potential scenarios is particularly important when input data are subject to uncertainty (e.g. variable CDW generation rates and/or recycling targets to fulfil) and can be useful for the adoption of the best management framework (Coelho and de Brito, 2013b; Zambrana-Vasquez et al., 2016). In the present work, four different scenarios with the combination of two different segregation levels and two homogeneity levels of CDW were developed (Tables 2 and 3). The percentages (by weight) of the different components in the

inlet stream of a typical Spanish recycling plant are given in Table S1 (Supplementary Information). In southern European countries, due to the construction traditions, the petrous fraction of the CDW is around 80%, while 20% is non-petrous. The actual situation in Cantabria shows that the largest quantity of CDW is mixed streams (39,271 tonnes/year) coming from a low segregation level (Table S2, supplementary information). The significant difference between the tonnes/year in the present (scenario 1 with low segregation level) and in the future (scenario 2 with high-segregation level) is shown in Table S2. Scenario 1-B is the worst scenario (low segregation and high heterogeneity/mixing) since mixed CDW has the highest value (32,982 tonnes), and scenario 2-A is the best scenario (premium segregation and low heterogeneity/mixing) since mixed CDW has the lowest value (5,333 tonnes).

Additionally, two recycling plants with different technological levels are considered in the present work. The implementation of effective separation systems is key for improving the competitive performance of recycled aggregates, both in price and quality, compared to natural aggregates (Cazacliu et al., 2014; Ambrós et al., 2017). Several studies have shown the effect of recycled technology on different aspects of the CDW recycling performance. Olivera-Neto et al., 2017 proposed an economic analysis of three different types of CDW sorting recycling platforms in terms of internal rate of return (IRR), and showed that current advanced processes exhibit improved economic performance; moreover, they also showed that the IRR for the most advanced sorting processes depends on the market conditions and fiscal or incentive policies.

Considering the actual low segregation level at Cantabria and the target of recycling of non-hazardous CDW set at 70% (minimum) by the EU, Cantabria fulfils this target. However, to reach this target without considering downcycling, it would be necessary to utilise the advanced recycling plant; furthermore, careful segregation is required to avoid the contamination of petrous fractions with uneven waste. The future in Cantabria (to reach 70% of the recycling rate without backfilling) is similar to that in the rest of Europe. The usage of advanced recycling plants is essential; higher segregation rates and lower heterogeneity of CDW are favourable.

In relation to the final products from recycling plants, if the quality of the materials is assured by a reputable brand, builders will be more willing to use the materials. The properties of recycled aggregates need to be studied in-depth according to their source to generalize their utilisation into relatively high-performance applications. At the European level, a set of legal,

technical, and economic measures has been adopted by the member states to promote recycled aggregate production and use. Similarly, Austria, Belgium, France, The Netherlands, and the United Kingdom have EoW criteria in their national legislation mainly for recycled aggregates (Deloitte, 2017). Spain is at the lowest level of maturity concerning the incorporation of reclaimed and recycled content; in particular, in Cantabria, only an average of 9% of the demand for aggregates was met with recycled aggregates, and most of the recycled products are used as backfilling (Cantabria Economica, 2017). Consequently, regulatory and market barriers have been highlighted as the main obstacles observed in Spain to the effective recycling of the aggregates (Galvez-Martos et al., 2018).

If a waste-derived aggregate achieves EoW status, it will become a construction product, which will be regulated by the CPR. The CPR and its *Basic Requirement of Construction Works (BRCW) 7-Sustainable use of natural resources* would be a driver for reuse. The conditions for the use of construction products and the requirements on the construction product are set at the national level, and currently, there are differences at member states or even at the regional level, for the implementation and use of standards and specifications of recycled aggregates. Construction sector industries are increasingly obtaining environmental product declaration (EPD) to communicate transparent information about the life-cycle environmental impact of products, which allows facile comparison among products.

From the results of the present work, it is observed that the percentage of concrete aggregates obtained using an advanced CDW recycling plant varies from 6% to 12% of the total CDW in scenarios of low and high segregations, respectively, and the percentage of ceramic aggregates varies from 65% to 60% of the total CDW (Table 5). The use of recycled aggregate from CDW in different types of concrete contributes towards the sustainable growth and development of the construction industry (Santos et al., 2019; Behera et al., 2014). Conversely, ceramic and mixed recycled aggregates exhibit good mechanical performances and can be applied in the sub-base and base layers of low traffic roads (Vieira and Pereira, 2015).

Different criteria and methodologies have been used in literature for the location, design, and performance of CDW recycling plants (Bovea and Powell, 2016; Ulubeyli et al., 2017; Madi and Srour, 2019). Recycling percentages, resource recovery, and CO₂eq emission criteria have been used in the present work to compare alternatives; large differences are observed between recycling percentages and resource recovery percentages for both types of plants. The EU recovery target for CDW does not favour the most sustainable operations since backfilling is a recovery option that generally results in both low benefits and future environmental risks. Arm

et al., 2017 recommended not considering backfilling as equal to other operations; the authors of this work, based on the results of recycling and recovery rates, agree with this recommendation.

CO₂eq emission from a CDW recycling plant has been used previously in the comparative analysis of the environmental impact as a simplified indicator since CO₂eq emission is one of the most important environmental factors to be determined in current industrial systems (Coelho and de Brito, 2013a,b). The results of CO₂ emission in the present work are slightly higher than those obtained by Coelho and Brito, 2013a, probably due to the different mixes of energy and facility capacity. The impacts per processed mass unit increase with decreasing capacity. The behaviours of the two types of recycling plants are different: the basic plant is not influenced by the inlet stream, except for the emissions of tCO₂e/year; however, even in that case, high segregation rates decrease the CO₂ emissions. Conversely, the advanced plant behaves better for high segregated input stream even though the difference between low segregation-low heterogeneity and high segregation-high heterogeneity is not wide. However, as expected, the best option is the high segregation-low heterogeneity.

The present study allows the classification of different CDW treatment alternatives through different scenarios; however, supplementary research focusing on accurate economic, technical, environmental, and social information would be suitable for tackling all the issues related with CDW recycling plants from a broad point of view.

5.- Conclusions

Demolition processes directly impact the products obtained in CDW recycling plants since the input streams to the recycling plant present different compositions. The characteristics of the input streams and the final product from two types of recycling plants were studied in this work considering two factors: the percentage of segregation during demolition and heterogeneity of the CDW composition.

A methodology for the preliminary classification of CDW management alternatives has also been proposed using real data. The influence of *the technological level of the recycling plants* and *CDW characteristics* was analysed based on two technical criteria (resource recovery percentage and recycling percentage) and one environmental criterion (CO₂ emission).

MFA was carried out to obtain the quantity and composition of the final product from the recycling facilities. The results indicate that, presently, in Cantabria, in which basic recycling plants are dominant, neither segregation nor heterogeneity influences the product streams;

furthermore, the basic recycling plants can reach the minimum non-hazardous CDW target set at 70% by the EU. However, if backfilling is excluded, high levels of segregation and advanced plants would be necessary in Cantabria to obtain high percentages of recycled products. The concrete aggregates (6% to 12% of the total CDW) and the ceramic aggregates (65% to 60% of the total CDW), obtained under different scenarios in the plants, can be utilised by the construction industry in Cantabria.

Acknowledges

This work has been supported by the Cantabrian government R&D project 2018-2020 entitled “Obtaining, processing and dissemination of data on production and waste management and adaptation of the current indicators to the new waste plan of Cantabria”.

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Table 1. Components and destinations of different type of CDW streams

Table 2. Four scenarios obtained from the combination of at-source segregation grade and mixing grade

Source Segregation Grade			
Scenario 1		Scenario 2	
Low		High	
Heterogeneity (mixing) of fractions			
1-A	1-B	2-A	2-B
Low	High	Low	High

Table 3. Distribution of the component at each scenario.

WASTE STREAM	Scenarios (Tonnes)			
	1-A	1-B	2-A	2-B
Petrous	80%			
Segregated Streams	15%		85%	
Mixed Streams	85%		15%	
Percentage	80% MP 20% MCDW	20% MP 80% MCDW	80% MP 20% MCDW	20% MP 80% MCDW
Non-Petrous	20%			
Segregated Streams	15%		85%	
Mixed Streams	85%		15%	
Percentage	70% MM 30% MCDW	30% MM 70% MCDW	70% MM 30% MCDW	30% MM 70% MCDW

Mixed Petrous (MP); Mixed metals (MM); Mixed CDW (MCDW)

Table 4. Final products from a basic CDW recycling plant.

OUTPUT	Scenarios (Tonnes)			
	1-A	1-B	2-A	2-B
Stone and soil	1,702	1,702	1,702	1,702
Bituminous material	2,008	2,008	2,008	2,008
Gypsum	49	49	89	88,9
Wood	1,124	1,124	1,800	1,800
Wooden plank	506	506	506	506
Glass	62	62	11	11
Paper/cardboard	269	269	269	269
Reinforced concrete block	1,776	1,776	888	888
Mixed metals	7	245	20	47
Metal (Fe and steel)	270	317	51	80
Low density materials	2,504	2,504	993	993
Other waste	1,636	1,636	3,092	3,092
Plastic	Other plastic	203	203	354
	PVC	180	180	314
	Film	144	144	144
Mixed aggregates	Coarse	15,293	15,332	15,266
	Fine	12,150	12,166	11,810
	All-in-one	7,955	7,958	8,041
Recycling percentage (%)		45,85	45,81	48,02
Resource recovery percentage (%)		87,69	87,66	87,83

Table 5. Final products from advanced CDW recycling plant.

OUTPUT			Scenarios (Tonnes)			
			1-A	1-B	2-A	2-B
Stone and sand			1,702	1,702	1,702	1,702
Bituminous material			2,037	2,037	2,037	2,037
Gypsum			51	51	89	89
Wood			1,294	1,294	1,830	1,830
Glass			62	62	11	11
Wooden planks			620	620	620	620
Paper/cardboard			333	333	333	333
Mixed metals			147	316	34	67
Other waste			1,761	1,761	3,114	3,114
Metal (Fe)			215	332	81	103
Metals (Al, Cu,...)			0.14	0.33	0.03	0.06
Sludge			1,635	3,400	843	1,821
Low density materials			2,095	2,095	811	811
Gypsum and light materials			1,256	1,258	290	290
Plastic	Other plastic		247	247	418	418
	PVC		199	199	261	261
	Film		176	176	176	176
Ceramic aggregates	Coarse	High G.	1,694	1,694	9,599	9,599
		Medium	7,956	1,989	2,231	557
		Low G.	2,784	8,792	1,022	2,704
	Fines and all-in-one	High G.	2,245	2,245	12,724	12,724
		Medium	13,530	3,382	3,276	819
		Low G.	2,863	11,261	505	1,987
Concrete aggregates	Coarse	High G.	383	383	2,151	2,151
		Medium	1,567	392	279	6
		Low G.	486	1,662	87	296
	Fines and all-in-one	High G.	501	501	2,833	2,833
Recycling percentage (%)			80	59	88	82
Resource recovery percentage (%)			85	82	88	86

Table 6. CO₂ Emissions from diesel and electricity consumption.

Teq CO ₂ /year		Scenarios for Basic Plant				Scenarios for Advanced plant			
		1-A	1-B	2-A	2-B	1-A	1-B	2-A	2-B
Diesel	tCO ₂ e/year	76	76	62	62	49	50	42	42
Electric	tCO ₂ e/year	36,5	35	33	31	70	71	61	61
Total (tCO₂e/year)		113	111	95	93	120	121	103	103

Figure 1.-Proposed methodology for selection of the best CDW management alternative

Figure 2: Flowchart of the experimental program applying the proposed methodology to the case study.

Figure 3. Flow diagram of basic recycling plant.

Figure 4. Flow diagram of advanced recycling plant.