# An economic analysis of the processing technologies in CDW recycling platforms

Raul Oliveira Neto, Pascal Gastineau, Bogdan Cazacliu, Laurédan Le Guen, Régis Sebben Paranhos, Carlos Otavio Petter

# An economic analysis of the processing technologies in CDW recycling platforms

Raul Oliveira Neto[1], Pascal Gastineau[2], Bogdan Grigore Cazacliu[3], Lauredan Le Guen[3], Régis Sebben Paranhos[1], Carlos Otávio Petter[4]

[1]LATRAM, Federal University of Pampa (UNIPAMPA), Mining Planning and Mineral Processing Laboratory, Caçapava do Sul, Brazil.
[2]LUNAM Université, IFSTTAR, AME, EASE, F-44340 Bouguenais, France.
[3]LUNAM Université, IFSTTAR, MAST, GPEM, F-44340 Bouguenais, France
[4]Federal University of Rio Grande do Sul (UFRGS), Engineering School, Department of Metallurgy, Av. Bento Gonçalves, 9500, Agronomia, 91501-970, Porto Alegre, Brazil.

This paper proposes an economic analysis of three different types of processing in CDW (construction and demolition waste) recycling platforms, according to the sophistication of the processing technologies (current advanced, advanced and advanced sorting). The methodology that is adopted is in the economic evaluation concept of projects and is classified with a scoping study phase. In these contexts, three levels of CDW processing capabilities for recycling platforms are analyzed (100, 300 and 600 thousand tons per year). This article considers databases obtained from similar projects that have been published in the specialized literature; the data sources are primarily from the European continent.
The paper shows that current advanced process has better economic performance, in terms of IRR, related to the other two processes. The IRR associated with advanced and advanced sorting processes could be raised by, (i) higher price of secondary primary material, and/or (ii) higher capacity of platforms, and/or (iii) higher sharing of secondary primary material in the total production. The first two points depend on the market conditions (prices and total quantity of CDW available) and (potential) fiscal or incentive policies. The last one depends on technological progress.

## 1. Introduction

The theme of construction and demolition waste recycling has been the subject of studies and research since the 1970s, and the main reasons for these studies are the growing awareness of the importance of waste recycling from all sources in the context of "Sustainable Development" (Pacheco-Torgal et al., 2013). Governments inserted in this context began to conduct surveys to estimate the level of waste generation from construction and demolition; the numbers are truly alarming. In the European Union (EU), construction and demolition waste (C&DW) is one of the heaviest and most voluminous waste streams generated, and it is a priority sector for investments.[1]

The construction industry generated more than 850 million tons per year of waste throughout the EU in 2008, and this waste stream was approximately 33% of all waste produced (Staunton et al, 2015). Among the countries whose amounts of C&DW generation are known, France has an average of 359 million tons per year (ADEME, 2011) and the United Kingdom (UK) has an average of 90 million tons per year (Williams & Turner, 2011); these two countries account for approximately 70% of the estimated waste generation in Europe.

[1] http://ec.europa.eu/environment/waste/construction_demolition.htm (07/20/2016)

The legislation has an important role in C&DW recycling, and in this sense, through the revised Waste Framework Directive 2008/98/EC (WFD), the member states set an ambitious goal of achieving a 70% level for the recovery of waste generated at building and public works construction sites by the year 2020. These regulations forced even further financial investment in research projects to develop C&DW sorting technologies that are increasingly efficient to generate recycled products with uses in the manufacturing of construction materials. However, EU statistics from 2011 showed that the level of recycling and recovery of materials CDW varies greatly between less than 10% and over 40% across the Union. For example, in 2012, the valorization rate of CDW reached 95.5% in Germany and the main goal of the involved parties is to keep this rate in the future. In Denmark, the overall goal is to obtain a better quality of recycled C&DW and at the same time maintain a high recycling rate. At the opposite, in France, C&DW management is an emerging issue, very dynamic in terms of technical innovation, but which suffers from the lack of political will and customers' interest in general and which also depends heavily on logistics, cost conditions and tax policy.

To confirm this fact, the French General Council of the Environmental and Sustainable Development (CGEDD, 2015) observes that there is a lack of investment in order to respect the WFD objectives. The same observations are published in the academic research studies (Paula & Leroy, 2014). Studies in 2014 indicated that France recycled 50% of the total amount of generated C&DW.

This context has given the framework for some research programs, which have the objectives to define the technological tools to respect the WFD goals. Then, several research programs are carried out. For example, the subject of the C2CA European program (C2CA, 2016) is the advanced technologies for the production of cement and clean aggregates from construction and demolition waste.[2] In addition to the technological aspects of sorting process, the economic impact of sustainable concrete was included in the scope of research work. In the continuity, the HISER European project (HISER, 2016) begins in 2015.[3] The academic and industrial partnership wants to optimize the sorting process for construction materials. This recycling optimization could treat more C&D waste.

In parallel, many academic studies are performed such as these of de Brito (de Brito & Silva, 2016). In the more recent one, he proposes several orientations to bring added value to C&D waste on the base of the state of art about recycled concrete aggregates.

This general context shows the necessity to take overall measures to reduce environmental and cost impacts of this huge amount of waste that can still be recycled. Developed countries struggle hard to meet the general target of C&DW recycling. We generally distinguish three ways to improve the recycling rate: standards (regulation), economic instruments or technological progress. Most of countries use basic platform or landfill. We here focus on the financial analysis (scoping study) of three innovative processes that produce high-grade recycled aggregates.

Economic evaluation has fundamental importance in the context of these projects and efforts to improve construction and demolition waste sorting by applying advanced techniques to obtain an improvement in the separation performance of the different C&DW components. Many studies addressed economic analysis of C&DW management recycling (Nunes et al., 2007; Duran et al., 2006; Zhao et al., 2010, Huang et al., 2002; Coelho & de Brito, 2013). These studies involved such different assumptions and contexts (Brazil, Ireland, China, Taiwan, Portugal) that it would be invalid to compare their results directly. The assumptions of these analyses differ in a number of ways: discount rate, period length, technology, scale of the recycling centre, etc. Garbarino and Blengini G.A. (2013) provided a good overview of the literature on the economics of construction and demolition waste (C&DW) management facilities. The authors identified drivers and contraints for the development of recycling sector: taxation on natural aggregates, landfill taxation, quality of recycled/seconday aggregates from C&DW, etc. They also provided some estimates of the investment and operting costs associated with mobile and stationary plants for C&DW recycling.

To our best knowledge, there is no study that has already assessed the economic profitability of the three considered processes (especially the two most efficient processes). Our preliminary assessment of the economic feasibility of these C&DW sorting uses on the classical "discounted cash flow" method. We have a special

[2] www.c2ca.eu/ (07/20/2016)

[3] www.hiserproject.eu/ (07/20/2016)

focus on the investment decision indicators such as net present value, payback period and internal rate of return. Our analysis relies on assumptions concerning operating parameters of recycling facility, initial and operating costs. Here, we focus merely on the financial (economic) analysis and do not calculate the environmental costs and benefits causes by the three processes life cycle. As shown by the literature review provided by Bovea & Powell (2016), the environmental impacts associated with construction and demolition waste crucially depend on the context (i.e. transport distance is recognized as a critical process). As this preliminary analysis is undertaken prior to a more site-specific study, we were not able to offer a proper assessment of environmental impacts due to lack of data. Nevertheless it should be noted that it is commonly accepted that the environmental impacts of a material produced from virgin materials are higher than the ones of its equivalent produced using recycled C&DW (Bovea & Powell, 2016).

The main objectives of our analysis are:

i. search and estimate the basic economic data in the construction sector for recycling materials in the European continent;
ii. analyze the differences, from the economic point of view, between three types of technological sorting methods into three scales of C&DW recycling platforms, regarded as small, medium and large sizes;
iii. check the economic feasibility for each case using the method of discounted cash flow.

The article is organized as follows. Section 2 describes the considered C&DW sorting. Section 3 presents the data and the approach used to assess the economic profitability of the three platforms. Section 4 reports and discusses the results. Finally, Section 5 presents some concluding remarks.

## 2. Description of the Considered C&DW sorting

The C&DW sorting processes actually used in the recycling plant vary greatly amongst countries and amongst regions of the same country. For example, the inventory given by the French agency of energy (ADEME, 2011) shows a large variability in terms of technology and process used for the recycling platform. However, one can have a listing of the sorting process types. An overview about the C&DW management (Pacheco-Torgal et al., 2013) gives this inventory. According to this reference, three technical levels for C&DW management plants are identified:

- Level 1: mobile crusher and sieving plant;
- Level 2: same as level 1, plus metal collector and more complex sorting/sieving;
- Level 3: same as level 2, plus hand-sorting, washing plant and appliances for waste streams, other than aggregates such as wood.

However, this problematic of C&DW management demands to propose new processes more sophisticated and more efficient applied to the C&DW sorting so as to respect the European objectives. But the level of technology must be suitable with the economic and regulation context. Thus, we considered three types of sorting in C&DW recycling platforms, called:

- Current advanced process (CA);
- Advanced process (Ad);
- Advanced Sorting process (AdS).

Figure 1 explains how these different processes are implemented. For further details, the following sections describe the steps composing each sorting process.

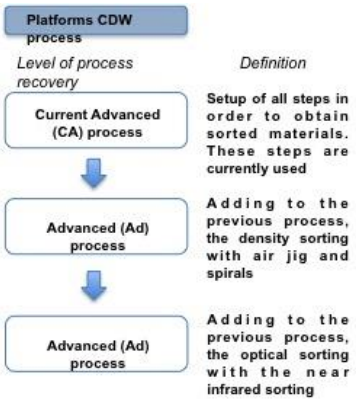


Figure 1 – Flow chart diagram of the CDW's sorting platforms.

### 1.1. Current advanced process - "CA"

"Current advanced process" is an improved current process, or an alternative based on the most common current recycling processes, including the most basic equipment, such as crushers and screens with magnetic separators, but including additional equipment that enable better sorting efficiency and generate material with the final quality of the recycled aggregate. According to Paranhos et al. (2016), this material is currently used in France on roads and terracing; it is rarely used on concrete structures because this type of aggregate is generally obtained from pre-screened sources. This kind of recovery process is composed by four steps (see Figure 2).

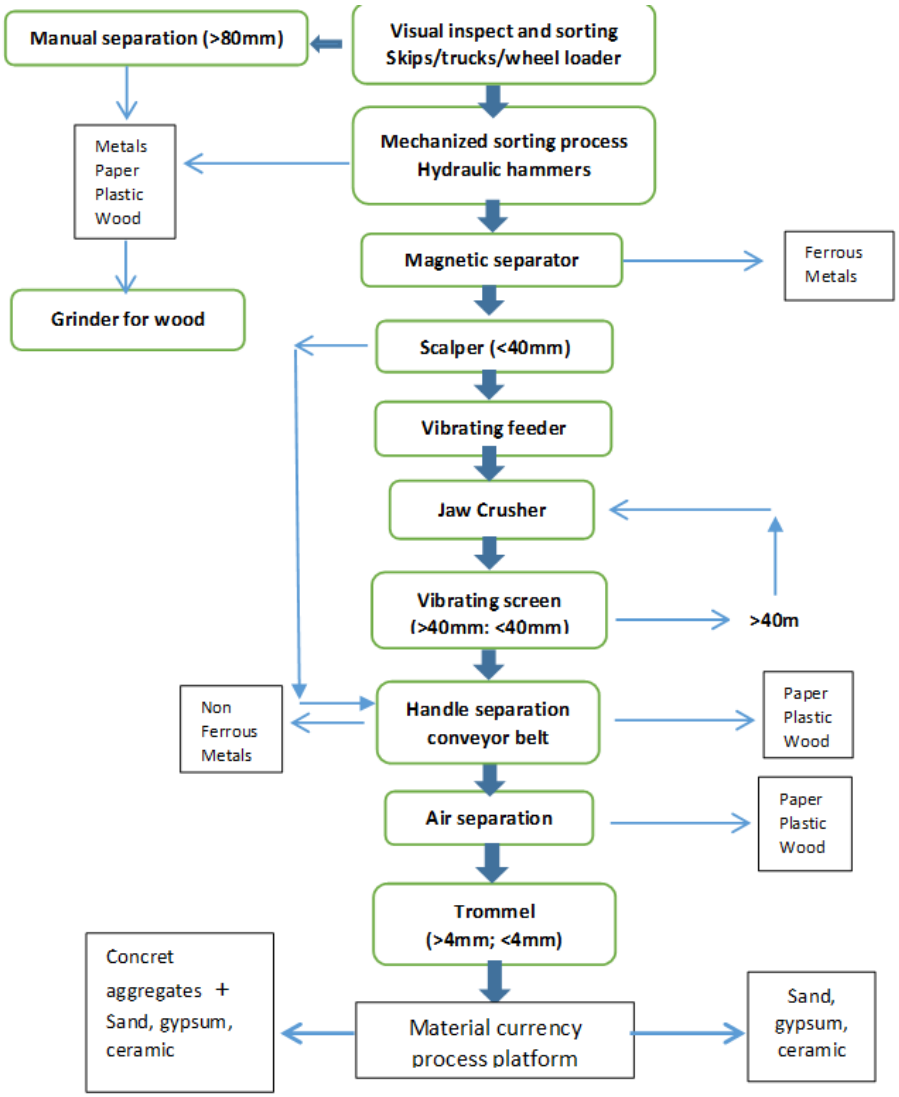


Figure 2 – Flow chart diagram of the Current Advanced (CA) process constituting of four steps using the disposal machines in the optimal way.

The initial step is to stock up on the receiving of the C&DW transported from generating sites by trucks; at first, the sorting was carried out by operators performing visual sorting, with the help of front loaders or bulldozers that can spread material to facilitate the work. This material normally has an average size greater than 80 mm and consists of C&DW with ferrous and non-ferrous metals, paper and cardboard, and wood and plastics components. This stage can be called “preliminary visual inspection and sorting".

The second stage of this first sorting phase in receiving materials is called the "Mechanized sorting process". The operation uses "Hydraulic hammers" installed in the arms of excavators. They have the function of reducing the size of the largest pieces of C&DW, contributing to improved efficiency in subsequent sorting equipment because they disintegrate C&DW components (crushed stone, brick, iron, concrete, etc.) and can generate other visual separations by operators.

After this first step where there is a prior separation in the received C&DW materials, the second phase of continuous sorting is started with the transfer of material through conveyor belts. The first stage of this second step is the loading of the C&DW material directly on the first conveyor that transports to the "Scalper" (fixed grid separator), before passing through the metal detector or "Magnetic separator", whose function is to collect all types of ferrous components (magnetic properties). Thus, these materials are removed in the ongoing process

for reusing or recycling purposes; removing these materials avoids the risk of damaging other mechanical equipment, such as the Crusher, Trommel and Air Separator.

The main function of the Scalper is to remove particles smaller than 4 mm that must pass through the gaps between the fixed grid beams forming a so-called "under-flow"; the Scalper increases the efficiency of the Crusher and vibrating screen.

The over-flow material from the Scalper goes to the Crusher Jaws and then through a vibrating screen whose function is to make the particle size of the crushed C&DW separate into two fractions: bigger than 40 mm and smaller than this size. The larger group is brought back to the crusher, forming a so-called "circulating charge". The particles smaller than 40 mm will be directed to the conveyor belt that proceeds to manual separation by trained operators in identifying different types of components (plastic, paper, cardboard, metals, and others) to be manually sorted and directed to containers after being screened for reuse or final recycling.

In the manual separation sequence on the conveyor, the material that was not screened by operators goes directly to the Air Separator where the particles fall by gravity in a counter-current of blown air that removes the lightweight material from the top of the equipment. This material mainly consists of paper, fine plastic and wood. Some fraction of materials containing gypsum into fine powder will be able to be removed by the air stream.

The next stage is to move the material to the Trommel, a revolving screen whose function is to separate larger fractions and ones smaller than 4 mm in size and to promote a breakdown of the material larger than 4 mm in size. This Trommel step is normally the last step that is employed in C&DW sorting platforms with a more basic level of technology; in this study, this type of platform is called the "Current advanced process - CA".

It is observed that this current level of C&DW processing that generates products after the Trommel step consists in recycled coarse aggregates and sand.

### 1.2. Advanced process - “Ad”

The second type of sorting process considered in this work is called “Advanced – Ad” because it has equipment that provides a higher quality of products. This type of improved process does not currently exist and is being proposed in this study. It is considered to be a new sorting method for recycled aggregates (Paranhos et al., 2015). This process uses the output of the precedent process such as its input flow. Figure 3 describes the synopsis of such process.

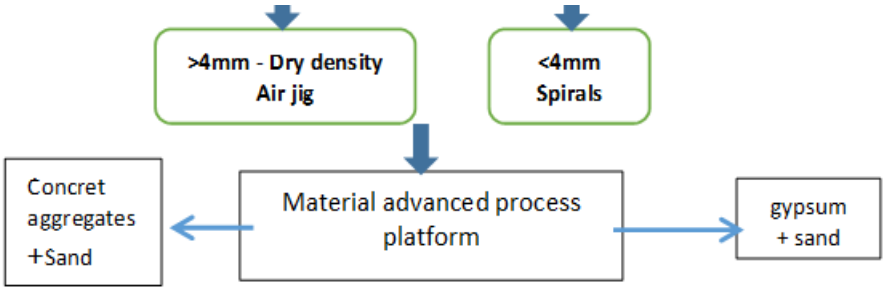


Figure 3 – Synopsis of the Advanced (Ad) process: its input flows are the output of the CA process.

The process to the Trommel follows the same treatment as for the current process. After this point, the processed material is directed into two separation density systems: "dry jigging" (Jig) and “spirals separation" (Spirals).

This equipment allows the generation of products for recycling as ceramic and gypsum aggregates. The Jig is under dry working conditions, without the presence of water as the fluid only in the presence of air. This equipment operates on the principle of particle separation by density difference when subjected to oscillating and pulsed movements in the fluid medium. According to several recent research works (Cazacliu et al., 2014; Sampaio et al., 2016), the dry jig shows a sorting efficiency relevant for C&DW sorting. Indeed, the laboratory experimental studies show the potential results at the industrial scale. The principle of the Spiral is also on

particle segregation by density, but they require aqueous medium fluid. The material flows in density action through spiral channels and separation occurs by action of the centrifugal force.

### 1.3. Advanced sorting process - "AdS"

For the "Advanced Sorting – AdS" process, the difference is the inclusion of equipment called "Near Infrared Sorting". As mentioned for the "Ad" process, "AdS" should be considered as a new method for sorting recycled aggregates (Paranhos et al., 2015). Figure 4 presents an example of such process.

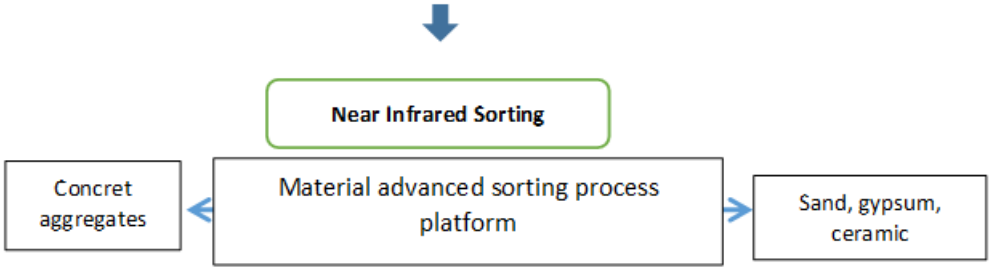


Figure 4 – Example of the Advanced Sorting (AdS) process.

The base of this equipment is the detection of the physical characteristics of materials by emitting infrared beams. The equipment detects the different components and, through a separation system, the different types of materials are separated from the flow, forming final products with higher purity. Thereby, the C&DW platform can produce recycled aggregates with higher quality, enabling usage in the manufacture of construction materials, such as concrete, with greater purity and reliability. This type of sorting process has the principal objective of generating high quality particles that are more liberated. In the C&DW recycling process, the material could not be separated by conventional optical sorting because it has similarities.

### 1.4. Capacities of recycling platforms

Three levels of C&DW sorting processing capabilities of recycling platforms were considered for this study, according to the following criteria:

i. research the input levels of recycling platforms currently in operation, mainly in Europe;
ii. estimate the average quantities that have been generated, considering the per capita annual generation in European countries that are listed in the bibliography;
iii. from these rates of per capita generation, define three levels of platform inputs, considering small, medium and large capacities;

Analyzing the data and information obtained in the bibliography and considering the criteria mentioned, it was decided to adopt production levels of 100, 300 and 600kt/y (thousand ton per year). These amounts correspond to small, medium and large capacity levels and are representative of the current reality of C&DW recycling in the European market.

Production capacities on the level of 100kt/y are the most commonly found currently in recycling platforms in the European continent. Levels of 300kt/y, despite being more uncommon, are found in metropolitan areas with higher populations. It is important to highlight that production levels of 600kt/y has been considered in this study as an extreme situation considering the fact that the higher the level of production, the lower the production costs.

## 2. Methodology

According to the publication of the Minerals Institute entitled "Cost Estimation Handbook" (AusIMM, 2012), this evaluation study is classified with "Scoping study – Phase 1", and the expected accuracy range varies between 30% and 35%.

Two basic concepts in this methodology are very important. The first, "Assessed", means that costs are general benchmarks, and the specific quantities are not yet available. The second, "Factored", means that the general benchmarks are based on extrapolations between different production scale levels.

This work considers data obtained from similar projects, data published in specialized literature and publications of the research organizations and governmental institutions. The experience of the authors was important to provide adjustments through discussion and analysis of the research data.

Figure 5 shows the flow or sequence of the activities adopted during this work.

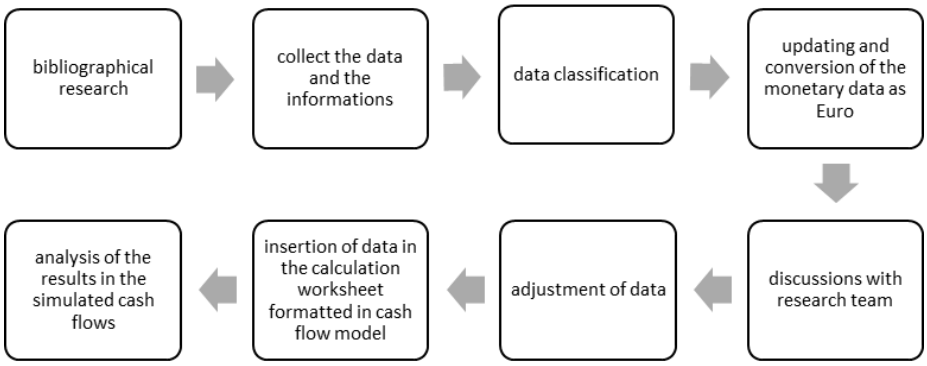


Figure 5 - Flow of activities adopted in the methodology.

The "discounted cash flow" (DCF) method was adopted for the economic order calculations and estimates. The cash flow is the difference between cash inflows and outflows associated with a project for a certain period, and for economic evaluation. Therefore, the composition and calculation of the cash flow should be determined for each year throughout the life of the project according to the following expression (1):

Cash Flow = Cash Entrance Flow (inputs) - Cash Exit Flow (outputs) (1)

Each cash flow period can have positive or negative results and usually the initial periods can be negative because it is the investment and maturation phase. Once you begin sales, the flows are generally positive, although there may be negative periods in cases of project expansion, modification, equipment replacement or equipment installation for environmental control.

The inflows and outflows include the following:

- Cash Entrance Flow (inflows): revenues for receiving the C&DW at the plant; revenues from the sale of the end products generated by C&DW's sorting at the plant;
- Cash Exit Flow (outflows): investment or capital costs; working capital; taxes; fixed and variable operating costs; depreciation;

The economic valuation techniques are used to estimate data for a project by using economic indicators to evaluate its profitability and risk compared to other investment alternatives. To this end, it is necessary to initially assemble the cash flows based on calculations of important economic indicators for analysis and required decision making.

This method considers the Net Present Value (NPV) which corresponds to the sum of the present values of all future cash flows (Zizlavsky, 2014). The calculation of NPV is performed by expression (2):

$$NPV = \sum_0^N \frac{NCF_t}{(1+i)^t} \quad (2)$$

with:

NPV – Net Present Value

$NCF_t$ – Net cash flow at time t (i.e. cash inflow-cash outflow)

t- Time of the cash flow

i - Discount rate

N- Number of periods (years)

The projected cash flow allows obtaining the NPV of financial results or the performance for a project in the adopted lifetime. The parameters that are used include the following:

- Discount rate = 4%
- Number of time periods = 20
- Process recovery = 90% (the final recovery of the amount of waste that feeds the recycling plant, or i.e., it is considered that 10% of the material is rejected by the process and should be discarded into a regular deposit)

After performing the cash flow simulations, it is possible to make an evaluation or economic analysis of the results, using economic indicators such as "Internal Rate of Return (IRR)" (or "Recovery Period of Investment (RPI)").

The Internal Rate of Return (IRR) is the discount rate that equals the present value of positive cash flows to the present value of negative cash flows in an investment alternative. In other words, IRR is the discount rate at which Net Present Value equals to zero.

The Recovery Period of Investment (RPI), or the "Pay-Back", demonstrates the time or period in months or years that is required to recover the value of the initial investment in the project; the lower this number is, better or more profitable the evaluation of the project.

## 3. Analysis of the data and cash flow simulations

The bibliography has thoroughly analyzed and compared the data disclosed in these studies; all data were compared and equalized for the same currency and is up to date for the year 2015, more specifically, the middle of the year, considering the inflation rates of the respective governments.

It was observed that the values have acceptable and appropriate differences to the phase or stage of this study, or "Scoping study – Phase 1", as defined in the previous section referring to the methodology, giving a good degree of reliability in these studies.

Table 1 shows a comparison between the data of these sources consulted in terms of the average variations, for more or less, according to the major classes of cost, capital and operation and general data such as prices, rates, types and equipment capacity.

Table 1 – Comparison between the data sources.

| Type of the data | Variations among the data sources (%) | References |
|---|---|---|
| Capital costs | 7 | Nunes 2004; Lima 2013; Tam 2008; Coelho & Brito 2013; Cortês et al 2013; Cunha & Miceli 2013; Williams & Turner 2011; Muller et al 2013; ADEME & FFB 2011; ADEME 2011; FFB 2014; Duran et al 2006; |
| Operational costs | 15 | |
| Others (prices, taxes, equipment capacity) | 20 | |

An important point that was considered in the analysis of this study is that practically 100% of the data sources are from Europe, indicating that the level of assessed costs is the European scenario.

Most of the data or almost the entire searched database refers to production capacities of recycling platforms that are approximately 50 t/h; the current situation shows that the majority of existing plants or platforms in Europe, with very few exceptions, show similar capacities. This is an important observation obtained during the study and is a result of poor market acceptance for the recycled products or recycled aggregates. This fact stems from the lack of consumer confidence about the quality of products used in construction and manufacturing with these recycled aggregates.

Thus, in accordance with the cost estimation methodology adopted in this preliminary study phase, an extrapolation or interpolation model was used to estimate values for the other production levels that were studied (AusIMM, 2012). The model is the estimation of investment and operation costs for the projects based

on curve fitting to “cost-capacity" data, known as the estimation technique for "exponential adjustment" considering the "scale effect ". This proposed model, covered by the concept of "Quick Evaluations", as known in economic projects evaluating fields, is used for research, analysis and decision-making in the preliminary scope of the project (Oliveira Neto, 2008).

These types of models are regularly used in mining projects, the best known are the so-called "*O'Hara Model*" (Oliveira Neto et al., 2009) and "*the six-tenths rules described by Mular*" (AusIMM, 2012), widely known and used in the mining industry worldwide. The estimation technique by cost-capacity exponential adjustment takes the evolution of costs to capacity into consideration. In this case, the relationship between cost and capacity is performed by expression (3):

$$y = b\ k^{a} \quad (3)$$

with:

- a <1 (constant parameter);
- b (constant parameter);
- y (cost);
- k (production);

Constants “a” and “b” are derived from historical raw equipment data collected by the estimator over time (AusIMM, 2012).

Another important factor considered in this type of cost estimation that is constantly adopted is the contingency factors. These expressed in terms of percentage added to the estimated total amounts to provide for other additional costs that may arise because of market factors or even economic conjuncture, both with the operational and capital costs. In this study, we adopted an increase of 5% as a contingency (AusIMM, 2012).

### 3.1. Investments costs

The investment list is by type, from purchase of the land and installation of the infrastructure to the purchase of each component of the envisaged equipment in the flowchart of each type of procedure that is provided. The data related to investment costs or capital costs are shown in Table 2.

Table 2 shows the results of research and estimation for the three types of processing considering a specified annual capacity of C&DW sorting: 100, 300 and 600 kt/y (thousand ton per year).

For the investment categories, the basic parameters assumptions are (AusIMM, 2012):

i. environmental permits: considering the costs of the environmental studies for the initial licenses;
ii. site: the purchase land site is estimated for an area requirement of 70,000 $m^2$ for all types of platforms that are considered;
iii. infrastructure: includes the cost of construction access and haulage roads, land preparation, water facilities, construction of offices for administrators and scale facilities, purchase of software for operation and plant management;
iv. plant: cost of construction includes engineering of the building and cost of the equipment installation;
v. equipment: purchase prices.

Figure 6 shows the share of each investment category in the total initial cost. The importance can be observed related to the percent of the equipment and the infrastructure in each type of platform recycling process. These two investment costs participate in between 70 to 80% of the total investments.

The land purchase participates with an average of the 8% of total investments. The share of the equipment investment increases with the platform capacity.

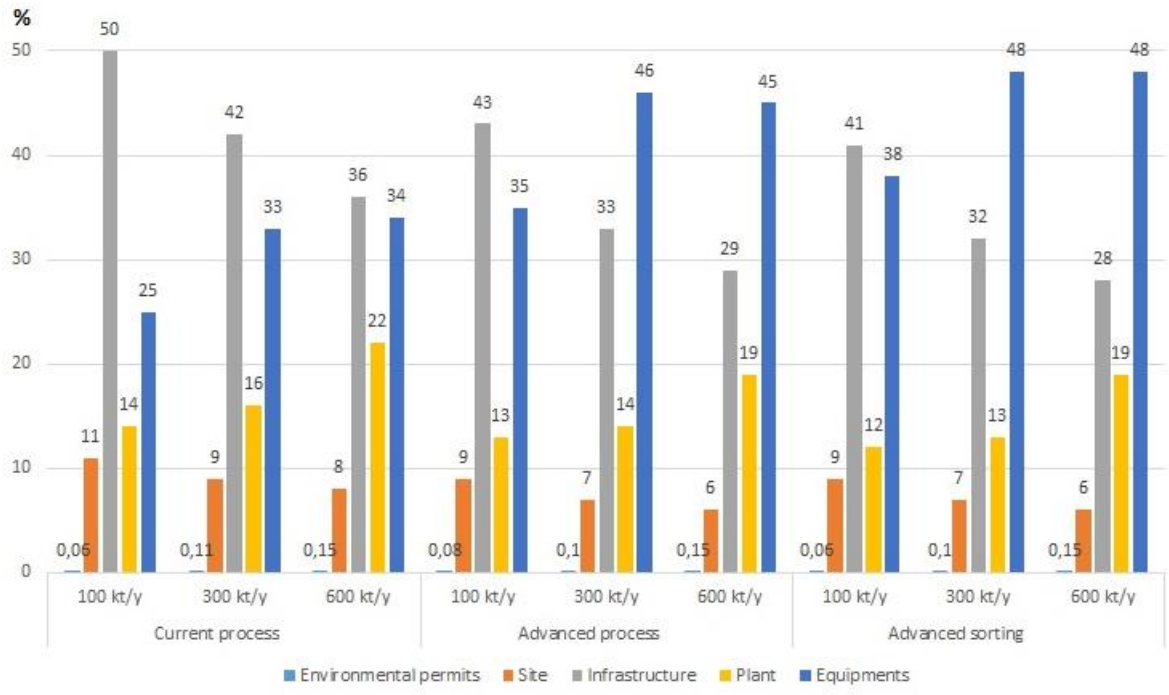


Figure 6 – Share of investment category in total initial cost

### 3.2. Operating costs

Table 3 shows the data related to operating costs. This table shows the results of research and estimations for the three types of sorting process, considering a specified annual capacity for C&DW processing of 100, 300 and 600 kt/y (thousand tons per year). The operating costs include:

- energy costs: diesel and electricity;
- labor costs : qualified workers, unqualified workers and engineers;
- maintenance costs: repairs, cleaning, etc.;
- water consumption;
- waste disposal costs: materials rejected;
- insurance costs.

The database search for estimating operating costs is the same as listed in Table 1. There was a data adjustment in accordance with the team experience because there are significant differences between the compositions of certain variable costs among European countries, such as labor costs that may contain large variations.[4]

The basis for parameter assumptions for the operating costs are shown in Table 3 and Table 4.

4 In 2014, hourly labor costs in the whole economy (excluding agriculture and public administration) ranged from 3.8 € to 40.3 € across the EU Member States. http://ec.europa.eu/eurostat/documents/2995521/6761066/3-30032015-AP-EN.pdf/7462a05e-7118-480e-a3f5-34e690c11545 (07/20/2016 )

Table 2 – Initial costs (in €)

| Investments | | current process CA | | | advanced process Ad | | | advanced sorting AdS | | | sources |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type** | **Description** | **100 kt/y** | **300 kt/y** | **600 kt/y** | **100 kt/y** | **300 kt/y** | **600 kt/y** | **100 kt/y** | **300 kt/y** | **600 kt/y** | a |
| **Environmental permits** | studies and reports | 4,500 | 9,800 | 15,900 | 5,300 | 11,500 | 18,630 | 5,600 | 12,150 | 19,680 | |
| **Site** | land purchase | 776,100 | 776,100 | 776,100 | 776,100 | 776,100 | 776,100 | 776,100 | 776,100 | 776,100 | |
| **Infrastructure** | ground and ways | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | |
| | admin. Building | 40,000 | 60,000 | 90,000 | 40,000 | 60,000 | 90,000 | 40,000 | 60,000 | 90,000 | |
| | operating software | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | |
| | scale | 40,000 | 115,000 | 72,000 | 40,000 | 115,000 | 72,000 | 40,000 | 115,000 | 72,000 | |
| **Plant** | operations building | 750,000 | 1,000,000 | 1,600,000 | 750,000 | 1,000,000 | 1,600,000 | 750,000 | 1,000,000 | 1,600,000 | |
| | equip. installation | 240,000 | 432,000 | 690,000 | 300,000 | 540,000 | 860,000 | 300,000 | 540,000 | 860,000 | |
| **Equipments** | skips | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | 25,000 | |
| | trucks | 160,000 | 320,000 | 480,000 | 320,000 | 480,000 | 600,000 | 320,000 | 480,000 | 600,000 | |
| | wheel loaders | 430,000 | 430,000 | 430,000 | 430,000 | 430,000 | 430,000 | 430,000 | 430,000 | 430,000 | b |
| | mechanized sorting | 150,000 | 360,000 | 360,000 | 150,000 | 360,000 | 360,000 | 150,000 | 360,000 | 360,000 | |
| | grinder for wood | 200,000 | 360,000 | 360,000 | 200,000 | 360,000 | 360,000 | 200,000 | 360,000 | 360,000 | |
| | scalper | 50,000 | 90,000 | 100,000 | 50,000 | 90,000 | 100,000 | 50,000 | 90,000 | 100,000 | |
| | vibrating feeder | 30,000 | 54,000 | 60,000 | 30,000 | 54,000 | 60,000 | 30,000 | 54,000 | 60,000 | |
| | hand sorting | 15,000 | 27,000 | 40,000 | 15,000 | 27,000 | 40,000 | 15,000 | 27,000 | 40,000 | c |
| | trommel | 200,000 | 270,000 | 300,000 | 200,000 | 270,000 | 300,000 | 200,000 | 270,000 | 300,000 | |
| | magnetic separation | 20,000 | 40,000 | 40,000 | 20,000 | 40,000 | 40,000 | 20,000 | 40,000 | 40,000 | |
| | vibrating screens | 50,000 | 100,000 | 160,000 | 100,000 | 200,000 | 320,000 | 100,000 | 200,000 | 320,000 | d |
| | crusher | 250,000 | 500,000 | 800,000 | 250,000 | 500,000 | 800,000 | 250,000 | 500,000 | 800,000 | e |
| | conveyors belts | 175,000 | 350,000 | 400,000 | 245,000 | 490,000 | 560,000 | 350,000 | 680,000 | 784,000 | f |
| | pulverized sorting | - | 0 | 0 | 150,000 | 300,000 | 300,000 | 150,000 | 300,000 | 300,000 | |
| | jigs | 0 | 0 | 0 | 596,500 | 1,200,000 | 1,200,000 | 596,500 | 1,200,000 | 1,200,000 | g |
| | air separation | 0 | 0 | 0 | 65,000 | 120,000 | 120,000 | 65,000 | 120,000 | 120,000 | |
| | spirals | 0 | 0 | 0 | 65,200 | 130,000 | 130,000 | 65,200 | 130,000 | 130,000 | h |
| | infrared sorting | 0 | 0 | 0 | 0,000 | 0,000 | 0,000 | 320,000 | 320,000 | 320,000 | |
| | total | 7,115,600 | 8,828,900 | 10,309,000 | 8,333,100 | 11,088,600 | 12,671,730 | 8,758,400 | 11,599,250 | 13,216,780 | |
| | Eventual (5%) | 355,780 | 440,955 | 514,655 | 416,655 | 553,855 | 632,655 | 437,920 | 579,355 | 659,855 | |
| | Total investment | 7,471,380 | 9,260,055 | 1,0807,755 | 8,749,755 | 11,630,955 | 13,285,755 | 9,196,320 | 12,166,455 | 13,856,955 | |

a) research date about recycling plant of construction material in Brazil (Ladeira, 2004; Lima, 2013), Europe (Coelho,2013); b) loader; 2,5 m3, 0.073 €/ton; c) 10mx40"; d) 3 screens for advance process, 3 decks; e) primary jaw crusher; f) 5 conveyors for current process and 7 for advanced process, 8-10m, € 35,000/un; g) considered air jig; h) 4 units/spirals

Table 3 - Operating costs (assumptions)

| Operating Costs | Quantity | Amount | Sources |
|---|---|---|---|
| operating labor [(1)] | 7(100 kt/y) ; 15 (300 kt/y) ; 25 (600 kt/y) | € 2,950/month | |
| administration - maintenance labor[(1)] | 2(100 kt/y) ; 3 (300 kt/y) ; 5 (600 kt/y) | € 2,750/month | French labor cost (Eurostat) |
| engineer supervisor[(1)] | 1(100 kt/y) ; 2 (300 kt/y) ; 3 (600 kt/y) | € 7,725/month | |
| insurance[(5)] | - | 1% of the invest | Lima (2013) |
| Energy[(2)] | 150,000 kWh/month for CA | € 0.1/kWh | |
| | 200,000 kWh/month for Ad and AdS | € 0.1/kWh | Tam (2008), Coelho & de Brito (2013) |
| Fuel[(3)] | wheel loader 2,5 m3 | € 0.073/ton | Coelho & Brito (2013), Nunes (2004) |
| Water[(4)] | - | € 0.005/ton | Coelho & de Brito (2013) |
| Maintenance[(5)] | - | 1.5% invest. | Lima (2013) |
| Waste[(6)] | 10% of total capacity | € 50/t | Duran et al. (2006) |

The analysis of the distribution of operating cost categories shows that the major component is the labor costs that include operation, maintenance and administration labor. The share of labor costs in the total operating costs is approximately 45% (see Figure 8).

Another important component is the energy consumed that appears with the second major influencing factor in the total operating cost (25%). This is because all of the mechanical sorting in waste plants consists of equipment powered by electricity, and only one type of equipment is powered by diesel fuel; this equipment, an excavator or loader, is used only in receiving operations and the initial preparation of the waste.

### 3.3. Environmental measures

As shown in Table 2, this work considers the costs of environmental studies for the initial licenses and measures for mitigating and compensating for environmental impacts. The typical environmental impact for a sorting plant is considered, with the comminution, particle size separation and gravity separation unit operations. "*Environmental permits*" includes all the cost of the studies and reports of environmental impact required to obtain the installation and operation licenses (or permits). It also includes the fees paid to regulatory agencies. In Table 4, "Environmental measures" includes the costs of control of dust generation, mitigation of noise, system drainage and treatment of rainwater.

This cost category is evaluated using the database from Oliveira Neto (1999). It is modeled according to the "rules of thumb" (AusIMM, 2012). The data or values obtained from Oliveira Neto (1999) were properly maintained and were considered to refer to the ability of 100 ton/h, referred to as the "average plant capacity" and corresponding to the same environmental impacts and, as a consequence, the same mitigating and compensating measures. It is important to note that the average percentage of environmental measure costs is 2% of the total operating costs; it is lower than the maximum acceptable level of 5% in this type of installation.

### 3.4. Cash flow simulations

The "discounted cash flow" simulations were carried out for capacities of 100, 300, and 600 kt/y for each of the three types of technologies or recycling platforms. We consider three levels of final selling prices of the recycled aggregates, i.e., 10 €/ton, 20 €/ton and 30 €/ton. A total of 27 cash flow simulations were performed.

Based on the assumption that a C&DW sorting facility is not feasible without charging a fee or entry price (Pe), it was opted for the value of 10 €/ton (ADEME, 2011; Petter et al.,2015).

## 4. Results and discussion

### 4.1. Internal Rate of Return

Figure 8 shows the results of all simulations. The tendency lines are the relationships between the IRR and the average sale price in the scope of each type of platform.

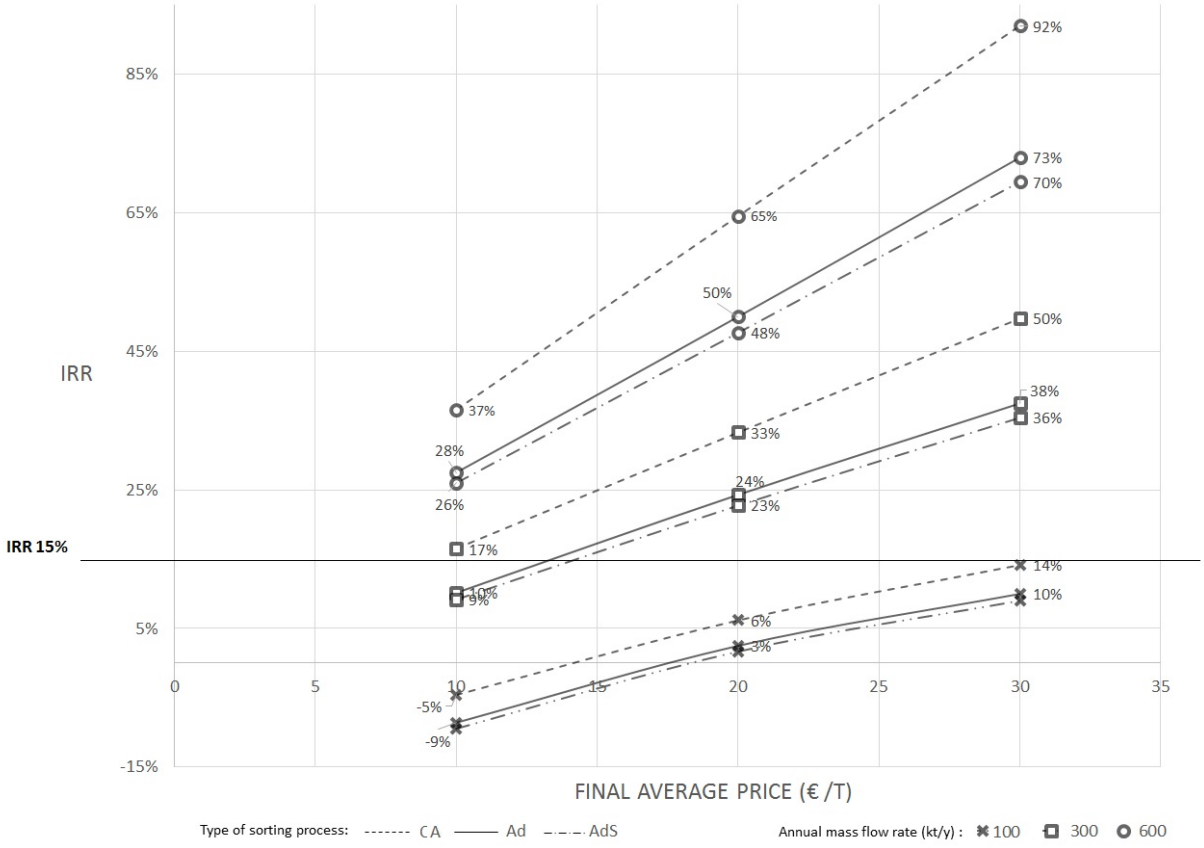


Figure 8– Internal rate of return (IRR) as a function of the final sale price for each type of recycling platform

The graph demonstrates the high profitability of the three platform types for capacities, such as 600 kt/y with an IRR above 25% for an average aggregate sale price of 10 €/ton; it is evident that the platforms are not viable under the simulated conditions for capacities of 100 kt/y.

The 15% limit for IRR indicates the cutoff points across the trend lines. This value of IRR is optimal according to studies such as Wilburn and Goonan (1998) that analyze the economic profitability of C&DW platforms with a minimum IRR of 12 %.

For the intermediate capacity of 300 kt/y, the platforms begin to be viable from the selling price of 9 €/ton. Table 5 summarizes the average sales prices for each platform type for a profitability IRR of 15%.

475 Table 4 - Operating costs in CDW's sorting recycling plants per type and level of annual production (in €).

| | **current process CA** | | | **advanced process Ad** | | | **advanced sorting AdS** | | |
|---|---|---|---|---|---|---|---|---|---|
| | 100 kt/y | 300 kt/y | 600 kt/y | 100 kt/y | 300 kt/y | 600 kt/y | 100 kt/y | 300 kt/y | 600 kt/y |
| operat. Labor | 247,800 | 531,000 | 885,000 | 247,800 | 531,000 | 885,000 | 247,800 | 531,000 | 885,000 |
| adm. maint. labor | 66,000 | 99,000 | 165,000 | 66,000 | 99,000 | 165,000 | 66,000 | 99,000 | 165,000 |
| engin. supervisor | 92,700 | 185,400 | 278,100 | 92,700 | 185,400 | 278,100 | 92,700 | 185,400 | 278,100 |
| insurance | 74,667 | 92,601 | 108,078 | 87,442 | 116,310 | 132,858 | 91,904 | 121,665 | 138,570 |
| energy | 180,000 | 396,000 | 665,000 | 240,000 | 528,000 | 887,000 | 240,000 | 535,000 | 899,000 |
| fuel | 7,300 | 16,000 | 26,800 | 7,300 | 16,000 | 26,800 | 7,300 | 16,000 | 26,800 |
| water | 612 | 2,270 | 3,000 | 612 | 2,270 | 3,000 | 612 | 2,270 | 3,000 |
| maintenance | 112,000 | 138,901 | 162,116 | 131,163 | 174,464 | 199,286 | 137,857 | 182,497 | 207,854 |
| waste | 50,000 | 150,000 | 300,000 | 50,000 | 150,000 | 300,000 | 50,000 | 150,000 | 300,000 |
| environmental. measures | 14,900 | 32,200 | 52,300 | 18,300 | 39,550 | 64,240 | 18,580 | 40,150 | 65,200 |
| **Total** | 845,978 | 1,643,371 | 2,645,394 | 941,317 | 1,841,994 | 2,941,284 | 952,753 | 1,862,981 | 2,968,524 |
| eventual (5%) | 42,299 | 82,169 | 132,270 | 47,066 | 92,100 | 147,064 | 47,638 | 93,149 | 148,426 |
| **Total** | **888,277** | **1,725,540** | **2,777,664** | **988,383** | **1,934,094** | **3,088,348** | **1,000,391** | **1,956,130** | **3,116,950** |

476

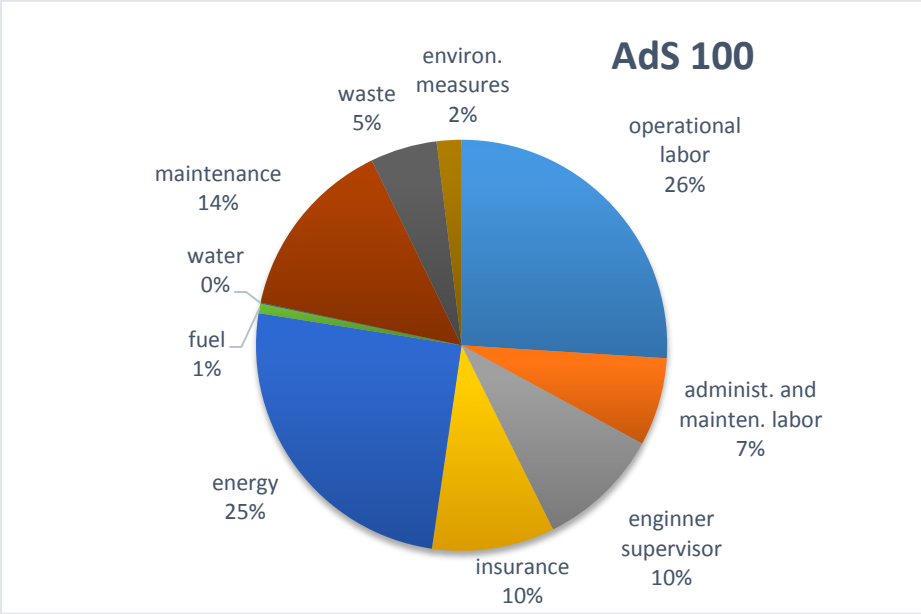


Figure 7 - Operating cost categories (for AdS 100 kt/y)

Table 5 – Average sales prices for each type of platforms for the profitability IRR of 15%.

| Platform Capacity | $P_M$CA €/ton | $P_M$Ad €/ton | $P_M$AdS €/ton |
|---|---|---|---|
| 100 kt/y | 32 | >35 | >35 |
| 300 kt/y | 9.0 | 13.5 | 14.0 |
| 600 kt/y | 2.1 | 3.7 | 4.4 |

$P_M$CA – Average price for the Current platform; $P_M$Ad – Average price for the Advanced platform; $P_M$AdS – Average price for the Advanced sorting platform;

Analyzing the results in Table 5, it appears that the prices in the case of 100 kt/y capacity are out of the current market reality and cannot be competitive if compared with the prices of natural aggregate or primary mined material from rock quarries. Therefore, it is not possible to consider in this study the feasibility of the recycled aggregate process at a production level of 100 kt/y as previously concluded.

However, the prices for the 300 kt/y level of production, determined by the condition that IRR equals 15% in the chart, are suitable to market reality, which is closer to the price of 10 €/ton related to the current process ($P_M$CA).

For the 600 kt/y production level, the prices are very low, logically indicating high profitability, but are also out of the market reality, which is much lower.

Considering the view of NPV, it is possible to find the average prices for the Advanced platform ($P_M$Ad)" and Advanced Sorting platform ($P_M$AdS)" considering the same value as the NPV obtained for the alternative Current with price 10 €/ton, which is considered closest to the current reality. Table 6 shows the prices for this case, and it is observed that the obtained values are more realistic and have greater possibilities for competing with consumer market aggregates for use in construction.

Table 6 – Average sales prices for each type of platforms for NPV CA = NPV Ad = NPV AdS.

| Platform Capacity | $P_M$CA €/ton | $P_M$Ad €/ton | $P_M$AdS €/ton |
|---|---|---|---|
| 300 kt/y | 10.0 | 13.0 | 13.6 |
| 600 kt/y | 10.0 | 11.7 | 12.0 |

$P_M$CA – Average price for the Current platform; $P_M$Ad – Average price for the Advanced platform; $P_M$AdS – Average price for the Advanced sorting platform;

## 4.2. Influence of product quality

Another view of the relationships between the quantities of products generated specifically by the type of process is the current process that produces only Recycled Material (RM). Advanced and advanced sorting processes produce both Recycled Material and Secondary Primary Material (named SPM for Advanced process and SPM+ for Advanced Sorting process). The quality (measured by the quantity of "high-grade" recycled concrete aggregate) of SPM is considered to be lower than that of SPM+. Figure 9 synthesizes the characteristics of three possibilities of generated products, according to the sophistication of the platform process.

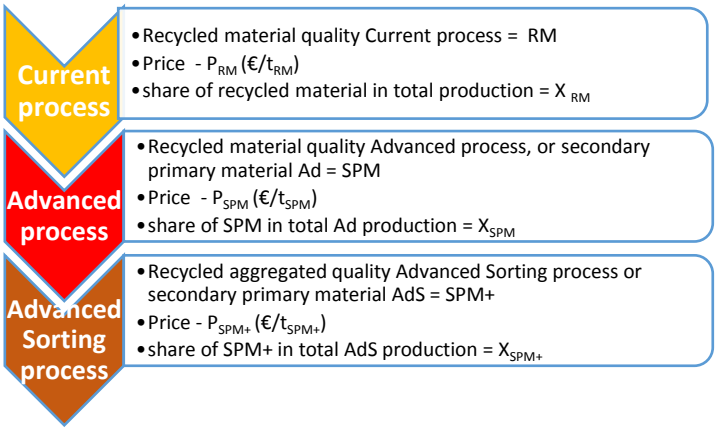


Figure 9 - Three possibilities for generating products,

according to the sophistication of the platform process (see Figure 1)

According to this view, it is possible to obtain a relation between the proportions of the quantities secondary primary material (SPM and SPM+) that is generated and the price of the products with more quality or the prices as a function of the proportion of quantities generated at the end of the process, using the following expression (4):

$$P_i = (P_M i - (1-X_i) * P_M CA) / Xi, \quad (4)$$

with

P=price;

X= share of recovery in total production;

i= SPM, SPM+.

Figure 10 demonstrates the relationships between $X_i$ and $P_i$ (with i=SPM, SPM+), considering $P_{RM}$ = 10 €/ton (Table 6).

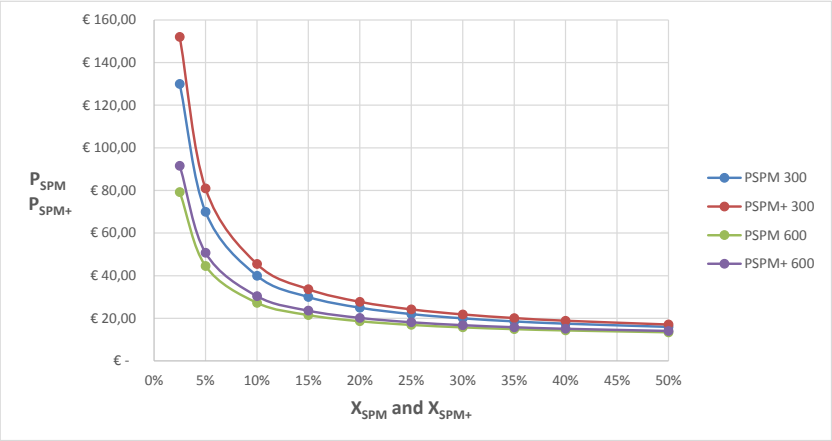


Figure 10 - Relationships between PSPM , PSPM+ and XSPM ,XSPM+, considering PMR= 10 €/ton, for NPV CA = NPV Ad = NPV AdS.

The general interpretation of Figure 10 is that for higher generation of products with the best quality, the final sale price will be lower or more competitive. The graph provides the price levels according to the recovery of products with Ad and AdS processes. Thus, e.g., in order for the "Advanced" process that employs separation equipment of gravimetric type Jig to be competitive and feasible in economic and market terms, the process should achieve a recovery of more than 30%, and it is desirable for levels to be at least near 40%.

The graphic illustrates an interesting tendency and shows the possibility to work with the capacities of recycling platforms near 300 kt/y that are competitively very close to major capacities such as 600 kt/y when the recovery of materials with better quality achieves the highest values.

### 4.3. Payback period

The payback period (or time for return of investment) is the length of time required to recover the cost of the investment. This simple analysis method is useful from a risk analysis perspective, since it gives of how risky an investment is (i.e. the length of time that the initial investment will be at risk. Investors tend to choose the investment having the shortest payback period. Payback period analysis is particularly useful in sector where investments depreciate quickly, and where a full return of the initial investment is a serious concern.[5]

Payback period can be determined using the following equation:

[5] The payback period must be lower than the lifetime of main equipment (Zhao et al., 2010).

$$Payback\ period = (last\ year\ with\ a\ negative\ NCF) + \left(\frac{Absolute\ value\ of\ NCF\ in\ that\ year}{Total\ Cash\ Flow\ in\ the\ following\ year}\right)$$

In our case, the payback period ranges, in the better case, from 5 years (platforms with capacity of 600 kt/y) to 8 years (platforms with capacity of 300 kt/y). These values fall in the higher range compared to the previous studies. Huang et al. (2002), Zhao et al. (2010), Coelho and de Brito (2013) evaluated a payback period of under 3 years. The main differences between the results are due to the underlying assumptions regarding technologies, discount rate, costs, market conditions, etc. Note that our assumptions are rather optimistic as we do not include credit cost (investment with no credit) and assume that the selling price of processed material (10 €//ton) is competitive with the natural alternatives.

### 4.4. Process recovery

The parameter or the level of the process recovery adopted for the cash flow analysis was equal to 90%. To ensure the relevance of this parameter, some simulations with recoveries equal to 80, 90 and 95% (corresponding respectively to CA, Ad and AdS processes) are carried out.

The results showed that there are no important influences of this parameter on the results of the cash flows that were analyzed because the IRR variations range between 1% and 2%; this is not significant for the conclusions in this study.

### 4.5. Discussion

This study illustrates the trade-off between technological development and economic performance. Specifically, investing better and more C&DW sorting technologies for recycling is not necessarily the most profitable strategy. The best compromise is desired, according to the market conditions (prices, demand), quantities of C&DW generated and available technologies.

Figure 10 shows that the necessary prices of products with better quality (SPM and SPM+) ranges between 15 €/ton and 18 €/ton if the share of these products in total production is 40%. This point of discussion can be very important for setting a target for the necessary level of recovery of SPM+ (recycled aggregated quality Advanced Sorting process or secondary primary material) in most advanced sorting processes.

Another point that is highlighted in the study is the key role played by C&DW recycling platform capacities. It is clearly shown that the platforms are profitable when the capacity of the platforms is not less than 300kt/y. Thus, an investment in the implementation of the C&DW platform in a particular region or locality is only justified if an "orebody" or "C&DW deposit" exists that generates a sufficiently high quantity of C&DW waste. This condition is fundamental for the economic success of this type of enterprise.

However, the capacity of the existing platforms is, most of the time, under 100 kt/y. This capacity has been chosen to be more economically profitable. These small units have a lower technology level than the more simple technology considered in this study. They only have a crusher step that keeps the levels of investment and operating costs lower. However, they generate a low quality recycling material. These units have been spreading all over the region to diminish the transport costs and attract more users.

Another aspect that occurs in this discussion is related to the economic sustainability of the CDW platforms or "is governmental intervention necessary to stimulate the CDW market?"

Developing construction and demolition waste management is a combination of legal, financial, engineering and planning functions (Söderholm, 2011). Here, we identify some levers for change:

- *improvement of technologies and diffusion policies*: as highlighted by Li & Yan (2011), increasing the use of recycled aggregates depends on their ability to be competitive with natural materials in terms of cost and quality. On the one hand, enhancing sorting, separation and processing may increase costs, but on the other hand, using new technologies and improving process efficiency may decrease costs. R&D policies may impact the improvement of developed technologies. Because secondary raw materials (SPM) are still perceived to be inferior to virgin ones, policy intervention that spreads awareness and knowledge of these new materials may be desirable;
- *economic instruments*: increased recycling could be achieved by economically viable measures to improve global waste management. The competitiveness of recycled materials and secondary raw

materials could be increased by raising the relative price of primary raw materials. Countries with high tax rates have higher recycling rates, but tax rates are not a "*silver bullet*" (Söderholm, 2011). As previously stated, efficient raw material management policies require a combination of policy instruments addressing both upstream and downstream constraints;

- *planning*: efficient planning and sustainable material logistics management may have a significant effect on the cost efficiency of recycling platforms. There is a need to address regional differences;
- *legal*: implementation of national legal requirements for the reuse of waste materials (recycled materials and/or secondary raw materials) may impact the diffusion of C&DW sorting processes. A more active diversion policy (i.e., a policy diverting C&D waste material from landfills) may also have an impact;
- *infrastructure*: Increase the net of C&DW deposit areas to reduce transport costs with the objective of accumulating stock to supply recycling platforms with capacities greater than 300kt/y.

## 5. Conclusions

The paper proposes an economic analysis of three different types of C&DW sorting recycling platforms, named current, advanced and advanced sorting. The development of such recycling platforms could be a way to achieve a sustainable management of construction and demolition waste. From our analysis, a number of conclusions can be drawn. Given the available data, this "Scope study – Phase 1" shows that current process has better economic performance (in terms of internal rate of return) than other two processes. The explanation of this result lies in the fact that the difference of investment cost between these technologies cannot be offset by the (too) low difference between recycled material price and secondary primary material price. Given the current market conditions these "high-performing" processes seem to be less profitable than more simple technologies in most of the European countries,

The IRR associated with Advanced and Advanced sorting processes could be raised by, (i) higher price of secondary primary material, and/or (ii) higher capacity of platforms, and/or (iii) higher share of secondary primary material in the total production. The first two points depend on the market conditions (prices and total quantity of C&DW available) and (potential) fiscal or incentive policy. The later one depends on technological progress. Recent studies in European Union seem to put more emphasis on the resource efficiency in the C&DW sector and formulate some recommendations (mandatory percentages of recycled aggregates in large civil engineering projects, deployment of financial incentives to use recycled aggregates (e.g. reduction on VAT for recycled materials…)) that could influence change in practices.[6]

Finally, there is a clear need for additional research. More accurate economic and financial data would enable us to tackle all the issues related to these C&DW sorting recycling platforms: assessment of the external costs and benefits, more precise economic evaluation results,...

## 6. Acknowledgements

The CAPES-COFECUB cooperation program between Brazil and France, Federal University of Pampa (UNIPAMPA), Federal University of Rio Grande do Sul (UFRGS) and The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) are acknowledged.

## 7. References

ADEME - Agence de l'Environnement et de la Maitrise de l'Energie, 2011. Analyse technico-économique de 39 plateformes françaises de tri/valorisation des déchets du BTP.

ADEME & FFB, 2011. Les matériaux de recyclage en Languedoc-Roussillon.

[6] "Resource Efficient Use of Mixed Waste" is a project of the European Commission that try to identify the good practices in terms of creating conditions for increasing C&DW recycling. http://ec.europa.eu/environment/waste/studies/mixed_waste.htm (07/20/2016 )

665 FFB - Fédération Française du Bâtiment, 2014. Guide de conception et de fonctionnement des installations
666 des déchets du BTP.
667 AusIMM – The Minerals Institute, 2012. Cost Estimation Handbook – Second Edition Monograph 27. The
668 Australasian Institute of Mining and Metallurgy. BPA Digital, Australia, p. 1-82.
669 Bovea M.D., Powell J.C. 2016. Developments in life cycle assessment applied to evaluate the
670 environmental performance of construction and demolition wastes. Waste Management 50, p. 151-172.
671 de Brito J., Silva R., 2016. Current status on the use of recycled aggregates in concrete : Where do we go
672 from here ? RILEM technical letters 1, p. 1-5.
673 Byrne R., O'Regan B., 2014. Increasing the potential for reuse and recycling of construction and demolition
674 waste – a case study from Ireland. Environment and Natural Resources Research 4(4).
675 Cazacliu B., Sampaio C., Miltzarek G., Petter C., Le Guen L., Paranhos R., Huchet F., Kirchmein A., 2014.
676 The potential of using air Jigging to sort recycled Aggregates. Journal of Cleaner Production 66, p. 46-
677 53.
678 CGEDD, 2015. L'économie circulaire, état des lieux et perspectives. Rapport n°009548, Conseil Général
679 de l'Environnement et du Développement Durable, France.
680 Coelho A., de Brito J., 2013. Economic viability analysis of a construction and demolition waste recycling
681 plant in Portugal part I: location, materials, technology and economic analysis. Journal of Cleaner
682 Production 39, p. 338-352.
683 Coronado M., Dosal E., Coz A., Viguri J.R., 2011. Estimation of Construction and Demolition Waste
684 (C&DW) Generation and Multicriteria Analysis of C&DW Management Alternatives: A Case Study in
685 Spain. Waste and Biomass Valorization 2, p. 209-225.
686 Cortês P.L., Dias A.G., Filho J.A.P., 2013. Reuse and recycling of construction waste: a comparative study
687 between Brazil and Portugal. In: 28th International Conference on Solid Waste Technology and
688 Management, 2013, PHILADELPHIA. The 28th International Conference on Solid Waste Technology
689 and Management, 2013.
690 Craighill A., Powell J.C., 1999. A lifecycle assessment and evaluation of construction and demolition
691 waste. Working Paper Center for Social and Economic Research on the Global Environment
692 (CSERGE), WM 99-03, University of East Anglia, Norwich, UK, 52p.
693 Cunha G. N. M., Miceli V. M. 2013. Análise da Viabilidade Econômica de Usinas de Reciclagem de
694 Resíduos da Construção Civil a partir de Sistemas Dinâmicos. Projeto de Graduação apresentado ao
695 Curso de Engenharia de Produção da Escola Politécnica, Universidade Federal do Rio de Janeiro.
696 Orientador: Prof. Amarildo da Cruz Fernandes, DSc.
697 Duran X., Lenihan H., O'Regan B. 2006. A model for assessing the economic viability of construction and
698 demolition waste recycling—the case of Ireland. Resources, Conservation and Recycling 46, p. 302–
699 320.
700 European Commission, 2015. Environmental, waste streams – Directorate General for Environment.
701 Brussels, Belgium. http://ec.europa.eu/environment/index_en.htm
702 Garbarino E., Blengini G.A., 2013. " The economics of construction and demolition waste (C&DW)
703 management facilities", p.108-138, In Pacheco-Torgal F., Tam W.M.Y., Labrincha J.A., Ding Y., de Brito
704 J., 2013. Handbook of Recycled Concrete and Demolition Waste Woodhead Publishing, 672 p.
705 Huang W.L., Lin D.H., Chang N.B., Lin K.S., 2002. Recycling of construction and demolition waste
706 via a mechanical sorting process. Resources, Conservation and Recycling 37(1), p. 23-37.
707 Lima, F.R.M.S., 2013. Tese de doutorado: A formação da mineração urbana no Brasil – Reciclagem de
708 RCD e produção de agregados. Universidade Politécnica de São Paulo, Brasil, 178 p.
709 Lu W., Yuan H. 2011. A framework for understanding waste management studies in construction. Waste
710 Management 31, p. 1252-1260.
711 Müller A., Landmann M., Palzer S., Leydolph B., Palzer U., 2013. Recovery of Homogeneous Materials
712 from Composite Masonry Structures by Crushing and Mechanical Separation – Limitations of Prevalent
713 Processes. IAB – Weimar Institute of Applied Construction Research gGmbH. International Conference
714 of Solid Waste Management - ICSW 2013, Philadelphia, EUA.
715 Nunes, K. R. A., 2004. Avaliação de Investimentos e de Desempenho de Centrais de Reciclagem para
716 Resíduos Sólidos de Construção e Demolição. Tese – Universidade Federal do Rio de Janeiro,
717 COPPE/UFRJ, Engenharia de Produção, 276 p.
718 Nunes K.R.A., Mahler C.F., Valle R., Neves C. 2007. Evaluation of investments in recycling centers for
719 construction and demolition wastes in Brazilian municipalities. Waste Management 27(11), p. 1531-
720 1540.

Oliveira Neto R., 1999. Avaliação do sistema de licenciamento ambiental vigente para a mineração. Uma nova proposta de metodologia e procedimentos. Dissertação de mestrado – Universidade Federal do Rio Grande do Sul, PPGEM/UFRGS.85 P.

Oliveira Neto R., 2008. Modelo de estimativa dos custos em aterros sanitários para apoio de estudos de pré-viabilidade no gerenciamento de resíduos sólidos urbanos. Tese – Universidade Federal do Rio Grande do Sul – UFRGS, Programa de Pós-Graduação em Engenharia de Minas, Metalurgia e Materiais – PPGEM. Porto Alegre, Brasil, 119 p.

Oliveira Neto R., Petter C.O., Cortina J.L., 2009. The current situation of sanitary landfills in Brazil and the importance of the application of economic models. Waste Management & Research 27, p. 1002–1005.

Pacheco-Torgal F., Tam W.M.Y., Labrincha J.A., Ding Y., de Brito J., 2013. Handbook of Recycled Concrete and Demolition Waste Woodhead Publishing, 672 p.

Paranhos R., Oliveira Neto R., Cazacliu B.G., Huchet F., Sampaio C.H., Petter C., 2015. Gravity concentration and sensor-based sorting to value recycled aggregates. In: Proceedings, XXIV International Mining Congress and Exhibition of Turkey, Antalaya Congress, Turkey, 2015, p. 1088-1095.

Paranhos R.S., Cazacliu B.G., Huchet F., Sampaio C.H., Petter C., Oliveira Neto R., Huchet F., 2016. A sorting method to value recycled concrete. Journal of Cleaner Production 112(4), p. 2249-2258.

Paula, J. S. de, Leroy R., 2014. Recyclage de déchets du chantier. Université de Brasília, Brésil, 25 p.

Petter R., Sampaio C.H., Paranhos R., Oliveira Neto R., Petter C., 2015. A técnica de análise de risco econômico aplicada a diferentes cenários de plantas de reciclagem de material de construção e demolição. Universidade Federal do Rio Grande do Sul – UFRGS, Universidade Federal do Pampa – UNIPAMPA. IV Encontro Nacional sobre Aproveitamento de Resíduos na Construção Civil – ENARC, São Paulo, 2015.

Sampaio C.H., Cazacliu B.G., Miltzarek G.L., Huchet F., Le Guen L., Petter C., Paranhos R.S., Ambrós W.M., 2016. Stratification in air jigs of concrete/brick/gypsum particles. Construction and Building Materials 109 (2016), p. 63-72.

Söderholm P., 2011. Taxing virgin natural resources: Lessons from aggregates taxation in Europe. Resources, Conservation and Recycling 55(11), p. 911-922.

Staunton J., Williams C. D., Morrison L., Henry T., Fleming G.T.A., Gormally M.J., 2015. Spatio-temporal distribution of construction and demolition (C&D) waste disposal on wetlands: A case study. Land Use Policy 49, p. 43-52.

Tam V.W.Y., 2008. Economic comparison of concrete recycling: A case study approach. Grifith University – Australia.

Wilburn D.R., Goonan T.G., 1998. Aggregates from Natural and Recycled Sources, Economic Assessments for Construction Applications – A Material Flow Analysis. U.S. Department of the Interior – U.S. Geological Survey, 37 p.

Williams I.D., Turner D.A., 2011. Waste Management Practices in the Small-Scale Construction Industry. Waste Management Research Group, School of Civil Engineering and the Environment, University of Southampton. Thirteenth International Waste Management and Landfill Symposium - Sardinia 2011.

Zhao W., Leeftink R.B., Rotter V.S., 2010. Evaluation of the economic feasibility for the recycling of construction and demolition waste in China – The case of Chongqing. Resources, Conservation and Recycling 54(6), p. 377-389.

Zizlavsky O., 2014. Net present value approach: method for economic assessment of innovation projects. 19th International Scientific Conference: Economics and Management 2014, ICEM 2014, 23-25, April 2014, Riga, Latvia.