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An economic analysis of the processing technologies in CDW recycling platforms

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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)

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

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

64 This context has given the framework for some research programs, which have the objectives to define the
65 technological tools to respect the WFD goals. Then, several research programs are carried out. For example,
66 the subject of the C2CA European program (C2CA, 2016) is the advanced technologies for the production of
67 cement and clean aggregates from construction and demolition waste.² In addition to the technological aspects
68 of sorting process, the economic impact of sustainable concrete was included in the scope of research work. In
69 the continuity, the HISER European project (HISER, 2016) begins in 2015.³ The academic and industrial
70 partnership wants to optimize the sorting process for construction materials. This recycling optimization could
71 treat more C&D waste.

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

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

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

93 To our best knowledge, there is no study that has already assessed the economic profitability of the three
94 considered processes (especially the two most efficient processes). Our preliminary assessment of the economic
95 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)

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

106

107 The main objectives of our analysis are:

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

114

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

118

119 **2. Description of the Considered C&DW sorting**

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

126

- Level 1: mobile crusher and sieving plant;

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- Level 2: same as level 1, plus metal collector and more complex sorting/sieving;

128

- Level 3: same as level 2, plus hand-sorting, washing plant and appliances for waste streams, other than
129 aggregates such as wood.

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

134

- Current advanced process (CA);

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- Advanced process (Ad);

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- Advanced Sorting process (AdS).

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

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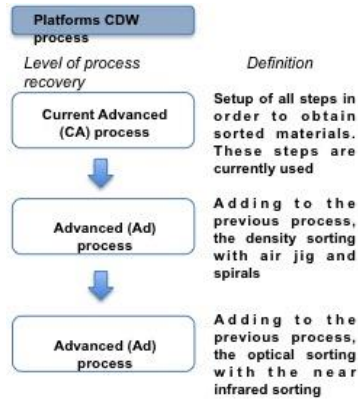


Figure 1 – Flow chart diagram of the CDW’s sorting platforms.

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143 1.1. Current advanced process - “CA”

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

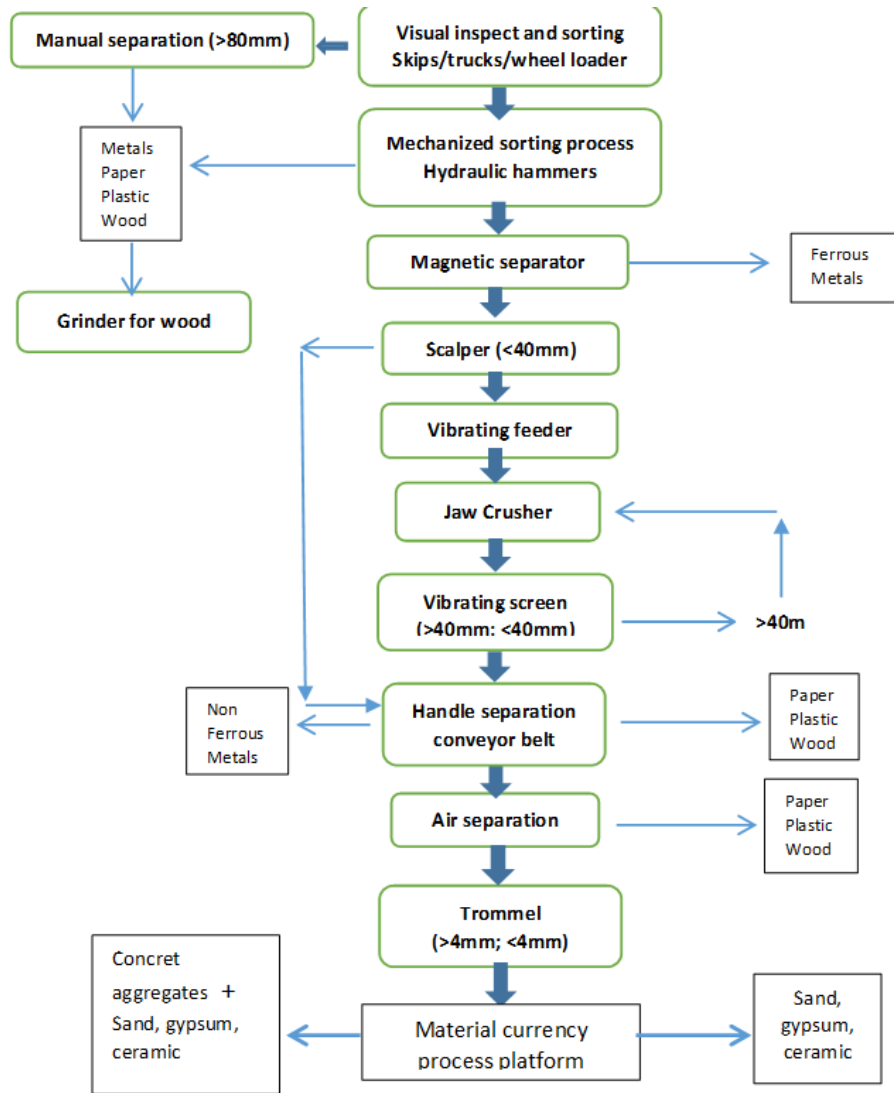


Figure 2 – Flow chart diagram of the Current Advanced (CA) process constituting of four steps using the disposal machines in the optimal way.

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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

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

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

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

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

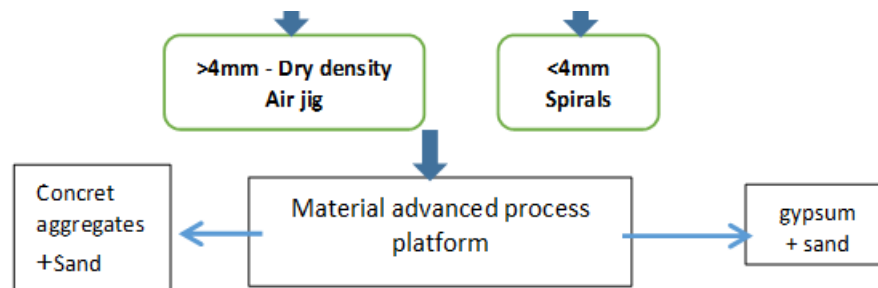
187 The next stage is to move the material to the Trommel, a revolving screen whose function is to separate
188 larger fractions and ones smaller than 4 mm in size and to promote a breakdown of the material larger than 4
189 mm in size. This Trommel step is normally the last step that is employed in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

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

194 1.2. Advanced process - "Ad"

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

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203

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

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

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

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

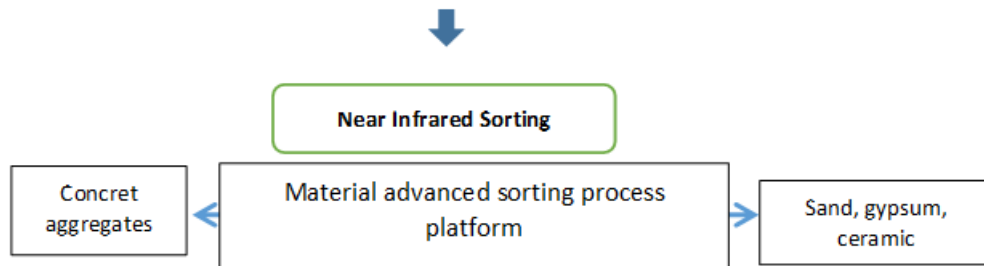
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218 1.3. Advanced sorting process - “AdS”

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

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

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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.

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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;

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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.

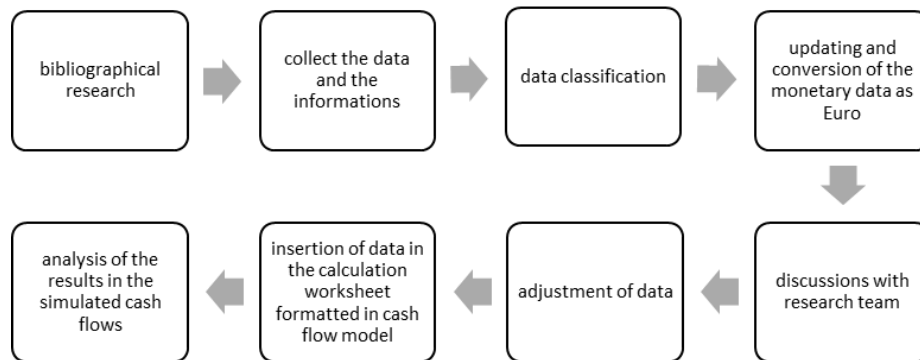
2. Methodology

257 According to the publication of the Minerals Institute entitled “Cost Estimation Handbook” (AusIMM,
 258 2012), this evaluation study is classified with “Scoping study – Phase 1”, and the expected accuracy range
 259 varies between 30% and 35%.

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

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

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



268
 269 Figure 5 - Flow of activities adopted in the methodology.
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271 The “discounted cash flow” (DCF) method was adopted for the economic order calculations and estimates.
 272 The cash flow is the difference between cash inflows and outflows associated with a project for a certain period,
 273 and for economic evaluation. Therefore, the composition and calculation of the cash flow should be determined
 274 for each year throughout the life of the project according to the following expression (1):

$$275 \text{ Cash Flow} = \text{Cash Entrance Flow (inputs)} - \text{Cash Exit Flow (outputs)} \quad (1)$$

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

280 The inflows and outflows include the following:

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

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

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

$$291 \text{ NPV} = \sum_0^N \frac{\text{NCF}_t}{(1+i)^t} \quad (2)$$

- 292 with:
- 293 NPV – Net Present Value
 - 294 NCF_t – Net cash flow at time t (i.e. cash inflow-cash outflow)
 - 295 t- Time of the cash flow
 - 296 i - Discount rate

297 N- Number of periods (years)

298

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

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

306

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

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

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

316

317 3. Analysis of the data and cash flow simulations

318

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

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

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

328

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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	

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

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

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

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

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

$$351 \quad y = b k^a \quad (3)$$

352 with:

- 353 ▪ a <1 (constant parameter);
- 354 ▪ b (constant parameter);
- 355 ▪ y (cost);
- 356 ▪ k (production);

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

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

365 3.1. Investments costs

366
367 The investment list is by type, from purchase of the land and installation of the infrastructure to the purchase
368 of each component of the envisaged equipment in the flowchart of each type of procedure that is provided. The
369 data related to investment costs or capital costs are shown in Table 2.

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

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

- 373 i. environmental permits: considering the costs of the environmental studies for the initial licenses;
- 374 ii. site: the purchase land site is estimated for an area requirement of 70,000 m² for all types of platforms
375 that are considered;
- 376 iii. infrastructure: includes the cost of construction access and haulage roads, land preparation, water
377 facilities, construction of offices for administrators and scale facilities, purchase of software for
378 operation and plant management;
- 379 iv. plant: cost of construction includes engineering of the building and cost of the equipment installation;
- 380 v. equipment: purchase prices.

381
382 Figure 6 shows the share of each investment category in the total initial cost. The importance can be
383 observed related to the percent of the equipment and the infrastructure in each type of platform recycling
384 process. These two investment costs participate in between 70 to 80% of the total investments.

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

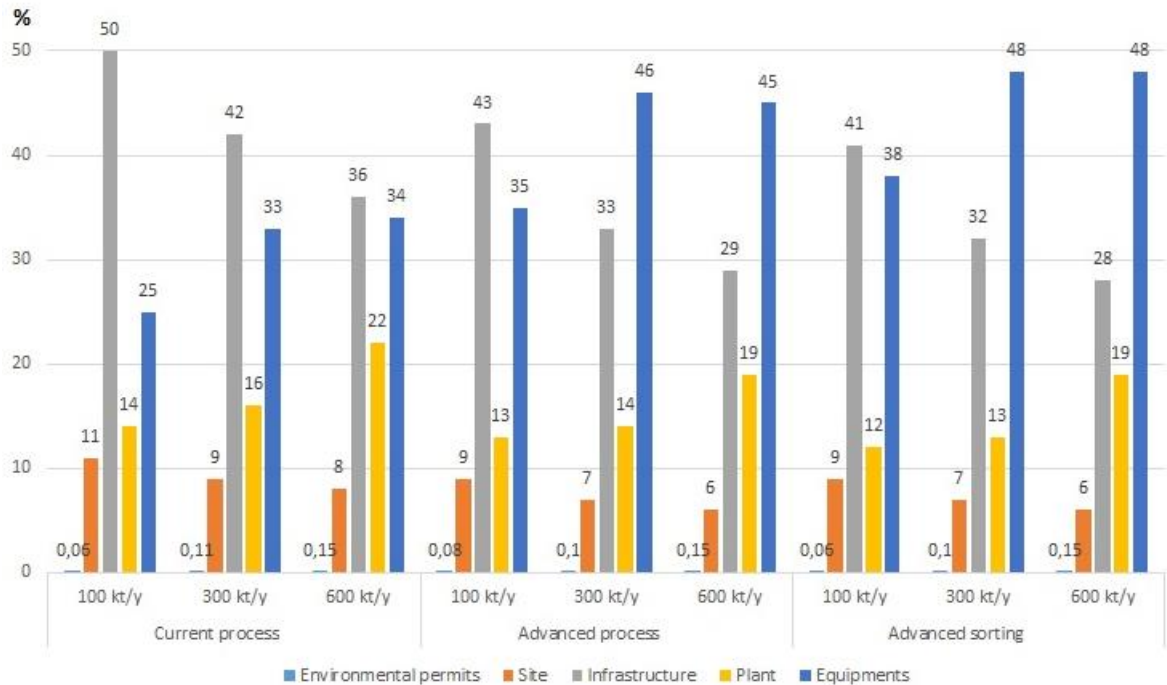


Figure 6 – Share of investment category in total initial cost

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3.2. Operating costs

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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)

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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	b
	wheel loaders	430,000	430,000	430,000	430,000	430,000	430,000	430,000	430,000	430,000	
	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

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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	French labor cost (Eurostat)
administration - maintenance labor ⁽¹⁾	2(100 kt/y) ; 3 (300 kt/y) ; 5 (600 kt/y)	€ 2,750/month	
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	Tam (2008), Coelho & de Brito (2013)
	200,000 kWh/month for Ad and AdS	€ 0.1/kWh	
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)

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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

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

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

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454 **4. Results and discussion**

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456 4.1. Internal Rate of Return

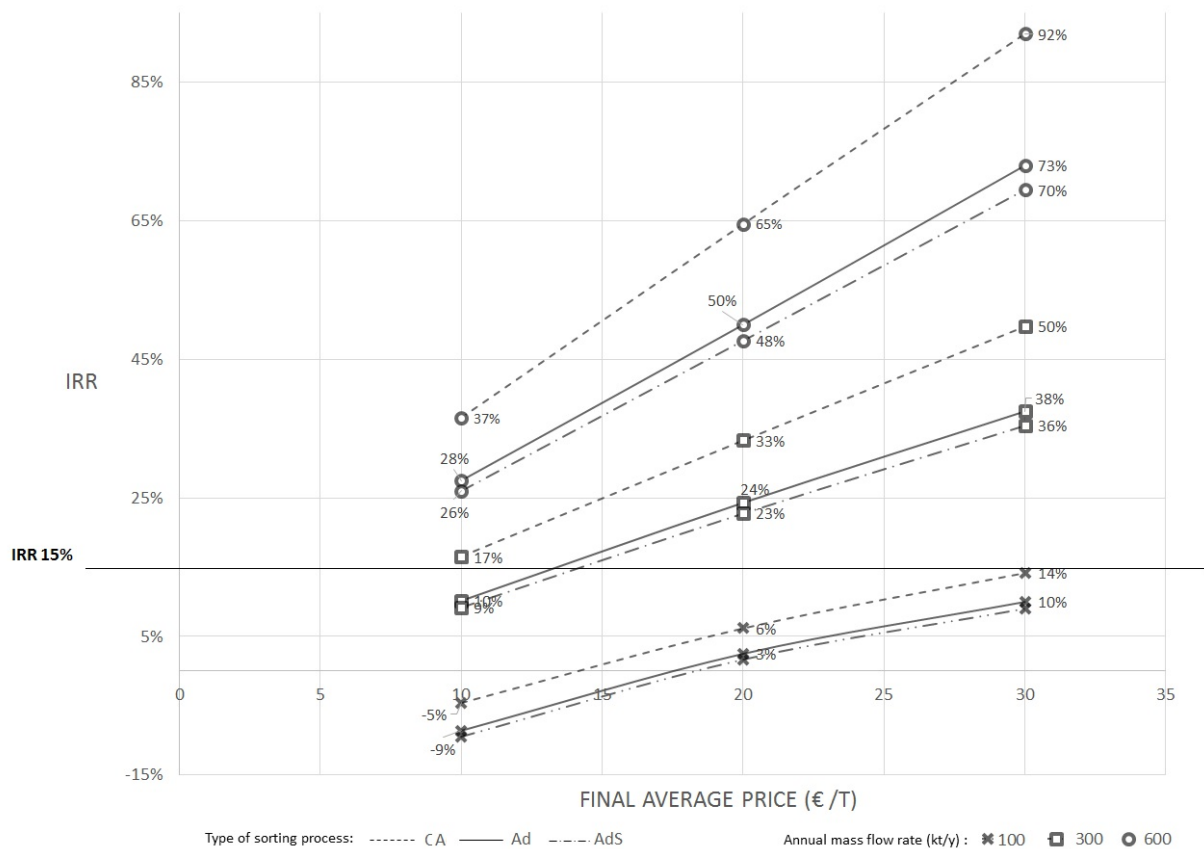
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458 Figure 8 shows the results of all simulations. The tendency lines are the relationships between the IRR and
 459 the average sale price in the scope of each type of platform.

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464 Figure 8– Internal rate of return (IRR) as a function of the final sale price for each type of recycling
 465 platform
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468 The graph demonstrates the high profitability of the three platform types for capacities, such as 600 kt/y
 469 with an IRR above 25% for an average aggregate sale price of 10 €/ton; it is evident that the platforms are not
 470 viable under the simulated conditions for capacities of 100 kt/y.

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

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

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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

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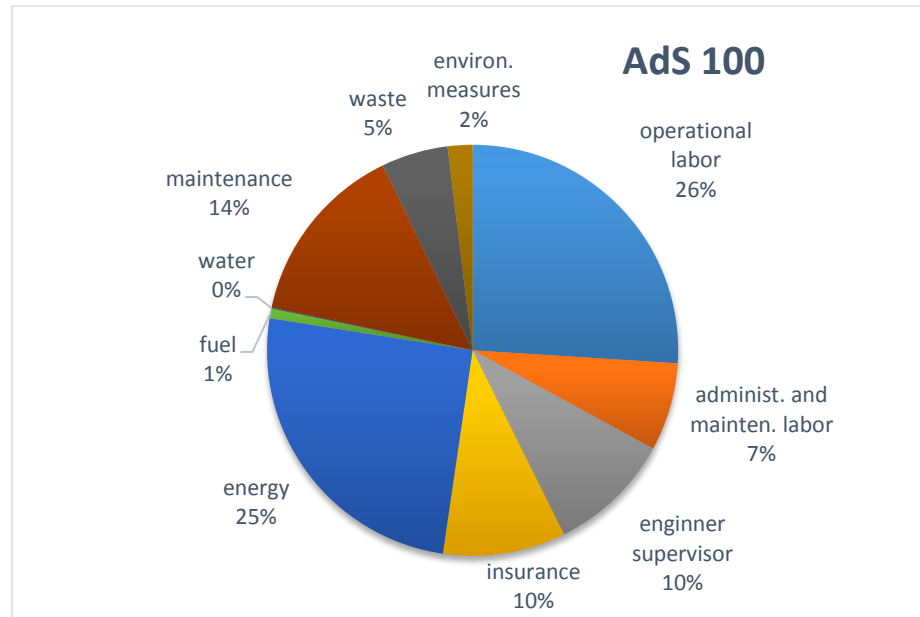


Figure 7 - Operating cost categories (for AdS 100 kt/y)

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

Platform Capacity	P _{MCA} €/ton	P _{MAd} €/ton	P _{MAdS} €/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

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P_{MCA} – Average price for the Current platform; P_{MAd} – Average price for the Advanced platform;
P_{MAdS} – Average price for the Advanced sorting platform;

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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.

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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_{MCA}).

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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.

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Considering the view of NPV, it is possible to find the average prices for the Advanced platform (P_{MAd})" and Advanced Sorting platform (P_{MAdS})" 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.

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

Platform Capacity	P _{MCA} €/ton	P _{MAd} €/ton	P _{MAdS} €/ton
300 kt/y	10.0	13.0	13.6
600 kt/y	10.0	11.7	12.0

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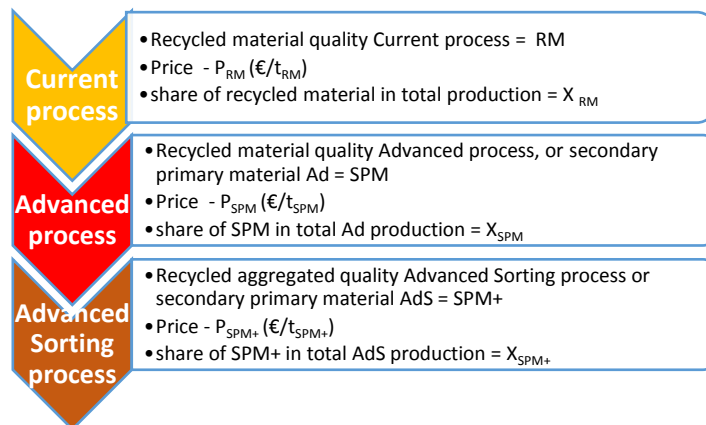
P_{MCA} – Average price for the Current platform; P_{MAd} – Average price for the Advanced platform;
P_{MAdS} – Average price for the Advanced sorting platform;

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4.2. Influence of product quality

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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.



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Figure 9 - Three possibilities for generating products,

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

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

524

$$525 \quad P_i = (P_{Mi} - (1 - X_i) * P_{MCA}) / X_i, \quad (4)$$

526 with

527 P =price;

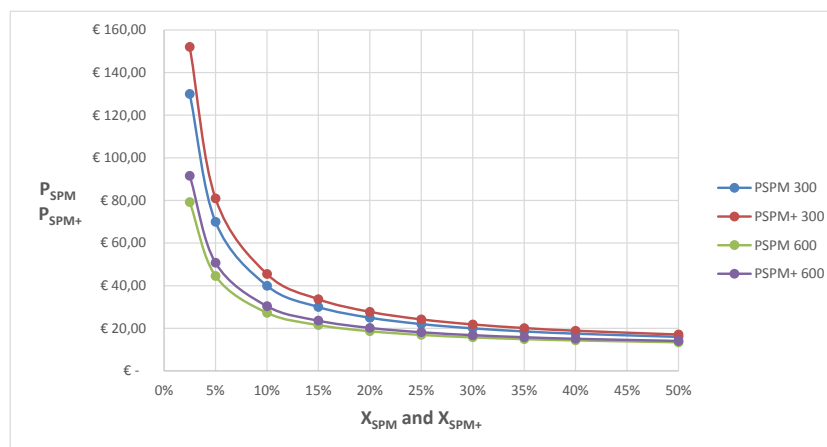
528 X = share of recovery in total production;

529 i = SPM, SPM+.

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531 Figure 10 demonstrates the relationships between X_i and P_i (with i =SPM, SPM+), considering $P_{RM} = 10$
532 €/ton (Table 6).

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

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

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

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549 4.3. Payback period

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

557 Payback period can be determined using the following equation:

558

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

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

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

614 materials could be increased by raising the relative price of primary raw materials. Countries with
615 high tax rates have higher recycling rates, but tax rates are not a “*silver bullet*” (Söderholm, 2011).
616 As previously stated, efficient raw material management policies require a combination of policy
617 instruments addressing both upstream and downstream constraints;
618 - *planning*: efficient planning and sustainable material logistics management may have a significant
619 effect on the cost efficiency of recycling platforms. There is a need to address regional differences;
620 - *legal*: implementation of national legal requirements for the reuse of waste materials (recycled
621 materials and/or secondary raw materials) may impact the diffusion of C&DW sorting processes.
622 A more active diversion policy (i.e., a policy diverting C&D waste material from landfills) may
623 also have an impact;
624 - *infrastructure*: Increase the net of C&DW deposit areas to reduce transport costs with the objective
625 of accumulating stock to supply recycling platforms with capacities greater than 300kt/y.
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628 5. Conclusions

629
630 The paper proposes an economic analysis of three different types of C&DW sorting recycling platforms,
631 named current, advanced and advanced sorting. The development of such recycling platforms could be a
632 way to achieve a sustainable management of construction and demolition waste. From our analysis, a
633 number of conclusions can be drawn. Given the available data, this “Scope study – Phase 1” shows that
634 current process has better economic performance (in terms of internal rate of return) than other two
635 processes. The explanation of this result lies in the fact that the difference of investment cost between these
636 technologies cannot be offset by the (too) low difference between recycled material price and secondary
637 primary material price. Given the current market conditions these “high-performing” processes seem to be
638 less profitable than more simple technologies in most of the European countries,

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

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

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654
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