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# Concentration Plants of Construction and Demolition Waste for Coarse Aggregate Recycling

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**Abstract:** This paper presents simulations of different concentration plants that use Inert Construction and Demolition Waste as feed to generate coarse aggregates from old concretes. Different feed materials were studied: CDW generated in Spain; low-strength concretes, C16/20, which are ordinary concrete used in civil construction; and high-strength concretes, C50/60, from specific demolitions, such as old viaducts and bridges. Granulometric and densimetric analyses were performed, and the composition of the granulometric fractions of the proposed concretes were analyzed based on previous studies carried out, to understand the materials that can be recovered and considered for reinvestment in the market. Investment analysis considering the CAPEX, OPEX, revenue, IRR, MIRR, NPV, and DPP of the different concentrating plants with varying streams of concentration to recover the materials of interest (coarse aggregates) are presented and discussed. The results of the analyses indicate greater viability in plants that use mobile plants and the use of water jigs.

**Keywords:** CDW; concrete recycling; concentration plants; investment analysis



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## 1. Introduction

Construction and Demolition Waste (CDW) is a mixture of different particles used in civil construction, such as concrete, bricks, red ceramics, coatings, gypsum, etc. [1–3]. These materials, when separated and concentrated, can be recycled in civil engineering as aggregates [4]. Nowadays, thousands of tons of CDW are generated, with a constant and significant increase each year. In 2014, construction and demolition activities generated 1.13 billion tons of CDW in China [5]; more than 850 million tons in the European Union (EU) [6]; and more than 530 million tons in the United States [7]. Today, CDW represents about 30% of all solid waste generated in Europe [4].

CDW management is one of the great challenges for scientists of this century due to the huge volume of material generated, energy expended, $CO_2$ emissions, etc. A possible solution to the problem is its partial recycling as aggregates in the manufacture of new concrete [8–10]. For this, it is necessary to separate and concentrate these materials in processing plants.

A part of the generated CDW can be used as coarse aggregates in new concretes, especially the liberated rocks that are present in old concretes [11]. The use of this material would represent millions of tons less of new aggregates generated in the world, providing a decrease in production and consequent $CO_2$ emissions and energy used.

A reasonable way to improve the quality of CDW is the classification and concentration by type of material, which can be performed using different types of equipment that use density as a separation factor, such as, e.g., water or air jigs [12–15]. These plants usually crush CDW and remove particulates such as plastics, paper, wood, etc., as well as metal parts (both ferrous and non-ferrous). The residual material is known as Inert CDW (the abbreviation CDW is used in this paper instead of Inert CDW) and basically contains bricks, tiles, plaster, concrete, mortar, and coarse aggregate [16,17].

Today, CDWs are rarely used as a substitute for natural aggregates in structural concrete [18–20]. They are only used as aggregates for low-strength concrete, road sub-base, landfills in cities, and other low-performance applications [4,21]. The main reason that CDW does not replace natural aggregates in structural concretes is the high variability presented by CDW produced in recycling plants [22,23], which makes it necessary to change the mix design each time the concrete is produced. Another reason is the low density presented by most inert CDW, which imposes a high consumption of cement [22].

Another restriction on the use of CDW in concrete manufacturing is the fact that the gypsum content is highly restricted to a maximum of about 1%. CDW preparation plants do not accept gypsum remains, but the control is only visual and not always effective. Thus, the risk associated with the use of CDW in new concrete is high due to the possible presence of gypsum particles.

The purpose of this paper is to carry out simulations of different concentration plants that use CDW as feed to generate coarse aggregates from demolished concretes, using air jigs, water jigs, and sensor-based sorting methods as a concentration way in the processing plants' streams. Different feed materials are studied in these plants: CDW generated in Spain, low-strength concretes (C16/20, ordinary concrete in civil industry) that can be found and manually separated in classification and selection plants, and high-strength concretes (C50/60, high-strength concrete) used in specific demolitions (e.g., old viaducts and bridges). Investment analysis considering the CAPEX, OPEX, revenue, IRR, MIRR, NPV, and DPP of the different concentrating plants are presented and discussed.

## 2. Composition and Properties of Recycled Materials

The following materials were used in this paper to carry out the simulation:

- CDW generated in Spain.
- Ordinary concrete (C16/20), denominated here as Concrete 16 MPa.
- High-strength concrete (C50/60), denominated here as Concrete 54 MPa.

### *2.1. Composition and Chemical Characteristics of Recycled Aggregates*

#### 2.1.1. Composition of CDW in Spain

The CDW generated in Spain presents the composition shown in Figure 1. It is possible to see that 12% of CDWs in Spain consist of concrete particles [24]. This concrete is basically composed of ordinary concrete (about 15–20 MPa), the most commonly used in the construction of houses and small buildings. The authors assume in this paper that all this material is Concrete 16 MPa (Ordinary concrete—C16/20).

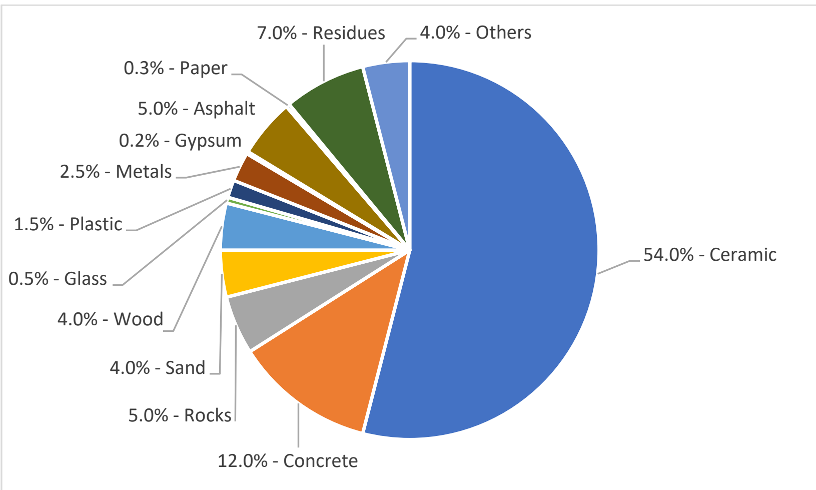



**Figure 1.** Composition of CDW in Spain [24].

2.1.2. Size Distribution of the Concretes 16 MPa and 54 MPa

The size distribution of the concretes 16 MPa and 54 MPa crushed under 20 mm can be seen in Table 1 (table adapted from Sampaio et al. [11]). In the work developed by Sampaio et al. [11], the concrete samples were crushed in a jaw crusher at a top size of 19.1 mm and sized in the following size ranges: <4.75 mm; 4.75/8.0 mm; 8.0/12.7 mm; and 12.7/19.1 mm.

**Table 1.** Size distribution of 2 different concretes (16 MPa and 54 MPa) comminuted at a top size of 19.1 mm (adapted from Sampaio et al. [11]).

| Size Distribution Concrete | <4.75 mm (%) | 4.75/8 mm (%) | 8/12.7 mm (%) | 12.7/19.7 mm (%) | Total (%) |
|---|---|---|---|---|---|
| 16 MPa (<19.1 mm) | 25.98 | 10.04 | 30.86 | 33.12 | 100.00 |
| | 25.98 | | 74.02 | | 100.00 |
| 54 Mpa (<19.1 mm) | 24.65 | 10.84 | 32.60 | 31.91 | 100.00 |
| | 24.65 | | 75.35 | | 100.00 |

2.1.3. Density Distribution of the Concretes 16 MPa and 54 MPa

In the experiment carried out by Sampaio et al. [11], the densimetric analysis of concretes was carried out with dense liquids: Bromoform (CHBr3—Trimethyl bromide), with a density of 2.81 g/cm$^3$, and Perchloroethylene (Tetrachloroethylene), with a density of 1.62 g/cm$^3$. The concrete samples had the following size ranges: 4.75/19.1 mm, 4.75/8.0 mm, 8.0/12.7 mm, and 12.7/19.1 mm (Table 1). These were submitted to sink–float tests. The concrete samples were separated into the following density ranges: <2.1 g/cm$^3$, 2.1 < β< 2.2 g/cm$^3$, 2.2 < β< 2.3 g/cm$^3$, 2.3 < β< 2.4 g/cm$^3$, 2.4 < β< 2.5 g/cm$^3$, 2.5 < β< 2.6 g/cm$^3$, 2.6 < β< 2.7 g/cm$^3$, 2.7 < β< 2.8 g/cm$^3$, and >2.8 g/cm$^3$.

Figure 2 presents the densimetric studies (mass function of the density range) with 16 MPa and 54 MPa concrete samples. It can be seen from Figure 2 that the two concretes have a significant mass in the densimetric fraction, with over 2.8 g/cm$^3$.

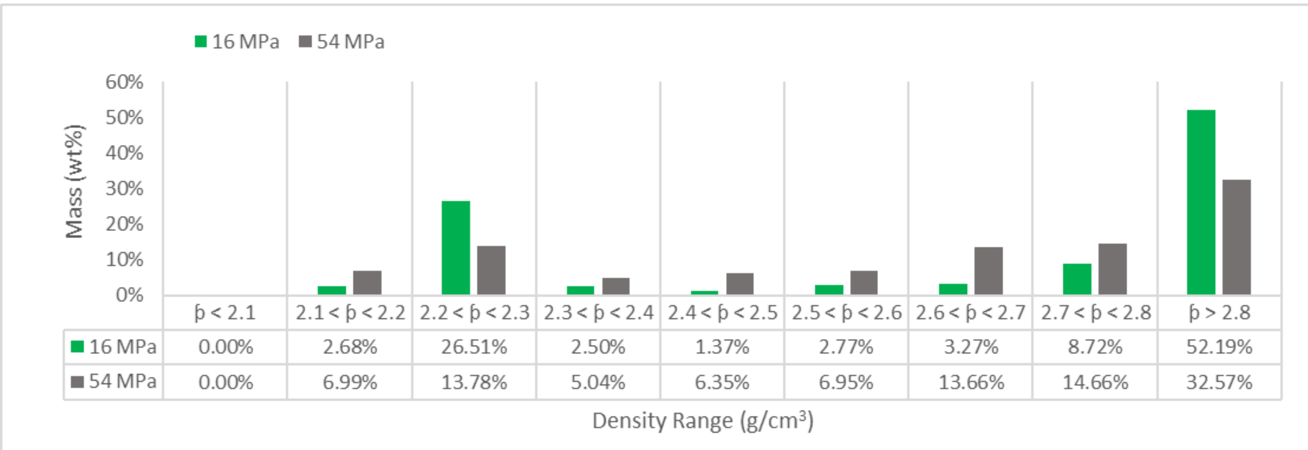



**Figure 2.** Density distribution of the concretes comminuted at 19.1 mm (size 4.75/19.1 mm). Figure adapted from the paper by Sampaio et al. [11]. Reproduced with permission from Sampaio C.H.; 11, 803, Minerals; published by MDPI, 2021.

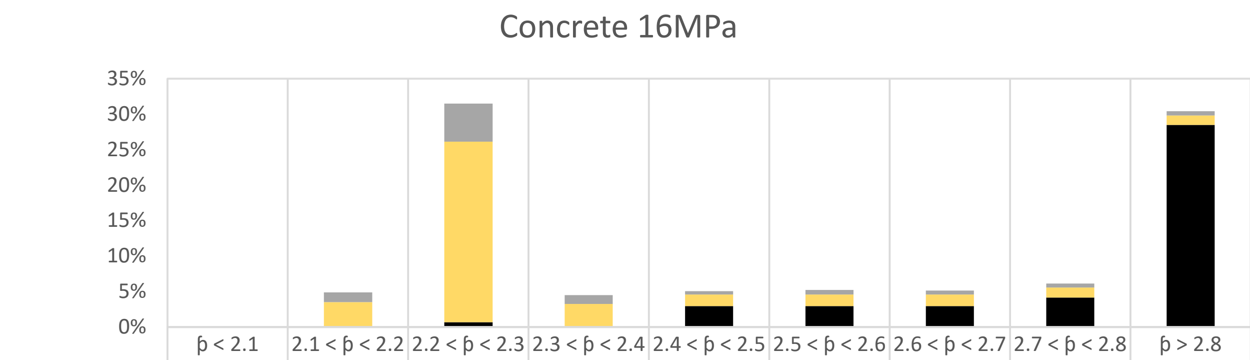
2.1.4. Analysis of Concrete Substrate Composition (16 Mpa and 54 Mpa)

To analyze the composition of the concretes, the materials were placed in a muffle furnace at 900 ± 50 °C for a period of 120 ± 20 min. After reaching room temperature, the samples were placed in a Becker with ammonium hydroxide ($NH_4OH$) for 3 days. The remaining material was washed with water and dried. The samples were then submitted to a solution of hydrochloric acid (30% dilution) for 4 h. Afterward, the samples were washed and dried. The remaining material was fractionated in sizes for sand and coarse aggregate. The cement paste was calculated by weight difference.

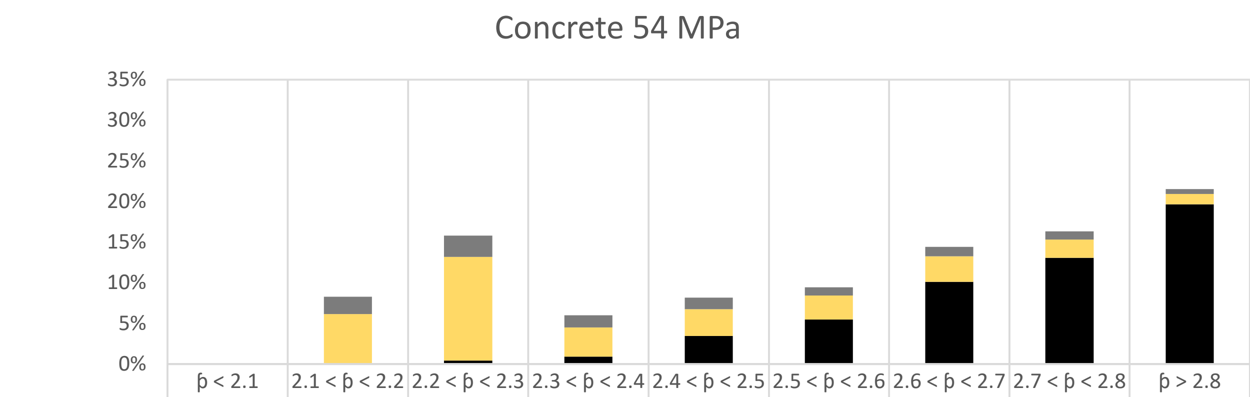
The concrete test tubes were prepared in the laboratory (according to the methodology cited in the work by Sampaio et al. [11]) to emulate the characteristics found in concrete that is commonly used in civil construction.

The granulometric and densimetric characteristics of 16 Mpa concrete were analyzed due to the greater presence of this material in CDW plants. Such concretes are commonly found in buildings where simple structural concretes are required. The analysis of 54 Mpa concrete is due to the increase in recent years in demolitions carried out in specific structures, where high-performance concrete is needed, such as bridges, stadiums, viaducts, and larger buildings. With the increase in such demand, the analysis of the processing of this material can lead to more effective and efficient recoveries of the materials that make up these wastes.

Figure 3 shows the composition of each densimetric fraction, that is, the amount of cement paste, coarse aggregate, and sand. It can be seen from Figure 3 that the material with a density over 2.8 g/cm$^3$ is basically constituted by coarse aggregates. It was considered for this paper that the concrete particles with a density over 2.8 g/cm$^3$ are completely liberated coarse aggregates.




| | þ < 2.1 | 2.1 < þ < 2.2 | 2.2 < þ < 2.3 | 2.3 < þ < 2.4 | 2.4 < þ < 2.5 | 2.5 < þ < 2.6 | 2.6 < þ < 2.7 | 2.7 < þ < 2.8 | þ > 2.8 |
|---|---|---|---|---|---|---|---|---|---|
| Cement Paste | 0.00% | 1.34% | 5.40% | 1.25% | 0.46% | 0.64% | 0.55% | 0.55% | 0.57% |
| Sand | 0.00% | 3.53% | 25.43% | 3.21% | 1.62% | 1.62% | 1.62% | 1.43% | 1.34% |
| Coarse Aggreg | 0.00% | 0.00% | 0.68% | 0.05% | 2.96% | 2.96% | 2.96% | 4.14% | 28.49% |




| | þ < 2.1 | 2.1 < þ < 2.2 | 2.2 < þ < 2.3 | 2.3 < þ < 2.4 | 2.4 < þ < 2.5 | 2.5 < þ < 2.6 | 2.6 < þ < 2.7 | 2.7 < þ < 2.8 | þ > 2.8 |
|---|---|---|---|---|---|---|---|---|---|
| Cement Paste | 0.00% | 2.12% | 2.60% | 1.51% | 1.39% | 1.02% | 1.13% | 1.01% | 0.63% |
| Sand | 0.00% | 6.12% | 12.77% | 3.59% | 3.29% | 2.95% | 3.14% | 2.24% | 1.27% |
| Coarse Aggreg | 0.00% | 0.05% | 0.43% | 0.91% | 3.48% | 5.49% | 10.14% | 13.09% | 19.65% |

**Figure 3.** Cement paste, sand, and coarse aggregate contents in different density fractions and concrete strengths (16 and 54 MPa). Concretes comminuted at 19.1 mm (size 4.75/19.1 mm). Table adapted from the paper by Hoffmann Sampaio [11]. Reproduced with permission from Sampaio C.H.; 11, 803, Minerals; published by MDPI, 2021.

Table 2 presents the mass balance of the different products used in this paper that feed the preparation plants. For example, the CDW generated in Spain presents 12% of concrete particles (it is assumed in this paper that most of this concrete is ordinary concrete, C16/20). About 75% of this concrete, when comminuted to a top size of 20 mm, is in the 20/4 mm range (Table 1). Thus, about 9% by mass of the feed is concrete in the 20/4 mm granulometric fraction. Ordinary concrete, when comminuted to a top size of 20 mm contains about 52% of liberated coarse aggregate particles (density over 2.8 g/cm$^3$). This material (coarse aggregate liberated with a density over 2.8 g/cm$^3$) represents 4.7% of the feed mass.

**Table 2.** The mass balance of the concentration plants' feed.

| Concentration Plant Feed | Concentration Plant Feed (% of the Concrete) | Mass in the Size 20 × 4 mm (%) | Concrete Particles (%) | Coarse Aggregate Liberated (%) | Mass of Coarse Aggregate Liberated > 2.8 g/cm$^3$ (%) |
|---|---|---|---|---|---|
| CDW | 12 | 75 | 9 | 52 | 4.7 |
| Ordinary Concrete—C16/20 | 100 | 75 | 75 | 52 | 39 |
| High-Strength Concretes—C50/60 | 100 | 75 | 75 | 52 | 24 |

Low-strength concretes (C16/20, ordinary concrete in civil industry) that are manually separated and concentrated and high-strength concretes (C50/60, high-strength concrete) from specific demolitions (e.g., old viaducts and bridges) present 39% and 24% of coarse aggregate liberated materials, respectively, of the feed mass.

## 3. Preparation Plants

The following concentration circuits (CDW Plants) were studied:

Concentration Plant 1 (Figure 4). In this circuit, CDW (Inert CDW) is comminuted to a top size of 20 mm and sized at 4 mm. The fraction under 4 mm is discharged as tailings. The fraction of 20 to 4 mm feeds a preparation plant (air jig, water jig, or sensor-based sorting). The concentrate presents 4.7 t/h of concrete particles, with a density over 2.8 g/cm$^3$.

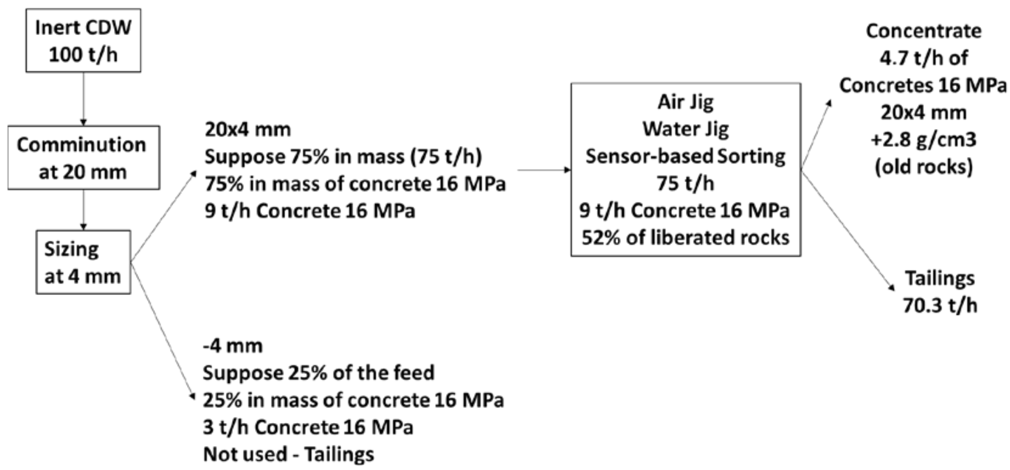



**Figure 4.** Concentration Plant—INERT CDW. Simulation with air jig, water jig, and sensor-based sorting.

Concentration Plant 2 (Figure 5). In this circuit, concretes of 16 MPa are comminuted to a top size of 20 mm and sized at 4 mm. The fraction under 4 mm is discharged as tailings. The fraction of 20 to 4 mm feeds a preparation plant (air jig, water jig, or sensor-based sorting). The concentrate presents 39 t/h of concrete particles, with a density over 2.8 g/cm$^3$.

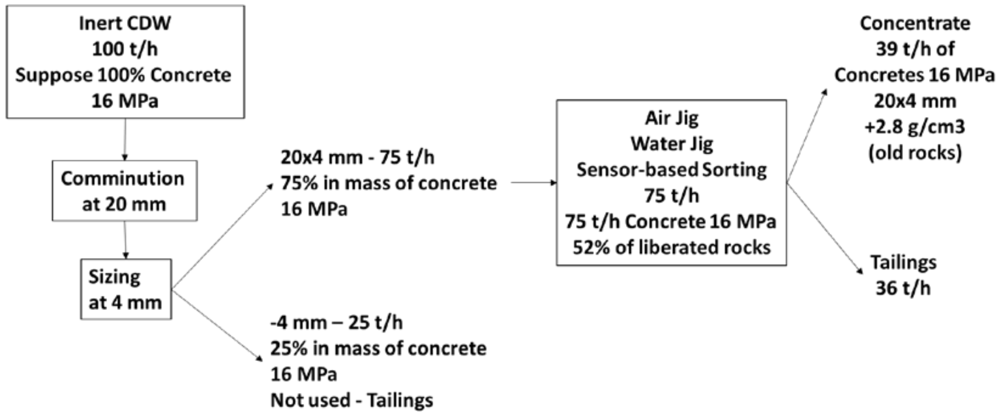



**Figure 5.** Concentration Plant 2—CONCRETE 16 Mpa. Simulation with air jig, water jig, and sensor-based sorting.

Concentration Plant 3 (Figure 6). In this circuit, concretes of 54 MPa are comminuted to a top size of 20 mm and sized at 4 mm. The fraction under 4 mm is discharged as tailings. The fraction of 20 to 4 mm feeds a preparation plant (air jig, water jig, or sensor-based sorting). The concentrate presents 24 t/h of concrete particles, with a density over 2.8 g/cm$^3$.

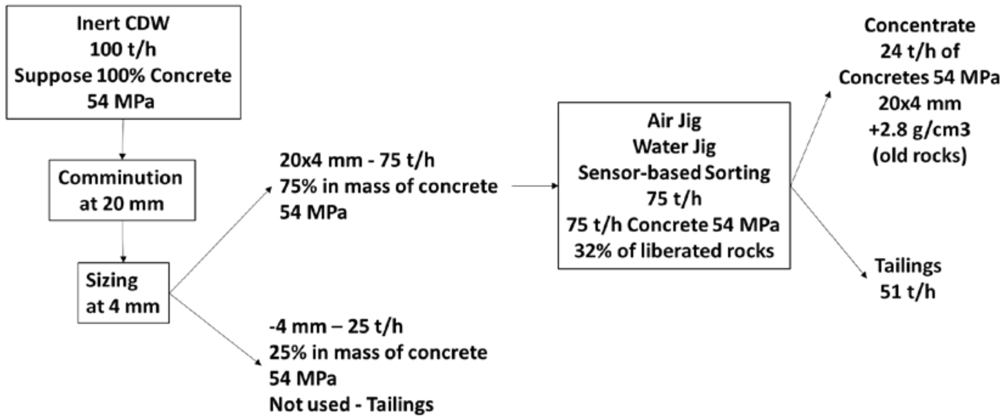



**Figure 6.** Concentration Plant 3—CONCRETE 54 MPa. Simulation with air jig, water jig, and sensor-based sorting.

## 4. Preliminary Economical Assessment of Three Construction and Demolition Waste (CDW) Plants

This assessment aims to provide insights into the financial viability of these plants by estimating the Capital Expenditure (CAPEX), Operating Expenditure (OPEX), and potential revenue. The business plan level, the so-called opportunity assessment [25], has an expected accuracy level of +/−50% [26]. As the processing tests were based on selected feeds for research purposes, the economic appraisal was kept as general as possible for this study.

To determine the CAPEX, we considered the capital costs associated with acquiring and installing the necessary equipment (Table 3). Considering industry standards, we also factored in costs for equipment installation using Mular's factorized estimation [26,27].

To assess the operational costs associated with running these plants, the source we relied on was the CostMine [28], where various factors such as labor, maintenance, utilities, and other expenses are tailored, aiming for an estimation of the expenditures in the operation of the CDW plants.

The revenue projections are based on the average figures obtained by different sources such as [15,29,30]. By combining insights from these sources, we formulated an approximation of the revenue that can be expected from the CDW plants, as the transport distance, supply and demand, and acceptance of recycled products vary greatly from country to country and from the local region to local region.

For this study, it was considered that the Levy (recycling services), which can be as high as 40 USD/ton of CDW [31], compensates for transportation costs and the low or negative prices to manage the amount of waste and/or water treatment, such as in the case of water jig solutions. The amount of metals that can be potentially recovered, which can be a game changer [31], was not considered here.

Starting with this established scenario, as a starting point, USD 12 was fixed as the income per ton of saleable product, independently of the amount and quality of the concrete fed.

It was considered that 22.6 ton/h of product could be processed, which is the average for the three different qualities of concrete. For a plant operating effectively for 17.45 h/day for 360 days per year, the potential income is around USD 1.704 million/year.

The treatment plant was structured as follows:

The three options have the same comminution unit as the first step, differing from each other through the gravity solution (water jig, air jig, or sensor-based sorting—SBS) used in the second step.

For the comminution step, we proposed a Jaw Crusher 200 HP electric mobile plant/magnetic separator 3 HP & Cone Crusher/screening mobile plant 300 HP electric—cost: USD 1,350,000.

For the gravity separation step, we have the following parameters:

Water Jig Concentration Plant 1: Water jig (4 un × Bandelari Jig 20 HP 36″ × 36″)/thickener 6 m diameter, steel wall—Cost: USD 340,000.

Air Jig Concentration Plant 2: Air jig (2 un 75 HP)—Cost: USD 300,000.

SBS Concentration Plant 3: Sensor based sorting (2 un)—Cost: USD 600,000.

**Table 3.** The three options' calculated costs for efficient equipment installation using Mular's [30] factorized estimation.

| | Item | Mobile Crushing (USD) | Factor | (1) Water Jig Cost (USD) | Factor | (2) Air Jig Cost (USD) | Factor | (3) Sorter Cost (USD) |
|---|---|---|---|---|---|---|---|---|
| 1 | Direct cost main equipment | 1,350,000.00 | | 340,000.00 | | 300,000.00 | | 600,000.00 |
| 2 | Piping | (7–25%) | 25% | 85,000.00 | 10% | 30,000.00 | 7% | 42,000.00 |
| 3 | Electrical | (12–25%) | 20% | 68,000.00 | 25% | 75,000.00 | 15% | 9000.00 |
| 4 | Instrumentation and Control | (3–10%) | 5% | 17,000.00 | 7% | 21,000.00 | 10% | 60,000.00 |
| 5 | Spares | (1–5%) | 3% | 10,200.00 | 4% | 12,000.00 | 5% | 30,000.00 |
| 6 | First-fill | (1–3%) | 1% | 3400.00 | 1% | 3000.00 | 1% | 6000.00 |
| 7 | Buildings | (7–15%) | 12% | 40,800.00 | 15% | 45,000.00 | 15% | 90,000.00 |
| 8 | Direct Costs | | | 564,400.00 | | 486,000.00 | | 918,000.00 |
| 9 | Owner's costs | (5–15%) | 7% | 39,508.00 | 7% | 34,020.00 | 7% | 64,260.00 |
| 10 | Freight and taxes | (3–10%) | 8% | 45,152.00 | 8% | 38,880.00 | 10% | 91,800.00 |
| 11 | EPCM Costs (Eng., Procur., Constr. And Management) | (5–30%) | 20% | 112,880.00 | 15% | 72,900.00 | 25% | 229,500.00 |
| 12 | Construction camp | (4–10%) | 4% | 22,576.00 | 4% | 19,440.00 | 4% | 36,720.00 |
| 13 | Contingency (direct and indirect) | (15–40%) | 30% | 169,320.00 | 30% | 145,800.00 | 30% | 275,400.00 |
| 14 | Indirect costs | | | 389,436.00 | | 311,040.00 | | 697,680.00 |
| 15 | Processing Plant Cost (USD) | | | 953,836.00 | | 797,040.00 | | 1,615,680.00 |
| | (with mobile crushing) CAPEX TOTAL COST (USD) | | | 23,030,836.00 | | 2,147,040.00 | | 2,965,680.00 |

In terms of operational cost, we have the following costs:

- Comminution—Jaw Crusher 150 HP electric mobile plant/magnetic separator 3 HP & Cone Crusher/screening mobile plant 300 HP electric—Cost: 2 USD/t feed;

- Water Jig Concentration Plant 1: Water jig (4 un × Bandelari Jig 20 HP 36″ × 36″)/thickener 6 m diameter, steel wall—Cost: 1 USD/t feed;
- Air Jig Concentration Plant 2: Air jig (2 un 75 HP)—Cost: 2 USD/t feed;
- SBS Concentration Plant 3: Sensor-based sorting (2 un)—Cost: 3 USD/t feed.

For Water Jig Concentration Plant 1, it involves setting up a plant with a total capital expenditure (CAPEX) of USD 2.304 million. The estimated operational expenditure (OPEX) for the project is USD 803,000 per year. The projected revenue from selling the CDW at USD 12/ton on average is estimated at USD 1.704 million annually.

For Air Jig Concentration Plant 2, it involves a total capital expenditure (CAPEX) of USD 2.147 million. The estimated operational expenditure (OPEX) for the project is USD 992,000 per year. The projected revenue remains the same as option 1, at USD 1.704 million annually.

For SBS Concentration Plant 3, it involves a total capital expenditure (CAPEX) of USD 2.966 million. The estimated operational expenditure (OPEX) for the project is USD 1,181,000 per year. The projected revenue remains the same as options 1 and 2, at USD 1.704 million annually.

To assess the financial viability of these projects, several metrics were calculated (Tables 4 and 5): the Internal Rate of Return (IRR), Modified Internal Rate of Return (MIRR), Net Present Value (NPV), and Discounted Payback Period (DPP).

**Table 4.** Internal Rate of Return (IRR), Modified Internal Rate of Return (MIRR), Net Present Value (NPV), and Discounted Payback Period (DPP) for the three options considered.

| Option | IRR (%) | MIRR (%) | NPV (M$) | DPP (Years) |
|---|---|---|---|---|
| Plant 1 | 37.8 | 19.1 | 3.53 | 3.2 |
| Plant 2 | 31.3 | 17.7 | 2.4 | 3.9 |
| Plant 3 | 13.9 | 12.7 | 0.29 | 12.2 |

**Table 5.** Internal Rate of Return (IRR), Modified Internal Rate of Return (MIRR), Net Present Value (NPV), and Discounted Payback Period (DPP), including a tax rate of 19% over the benefits and a depreciation of 10% per annum.

| Option | IRR (%) | MIRR (%) | NPV (M$) | DPP (Years) |
|---|---|---|---|---|
| Plant 1 | 21.5 | 15.4 | 1.31 | 6.5 |
| Plant 2 | 16 | 13.6 | 0.49 | 11.1 |
| Plant 3 | 11.6 | 11.7 | -0.07 | - |

The IRR represents the rate at which the investment's inflows match its outflows over a specific period [32]. The MIRR is a modified version of the IRR that assumes that positive cash flows are reinvested at a reinvestment rate of 12% per year [33]. The NPV represents the present value of the project's expected cash flows, discounted at a predetermined rate of 12% per year. A positive NPV indicates that the project is financially feasible.

Assuming a project lifespan of 15 years, the calculated metrics for Concentration Plant 1, 2, and 3 are as follows:

Considering a marginal tax rate of 19% and constant depreciation of 10% per year, the revised metrics are as follows:

Based on the calculated IRR, MIRR, and NPV, when considering taxation, only Concentration Plant 1 (Mobile Crushing and Water Jig) appears to be a financially attractive investment. The MIRR of 15.4% exceeds the discount rate of 12%, indicating a positive return on investment. Additionally, the positive NPV of USD 1,310,000 confirms its viability.

Concentration Plant 2 (Mobile Crushing and Air Jig) is mathematically viable but economically marginal. The IRR of 16% and MIRR of 13.6% both exceeds the discount rate of 12%, indicating a positive return on investment. However, the DPP of 11.1 years shows the project's weakness in terms of the payback period.

Concentration Plant 3 (Mobile Crushing and Sorter) is not viable at a discount rate of 12%, as it fails to meet the positive NPV requirement.

The Figure 7 shows a comparison between all options in the conditions established in the preliminary economic assessment.

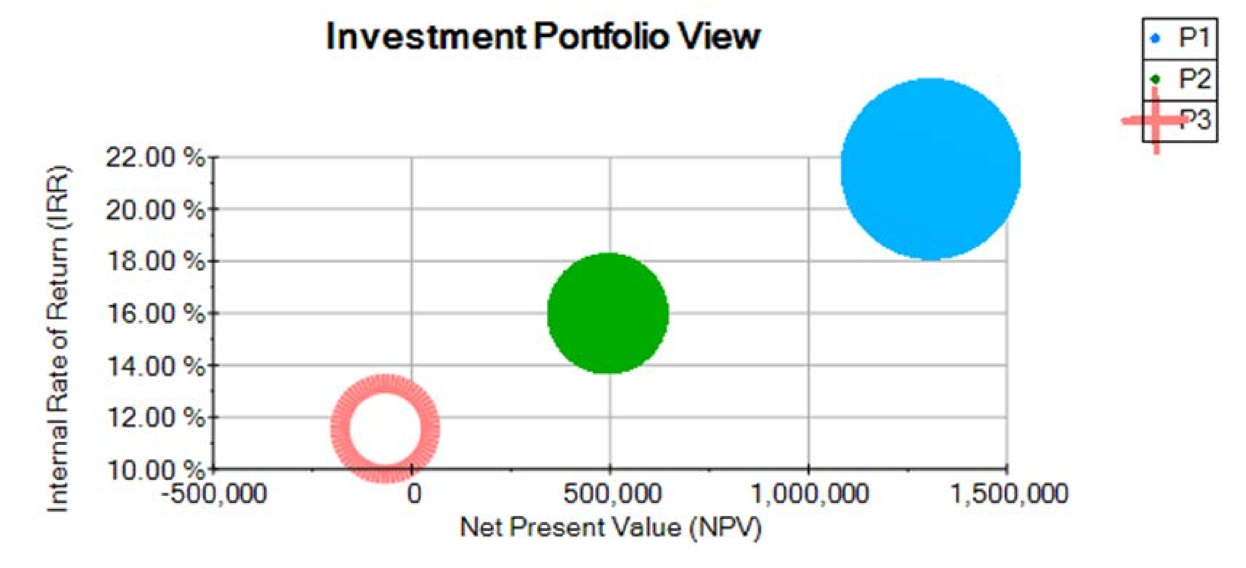



**Figure 7.** A comparison between all options shows that Concentration Plant 3 is viable in the conditions established in the preliminary economic assessment.

Furthermore, a Tornado Analysis is outlined for the best case (Concentration Plant 1), which considers the impact of variations in key inputs (revenues, OPEX, discount rate, CAPEX, tax rate, and reinvestment) on the NPV. A revenue decrease of 30% or a 30% increase in operational costs (OPEX) can result in a negative NPV, altering the previously announced attractiveness of the project. Figure 8 demonstrates a tornado analysis showing the impact of variations in key inputs on the NPV for the best case (Concentration Plant 1).

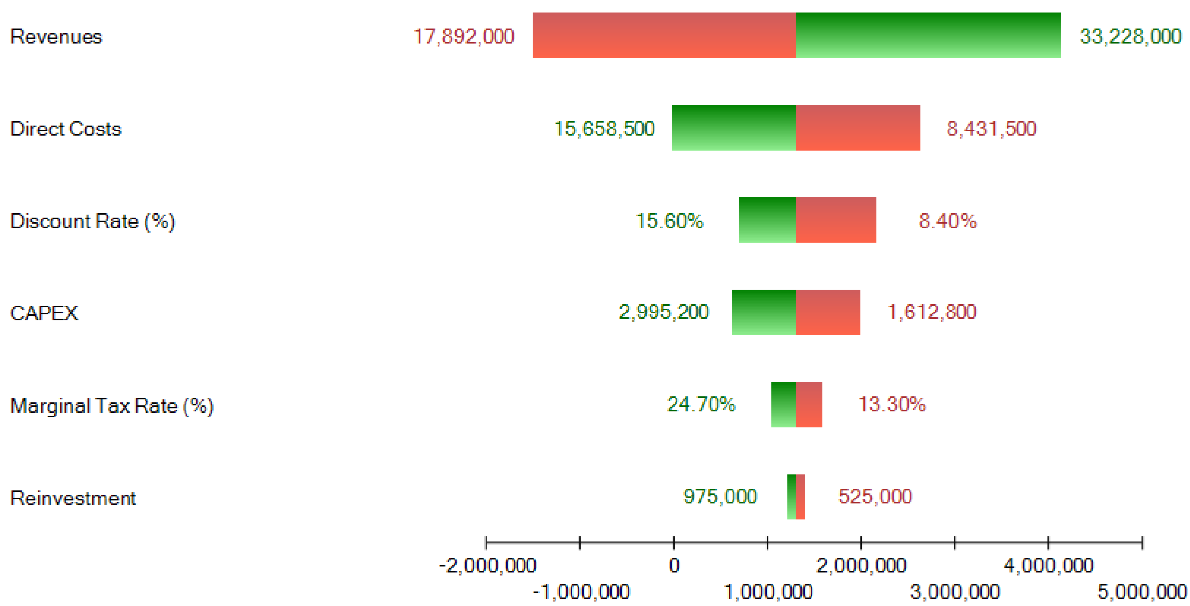



**Figure 8.** Tornado Analysis showing the impact of variations in key inputs (revenues, OPEX, discount rate, CAPEX, tax rate, and reinvestment) on the NPV for the best case (Concentration Plant 1).

In summary, based on the investment analysis considering the CAPEX, OPEX, revenue, IRR, MIRR, NPV, and DPP, only the Mobile Crushing and Water Jig appears to be a promising option. However, the final investment decision should also consider other factors such as market conditions, risk assessment, environmental concerns regarding water usage, and the strategic fit within the overall investment portfolio.

The economic viability of the different concentration plants studied could be greater if a reliable sales channel was found for the materials (considered tailings) not quantified in the work, but this revenue stream is not considered in this study.

## 5. Conclusions

The main conclusions of this paper are summarized as follows:

Concrete particles represent around 12% of the CDW generated in Spain.

Concretes comminuted at a top size of 20 mm present about 75% in the size range of 5 to 20 mm (size range of the coarse aggregates).

Low- and high-strength concretes account for 39% and 24% (particles under 20 mm) of liberated coarse aggregates, respectively.

The Mobile Crushing and Water Jig appears to be the most promising option.

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## References

1. Müller, A.; Sokolova, S.N.; Vereshagin, V.I. Characteristics of lightweight aggregates from primary and recycled raw materials. *Constr. Build. Mater.* **2008**, *22*, 703–712. [CrossRef]
2. Müller, A.; Angulo, S.C. Determination of construction and demolition recycled aggregates composition, in considering their heterogeneity. *Mater. Struct.* **2009**, *42*, 739–748.
3. Landmann, M.; Müller, A.; Palzer, U.; Leydolph, B. Limitations of Liberation Techniques for Mineral Construction and Demolition Wastes. In Proceedings of the EURASIA 2014, Waste Management Symposium, Istambul, Turkey, 28–30 April 2014.
4. Reis, G.S.d.; Quattrone, M.; Ambrós, W.M.; Grigore Cazacliu, B.; Hoffmann Sampaio, C. Current Applications of Recycled Aggregates from Construction and Demolition: A Review. *Materials* **2021**, *14*, 1700. [CrossRef] [PubMed]
5. Lu, W.; Webster, C.; Peng, Y.; Chen, X.; Zhang, X. Estimating and calibrating the amount of building-related construction and demolition waste in urban China. *Int. J. Constr. Eng. Manag.* **2017**, *17*, 13–24. [CrossRef]
6. Eurostat. Eurostat Statistics for Waste Flow Generation 2016. European Commision. 2018. Available online: http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/ (accessed on 12 May 2022).
7. Environmental Protection Agency. Advancing Sustainable Materials Management: 2018. Figures and Tables. 2018. Available online: https://www.epa.gov/sites/default/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf (accessed on 13 March 2024).
8. Menegaki, M.; Damigos, D. A review on current situation and challenges of construction and demolition waste management. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 8–15. [CrossRef]
9. Cardoso, R.; Silva, R.V.; de Brito, J.; Dhir, R. Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review. *Waste Manag.* **2016**, *49*, 131–145. [CrossRef] [PubMed]
10. Ambrós, W.M.; Sampaio, C.H.; Cazacliu, B.G.; Miltzarek, G.L.; Miranda, L.R. Usage of air jigging for multi-component separation of construction and demolition waste. *Waste Manag.* **2017**, *60*, 75–83. [CrossRef] [PubMed]
11. Hoffmann Sampaio, C.; Cazacliu, B.G.; Ambrós, W.M.; Kronbauer, M.A.; Tubino, R.M.C.; Dal Molin, D.C.C.; Oliva Moncunill, J.; Miltzarek, G.L.; Waskow, R.P.; dos Santos, V.L.G.; et al. Characterization of Demolished Concretes with Three Different Strengths for Recycling as Coarse Aggregate. *Minerals* **2021**, *11*, 803. [CrossRef]
12. Nunes, K.R.A.; Mahler, C.F.; Valle, R.; Neves, C. Evaluation of investments in recycling centres for construction and demolition wastes in Brazilian municipalities. *Waste Manag.* **2007**, *27*, 1531–1540. [CrossRef]

13. Oliveira Neto, R.; Gastineau, P.; Cazacliu, B.G.; Guen, L.L.; Paranhos, R.S.; Petter, C.O. An economic analysis of the processing technologies in CDW recycling platforms. *Waste Manag.* **2017**, *60*, 277–289. [CrossRef]
14. Cazacliu, B.; Sampaio, C.H.; Petter, C.O.; Miltzarek, G.L.; Guen, L.L.; Paranhos, R.S.; Huchet, F.; Kirchheim, A.P. The potential of using air jigging to sort recycled aggregates. *J. Clean. Prod.* **2014**, *66*, 46–53. [CrossRef]
15. Coelho, A.; De Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal—Part I: Location, materials, technology and economic analysis. *J. Clean. Prod.* **2013**, *39*, 338–352. [CrossRef]
16. Wu, Z.; Yu, A.T.W.; Shen, L.; Liu, G. Quantifying construction and demolition waste: An analytical review. *Waste Manag.* **2014**, *34*, 1683–1692. [CrossRef] [PubMed]
17. Hua, K.; Chen, Y.; Naz, F.; Zeng, C.; Cao, S. Separation studies of concrete and brick from construction and demolition waste. *Waste Manag.* **2019**, *85*, 396–404. [CrossRef] [PubMed]
18. Behera, M.; Bhattacharyya, S.; Minocha, A.; Deoliya, R.; Maiti, S. Recycled aggregate from C&D waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review. *Constr. Build. Mater.* **2014**, *68*, 501–516.
19. Silva, R.; Brito, J.; Dhir, R. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [CrossRef]
20. Xuan, D.; Poon, C.S.; Zheng, W. Management and sustainable utilization of processing wastes from ready-mixed concrete plants in construction: A review. *Resour. Conserv. Recycl.* **2018**, *136*, 238–247. [CrossRef]
21. Wong, C.L.; Mo, K.H.; Yap, S.P.; Alengaram, U.J.; Ling, T.C. Potential use of brick waste as alternate concrete-making materials: A review. *J. Clean. Prod.* **2018**, *195*, 226–239. [CrossRef]
22. Guo, H.; Shi, C.; Guan, X.; Zhu, J.; Ding, Y.; Ling, T.; Zhang, H.; Wang, Y. Durability of recycled aggregate concrete: A review. *Cem. Concr. Compos.* **2018**, *89*, 251–259. [CrossRef]
23. Bravo, M.; Brito, J.; Pontes, J.; Evangelista, L. Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. *J. Clean. Prod.* **2015**, *99*, 59–74. [CrossRef]
24. Ministerio de Transportes, Movilidad y Agenda Urbana. Catálogo de Residuos Utilizables en Construcción. Available online: http://www.cedexmateriales.es/catalogo-de-residuos/35/residuos-de-construccion-y-demolicion/ (accessed on 12 March 2024).
25. Ontario Securities Commission (OSC). *Mining Disclosure Essentials: NI 43-101 Reporting Fundamentals, Industry Best Practices, and Useful Guidance for TSX and TSXV Issuers*; PDAC: Toronto, ON, Canada, 2018. Available online: https://www.osc.ca/sites/default/files/pdfs/irps/ni_20180307_43-101_mineral-disclosure.pdf (accessed on 12 June 2024).
26. AUSSIM. Chapter I—Using the handbook. In *Cost Estimation Handbook: Monograph 27*; The Australasian Institute of Mining and Metallurgy, Ed.; The Australasian Institute of Mining and Metallurgy: Carlton, VIC, Australia, 2012; 526p.
27. AUSIMM. *Cost Estimation Handbook for Australian Mining Industry*; AUSIMM: Carlton, VIC, Australia, 1993.
28. CostMine. *Mine & Mill Equipment Cost Guide, Edited by Infomine*; CostMine: Spokane, WA, USA, 2014.
29. Nitichote, K.; Yodsudjai, W. Recycled Aggregates Production Through Economic Perspectives. *Int. J. Sustain. Constr. Eng. Technol.* **2022**, *13*, 257–263. [CrossRef]
30. USGS. *Recycled Aggregates—Profitable Resource Conservation*; USGS Fact Sheet FS–181–99, February, 2000; USGS: Reston, VA, USA, 2000.
31. Petter, R. The Technique of Applied Economic Risk Analysis—Case Study: Rare Earth Mines and Recycling of Construction Demolition Material. Master Degree Dissertation, Federal University of Rio Grande do Sul—UFRGS, Porto Alegre, Brazil, 2015.
32. Torries, T. *Evaluating Mineral Projects: Applications and Misconceptions*; SME: Englewood, CO, USA, 1998.
33. Runge, I. *Mining Economics and Strategy*; SME: Englewood, CO, USA, 1998.