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PREMISES FOR ECO-EFFICIENCY ANALYSIS ON CONSTRUCTION AND DEMOLITION WASTE RECYCLING

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Abstract

The construction industry is associated with significative impacts such a consumption of natural resources and waste generation. Eco-efficiency is an instrument for sustainable analysis which indicates the relation between environmental costs and impacts. While the most environmental method used is the lifecycle assessment (LCA), standardized by ISO 14040, the economic indicator should be selected according to the stakeholder. Total cost, Unit Cost, Net Present Value (NPV) and Internal Rate of Return (IRR) are some of the economic indicators used in the economic analysis of Construction and Demolition Waste (CDW) recycling, however, the search for literature regarding the Eco-efficiency analysis shows a tendency to use the total cost regardless of its objective. In this sense, the objective of this paper is to propose the main premises to be considered in the selection of the economic indicator and in the normalization of the analysis of the CDW recycling Eco-efficiency index results. The search method adopted was comprised for three steps: Systematic review of literature; Analysis and comparison of Eco-efficiency indicators (including economic and environmental inputs); Discussion about the main assumptions in the CDW recycling Eco-efficiency analysis. 14 articles were identified in the Science Direct and Springer platforms. This paper provides information to propose premises to the Eco-efficiency analysis on CDW recycling. As a result, was defined a standard Eco-efficiency analysis according the objective: assessment of the cost to minimizing impacts, a simple comparison between scenarios or economic and environmental viability. The first two objectives refer to the input data variation and the scenarios evaluated, respectively. The third objective needs to compare the results with the current scenario, the final disposal and established market material that recycled aggregate can replace. Using the simplified flowchart proposed for each CDW recycling Eco-efficiency analysis objective will allow to standardize studies of this aspect, thus enabling more credible, replicable and comparable development.

Keywords: eco-efficiency, construction waste, demolition waste; LCA, LCC, sustainability.

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Introduction

The civil construction industry is present in people's daily lives and their growth may reflect a region development stage. However, their processes are associated with potential sources of impacts, such as excessive consumption of natural resources and waste generation. It is known, however, that its own waste, recycled aggregate, can partly replace natural aggregates (Nagataki *et al.*, 2004; Cabral, 2007; e Pedro *et al.*, 2014), and the costs of the recycling process have been the focus of many researches (Waskow *et al.*, 2020).

Eco-efficiency is an instrument for sustainability analysis, which indicates the relation between environmental cost or value and environmental impact (Huppes e Ishikawa, 2005). For the World Business Council for Sustainable Development (WBCSD), Eco-efficiency is defined as "the delivery of competitively priced goods and services that meet human needs and bring the quality of life while progressively reducing the environmental impacts of goods and resources over time, in the whole life cycle" (WBCSD, 2000).

For Eco-efficiency analysis, Life Cycle Assessment (LCA) can be combined with approaches such as Life Cycle Costing (LCC) or total cost (Gabriel and Braune, 2005; Miah *et al.*, 2017). Ibbotson *et al.* (2013), Tatari and Kucukvar (2012, 2011), Lee *et al.* (2011), Park *et al.* (2006), Rigamonti *et al.* (2016) and Kulczycka and Smol (2016) adopt the cost/environmental impact ratio. However, considering ISO definition, "aspect of sustainability regarding the environmental performance of a product system to its product system value" (ISO 14045, 2012) it seems more rational apply the inverse relationship, Equation 1, as adopted for Auer *et al.* (2017), Ferrández-García *et al.* (2016), Lorenzo-Toja *et al.* (2016), Kim *et al.* (2013b), Rudenauer *et al.* (2005) and Piepenbrink and Kicherer (2004).

$$\text{Eco-Efficiency} = (\text{Environmental Impact})/\text{Cost} \qquad \textbf{Equation (1)}$$

Miah *et al.* (2017) provide a rich literature review on the integration of LCA with cost methods, composing the Eco-efficiency analysis. The most prominent life cycle method currently used is the Life Cycle Assessment (LCA), standardized by ISO 14040 (ISO, 2006).

The decision-makers can extract from the LCA the analysis of one or more indicators of the same impact assessment method (for example CO_2 emissions) or apply more than one method, depending on the stakeholders (client, investors, community). The economic indicator, however, should selected according to stakeholder. Total cost, Unit Cost, Net Present Value (NPV) and Internal Rate of Return (IRR) are some of the economic indicators used in the economic analysis of CDW recycling, selected, however, without explanation for their adoption. In response to this statement, Martinez-Sanchez *et al.* (2015) describe a lack of clarity in the methodologies and calculation principles adopted in the cost analysis in CDW recycling.

Waskow *et al.* (2020), in a systematic review on cost analysis of CDW recycling, shows that NPV, IRR and Payback indicators are the most widely used among economic indicators. Some authors provide reference values for these indicators in CDW recycling, such as Payback, between 3 and 11.2 years (Huang *et al.*, 2002; Neto *et al.*, 2017; and Di Maria *et al.*, 2018), and IRR, higher than 12% (Petterr, 2015; Doan, 2016). Unit cost is assessed by Di Maria *et al.* (2018) and Miah *et al.* (2018), however they have no reference values.

Another gap to be filled in the CDW recycling Eco-efficiency analysis is the adoption of a normalization value (reference). Auer *et al.* (2017) have reference in the future scenario evaluating the current scenario. Other authors that adopt the environmental impact/cost ratio, such as Ferrández-García *et al.* (2016), Lorenzo-Toja *et al.* (2016), Kim *et al.* (2013b), Rudenauer *et al.* (2005) and Piepenbrink and Kicherer (2004), do not employ a reference in the analysis of their Eco-efficiency indices.

In this sense, the objective of this paper is to propose the main premises to be considered in selection of economic indicator and analysis normalization of the CDW recycling Eco-efficiency index results..

Research metodology

A three-step search method was adopted, as described next:

Step 1: Systematic review of literature;

Step 2: Analysis and comparison of Eco-efficiency indicators (including economic and environmental inputs);

Step 3: Discussion about the main assumptions in the CDW recycling Eco-efficiency analysis.

The first step was to explore the knowledge about Eco-efficiency and its application on CDW recycling process. In order to obtain the most current literature about Eco-efficiency analysis on CDW recycling, the following procedure was performed:

- Systematic review: the identification of studies in scientific journals was performed by a systematic search in Science Direct and Springer platforms. The words searched on title, abstract or author-specified keywords were ''Eco-efficiency", "construction", "demolition", "waste" and "management". A screening of the literature was made evaluating if the Eco-efficiency analysis could be applied to CDW.
- A content analysis of the literature was performed to identify the main topics addressed. Only research articles make up the statistical data illustrated in this paper. Review articles identified in the systematic review contribute only to the discussion of the results. The elements evaluated are shown in Table 1a.

The second step discusses the main Eco-efficiency indicators adopted in the literature review and the economic and environmental inputs that compose it. The elements evaluated in this step are shown in Table 1b. The third stage presents the discussion on the use of Eco-efficiency indicators in CDW recycling, based on stages 1 and 2 of systematic review and exploration of the literature about the subject.

Table 1. (a) Criteria for classifying articles included in the systematic review. (b) Evaluated elements of input data that make up the CDW recycling Eco-efficiency index identified in the systematic literature review.

Criteria	Description
(a)	
General	Country, year.
Scope	Recycling plant, management.
Source	Building, road, private/municipal CDW.
Step	Construction, demolition, refurbishment.
Scenario	Final disposal, recycling, incineration.
(b)	
Eco-efficiency indicator	Cost/environmental impact; environmental impact/cost; other.
Reference in Eco-efficiency analysis	Current scenario, concurrent material, other.
Economic input	Total cost, NPV, Unit cost, IRR, other.
Environmental input	Impact assessment method, indicator, other.
LCA assumptions	System model, functional unit, other.
Comments	Results, main input data.

Eco-Efficiency Analysis on CDW Management

Initially 12 articles were identified in the Science Direct platform. The evaluation of the articles results in the exclusion of 5 of these works, as it is a review and / or articles related to other residues. 33 articles were identified on the Springer platform, however only 2 meet the research requirements adopted in this paper. _Figure 1_ illustrates the quantification of paper by countries, identified in the systematic literature review. Comments on scope, results and/or proposed methodology are described in Table 2.

As can be seen on Figure 1, Studies conducted in European countries such as Germany, Spain, Sweden/Norway and the Netherlands predominate (Tischer _el al.,_ 2013; Rodriguez _el al.,_ 2015; Ferrandez-García _el al._, 2017; Klang _el al._, 2003; Zhang _el al._, 2018). These papers have a common concern with the composition and mixing in the CDW generation source and the influence of these characteristics on the final results, especially with regard to economic criteria related to segregation costs and disposal of waste.

The works of Yuan *el al.* (2016), Xue (2012) and Mah *el al.* (2018) apply to countries of the Asian continent (Hong Kong, China and Malaysia respectively). While Xue (2012) does not assess scenarios, the other authors provide a specific index for a broader scope assessment, relating the change in sector impacts to the change in Gross Domestic Product (GDP) forming the Eco-efficiency index.
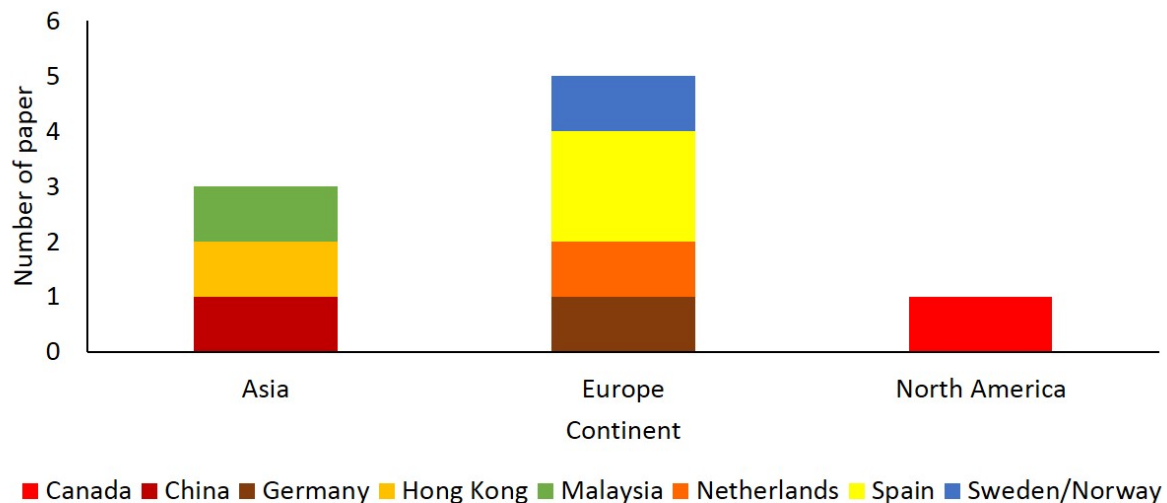
Figure 1. Geographic distribution of the papers identified in the systematic literature review on CDW recycling Eco-efficiency analysis.

Yuan *el al.* (2016) proposed that the Eco-efficiency of CDW management can be calculated through the relationship between Environmental improvement/impact reduction and CDW management cost, according to Equation 1. Mah *el al.* (2018) assessed different scenarios, relating the final CO2 emission, characterization factor results, and total cost (transportation, recycling, treatment, etc.). Despite the adoption of different Eco-efficiency index, in both studies, however, considering the possibility of CDW goes to landfill, allowing to infer a perception regarding the maintenance of the adoption of this type of destination in Asian countries.

Trochu *el al.* (2019) evaluated recycling scenarios with low, medium and high quality recycled aggregate production in a region of Canada. The main focus of this paper is the wood residue, resulting a predominant construction method in the study region. The authors describe better results of the Eco-efficiency index with the improvement of segregation in the generation source, suggesting a concern similar to that highlighted by the European papers.

´The CDW Recycling Eco-efficiency analysis papers mainly take two steps, construction and demolition, and generally referring to municipal waste (Figure 2). Only Zhang *el al.* (2018) performed the Eco-efficiency analysis by restricting the demolition stage.

Table 2. Comments related to the development and results of the CDW recycling Eco-efficiency analysis identified from the systematic literature review.

Authors	Comments
Ferrandez-García *el al.* (2017)	The scenarios evaluated vary with respect to the composition of the materials that make up the applied insulation systems. There are no further assessments or details regarding the end-of-life stage and its contributions to environmental, economic or Eco-efficiency impacts.
Klang *el al.* (2003)	Article evaluates the recycling of bricks, iron and ceramics, according to local RCD characteristics. More satisfactory Eco-efficiency results are identified for the RCD recycling scenario, yet resulting in lower social benefits.
Mah *el al.* (2018)	The Eco-efficiency indicator assesses the relationship of CO_2 emissions and the costs for each scenario. The results showed that the main environmental contributions were made by the natural aggregates mining process (given by the need for extraction by disposal) and the transport of CDW, the latter representing the main input of costs, including the scenario that considers disposal of CDW total.
Rodriguez *el al.* (2015)	The results reveal the difference in values by type of plant management / model.
Tischer *el al.* (2013)	The results showed a reduction of the environmental impacts due to the implementation of a logistic management plan of the CDW, mainly due to the increase of the recycling percentages. The authors pointed out that even higher costs of collecting mixed CDW may not compensate for disposal rates of waste materials.
Trochu *el al.* (2019)	Article focused on wood waste that makes up the local CDW. The results revealed the benefits of source separation that increases the recycling percentages and therefore reduces the final disposal percentage.
Xue (2012)	The authors concluded that there are gaps in the proposed indicator, such as no input data related to hazardous substances. The authors emphasized the need for a dissociative analysis of the results so that, for example, cities with reduced impact but high GDP rates are not taxed with considerable negative impacts.
Yuan *el al.* (2016)	The Eco-efficiency indicator is relative to the sum of impact and cost ratios between the two different methods.
Zhang *el al.*, 2018	The Eco-efficiency indicator is relativized in percentage terms considering the usual participation and new technologies in each scenario. Environmental impacts and transportation costs are the most significant in two of the four scenarios evaluated. The other scenarios have their costs and impacts reduced when this input data is excluded.

Figure 2 also illustrates the different scopes of work analysis, which may be analysis restricted to the recycling plant, one or more scenarios (e.g. current scenario and/or final disposal) or the CDW management system. The CDW management system predominates over other scopes, being adopted in the analyzes of Tischer *el al.* (2013), Rodriguez *el al.* (2015), Yuan *el al.* (2016), Xue (2012) and Trochu *el al.* (2019).
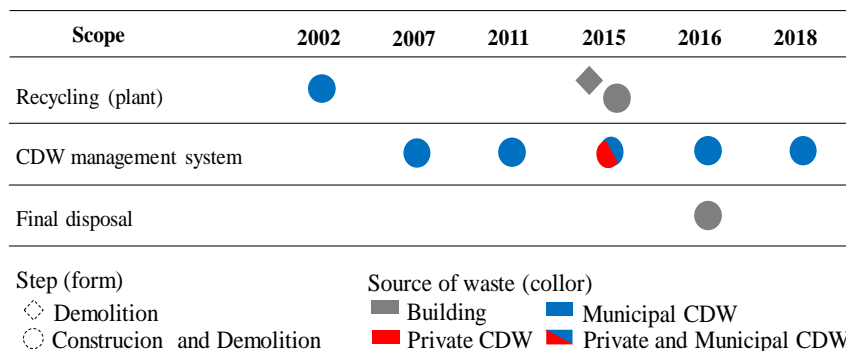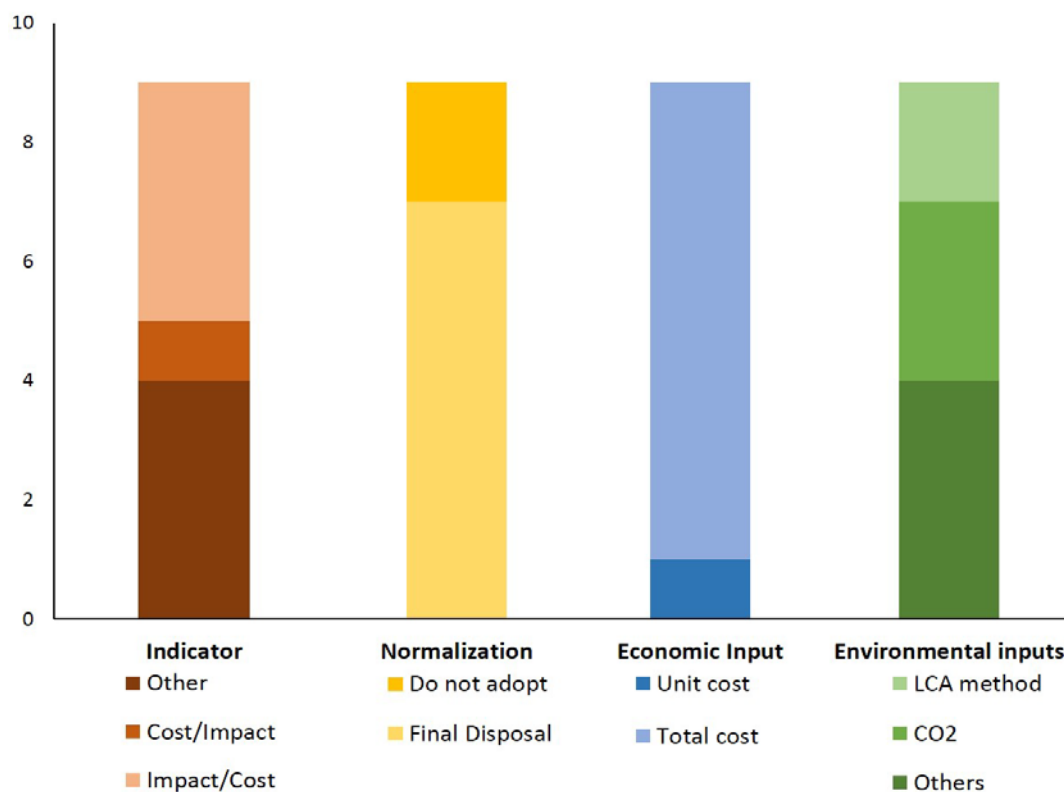

Figure 2. Characteristics of the papers identified in the systematic literature review on CDW recycling Eco-efficiency analysis.

Characteristics related to the Eco-efficiency index applied in the works raised by the systematic literature review are illustrated in Figure 3. There is a predominance of impact/cost ratio (Yuan *el al.*, 2016; Ferrández-García *el al.*, 2017; Xue, 2012; Mah *el al.*, 2018;), as applied by Auer *el al.* (2017), Ferrández-García *el al.* (2016), Lorenzo-Toja *el al.* (2016), Kim *el al.* (2013b), Rudenauer *el al.* (2005) and Piepenbrink and Kicherer (2004). All of these works have in common the use of the Eco-efficiency index as a tool for using solutions/alternatives with better environmental and economic performance.

The use of the inverse relationship (cost/impact) does not seem to have the same features, being perhaps more relevant to situations of analysis where the financial contribution is proposed to minimize the environmental impacts of a given activity. With this relationship, then, the decision maker can identify how much investment will be required to minimize a certain percentage of the environmental impact of one or more indicators.

In the studies identified in the literature review, only Zhang *el al.* (2018) and Yuan *el al.* (2016) adopted a normalization, or reference, in the analysis of their results. Both authors evaluate recycling systems, considering the results of the final disposal scenario as normalizer.

However, considering the concepts of non-generation, reduction, reuse, recycling in waste management it seems coherent that the Eco-efficiency analysis of a waste recycling product system should refer to the product of an established marginal market that this waste may be replace. In the case of recycled aggregates, they may even partially replace natural aggregates such as natural coarse aggregate and sand.

Figure 3. Characteristics of the Eco-efficiency index adopted in the studies identified in the literature review. (a) ratio applied in the Eco-efficiency index, (b) use of normalization (reference) in the analysis of the result, (c) economic input data, and (d) environmental input data.

The cost data from the Eco-efficiency analysis is entirely related to the total costs, either when evaluating the recycling plant/process or the CDW management system. The only work that uses the unit cost as input data refers to the complete evaluation of a thermal insulation system that considering the end-of-life waste management of this product, given by Ferrandez-García *el al.* (2017).

Waskow *el al.* (2020) evidenced, in their review, a predominance of economic analyzes of CDW recycling using indicators such as NPL, Payback and IRR, in this sense the use of the total cost cannot be generalized for different purposes of Eco-efficiency analysis. Thus, according to the stakeholder in the Eco-efficiency analysis, total costs, NPV, Payback and IRR can be adopted as the economic indicator in the impact/cost analysis.

The environmental input data are mostly composed of the use of the CO_2 emission indicator, as a result of different characterization factors. Some authors using the ILCD method (Zhang *el al.*, 2018) and Eco-Indicator99, ReciPE and EPS (Ferrandez-García *el al.*, 2017), considering all indicators. Other Environmental Indicators refer to amount of CDW processed (Tischer *el al.*, 2013; Rodriguez *el al.*, 2015) and other indicators. Unlike economic input data, environmental input data has no restrictions of interest on methods and/or indicators for each stakeholder. Thus, for environmental analysis, the input data inventory is more relevant, being the applied method or characterization factor adaptable to the objective or the stakeholder.

Main Premises in the CDW Recycling Eco-Efficiency Analysis

The data and discussions from the previous chapter converge on important information from the Eco-efficiency analysis in CDW management. This information allowing to propose premises to be standardized in the analysis of this type of activity. Among these premises, it is firstly emphasized the need to define the objective of Eco-efficiency analysis: assessment of the cost of minimizing impacts, a simple comparison between scenarios or economic and environmental viability.

The assessment of the impact minimization cost allows to identify the result of investments in product or process improvement and the final results in the variation of the environmental indicator. The use of this objective is in line with the initiative of investors seeking, or required to achieve, more Eco-efficient results.

The simple comparison between scenarios make possible to verify the changes of a current scenario and a future scenario, limiting the results to the statement of results. This objective is most closely related to an environmental product statement, evidence of environmental performance to be made available to stakeholders such as customers or society.

The economic and environmental viability allow to identify the environmental performance associated with achieving attractive business investment results. This objective reflects the investors interest in the prior assessment of the business viability.

Considering the evaluated and other studies on Eco-efficiency analysis addressed by Miah *el al.* (2016), the possibility of using the two correlations (cost/environmental impact and

environmental impact/cost) were defined as well as the possibility of normalization of some of the objectives, as illustrated in Figure 4.
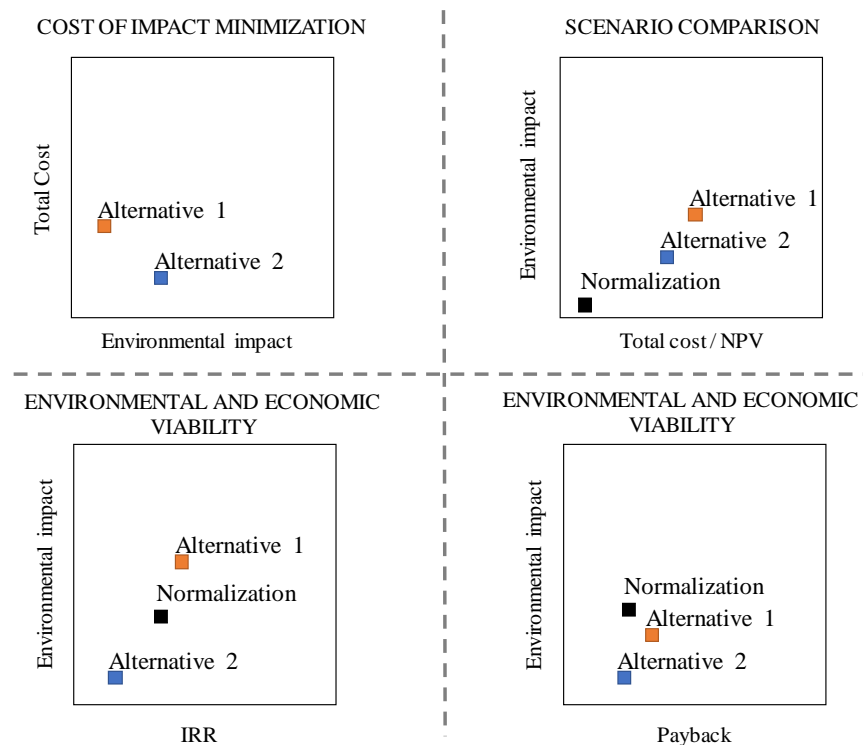
Figure 4. Correlations to be adopted according to the objective of the Eco-efficiency analysis. Alternatives and Normalization data imputed at random, and the analysis may consist of more of these elements.

Economic indicators such as Total Costs, NPV, IRR and Payback can be applied in Eco-efficiency analysis in conjunction with environmental indicators. The application of each of these, however, occurs according to the objective of the work that is directly related to the stakeholder that wishes to communicate the results.

Thus, the cost/impact ratio was defined as the analysis capable of supporting the assessment of the costs required to vary a given environmental indicator, with the economic indicator being Total Costs. The impact/cost ratio has a wider scope of application, being possible to apply together to the environmental indicator the economic indicators Total Cost, NPV, IRR and Payback. In this relation the use of the economic indicators Total cost and NPV make the simple comparison of scenarios available, being then applied to the consumed, society, public agencies, etc.

The use of IRR and Payback indicators in the impact/cost correlation of investor support on business profitability or viability, associated with environmental impacts. The analysis of the results, however, should not be limited to the simple relationship of environmental and economic indicators. Thus, one should adopt references to these two axes (x and y) that will delimit zones that suggest better and lower Eco-efficiency.

The literature review performed in this paper shows the continued adoption of landfill as a final destination to CDW. The use of this scenario as normalization, as considered by Zhang *el al.* (2018) and Yuan *el al.* (2016), illustrates that this destination is still a reality. Considering the adoption of the final disposal as standardization (reference) seems to be coherent, as regional issues, such as lack of recycling incentive and low disposal cost, make the landfill still an attractive worldwide.

At the same time, sites with established recycling scenarios, although not the most economically attractive, deserve to be taken into account in the Eco-efficiency analysis in the search for alternative solution, as performed by Auer *el al.* (2017). Considering also the concepts that guide the management of waste from any source (non generation, recycling and reuse) combined with concepts of avoided impact, widespread in LCA analysis, the comparison of the results with the materials established market and that may be replaced for (by) products resulting from recycling can become an incentive for recycling.

Thus, when analyzing the Eco-efficiency, focusing on results of better environmental and economic performance, of an alternative CDW recycling solution, the illustration of the impact / cost ratio results should be composed of at least the following favorable zones: current recycling scenario; final disposal scenario; and by the production of the natural aggregate that can be replaced by the recycled aggregate produced. An example of the boundaries of these zones is illustrated in Figure 5. The position of the cost-impact ratios of the final disposal, current scenario and natural aggregate was randomly defined, requiring adjustment according to each case study.
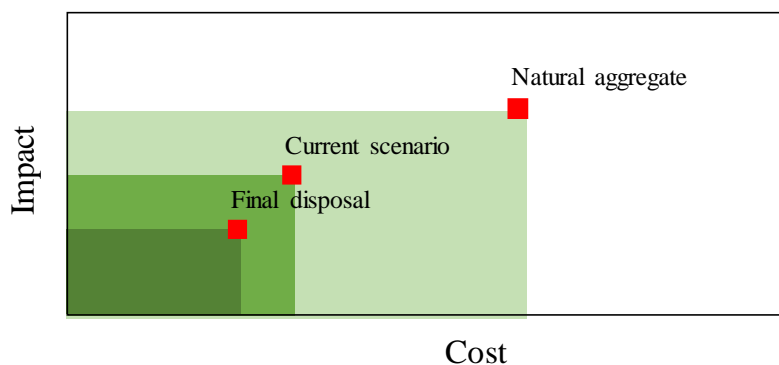
Figure 5. Proposed model to illustrate the results of the CDW recycling Eco-efficiency analysis.

Intermediate green, more Eco-efficient than two of the normalizations and light green, more Eco-efficient than just one of the standardizations. Eco-efficiency analysis with cost analysis bias to minimize impacts (cost/impact) has as normalization the very variation of the results expressed graphically.

Although the availability of CDW Recycling Eco-efficiency analyzes is very small, starting to use this tool in this industry based on assumptions seems to lead to the achievement of standardized and comparable results. Other tools that support Eco-efficiency, such as LCA and LCC, have specific standards or manuals designed for the same purpose, allowing them to thrive and have their credibility and application expanded. The assumptions defined for each objective of the Eco-efficiency analysis proposed by this paper are summarized in Figure 6.
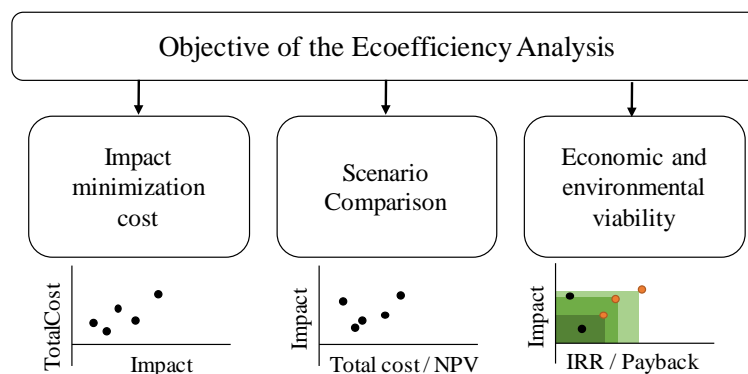
Figure 6. Simplified flowchart of assumptions to be adopted for CDW recycling Eco-efficiency analysis.

Final remarks

South America is still lacking work on CDW recycling Eco-efficiency analysis. However, the work of other countries brought important contributions regarding the existence of common concerns with this type of activity, the mixture of recycled aggregates and the reality of the need to maintain the final disposal destination.

Before the use of cost/environmental impact when the environmental impact/cost were applicable, the first one was related to investment to minimize impacts of one or more indicators and the second one was for scenario comparison and performance analysis.

The adoption of normalization (reference) is still rarely explored in CDW recycling Eco-efficiency analysis studies. It is concluded, however, that there is a need for comparison and if possible, by

adopting at least the current recycling scenario, the final disposal scenario and the established market material that the recycled aggregate can replace.

The use of the simplified flowchart proposed for each objective in the CDW recycling eco-efficiency analysis will allow the standardization of such studies, enabling a more credible, replicable and comparable development.

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