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Life Cycle Assessment applied to construction and demolition waste treatment: proposal of a Brazilian scenario

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Abstract. Important amounts of construction and demolition wastes (CDW) are currently generated in several countries. Considering the correct management of this kind of residue, and the search for its noblest use, several studies have focused on the environmental potential impacts from CDW management. Life Cycle Assessment (LCA) is often used to investigate the potential environmental impacts over the life cycle of a product, thus becoming an important tool to support decision-making. CDW recycling process produces coarse, fine and mix aggregate as outputs, characterizing a multifunctional process. But, how CDW's LCA should be run, considering a circular and more sustainable built environment? Thus, the objective of this work is to explore the basic premises in proposing a product system for the CDW recycling process in Brazil. For this, data available in the literature on the recycling process in Brazil and in other countries support the definition of the product system. The complexity of this management option is explored, considering how the use of the recycled materials interfere in the scope, objective, unit function and other modelling choices, as well as reliability of CDW studies. Finally, the datasets provided by Ecoinvent are examined in order to promote debate on data adaptation, followed by remarks on the most appropriate choices on allocation in the CDW LCA. The cut-off system modelling associated with the new perspective on the avoided burden approach is concluded by the authors to be the most suitable for this waste recycling multifunctional processes. Understanding system models is key. When no inventory adaptation is intended, available inventory datasets are more advisable to be used when performing end of life scenarios only, once burdens differ according to countries management scenarios, as well as life cycle inventory approaches.

1. Introduction

The construction industry plays an important role in society. The processes of urban expansion or connection between cities demand the construction of buildings, residences, paving and urban maintenance, roads, train lines, among others.

The execution of engineering works requires the use of natural resources, such as coarse aggregates. Brazilian aggregate consumption in 2014 was 741 million tons, of which 302 million tons correspond to the consumption of natural coarse aggregates (NA), from 4.74 -19.1 mm. The potential per capita demand for aggregates for Brazil in 2014 was 3.7 tons, still lower than European Community (5.2 tons), USA (9 tons), China (12 tons) and Finland (17 tons). The Brazilian regions that consume the most natural aggregates are Southeast (47%) and Northeast (21%), followed by South (16%), Central West (9%) and North (7%) [1].

Associated with this large amount of natural resources extracted, there are potential environmental impacts that must be considered. The assessment of potential environmental impacts should serve as a basis for decision-making in actions to make building processes more sustainable.

The aggregates from construction, maintenance and/or demolition stages of construction works, called recycled aggregates (RA) from construction and demolition wastes (CDW), can be considered as potential surrogates for NA, observing their environmental viability, in addition to performance and costs.

The use of the Life Cycle Assessment (LCA) in a study of CDW recycling scenarios has gained attention, with growth in the number of publications in recent years [9] [21]. The definition of the product system in these studies, however, lack the application of concepts, such as allocation, multifunctionality of processes, system models and among others.

Thus, the objective of this paper is to explore the basic premises in proposing a product system for the CDW recycling process in Brazil. For this, data available in the literature on the recycling process in Brazil and in other countries support the definition of the product system. The system models proposed by Ecoinvent and background data available by the database are observed. Available data in the Ecoinvent are suggested as background data, considering the cut-off system modeling associated with the new perspective on the avoided burden approach, suitable for the multifunctional process.

2. Method

A literature review on the topics was conducted in other to add information into the product system definition, as well as system modeling choice to conduct LCA studies for CDW management. The first stage consists of a literature review on the existing research models. Secondly, an analysis of the CDW market in Brazil is presented as a case study. The product system is then defined. Finally, the datasets provided by Ecoinvent are examined in order to promote debate on data adaptation, followed by remarks on the most appropriate choices on system model and allocation in the CDW LCA.

3. Life Cycle Assessment and Construction and Demolition Waste

Bovea and Powell [21] showed growth in researches of LCA of CDW between 1999 and 2015, in consequence of European directives and ISO 14040 series standards. Yet, most CDW LCA studies present a lack of information about the system model adopted in the calculations, among others [22][23][24].

In a recent literature review [22], the authors identified a total of 91 published researches on LCA of CDW. Most of the reviewed researches focus on the cradle-to-grave analysis of buildings, considering the waste management into the EoL scenarios after demolition. Although the analysis are reasonable for EoL scenarios, there is a misinterpretation of the term “construction and demolition waste” management once most papers assess only demolition wastes. Moreover, the majority of the research papers assess the EoL for a variety of materials, as a result of the entire building demolition. The EoL inventory and processes are rarely detailed, however, several scenarios were assessed, as re-use, recycle, landfilling, incineration and composting for wood material. Only 5% of the researches informed the life cycle inventory (LCI) analysis’ modeling approach. Considering that the recycling of CDW for RA production is a growing market for substitution of NA, the modeling approach could reflect a significant difference in the impact results, e.g. for natural resources depletion. Systems with high recycling rates have the choice of the system model adopted as a key factor [25].

Besides the studies, the treatment in waste management is strongly addressed in an update of the System Models carried out by one of the most worldwide used databases, Ecoinvent. In its version 3, in addition to the introduction of the Consequential approach, the attributional approach is presented in two system models, allocation at the point of substitution (APOS) and Cut-Off. In the cut-off model, for example, all intermediate exchanges (i.e., exchanges within the technosphere) are classified into either “allocatable by-products”, “recyclable materials” or “wastes”. The classification is based on the expert judgment of an exchange’s value, use potential, and predicted fate [25][26]. Depending on this classification, byproducts (i.e., products that are not the reference flow) in multi-functional activities are handled differently [25][27][28][29][30].

4. Brazilian CDW Market

The literature review showed that most of the LCA application to CDW management is connected to the building's LCA. However, the market for this kind of waste still developing and information is needed to support decisions related to CDW recycling.

4.1. Source and composition of the Brazilian CDW

CDW is a generic term that defines the waste generated by the economic activities involving the construction, maintenance, demolition and deconstruction of buildings and civil works [2]. The CDW can be generated in activities like construction and demolition of buildings and infrastructures, roads and their maintenance, disaster debris, among others. Data available from Brazil suggest a higher generation of new reforms and repairs, followed by new constructions, reaching 76% and 67%, respectively, of the total CDW in some important Brazilian cities [3][4][5][6][7]. According to the same sources, another significant source of CDW in Brazil is demolition, although this does not represent 50% of the CDW in any evaluated city.

In a previous work [9], a systematic review identified that in the average composition of Brazilian CDW, the most representative materials are concrete, ceramics and mortar (Figure 1). However, the amount (in %) of each material may vary considerably.

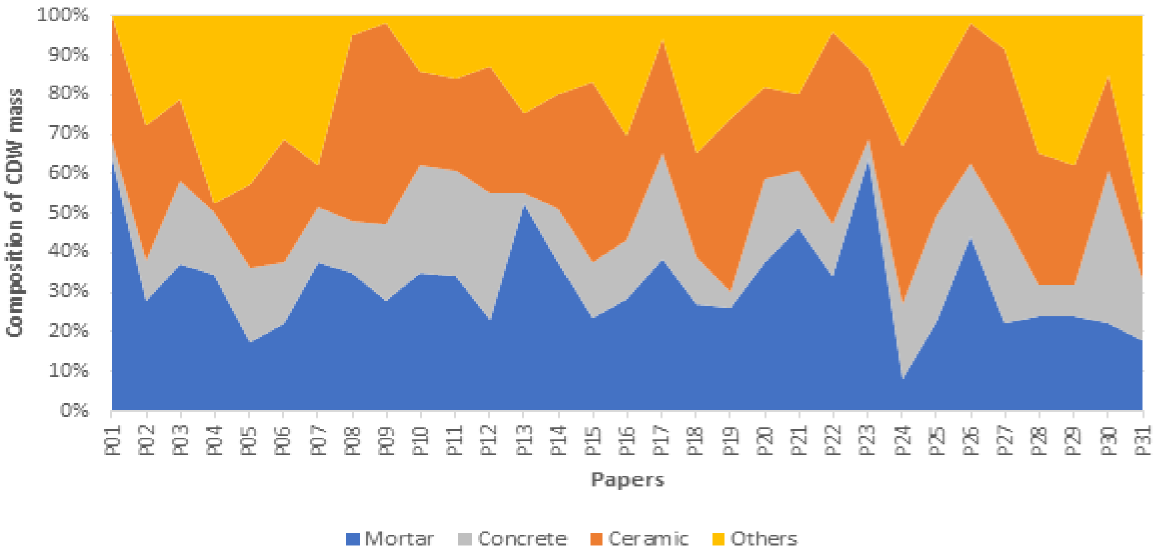


Figure 1. The composition of Brazilian CDW from 31 papers published available in a systematic review realized [9].

4.2. Future use and RA performance

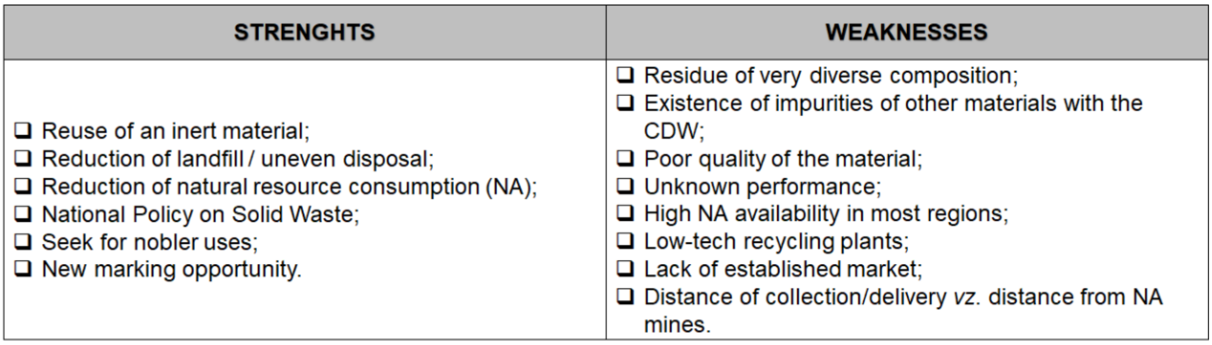
RA is a coarse material derived from the beneficiation of CDW. The use of RA in concrete has still some technical limitations since their performance varies depending on the source material and its properties, such as compressive strength, shape, abrasion resistance, presence of cement incompatible materials, among others. Associated to this, there is a low level of confidence on the mechanical performance of the concrete with RA when compared to the concrete composed by NA, a commonly used material with known properties.

Although concrete applications are the noblest, the use of RA as sub-base materials for roads, backfilling and maintenance for unpaved roads, and higher grade applications (e.g. aggregate for new structural and non-structural aggregate) also has a high potential. However, assuming that the product complies with high-quality standards, the use of RA in structural concrete manufacture is widely accepted in the scientific community as an alternative to replace NA [10][11][12][13].

According to Gálvez-Martos et al. [15], RA from mixed wastes, usually with a minimum of 50% concrete content, can be used for buildings and other civil works, for non-structural concrete.

Cabral [11] generated a series of models to simulate properties such as compressive strength (fc) and demonstrated that the partial replacement of NA by RA can achieve the same compressive strength of concrete composed in 100% of NA, when adjusting water/cement ratios.

Figure 2 shows the main impediments in the reuse of the Brazilian CDW, mainly related to composition and quality, available technology and market of RA. Positive issues that need to be highlighted for the purpose of expanding recycling of Brazilian RCDs are also described in the same figure.



STRENGHTS	WEAKNESSES
☐ Reuse of an inert material; ☐ Reduction of landfill / uneven disposal; ☐ Reduction of natural resource consumption (NA); ☐ National Policy on Solid Waste; ☐ Seek for nobler uses; ☐ New marking opportunity.	☐ Residue of very diverse composition; ☐ Existence of impurities of other materials with the CDW; ☐ Poor quality of the material; ☐ Unknown performance; ☐ High NA availability in most regions; ☐ Low-tech recycling plants; ☐ Lack of established market; ☐ Distance of collection/delivery *vz.* distance from NA mines.

Figure 2. Strengths and weaknesses related to CDW recycling in Brazil, based on [7][12][15][16][17][18][19].

4.3. *Growth and economic representativeness of CDW in Brazil*

There is no consolidated information available on the CDW market or its economic representativeness in Brazil. In 2014, construction consumed 811 million tons of cement and natural aggregates [1], thus considering the generation of the residues only in the construction phase, an important market can be exploited. In addition to these values, we must consider the waste generated in renovations or demolitions, the main CDW generators in Brazil [3][4][5][6][7].

According to Brazilian Association of Public Cleaning and Special Waste Companies - ABRELPE [20], the Brazilian municipalities collected about 45 million tons of CDW in 2017, an average of 123 thousand tons of CDW per day or 600 g.person-day. Although the RA market is not yet exploited, there are still some challenges to overcome. The latest sectoral research by the Brazilian Association for the Recycling of Civil Construction and Demolition Waste [17] shows an optimistic perspective based on the capacity of treatment plants in operation. Over 52% of plants have a nominal capacity to produce up to 3000m^3/month, and another 31% over 10,000m^3/month. Still, until 2015, only 11% of those operated with full production. At the time, 93 plants were producing around 431,500 m^3 of RA per month, while the total installed capacity was 958,000 m^3. Moreover, the research also showed that RA price is up to R$20.00 per m-3 (around US$ 5 per m-3).

Considering the total generation [17] and the maximum total production capacity of the mills [20], it is possible to infer that only 0.5% of the total CDW generated per year in Brazil is recycled, the other 99.5 % is mainly destined for landfill. Thus, the installed capacity of CDW recycling plants is underappreciated but still much below CDW availability.

In 2009, Miranda et al. [7] have already identified the basic structure available in the Brazilian recycling plants: loader or backhoe, vibrator feeder, conveyor belt, jaw crusher or impact, permanent magnetic separator or electromagnet, and vibrating screen. In this way, the material is comminuted and separated by size without any quest to improve its quality. Thus, the final product carries characteristics equal to the input material.

5. Proposal of Brazilian CDW product system and modeling approach

The results from the Literature review are summarized in the proposed product system for the Brazilian market (figure 3). The figure shows the potential input wastes according to Brazilian classification and the path to be followed by the waste until the output for the recycled products, using the waste concrete gravel as the desired RA output. The dotted line in the system represents by-products. The dashed line that separate flows represent the change on waste management responsibility (from construction managers to recycling plants' managers), also representing a monetary change between stakeholders (the waste disposal or recycling services). The authors suggest that to avoid misinterpretations on the allocation for recycling product, when the recycling processes depend upon a tertiary service, the recycling process should be treated separately from the construction and demolition process, and to the future use, and only further connected to them.

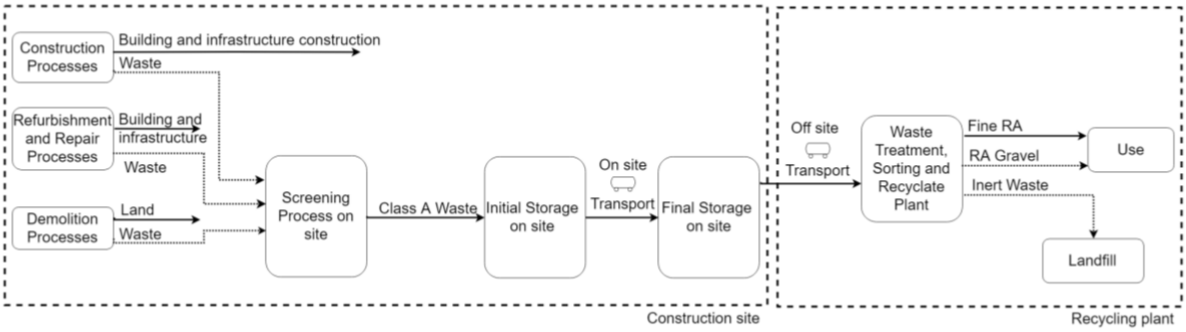


Figure 3. The potential input wastes according to Brazilian classification and the path to be followed by the waste until the output for the recycled products, using the waste concrete gravel as the desired RA output.

From there, the questions that arise are: how to allocate environmental impacts, from an LCA perspective, in this system? Should burdens from waste management be allocated to waste provider, or to the disposable and recycling services? And how to represent avoided burdens from recycling to the consumers of the recycled materials? These questions concerned the following discussion of approach and decision while modeling an LCA on CDW management. As well as the definition of the proposed product system for the Brazilian CDW recycling scenario, the definition of the system model and allocation should be considered since it is a multifunctional process.

5.1. The Ecoinvent® database and the CDW EoL

The Ecoinvent database provides data, generally generic and average data, that can serve as a background in defining or adapting datasets. The dataset regarding the recycling of CDW, for example, has its origin in Switzerland. According to the "Life Cycle Inventories of Waste Treatment Services" report from Ecoinvent® [31], there are three main disposals/recycling of CDW options in Swiss, direct recycling, partial recycling after sorting, and direct final disposal without recycling - represented in the Figure 4 as "A", "B" and "C", respectively.

The inventory distinguishes the construction materials according to the recyclability, for example, those destined for recycling and those destined for disposal in a landfill. No distinction is made between different building phases source of wastes (construction, refurbishment, and repair or demolition), and all datasets consider the same demolition energy within the system boundaries. Thus, CDW is only originated from the demolition stage, diverging from the Brazilian reality.

Following the methodology provided by Ecoinvent® [31], no bonus or burden compensation are given for recycling material, on the versions preview to v. 3. No partial allocation of burdens from recycling processes to the first product and recycled products were made. Instead, the system boundary for both "A" and "B" disposal options does not include the recycling process, but includes sorting plants and the disposal of non-recyclable material. In this sense, waste concrete gravel, for example, does not include the recycling plant burdens, once the data “cut-off attributes all further processes (transport, sorting, recycling, etc.) to the recycled product consumer and not to the first user of the (raw) material” allowing, in this way, to conclude that the data is directed towards the end of life of the building.

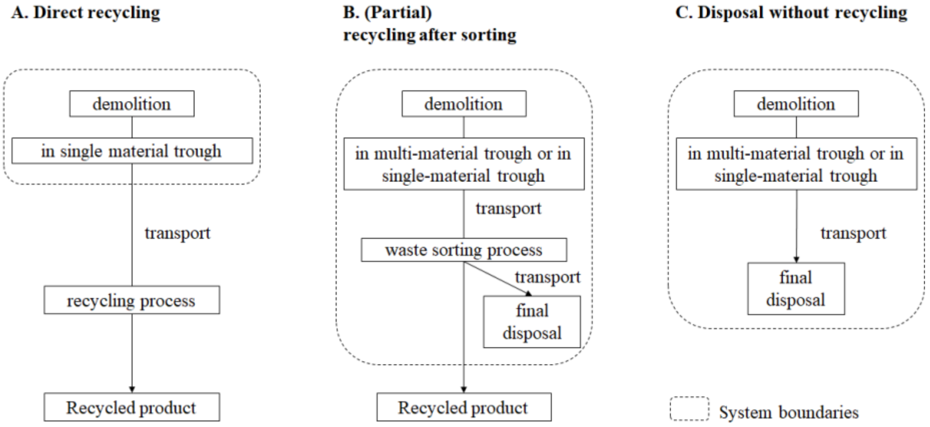


Figure 4. System boundaries of the three types of CDW disposal options according to Doka [31].

5.2. *A new perspective in LCA of CDW management*

According to Baumann and Tillman [32] the allocation problem happens in three basic cases: (I) when processes result in several products, meaning multi-outputs; (II) waste treatment processes that have different input sources, meaning multi-inputs; and (III) open loop recycling, meaning that a product is recycled into a different product, which implies that they share common activities, as the extraction of the virgin materials. The allocation can be avoided in the two first cases by detailing the model, but it is not true for the third case. Baumann and Tillman (2004) indicate the procedure to be adopted is either allocation through partitioning or system expansion. Partitioning would be applicable to traditional attributional LCAs, as the system expansions would work better to LCAs modeling effects of changes (consequential).

In the case presented on CDW recycling market in Brazil, the three allocation problems are observed, due to multi-inputs (construction, demolition, refurbishment, etc.), multi-outputs (different class of residues), and to the fact that the recycled products as concrete gravel have an open loop recycling process.

Also, the replacement of NA by RA is not expressive in the Brazilian market due to the lack of offer (low recycling content rates). Thus, the consequential approach based on Ecoinvents datasets wouldn’t be appropriated in this case, once it would take a long time or an extreme change in CDW management policies so that the replacement affects NA market. In this last case, the consequential approach would feature the potential effects of RA use in the new constructions. Moreover, a system expansion would be needed, and the other materials recycled included as by-products in the same process, which is not integrated into the Ecoinvent consequential datasets.

That being agreed, the attributional approach would then be used with the need for an additional allocation procedure. Among the literature, Saade [33] presents a new approach to the decision-making process by the co-product user industry. Some factors contributed to the definition of this new approach, such as: the inadequacy associated with the use of the most common allocation criteria (mass and economic value), where the scarcity of virgin raw material is replaced by the co-product and benefit of the recycling of a co-product to the detriment of raw material consumption; the avoided impact approach, as typically adopted, fails to distribute the benefit fairly, since the environmental burdens that cease to exist with the replacement of virgin raw material by the co-product are reduced in their entirety from the multifunctional process which generated the co-product without considering, for example, the impacts associated with the processing of the co-product, avoided loads (eg end-of-life) and other results for co-product reuse. The author then proposes an alternative manner of calculating the avoided impact. This proposed approach consists of adding or subtracting from the avoided impact associated with the replaced product, all potential loads caused and/or avoided by the replacement. The net avoided impact is then the avoided impacts from the substituted product (value given by conventional allocation), minus the impacts associated with the processing of the by-product or waste, and other burdens from the recycled material life-cycle until its uses (such as transport), plus the impacts associated with the business as usual (BaU) final disposal of the waste [33]. Thus, it is possible to evaluate the environmental viability of the recycling process.

In the case of CDWs, the use of RA minimizes the potential impacts of NA extraction that is not extracted. Then, first the environmental load of the amount of NA that can be substituted by the RA in the assessment inventory should be considered as negative inputs. Secondly, there are impacts through the CDW beneficiation process, mainly related to transportation of waste and distribution of the recycled material, and electricity consumption for the comminution process. Those would be considered as positive inputs. Similarly, within the approach suggested by Saade [33], are considered the negative input the not disposing of the waste. In this case, BaU scenario would be the landfilling, and the recycling or reuse of the material would also represent avoided burdens.

6. Final remarks

According to the system resulted from the literature review, the background databases and literature reference may be used for analysis with some regards.

The first important issues to pay attention is the objective of the analysis and boundary of the system to be analysed. The review made in this study, as well as the guidelines for calculation method on assessment of the environmental performance of buildings in the BS EN 15978:2011, might suggest the differentiation of two types of analysis regarding the CDW: the EoL scenario for construction demolition, and CDW recycling and reuse analysis. Both are not mutually exclusive. One may carry an analysis of EoL scenario for one building and include the recycling and reuse avoided burdens (Module D, according to EN 15978). However, the analysis does not exemplify the market for recycled construction materials, once it would be representing only that demolition waste portion of the market. For analysis considering the recycled materials, the origin and composition are meaningful for the inventory of sorting and recycling process, and the intended use is critical regarding the rates of recycled content use.

Regarding Ecoinvent® datasets, some inputs need to be removed during inventory adaptation because they are not part of the analysis by the system model and product system suggested for the Brazilian scenario. Considering the recycling market, the construction waste burdens would be spared. As previously discussed, in developing countries these burdens could be significant, due especially to the transport of waste. Adjustments of the current data available are necessary in order to reflect the scenario of the CDW Brazilian recycling management and plants. Following the discussion made, these datasets are more advisable to be used when performing EoL scenarios only. RA, for example, is not a co-product of construction, however, the avoided burdens should be accounted when performing new constructions or materials LCA with recycled content. Local inventories should be used when analysing these avoided burdens.

The characteristics adopted by the systems models currently available in the Ecoinvent® database suggest that the adoption of the cut-off system is the most appropriate, and it is possible to combine this system model with the new approach proposed by Saade [33] in order to consider the potential impacts avoided serving as an incentive to the recycling process. With such integrated modelling, all life-cycle process of waste recycling is added to the environmental avoided impacts. The integrated modelling can then represent a better approach to the realistic benefits of recycling.

The identification and availability of information on the representation of CDW recycling in the Brazilian economic scenario may, together with the inventory of other information, corroborate with the elaboration of market data for Brazil.

Acknowledgments

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