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Life Cycle Assessment in Construction and Demolition Waste Management: A Critical Review

Leo Maia do Amaral[1], Kesley Antônio Santos[2], Laísa do Rosário Souza Carneiro[3], Flávia Spitale Jacques Poggiali[4], Péter Ludvig[5]
[1,2,3,4,5]Department of Civil Engineering, Federal Center for Technological Education of Minas Gerais - Av. Amazonas, 7675, Nova Gameleira, CEP, 30510-000, Belo Horizonte, Minas Gerais, Brazil
([1]leoamaralepc@gmail.com, [2]kesleysantos25@hotmail.com, [3]carneirola@hotmail.com, [4]flaviaspitale@gmail.com, [5]ludvig.peter@gmail.com)

Abstract- The management of Construction and Demolition Waste (CDW) in construction sites is an important tool for sustainability in construction, considering the large amount of waste commonly produced in this industry. To select the harmless management approach, deeper analyzes must be carried out, mainly due to the transportation role in the environmental impact. Life Cycle Assessment (LCA) is a tool that analyzes the environmental impacts of a process at all stages of its life cycle and has helped engineers in decision-making. Due to the large number of existing LCAs related to CDW management and due to the geographic and temporal limitations of such tool, this article aims to critically analyze recent LCA studies applied to CDW management through a systematic literature review, assessing which parameters can be applied in different locations, as well as the main differences between the existing LCAs. Suggestions for future studies are also made. A bibliographic portfolio was analyzed, and the following points of interest were examined: study location, applied method, the simulated scenarios, functional units, impact categories, and study conclusion. The analysis results suggest that recycling CDW is beneficial when compared to the disposal of wastes in landfills, regardless of how the residues are recycled. Nonetheless, factors such as transportation and the waste recycling process are responsible for considerable environmental impacts and must be carefully analyzed. The management approach related to the prevention of waste generation proved to be efficient and should be further explored in future studies.

Keywords- *Life Cycle Assessment, Construction and Demolition Residues, Environmental Impact, Systematic Review*

I. Introduction

The construction industry has an important role in the development of a nation, and when it comes to population growth and urbanization, the industry requirement is intensified [1]. Despite its productive potential, the construction industry is consensually recognized as the sector that most contributes to environmental degradation, given the large number of resources used and the waste generated [2]. It is estimated that civil construction is responsible for the consumption of, approximately, half of the natural resources available and for the production of a quarter of waste and CO_2 emissions on a world scale [3].

On the other hand, the sector itself has the potential to retain a large part of its own waste. Regarding construction and demolition waste (CDW), Japan managed to reach a recycling level of 99.5% [4]. In Australia, about 90% of CDW are recycled [5]. From their experience, the key to minimizing the impacts of CDW on the environment is the use of appropriate management techniques. Practices such as reducing, reusing, and recycling are the main alternatives for mitigating environmental impacts [6].

In developing countries, the use of sustainable management practices for construction and demolition waste faces several barriers. The composition heterogeneity as well as the large volume of waste, along with political and economic factors and the low-performance perception of recycled products by the market, lead to the discard of an expressive portion of CDW in sanitary landfills, or even directly in the environment [7].

Regarding regional diversity, several decision-making tools were developed to help professionals to select the most suitable management approach. Good waste management follows a hierarchical order, such as prevention, segregation for reuse, recycling, alternative types of recovery (such as energy recovery), and final disposal [8]. However, to visualize and control the reduction of environmental impacts, the systematization of data and methods of gathering and comparing information is recommended. In this sense, the European Communication Commission (COM 666) recommends the adoption of the Life Cycle Assessment (LCA) methodology.

LCA is a widely recognized tool for quantifying the environmental impact of a service or product at all stages of its life cycle, from the transport of raw materials, to recycling, and to final disposal, and has been used by engineers worldwide to help in the decision-making on CDW management [9]. Nonetheless, the LCA takes into account some local factors, such as the region's energy matrix and the available transport modal, which invalidates the replication of such analysis in another region with different characteristics [10].

For this reason, a large number of studies have recently been developed on this topic. Hence, the present paper aims to analyze Life Cycle Assessments studies on CDW management, published in the last few years, in order to identify which parameters are replicable for different locations, as well as the main differences between the current models and the information needed to improve future LCAs. A systematic review was carried out for acquiring an impartial and scientifically relevant portfolio. The following points of interest were analyzed: analysis location, used method, simulated scenarios, functional units, categories of environmental impacts, relevant processes, and study conclusion. Based on this information, this paper presents a critical analysis to stimulate further studies on this topic.

II. METHODOLOGY

Science Direct database was chosen as the main source of articles due to its large number of indexed journals related to Civil Engineering. Then, the first 500 articles (ordered by relevance) were exported to Mendeley software. Figure 1 presents the step-by-step process for filtering the bibliographic portfolio, the selected search terms, and the objectives of this research.

Once imported to Mendeley, articles were filtered by the alignment of the title with the scope of this study (64 remained). After a final step of reading the abstracts, 20 articles that were considered most aligned with the topic in question were selected.

A portfolio analysis was also carried out to identify relevant journals in the research field of Life Cycle Assessment and construction and demolition waste management. It is worth mentioning that this analysis of relevance was limited to journals indexed in the Science Direct database. Table 1 presents the updated bibliographic portfolio. The portfolio relevance analysis and the systemic analysis of the results will be presented and discussed in the following session.

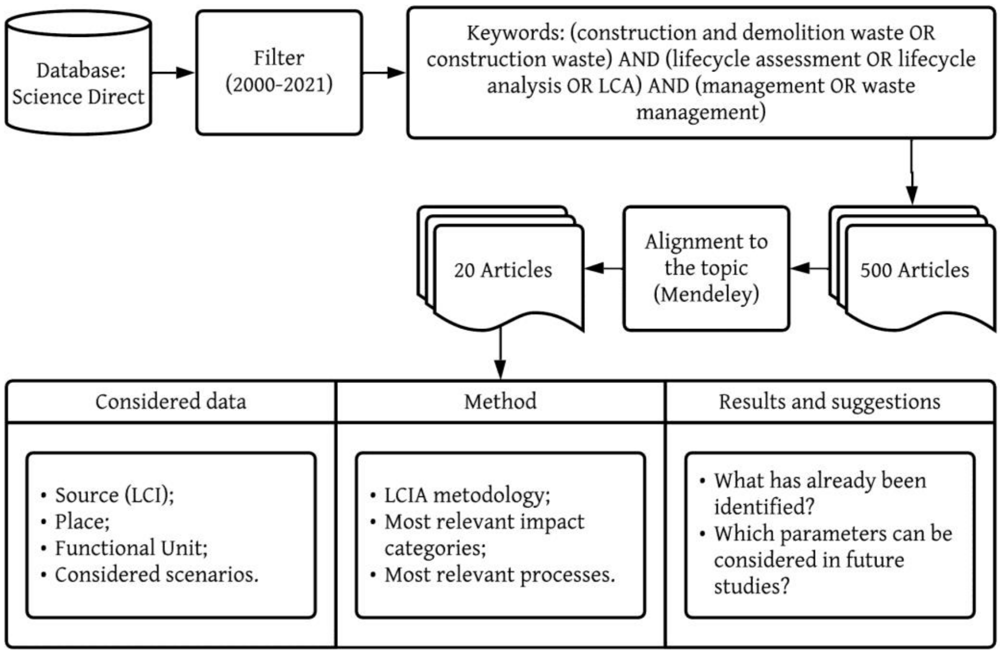

Figure 1. Articles selection and definition of systematic analysis objectives

TABLE I. SELECTED ARTICLES FOR THIS SYSTEMATIC REVIEW

#	YEAR	REFERENCES
[11]	2003	KLANG, Anders; VIKMAN, Per-Åke; BRATTEBØ, Helge. Sustainable management of demolition waste—an integrated model for the evaluation of environmental, economic and social aspects. **Resources, conservation and recycling**, v. 38, n. 4, p. 317-334, 2003.
[12]	2009	BLENGINI, Gian Andrea. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. **Building and environment**, v. 44, n. 2, p. 319-330, 2009.
[13]	2010	ORTIZ, Oscar; PASQUALINO, J. C.; CASTELLS, F. Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. **Waste management**, v. 30, n. 4, p. 646-654, 2010.
[14]	2012	COELHO, André; DE BRITO, Jorge. Influence of construction and demolition waste management on the environmental impact of buildings. **Waste Management**, v. 32, n. 3, p. 532-541, 2012.
[15]	2015	DAHLBO, Helena et al. Construction and demolition waste management–a holistic evaluation of environmental performance. **Journal of Cleaner Production**, v. 107, p. 333-341, 2015.
[9]	2015	BUTERA, Stefania; CHRISTENSEN, Thomas H.; ASTRUP, Thomas F. Life cycle assessment of construction and demolition waste management. **Waste management**, v. 44, p. 196-205, 2015.
[16]	2017	HOSSAIN, Md Uzzal; WU, Zezhou; POON, Chi Sun. Comparative environmental evaluation of construction waste management through different waste sorting systems in Hong Kong. **Waste Management**, v. 69, p. 325-335, 2017.
[17]	2018	WANG, Jiayuan et al. Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study. **Journal of cleaner production**, v. 172, p. 3154-3166, 2018.
[18]	2018	DI MARIA, Andrea; EYCKMANS, Johan; VAN ACKER, Karel. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. **Waste management**, v. 75, p. 3-21, 2018.
[19]	2018	WANG, Ting et al. Estimating the environmental costs and benefits of demolition waste using life cycle assessment and willingness-to-pay: A case study in Shenzhen. **Journal of cleaner production**, v. 172, p. 14-26, 2018.
[20]	2018	MAH, Chooi Mei; FUJIWARA, Takeshi; HO, Chin Siong. Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. **Journal of Cleaner Production**, v. 172, p. 3415-3427, 2018.
[21]	2018	BORGHI, Giulia; PANTINI, Sara; RIGAMONTI, Lucia. Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). **Journal of cleaner production**, v. 184, p. 815-825, 2018.
[22]	2019	ROSADO, Laís Peixoto et al. Life cycle assessment of construction and demolition waste management in a large area of São Paulo State, Brazil. **Waste management**, v. 85, p. 477-489, 2019.
[23]	2020	RAM, V. G.; KISHORE, Kumar C.; KALIDINDI, Satyanarayana N. Environmental benefits of construction and demolition debris recycling: Evidence from an Indian case study using life cycle assessment. **Journal of Cleaner Production**, v. 255, p. 120258, 2020.
[24]	2020	LI, Jingru et al. Environmental impact assessment of mobile recycling of demolition waste in Shenzhen, China. **Journal of Cleaner Production**, v. 263, p. 121371, 2020.
[25]	2020	JAIN, Sourabh; SINGHAL, Shaleen; PANDEY, Suneel. Environmental life cycle assessment of construction and demolition waste recycling: A case of urban India. **Resources, Conservation and Recycling**, v. 155, p. 104642, 2020.
[26]	2021	SU, Shu et al. A building information modeling-based tool for estimating building demolition waste and evaluating its environmental impacts. **Waste Management**, v. 134, p. 159-169, 2021.
[27]	2021	LLATAS, Carmen et al. An LCA-based model for assessing prevention versus non-prevention of construction waste in buildings. **Waste Management**, v. 126, p. 608-622, 2021.
[28]	2021	WU, Huanyu et al. Environmental impacts of cross-regional mobility of construction and demolition waste: An Australia Study. **Resources, Conservation and Recycling**, v. 174, p. 105805, 2021.
[29]	2021	IODICE, Silvia et al. Sustainability assessment of Construction and Demolition Waste management applied to an Italian case. **Waste Management**, v. 128, p. 83-98, 2021.

III. RESULTS AND DISCUSSION

A. Relevance analysis of the selected portfolio

To assess the relevance of the selected articles and their respective journals, a bibliometric analysis proposed by Azevedo and Ensslin [30] was carried out. Therefore, the citation number of each article was informed, extracted from the Google Scholar platform. Similarly, the citation number of each journal was obtained from the h5 (Google Scholar) and JCR (Journal Citation Report) indexes. The h5 index takes into account the journal's performance in the last five years and the JCR index, the performance in the last couple of years. Table 2 presents the journals performance according to the above-mentioned indexes.

According to the analysis, the *Journal of Cleaner Production* has the portfolio's highest h5 index, being the first in the *SUSTAINABLE DEVELOPMENT* ranking, followed by *Waste Management*, which is the first one in the *ENVIRONMENTAL & GEOLOGICAL ENGINEERING* ranking. Together, these journals correspond to 80% of the portfolio. Regarding the JCR index, the journals *Resources, Conservation and Recycling* and *Journal of Cleaner Production* present impact factors of 10.204 and 9.297, respectively, and occupy the 5th and 6th positions in the *ENGINEERING, ENVIRONMENTAL* ranking. The *Journal of Cleaner Production* also ranks third in GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY.

TABLE II. JOURNALS RELEVANCE ACCORDING TO BIBLIOMETRIC INDEXES

Journal Title	Articles per Journal	JCR	h5
Building and Environment	1	6,456	85
Waste Management	9	7,145	104
Resources, Conservation and Recycling	3	10,204	96
Journal of Cleaner Production	7	9,297	182

Figure 2 shows the total number of citations per article from the portfolio. Among them, Blengini [12] was the most cited article, with 530 citations. The median number of citations was 71. Most of the articles that did not reach such a score have been published from 2019 onwards. The bibliometric analysis made it clear that the selected portfolio is composed of relevant articles, published in quality journals.

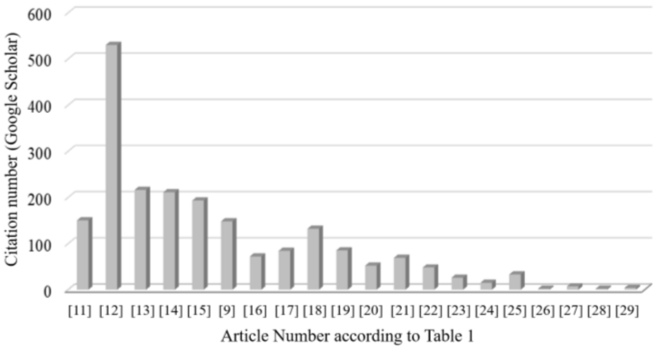

Figure 2. Citations per article from the portfolio

B. Geographic distribution of LCA studies and of CDW generation

According to the portfolio, waste management studies via Life Cycle Assessments are mainly focused on Europe, where 50% of the current models were developed. Figure 3 shows the geographic distribution of such studies worldwide. Italy was the most representative country in the European Union with 3 studies on the topic, and is the fourth EU country (the United Kingdom included) in the ranking of generating construction and demolition waste (39.94 million tons in 2014) [31]. China has the largest number of researches related to the Life Cycle Assessment of construction and demolition waste in the portfolio (5 studies, considering Hong Kong as part of the territory), and is the largest generator of CDW in the world, with an annual production of 2.36 billion tons of CDW between 2003 and 2013 [32].

An interesting point to be highlighted, when analyzing the portfolio, is the lack of LCAs studies in North America, specifically in the United States, whose civil construction sector was responsible for the generation of 569 million tons of CDW in 2017 [33]. Life Cycle Assessment from countries such as Germany (90.97 Mton), France (72.11 Mton), and the United Kingdom (55.42 Mton) also did not appear among the selected articles [31]. The generation of civil construction waste in Spain, for example, was 5.65 million tons in 2014, while in India was about 112 and 431 Mton in 2016 [31], [34]. Both countries had two CDW LCAs studies.

C. LCAs analyzes and results

Table 3 presents the characteristics of the LCAs developed in the portfolio articles.

Country	Total	Continent	Total
Belgium	1	Europe	11
Denmark	1		
Spain	2		
Finland	2		
Italy	3		
Portugal	1		
Sweden	1		
China	4	Asia	8
Hong Kong*	1		
India	2		
Malasia	1		
Australia	1	Oceania	1
Brazil	1	South America	1

Figure 3. Geographic distribution of RCD Life Cycle Analyzes.

TABLE III. LCAs CHARACTERISTICS

#	Approach	Impacts			Method	Functional Unit
		Environmental	Economic	Social		
[11]	-	✓	✓	✓	Literature data	Work hour
[12]	-	✓	×	×	Eco-Indicator 99	m² floor/1 year
[13]	-	✓	×	×	CML 2 baseline 2000	kg of residue/m² built
[14]	-	✓	×	×	Eco-Indicator 95	m²
[15]	-	✓	✓	×	Literature data	1 ton of CDW
[9]	Consequential	✓	×	×	IPCC 2007, WMO 1999, Humbert, Dreicer, ReCiPe, CML, USEtox, Acumulated Exceedance	1 ton of CDW
[16]	-	✓	×	×	IMPACT 2002+	1 ton of CDW
[17]	-	✓	×	×	IPCC 2013 GWP 100a V1.01	-
[18]	Attributional	✓	✓	×	ReCiPe 1.08	840,000 ton/year
[19]	-	✓	✓	×	BEPAS	1 ton of CDW
[20]	-	✓	✓	×	IPCC 2013 GWP 100a	1 ton of CDW
[21]	-	✓	×	×	ILCD 2011 e CED	1 ton of CDW
[22]	Attributional	✓	×	×	CML baseline v3.03 e IMPACT 2002+ v2.12	10,000 ton of CDW/year
[23]	-	✓	×	×	IMPACT 2002+	1 ton of CDW
[24]	-	✓	✓	×	Literature data + social WTP (monetize the impacts)	1 ton of CDW
[25]	Attributional	✓	×	×	ReCiPe2016	1 ton of CDW
[26]	-	✓	×	×	Literature data	CDW of a building
[27]	-	✓	×	×	CML 2001 e CED	CDW of a building
[28]	-	✓	×	×	CML 2015	1 ton of CDW
[29]	Consequential	✓	✓	✓	AoPs + ELECTRE II MultiCriteria	1 ton of CDW

Table 3 shows that a few articles have classified the LCA's approach they have selected, as attributional or consequential (only [9], [18], [22], [25], and [29] did that). Although the selected approach can be inferred by reading the articles, this topic is relevant for defining the objectives and the scope of the LCA method used, since it directly influences the definition of which stages and processes should be analyzed, *e.g.* if different decisions/demands change the production process of a particular service/product. This issue may be a consequence of the lack of consensus, in the academic community, in defining what actually represents an attributional and consequential approach [35]. Hence, there is a need of specifying which processes will be included in the LCAs, deliberating if technological advances and market demand will be taken into account.

Regarding the impacts considered in the Life Cycle Assessment of CDW management, it is clear that only a few studies have considered social aspects [11 and 29] (Table 3). Besides, there is a difference in the way each of these articles have quantified the effects waste management has on society. Klang et al. [11] evaluated the physical and social issues related to the work environment by applying questionnaires to employees in a case study of selective demolition. Iodice et al. [29] applied several related social, economic and environmental indicators to quantify cause and effect relationships due to changes in LCA processes (*e.g.* operating cost, devaluation of m², odor, employment rate, accidents, scarcity of natural resources, global warming, water use, among others). The difficulty in obtaining and quantifying social indices makes this type of methodology less reproducible. Nonetheless, the results of such an approach usually allow a holistic view of the influence of products and services life cycle, being more reliable for decision-making.

Seven articles from the portfolio included the economic aspects in the LCA [11], [15], [18], [19], [20], [24] and [29]. Dahlbo *et al*. [15] evaluated the costs and advantages related to CDW recycling. They found that the recycling of metals, although representing a small volume, is a profitable process, while the recycling of concrete and mineral fractions, although representing a large volume, has small economic potential. Di Maria et al. [18] concluded that the high landfilling rate practice in Belgium, along with the CDW transportation cost, makes CDW recycling economically advantageous, while selective demolition is still expensive. Such findings contribute to large-scale decision-making (public policies) and might stimulate stakeholders to practice recycling.

The Functional Unit most practiced in the analyzed studies is the FU of 1 ton of CDW. Such definition allows accurate comparisons between different studies. However, it is worth mentioning that the boundaries and processes considered in each LCA may significantly alter the environmental impacts attributed to waste management.

The environmental analysis allows quantifying and identifying the recycling chain processes in terms of environmental impact. Different methods have different categories of impact and weights attributed to the processes. Nonetheless, by using both CML baseline and IMPACT 2002+, Rosado et al. [22] noticed that serious environmental impact could be avoided by substituting virgin raw materials for recycled materials, especially recycled steel, as well as by reducing the transport distances of materials. Dahlbo et al. [15] reiterate that recycling some types of waste, such as metals, is profitable and beneficial, and that energy recovery, made possible by recycling wood waste, is a relevant factor in reducing environmental impacts. By applying the BIM methodology along with LCA, Wang et al. [17] highlight the relevant environmental benefit associated with the recycling of metals, *e.g.* steel, copper, aluminum, although they have a low volume compared to mineral fraction waste.

After analyzing the environmental and economic impacts, Klang *et al.* [11] concluded that the reuse of bricks and sanitary porcelain, as well as the recycling of steel, considerably reduces the environmental impact and the economic costs when compared to the purchase of new materials. The transport costs and the energy loss related to reuse and recycling did not have a great influence on this case study, since the materials would be reused in the same place.

Blengini [12] stated that reducing the deposition of waste in landfills is of great significance for reducing environmental impacts and that the production of CDW in Italy should be considered as a supplement, not a substitute, for virgin raw material. By carrying out a Life Cycle Assessment in the city of Shenzhen/China, Li et al. [24] also verified a great environmental impact associated with the deposition of tailings in landfills. After monetizing such environmental impacts, it is clear that the lesser the availability of land (urban areas), the greater the cost of using a landfill, as well as the difficulty in finding an appropriate location for installation, besides the greater distances to be covered. All that leads to greater environmental, economic, and social impacts associated with the non-recycling of CDW.

Through LCA studies, Mah et al. [20] observed that all scenarios that consider the recycling of CDW are advantageous compared to landfilling, having a lower cost. In addition, the authors concluded that recycling waste in mobile industries and considering the use of CDW in building projects is the best scenario, economically and environmentally speaking.

Iodice *et al.* [29] found that the current recycling scenario still leads to several environmental impacts, but it is still more beneficial than disposing of waste in landfills. In addition, the authors observed that selective demolition has great potential, but its high-cost limits further use of such technique. They highlighted the need for a good conception and design planning of a new building. In this sense, Su et al. [26] developed a platform to predict the environmental impacts caused by the construction materials of a building. Such prediction is made still in the building design phase, by combining BIM, LCA, and GIS (Geographic Information Science) methodologies. They observed that the higher the recycling rate, the greater the environmental benefits, *i.e.* the reduction of environmental impacts. Nonetheless, the authors emphasize that the environmental impacts quantified at the design stage will not correspond exactly to the environmental impacts at the time of demolition, since it is not possible to predict all the economic, social, and technological changes that might take place throughout the process. Finally, Llatas et al. [27] concluded that preventing waste generation is more beneficial than recycling and landfilling for most materials associated with CDW.

Several studies consider the transport of waste and raw materials as one of the most relevant processes in terms of environmental impacts [13], [14], [9], [20-25]. This demonstrates the importance of reducing distances between the waste origin, the recycling industry, and the final location for the recycled material. Hence, it is worth comparing the cost-benefit between mobile industries, which produce lower quality recycled products, and fixed industries, studying the feasibility/need to implement new industries, etc. Butera et al. [9] state that recycling CDW on highways is more beneficial than disposing of these materials in landfills, although the transport distance of CDW represent a great impact as a whole. Therefore, the authors suggest the construction of local small crushing facilities in order to reduce long transport distances. Nevertheless, in a study carried out in Australia, the authors concluded that, if the rate of recycling or landfill use does not change, the transport of CDW between regions does not significantly influence the impacts associated with waste management [28].

By LCA studies, Jain et al. [25] concluded that the production of recycled aggregates usually causes more negative impacts than the production of natural aggregates. However, when considering the impacts related to disposal in landfills and transport of natural raw materials, recycling becomes beneficial. Some similar conclusions were drawn by Ram et al. [23]. In all the evaluated scenarios, recycling had lower impacts compared to disposal in landfills.

Hossain et al. [16] pointed out that separating and reusing waste at the construction site is the most beneficial solution from an environmental point of view, and that, although the CDW separation outside the construction site allows waste recycling, this practice can cause as much environmental damage as the disposal in landfills. From this perspective, Coelho and De Brito [14] state that surface deconstruction is not capable of reducing environmental impacts in most of the analyzed categories. Nonetheless, a more selective separation during the demolition stage, and subsequent reuse/recycling, can considerably reduce the environmental impacts associated with CDW. Wang et al. [17] also verified that *in situ* recycling and reuse have more benefits in terms of reducing greenhouse gases when compared to recycling at the factory.

In general, the processes considered to be of great impact on waste management are transport (either raw material, CDW for industry, or CDW for landfill), CDW recycling (since technology and energy source impact efficiency), and impacts related to the extraction of raw materials. Greater attention should also be given to the CDW separation and demolition stages, whether selective or not. The conception and design of a new building are also relevant due to the materials selection stage.

Although LCAs were developed at different scales, different locations, and with different processes, a certain pattern could be observed: recycling tends to be beneficial from an environmental, social, and economic point of view. The higher the rate of urbanization, the lesser free area available for landfills; the further away from the raw material extraction mines, the more beneficial is the recycling of solid waste.

IV. CONCLUSIONS

Through a systematic review, the present work analyzed recent studies related to the use of Life Cycle Assessment methodologies for the management of construction and demolition waste in order to validate the recycling of CDW as a beneficial alternative to the environment in comparison with the disposal of waste in landfills. It was verified that, in most studies, the recycling of CDW causes less environmental impacts when compared to the disposal in landfills or incineration, given the reduction of damages related to the extraction of natural raw materials, transportation, and land consumption. Nonetheless, the recycling process still causes some damage to the environment. This is mainly due to the CDW transportation to the recycling industry and the consumption of energy and fuels by the recycling process. Alternatives such as waste separation and reuse at the construction site, mobile industries, prevention of waste generation, selective demolition, and deconstruction designs are suggested by the authors as a way to further reduce the environmental impact related to CDW.

Socioeconomic studies were also developed, although in smaller numbers. The economic viability of recycling depends on several factors: cost of natural raw material, cost for disposal in landfills, government incentives for recycling, availability of land (cost per m²), market demand for recycled materials and transportation costs. Social impacts, however, are more difficult to quantify, given the subjectivity of the factors and a lack of data in the literature.

Hence, it is suggested that future Life Cycle Assessments related to the management of construction and demolition waste explore the prevention of waste generation, in order to include the design stage of new buildings, as well as cost analyses related to demolition (conventional and selective demolition). More data related to the environmental impacts of the extraction of natural raw materials and the recycling process of CDW must be collected and gathered, in order to facilitate the design of new LCAs and comparison between them. As much as possible, socio-economic analyzes should be done along with environmental analyses to facilitate decision-making by stakeholders and local governments.

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