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Numerical method for carbon footprint assessment of recycled concrete aggregates

Método numérico para avaliação de pegada de carbono de agregado reciclado de concreto

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ABSTRACT

The construction sector is a major generator of atmospheric emissions and solid waste, denoting the need to account for its environmental impacts in contributing to climate change. One way to analyze these effects of the sector on the environment is through life cycle assessment (LCA), which considers the impacts of the entire product system. This research proposed a numerical method for the LCA of recycled concrete aggregate (RCA), related to carbon footprint, based on the procedures of NBR ISO 14040, using databases and other studies as references for modeling. This meets the need to simplify the LCA of the RCA determination process, given the complexity of material characteristics data, offering a practical alternative for academic and industrial applications. In the model, three main processes were adopted: concrete structure demolition, material transportation, and aggregate recycling; they were classified and quantified based on emissions from the use of electrical energy and the burning of fossil fuel. Thus, the LCA equation was modeled according to the final size of the aggregate and transport distances, making it possible to obtain a carbon footprint value. In the end, it was possible to conclude that the complete model was able to simplify the implementation of LCA in RCA, obtaining statistical consistency and reliability through validation with reference studies.

Keywords: numerical modeling; civil construction waste; life cycle assessment; CO_2 emission.

RESUMO

O setor da construção é um dos maiores geradores de emissões atmosféricas e de resíduos sólidos, o que denota a necessidade de contabilizar seus impactos ambientais na contribuição para mudanças climáticas. Uma forma de analisar esses efeitos do setor no meio ambiente é por meio da avaliação de ciclo de vida (ACV), que considera os impactos de todo o sistema de produto. Essa pesquisa propôs um método numérico para a ACV de agregado reciclado de concreto (ARCO), relacionado à pegada de carbono, baseado nos procedimentos da NBR ISO 14040, usando bases de dados e outros estudos como referências para a modelagem. Isso atende à necessidade de simplificação do processo de determinação de ACV de ARCO, tendo em vista à complexidade de dados de características do material, oferecendo uma alternativa prática para aplicações acadêmicas e industriais. No modelo, três processos principais foram adotados: a demolição da estrutura de concreto, o transporte do material e a reciclagem do agregado; e foram classificados e quantificados com base nas emissões do uso de energia elétrica e na queima de combustíveis fósseis. Assim, a equação de ACV foi modelada conforme o tamanho final do agregado e com a distância de transporte, possibilitando a obtenção de um valor de pegada de carbono. Ao final, foi possível concluir que o modelo completo foi capaz de simplificar a implementação da ACV em ARCO, obtendo consistência estatística e confiabilidade por meio de validação com estudos de referência.

Palavras-chave: modelagem numérica; resíduo da construção civil; avaliação de ciclo de vida; emissão de CO_2.

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Introduction

The construction industry has a significant environmental impact (Zhang et al., 2019; Mazurana et al., 2022). One of these effects is the unrestrained exploitation of natural resources, which accounts for 50% of all raw materials currently produced (Rosado et al., 2017). Another point is the considerable emissions of greenhouse gases since only the cement industry releases approximately 7% of all anthropogenic carbon dioxide emissions (Zhang et al., 2019; Mazurana et al., 2022). Besides, this industry has generated an expressive amount of solid waste, and only in 2021, the daily production of construction and demolition waste (CDW) represented 57% of all solid waste produced per inhabitant in Brazil (ABRELPE, 2021).

Thus, the use of recycled aggregates in the construction market has become more common, because it allows the reduction of raw material extraction and places for waste disposal (Visintin et al., 2020). In the developing countries context, a disseminated form of reusing CDW is its application in highway construction, as it does not require advanced waste treatment techniques, because its incorporation requires low mechanical performance and allows the reduction of asphalt highway impacts on the environment (Rosado et al., 2019). Thus, an assessment of the environmental impacts of recycled aggregate reuse is necessary.

One of these impacts is the carbon footprint defined by the quantification of greenhouse gases (GHG) emissions. This method is associated with accounting for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs) emissions, summarized by an equivalent carbon emission (WBCSD, 2004). Through this model, it is possible to establish emissions from fossil fuel burning, electricity use, and material consumption during construction (Rosado et al., 2019).

A way to measure carbon footprint is to combine this model with the life cycle assessment (LCA) method. LCA consists of the analysis of processes and stages to obtain a material, including natural resources, energy, and transportation (ABNT, 2014). According to the Brazilian standard, this methodology involves scope definition, inventory analysis, impacts assessment, and data interpretation, concerning local, temporal, and functional aspects. It allows quantifying and explaining some environmental impacts, such as global warming potential, through input and output flows (Schafhauser, 2019; Paz et al., 2023).

In the construction context, the LCA proves to be an interesting model for approaching materials, comparisons of constructive methods, and environmental certificates (Soares et al., 2006). Schafhauser (2019) presented an example of the LCA application in the construction context, addressing the LCA of mineral fraction of recycled aggregate used as the base and subbase of urban pavements compared with the LCA of natural aggregate, through the software SimaPro 8.5.2.0. The author analyzed the RCA of the city of Curitiba, in Paraná state, Brazil, from its transportation from the construction site to the processing plant, until the aggregate was delivered ready for use, highlighting the positive performance of the RCD in aspects of human health and ecosystem quality in comparison to the natural aggregate. Miyan et al. (2024) developed a study about the use of recycled waste concrete in alkali-activated paste, and its environmental and economic efficiency via LCA, through the software OpenLCA1.11 and the database Ecoinvent version 3.9. Miyan et al. (2024) produced paste with different proportions of RCA powder and metakaolin, and the lowest global warming potential results were from samples with RCA only. The regionalization of life cycle inventory (LCI) data was considered to avoid conflicts between inventory data and construction location, in association with the ReCiPe methodology to convert numerous results into a limited number of indicators (Miyan et al., 2024).

LCA studies of recycled materials have grown but the amount of data is still scarce and the traditional method is very complex (Paz et al., 2023). According to Miyan et al. (2024), the conventional LCA method consists of defining goal and system boundaries, setting all LCI inputs and outputs, allocating selected environmental impacts, interpreting results, and retrofitting the adopted criteria. Dias et al. (2022) and Atta and Bakhoum (2024) reported that to perform a recycled aggregate traditional LCA requires a lot of information about chemical composition, energy consumption, industrial processes, localization, and purpose of analysis, which can make the method laborious. Waste concrete aggregate LCI can have twice as many steps compared to natural aggregate, only in relation to the processes involved in its production (Aman et al., 2022, Atta and Bakhoum, 2024). Another point is that LCA is common for specific analyses; however, cementitious composites are diverse in their characteristics (Choi and Tae, 2024), which can affect the behavior of the waste generated, influencing the analysis of their post-demolition use.

Based on the current research scenario, developing a method that simplifies the execution of LCA can be interesting, as it can reduce the need for financial resources to obtain data and use software, promote faster analytics development, and allow a simpler understanding of its results. Choi and Tae (2024) developed something similar since their objective was to propose a method to determine the life-cycle sustainable assessment of concrete that other researchers could use without the need to apply the entire methodology of LCA, which denotes the novelty of the approach. The authors aimed to develop a method to analyze environmental impact and social and economic benefits from concrete, which were based in the Korean life cycle and prices databases and validated according to concrete business places data, disregarding disposal stages of concrete.

The need for simplified methods to account for environmental impacts becomes even greater in emerging countries, mainly in matters of reduction of technical training for the use of the tool and the facilitation of environmental data communication (Rack et al., 2013). Choi and Tae (2024) revealed the urge for numerical LCA data of cement-based composites in developing countries to expand research on sustainable construction materials, similar to that proposed by Rosado et al. (2017) in the Brazilian scenario. Other beneficiaries of easy-to-apply environmental assessment methods are small and medium-sized enterprises that aim to build a sustainable economy despite economic and operational limitations and reduced time for decision-making (Porciúncula Júnior and Andreoli, 2022).

Therefore, this study aimed to develop a numerical method for LCA and emission of GHG from coarse RCA for the Brazilian and other emerging countries scenario, which can be replicable and easy to use, through the scope and inventory identification of the CDW system and carbon footprint quantification according to the recycled aggregate. Using this method, the carbon footprint determination of recycled aggregates will be possible without the need for the complete development of the LCA methodology, simply by substituting values in a mathematical model. This proposal also involves validating the model developed based on other bibliographies and checking its reliability.

This type of proposal may be interesting for analyzing the possibilities of using recycled materials to mitigate carbon emissions from the construction industry, given its involvement in such environmental impact (Mazurana et al., 2022). According to Imtiaz et al. (2021), up to 1 ton of CO_2 is emitted in the production of 1 ton of Portland cement. However, other environmental, social, and economic impacts must be analyzed when making decisions about more efficient processes, in addition to the necessary precautions when using the proposed methodology, especially in cases where the energy and transportation matrices are different from those of the Brazilian scenario (Rosado et al., 2017) considered in this study.

Methodology

Figure 1 shows a summary of the proposed methodology for numerical modeling. This proposal is specifically an analysis of the climate change of RCA, based solely on LCA principles. The first step was to define the scope of the LCA, including all the research delimitations, following the NBR ISO 14040 (ABNT, 2014). Next, the processes that would be part of the LCI were listed, also under NBR ISO 14040 (ABNT, 2014), together with the equipment usage in the recycling and CDW treatment steps, and material transport. This CDW inventory was made from cradle-to-gate, i.e., it began with the concrete demolition and finished with the recycled aggregate treatment.

The GHG emissions for each stage were quantified according to other reports and EXIOBASE version 3 monetary database in the OpenLCA 1.11 open software (Stadler et al., 2018). The global warming potential values (GWP100) were considered, based on the 5th Intergovernmental Panel on Climate Change 2013 report, presented in FGVces (2016). The report data served as support for values arising from the software, due to the information reliability. Equation 1 representing this carbon footprint was modeled as follows:

$$E_{CO_2equi} = E_{CO_2demo} + E_{CO_2tran} \cdot S_T + E_{CO_2trea} \cdot d_{ave} \quad (1)$$

Where:

E_{CO_2equi} = final equivalent carbon dioxide emission of concrete recycled aggregate, including all greenhouse gases (in $KgCO_2eq/m^3$);

E_{CO_2demo} = carbon emission of concrete demolition (in $KgCO_2eq/m^3$);

E_{CO_2tran} = carbon emission of transport (in $KgCO_2eq/m^3 \cdot km$);

E_{CO_2proc} = carbon emission of waste treatment; the values of the indicated data will be determined based on this proposed methodology (in $KgCO_2eq/m^3 \cdot mm$);

S_T = variable of transport distance (in km); and

d_{ave} = variable of aggregate size (in mm).

In accordance with the model presented in Equation 1, directly obtaining the carbon footprint of 1 m³ of recycled aggregate defined the equation modeling. This method, based on the criteria previously presented, was composed of three steps: emissions of concrete demolition E_{CO_2demo} (see Equation 2) calculated based on GHG levels of electric demolition hammer use; emissions of waste treatment E_{CO_2trea} (see Equation 3) measured with the GHG emission of electric crusher use; and emissions from transporting waste E_{CO_2tran} (see Equation 4) determined by the GHG productions of 8 m³ bucket truck use. These emissions were quantified based on the total transport distance of CDW from the processing plant site and the average final diameter of the recycled aggregate, including the emissions calculated in the steps mentioned above. In the end, the developed LCA numerical method was statistically validated through the Wilcoxon test for paired data taking into account other researches that involved the use of LCA methodology to calculate RCA carbon footprint, considering the factors adopted in these researches.

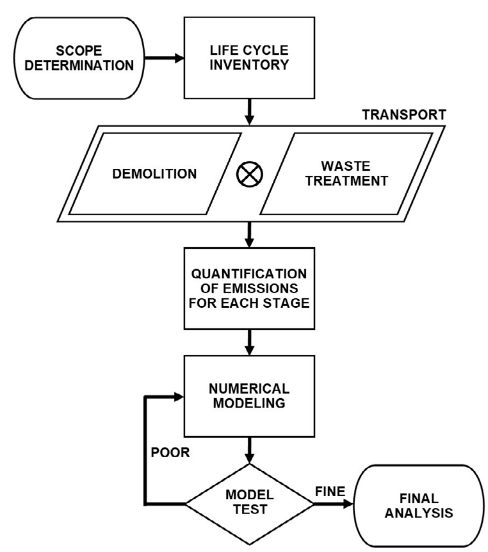

Figure 1 – Methodology flowchart for numerical modeling.

$$E_{CO_2demo} = \alpha_{ha} \cdot E_{CO_2ele} \quad (2)$$

$$E_{CO_2trea} = \gamma_{cr} \cdot E_{CO_2ele} \quad (3)$$

$$E_{CO_2tran} = \beta_{tr} \cdot E_{CO_2fue} \quad (4)$$

Where:
α_{ha} = use of electric demolition hammer for concrete demolition (in KWh/m³);
E_{CO_2ele} = carbon emission of electricity consumption (in $KgCO_2eq/kWh$);
γ_{cr} = use of electric crusher for aggregate treatment (in KWh/m³);
β_{tr} = use of fossil fuel from 8m³ bucket truck for transporting waste (in L/Km·m³); and
E_{CO_2fue} = carbon emission of burning fossil fuels (in $KgCO_2eq/L$).

Life cycle assessment scope and inventory

Table 1 lists the scope of the LCA and its features. The analysis of the recycled aggregates contribution to climate change based the setting of this study, passing through the demolition of concrete and the treatment of the generated waste. Therefore, this LCA considered only standard equipment, last year's GHG emissions, and mineral fraction of recycled concrete aggregate, although CDW also comprises materials such as organic fractions, metals, and plastics. These choices in technical characteristics influence the quantification of GHG production and the processes of the inventory. Figure 2 shows the processes that comprise the RCA production steps.

Figure 2 indicates that the CDW inventory begins with the demolition of concrete in the construction site, calculated in terms of $KgCO_2eq$ from electric energy used to demolish 0.7 m³ of concrete. This is because it takes into account the swelling of the material when producing 1 m³ of RCA, which is common in academic scenario (Park et al., 2019; Schafhauser, 2019; Paz et al., 2023). After this stage, 1 m³ of demolished concrete is transported in trucks to the CDW processing plant, whose emissions are accounted for in terms of $KgCO_2eq$ from diesel burning

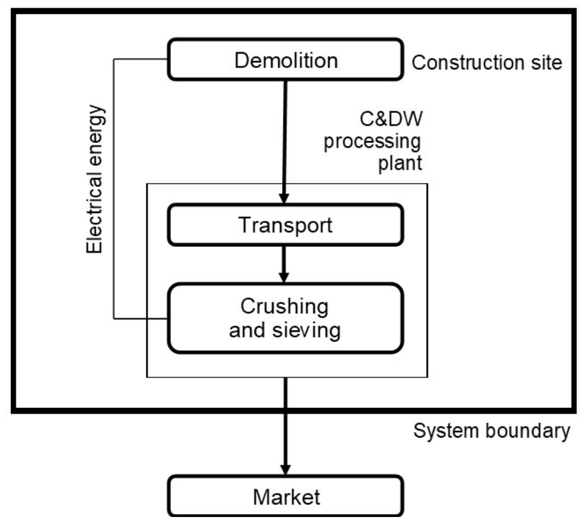

Figure 2 – Concrete recycled aggregate life cycle steps.

Table 1 – Recycled aggregate life cycle assessment form.

Step	Sub-step	Description	Content
Aim and scope definition	Purpose of the study	Application	Research to obtain a numerical model for life cycle assessment related to the carbon footprint of recycled aggregates
		Target public	Academic community
	Scope of the study	Product system	Production of the recycled aggregate
		System function	Recycled material
		Functional unit	Cubic meters of dry aggregate
		System boundary	Cradle-to-gate, in the period of one year, in the city of waste generation
		Category, methodology, and interpretation of the impact	Life cycle inventory focused on greenhouse gases emissions and carbon footprint
		Data requirement	Obtaining data through complementary databases and surveys
		Presupposed	Standardization of direct and indirect greenhouse gases emissions, mainly by energy consumption
		Limitations	Lack of life cycle assessment of Brazilian data and only greenhouse gases analysis
		Report type and format	Article addressing data, methodologies, and limitations
		Energy and raw material input	Obtaining data from databases and surveys regarding the use of electrical equipment and transport by vehicles
Life cycle inventory assessment	Data collection	Product	Concrete recycled aggregate
		Emissions to air, water, and soil	Emissions of greenhouse gases and carbon footprint

for every kilometer driven. The last stage involves crushing and screening, represented in $KgCO_2eq$ emitted in the use of electrical energy for the final production of 1 m^3 of RCA.

Thus, mechanical demolition and industrial waste treatment processes were chosen due to the diffusion of these processes compared with manual methods (Siqueira et al., 2018). If this LCI used manual methods, the quantification of atmospheric emissions would involve the subjectivity of human production, which is not considered in environmental impact assessments because it is difficult to analyze. Furthermore, it is important to remember that the geographic context of this study takes into account the use of energy from a hydroelectric matrix, since the use of coal-burning technologies for energy production would lead to an increase in the carbon footprint considered for processes that use electrical energy (Rosado et al., 2017). In this research, only emissions from energy use were analyzed, not including the emissions from their production. In this step, it is important to remember that the chosen variables for the LCA were the desired diameter of recycled aggregate, arising from the demolition and crushing process, and the transport distance.

Another highlight in Figure 2 is that if this inventory analyzed other factors, the result of the LCA carbon footprint would change. An example of this is the type of transport factor, where GHG emissions from full-electricity vehicles can differ by more than 60% from emissions from fuel cars (Machedon-Pisu and Borza, 2023). However, as Liu and Chao (2022) reported, electric vehicles have not yet become a reality worldwide. Therefore, the chosen means of transport were fossil fuel vehicles because they are still a reality in many countries, being one of the stages that contributes most to the assessment of environmental impacts in the Brazilian scenario of CDW recycling (Rosado et al., 2017). Moreover, the analysis could use other processes for aggregate recycling, like magnetic separator and classifier, which would increase the carbon footprint (Park et al., 2019). In this case, the LCA is carried out only on RCA; therefore, these recycling processes can be disregarded.

Modeling criteria

The selected data for the LCI seeks to standardize information, mainly for realities that require the LCA to be easy to apply. Thus, a single employee could operate the chosen demolition hammer electrically; the selected bucket truck had a capacity of 8 m^3 of material, and ran on fossil fuel; and the crushers selected were mobile, with a production capacity of up to 20 m^3/h, with electrical operation. Table 2 mentions the chosen criteria for data collection with the aim of identifying works that provided similar information, according to the previous parameters, to compose the numerical method.

The criteria for selecting data in the databases were based on the credibility of the study and publication, and the relevance of the study to the present research, with no limitation on the publication period. In this way, four publications were selected for the GHG emissions from electricity use and burning fossil fuels (specifically diesel), with 28 values in total (MMA, 2014; Sanquetta et al., 2017; Stadler et al., 2018; Paz et al., 2023). Emissions from the production of electricity and fuels were not considered, only those arising from the use of these energy sources. As for the equipment usage rate, two technical reports were considered for the demolition hammer usage, with three data (Caixa, 2022; DNIT, 2022); one data of fuel consumption for bucket trucks were selected (Paz et al., 2023); and four technical reports were selected for the crusher consumption, with nine values (Agostini Industrial, 2022; CSM, 2022; Komplet, 2022; Rubblecrusher, 2022).

Table 2 – Criteria for data collection.

Database	*Web of Science* *ScienceDirect* Theses and Dissertations Digital Library EXIOBASE version 3
Document type	Researches articles Dissertations Theses Technical reports
Language	English or Portuguese
Keywords	"LCA" OR "recycled aggregate" OR "GHG emission" OR "Usage rate" AND "electricity use" OR "burning fossil fuels" OR "Fossil fuel bucket truck" OR "Demolition hammer" OR "Crusher".
Publication period	Last seven years until the research period
Data collection questions	What are the GHG emissions from using a crusher? What are the GHG emissions from using a demolition hammer? What are the GHG emissions from using fossil fuel bucket truck? What is the usage rate of the demolition hammer for 1 m^3 of recycled aggregate? What is the usage rate of the crusher for 1 m^3 of recycled aggregate? What is the usage rate of the fossil fuel bucket truck for 1 m^3 of recycled aggregate?

LCA: life cycle assessment; GHG: greenhouse gases.

Results and Discussion

Numerical modeling

Based on the models presented in the methodology, the adoption of the parameters began with the emission of concrete demolition $E_{CO_2 demo}$ comprised of the usage rate of the demolition hammer, called α_{ha} in Equation 2, and Table 3 describes its respective usage and energy consumption. Table 4 presents the electricity use GHG emission called $E_{CO_2 ele}$ (in Equation 2), which multiplies the usage of the demolition hammer variable, addressed in the form of energy consumption.

Second, the $E_{CO_2 tran}$ GHG emission of waste transport between the construction site and the processing plant was calculated according to Equation 3), considering that a bucket truck with a capacity of 8 m^3 consumes 0.4 L of fuel per km (Paz et al., 2023). This factor, called β_{tr} (Equation 3), was multiplied by the fossil fuel consumption GHG emission, called $E_{CO_2 fue}$ (Equation 3, Table 4), considering that the emissions from this stage were calculated according to the transport distance.

The final step is composed of GHG emissions $E_{CO_2 trea}$ of the waste treatment in a CDW processing plant, considering only the equipment usage for the crushing of the waste, called γ_{cr} (Equation 4), according to values presented in Figure 3. In this step, the use of the crusher varies according to the required diameter for the recycled aggregate, as indicated by the manufacturers, in which the crusher power values considered were 2.2 kW, 7.5 kW, 28.0 kW, and 61.0 kW (Agostini Industrial, 2022; CSM, 2022; Komplet, 2022; Rubblecrusher, 2022).

Table 3 – Consumption rates of the equipment used for concrete demolition.

Equipment	Demolition hammer
Use (h/m^3)	2.31471
Energy consumption (kWh)	62.49730

Source: Caixa (2022) and DNIT (2022) modified.
It was adopted a demolition hammer with specifications between 25 and 28 kg.

Table 4 – Greenhouse gases emission rates by recycled aggregate production stage.

Emission	Fossil fuels (kg/L)	Electricity (kg/kWh)
CO_2	4.43384	0.11575
CH_4	0.00269	-
N_2O	5.38232·10-5	-
SF_6	1.6792·10-7	-
CO_{2eq}	4.52060	0.11575

Source: MMA (2014); Paz et al. (2023); Sanquetta et al. (2017); and Stadler et al. (2018) modified.
CO_2: carbon dioxide; CH_4: methane; N_2O: nitrous oxide; SF_6: sulfur hexafluoride; CO_{2eq}: carbon dioxide equivalent. If the parameter has not been found, its representation is given only with a "-".

Based on these data from technical reports, simple regression was carried out, seeking the best mathematical representation of the behavior of the variable x, where the model that represented a greater volume of data was the exponential (R^2=0.8045) in the indicated format at Equation 5.

The electricity use GHG emission $E_{CO_2 ele}$ presented in Table 4, also multiplies the crusher usage variable in Equation 4. The average crusher power, calculated based on the values mentioned above, multiplied the GHG emission from the equipment usage rate, obtaining the equation that represents the GHG emissions for crushing recycled aggregate, depending on the time of use and power of the equipment. Therefore, larger final diameters of the aggregate require less equipment, increasing its productivity and reducing its energy consumption, consequently generating a smaller carbon footprint.

$$\gamma_{cr\,(KWh)} = 0{,}7497\mathrm{e}^{-0{,}026\cdot d_{ave}} \tag{5}$$

Lastly, Equation 6 represents the numerical modeling of the recycled aggregate carbon footprint, in which the GHG emissions are calculated according to the desired aggregate diameter, called d_{ave}, and the transport distance between the construction site and the CDW processing plant, called S_T, considering the equations, variables, and constants presented previously. Table 5 shows a summary of the parameters adopted for the modeling.

$$E_{CO_2eq\left(\frac{KgCO_2eq}{m^3}\right)} = 1{,}75140\mathrm{e}^{-0{,}026\cdot d_{ave}} + 0{,}22603 \cdot S_T + 7{,}23406 \tag{6}$$

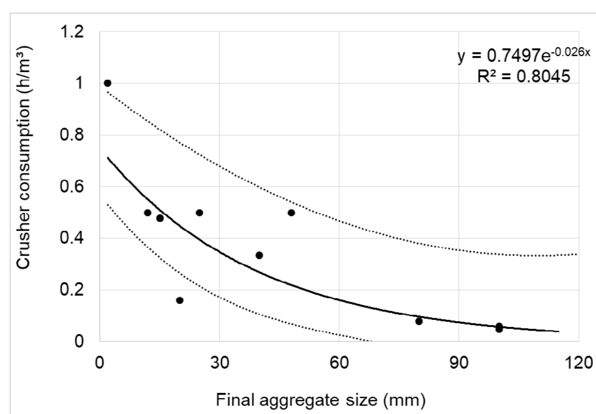

Figure 3 – Crusher consumption by the final size of the processed aggregate.
Source: Agostini Industrial (2022); CSM (2022); Komplet (2022); and Rubblecrusher, (2022) modified.
The crusher consumption curve was plotted with its standard deviation.

Model validation

To exemplify the applicability of this LCA numerical method to recycled aggregate, studies by SASA (2016), Schafhauser (2019), Imtiaz et al. (2021), Aman et al. (2022), and Paz et al. (2023) were analyzed, as shown in Table 6. In the table, $S_{T,re}$ correspond to the total transport distance mentioned in the research, even as $d_{ave,re}$ is the desired aggregate diameter in the respective paper. If the research did not indicate these variable values, a standard data that represents the research situation was adopted. E_{CO_2}re and E_{CO_2eq} are the carbon footprint mentioned by the author and the carbon footprint calculated by the proposed numerical method. Data were exhibited with their respective standard deviation. Figure 4 illustrates them graphically. It should be noted that some differences in energy and fuel matrix were identified between the studies, justifying the differences observed between the calculated and reference values.

Regarding the adopted data, Aman et al. (2022) compared the LCA of previous concrete production with natural and recycled aggregate in Malaysia, and a standard value for the diameter of aggregate was adopted for the values mentioned in the table. In SASA (2016), which is a technical report about recycled aggregate in Australia, a final aggregate diameter was adopted taking into account its use as paving aggregate. The distance between site and processing plant was settled by the authors, considering that the first one was an LCA located in Iskandar, Johor (MY) and the second was a research conducted in Adelaide (AU).

In addition, Imtiaz et al. (2021) analyzed the difference in the life cycle of concrete with recycled aggregate and geopolymers, in the Pakistan region, in which the adopted distance and average diameter values were estimated according to information on energy expenditure of production and transport. Paz et al. (2023) analyzed the production inventory of recycled aggregate in Cascavel (BR). Transport distance and average diameter were used in the method as mentioned by the author, considering that the demolished structures were residential buildings. Finally, Schafhauser (2019) studied an LCA of recycled aggregate for paving in Curitiba (BR). The diameter and the total distance of transport were settled as cited in the research.

For the E_{CO_2eq}, as can be seen in the Figure 4, it is possible to say that the final carbon footprint calculated by the numerical method was similar to the GHG emission value mentioned by the authors, which was confirmed by the Wilcoxon test for paired data (p-value=0.0625). The GHG emissions of the fossil fuel consumption and the electricity use may differ depending on the location, which can explain the divergences between the data, due to differences in fuel composition and energy matrix in each country (Visintin et al., 2020). Figure 5 shows the proportion of GHG emission in each step, through the Sankey diagram.

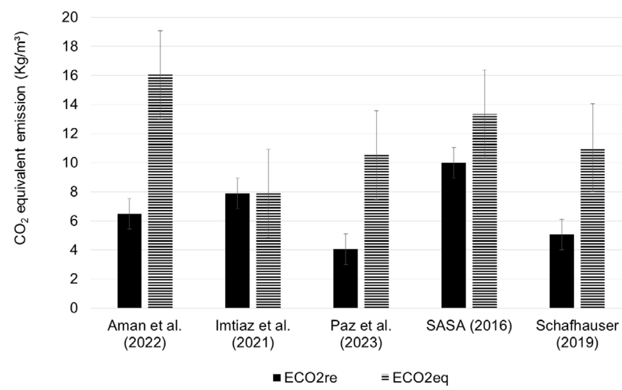

Figure 4 – Carbon footprint of recycled aggregate.
E_{CO_2}re: carbon footprint mentioned by the author; E_{CO_2eq}: carbon footprint calculated by the numerical method. Data were presented with their respective standard deviation.

Table 5 – Parameters adopted for modeling the equation.

Parameter	Symbol	Value adopted
Carbon footprint of electricity consumption	E_{CO_2ele}	0.11575 $KgCO_2eq/KWh$
Use of demolition hammer	α_{ha}	62.49730 kWh/m^3
Use of crusher	d	$c_{(KWh)} = 0.7497e^{-0,026 \cdot d_{ave}}$
Carbon footprint of burning fossil fuels	E_{CO_2fue}	4.52060 $KgCO_2eq/L$
Consumption of fuel for waste transport	S	0.05000 $L/m^3 \cdot S_T$
Transport distance	S_T	Factor, in km
Average diameter of the processed recycled aggregate	d_{ave}	Factor, in mm

Table 6 – Data adopted for applying the life cycle assessment numerical method to recycled aggregate.

Reference	$S_{T,re}$ (km)	$d_{ave,re}$ (mm)	$E_{CO_2}re$ ($KgCO_2eq/m^3$)	$E_{CO_2}eq$ ($KgCO_2eq/m^3$)
Aman et al. (2022)	36.10	38.10	6.5008	14.0441
Imtiaz et al. (2021)	$1.66 \cdot 10^{-4}$	38.10	7.8887	7.8845
Paz et al. (2023)	11.14	31.50	4.0614	10.52418
SASA (2016)	24.11	38.10	10.0000	13.33403
Schafhauser (2019)	15.00	56.25	5.0650	11.03023

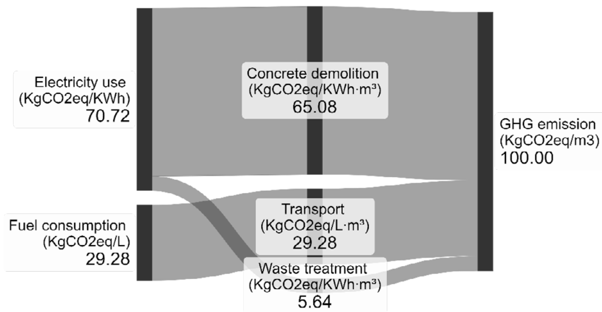

Figure 5 – Sankey diagram of greenhouse gases emissions percentage.

According to the diagram, the resulting emission from structure demolition represented 65.08% of total emissions, due to the high use of its equipment; this is the largest share in the GHG emission, similar to that found by Aman et al. (2022). Besides that, the emissions from transport represented 29.28% of the final value, also reported by Zhang et al. (2019), Visintin et al. (2020), and Paz et al. (2023), stating that transportation is an important part to be evaluated in the LCA of recycled aggregate. In the end, the emissions from waste treatment represented 5.64%, which demonstrates the efficiency of industrial crusher today, similar to that found by Schafhauser (2019).

Conclusion

Based on what this research proposed, it was possible to develop a numerical method for carbon footprint LCA of RCA. In this method, the selected variables to apply the equation were the desired diameter for the aggregate and transport distances. The complete model resulted in values that were similar to the reference papers, thus, the equation has the potential to represent well the carbon footprint of aggregate from CDW. Address recommendations for use of this numerical model assume that all processes and materials involved in production of recycled aggregate follow the aforementioned parameters, otherwise, the method and the inventory may need some adjustments.

The proposal contributes to simplifying the LCA process for recycled aggregate, given the complexity of determining material characterization data. Therefore, this method is recommended to evaluate forms of compensation for GHG emissions in construction, such as determining reforestation areas to capture these atmospheric emissions; or to evaluate improvements to the production process of RCA, such as decreased cement consumption and increased efficiency of transportation. For the application of the numerical method to compare the use of natural aggregate and recycled aggregate, it is necessary to reevaluate the inventory adopted for the system.

The proposed method does not include all the features of recycled aggregates; thus, it is indicated to enrich the emission and consumption data assumed as future analyses. In addition, it is necessary to analyze the adoption of other processes for treating, selecting, and classifying recycled aggregate, its transportation, and the statistical comparison of these changes with the initially proposed method.

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Authors' Contributions

Dobrovolski, E.R.G.: conceptualization, formal analysis, writing – original draft, writing – review & editing. **Kruger**, P.: project administration, resources, validation.

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