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Appropriateness of environmental impact distribution methods to model blast furnace slag recycling in cement making

Marcella Ruschi Mendes Saade[a,*], Maristela Gomes da Silva[b], Vanessa Gomes[a]

[a] University of Campinas, School of Civil Engineering, Architecture and Urbanism, Department of Architecture and Construction, Albert Einstein Avenue, 951, PO Box 6021, 13083-852 Campinas, São Paulo, Brazil
[b] Federal University of Espírito Santo, Technology Center, Department of Civil Engineering, Fernando Ferrari Avenue, 514, 29075-910 Vitória, Espírito Santo, Brazil

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ABSTRACT

Purpose: Environmental impact allocation has been noted as one of the life cycle assessment's (LCA) most controversial methodological issues given that it highly influences the study's final result. This paper analyses the appropriateness of available multifunctional modeling methods to distribute environmental loads between pig iron and bfs produced in the steelmaking process, and the influence that modeling choices have on LCA results for different blended cement types commercialized in Brazil.
Methods: Allocation by mass and by economic value, as well as system expansion, are examined for ordinary Portland cement and two types of blended cements with higher ggbfs contents as clinker replacement. The support platform used for performing the LCA was SimaPro 7.3, and the impact evaluation method was CML 2001 (baseline). The data for the production processes' modeling came from national and/or local reports; when national data were unavailable, the corresponding processes found in the SimaPro built-in Ecoinvent database were adapted to better represent the Brazilian context.
Results and discussion: As expected, impact allocation based on mass induces large impacts on bfs and the environmental loads of blended cements gradually increase with the increased bfs content. A similar trend was observed for economic allocation, except for global warming and terrestrial ecotoxicity, which are particularly sensitive to the allocation procedure choice. In the system expansion approach, impact values in all categories decreased with increased ggbfs content in cement.
Conclusion: Impact distribution across products is a legitimate way for an industry to be held accountable only for the true impacts of a given process. Each method presents its advantages and disadvantages. Independently of the criterion chosen, the conceptual limitations of allocation methods are that they do not look beyond impacts partitioning, and awkward ratios between physical characteristics and market value blur the vision and distort results. In our case, the system expansion approach precisely modeled the studied processes, following a complete and conceptually consistent description, which also allows for consideration of potential improvements at whole-system level.

1. Introduction

Cement is a material of great economic and social relevance. Its substantial contribution to supporting construction, infrastructure improvement and overall development comes, however, at a high price: the cement industry emits approximately 5% of the global anthropogenic CO_2 emissions (Humphreys and Mahasenan, 2002) and consumes large amounts of natural resources. The use of ground granulated blast furnace slag (ggbfs) in cements reduces raw material consumption and consequently cuts down CO_2 emissions (Lee and Park, 2005) and other environmental impacts (Silva et al., 2013), while improving their technical properties (Malhotra and Hemmings, 1995).

Brazil has long profited from the industrial synergy between the steelmaking and construction sectors. Standardization of Portland clinker replacement with ggbfs dates back to 1964. Experience on the use of ggbfs cements in the production of concrete elements has been consolidated over the decades, and has consistently pointed out their benefits to concrete's resistance, durability and decreased maintenance and repair needs (Camarini, 1995; Silva, 2006, 2007; Tanesi, 2010).

* Corresponding author. Tel.: +55 19 3521 2399; fax: +55 19 3521 2411.
E-mail addresses: marcellarms@hotmail.com (M.R.M. Saade), margomes.silva@gmail.com (M.G.d. Silva), vangomes@gmail.com (V. Gomes).

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Although ggbfs use in cement making is fairly common worldwide, Brazil stands out for the high replacement percentage applied: the *blended Portland cement* (CP II-E-32) contains up to 35%, in mass, of ggbfs (NBR 11578, 1991), while the *blast furnace Portland cement* (CP III-32) may have up to 70% of ggbfs, in mass (NBR 5735, 1991). Such approach had been favored by a unique combination of abundance of the by-product, more stringent environmental legislation through time, and a climate exempt of important deterioration triggers such as freeze-thaw cycles. In 2012, over 6 million tons of blast furnace slag (bfs) were diverted to Portland cement production (IAB, 2013). The same report shows that the clinker replacement with this by-product seems to have peaked, since the cement industry already buys all bfs made available annually. Despite that, it becomes also clear that other alternatives should be pursued to decouple environmental impacts from increased clinker production trends.

National studies dedicated to estimating the environmental loads of Portland cement with ggbfs as clinker replacement have so far typically considered slag merely as a consequence of the pig iron-making process, therefore with no impact attributed to it. A relatively recent European directive has shifted some wastes to by-product status, meaning they should be affected by allocation coefficients (European Commission-Joint Research Centre, 2010, European Union, 2008). Though not replicated in Brazil yet, this paradigm shift calls for appropriate approaches to assess the contribution and environmental liabilities of their insertion into new production cycles.

From a life cycle perspective, consideration of recycled by-products input to other production cycles requires that steelmaking is understood as a multifunctional process, i.e. an activity that fulfills multiple functions within a given analyzed system. A multifunctional process can be a single process generating multiple products (e.g. steel and by-products, such as bfs), a management program dealing with multiple waste flows, or a recycling process that provides waste management and material production (Ekvall and Finnveden, 2001). In life cycle assessment (LCA), when a production system generates several products, material and energy flows and the associated environmental impacts must be partitioned accordingly to accurately reflect their individual contribution to the overall burden. Decision-making regarding production cycling modeling in general and impact allocation, in particular, becomes critical.

This paper analyses the appropriateness of available multifunctional modeling methods to distribute environmental loads between pig iron and bfs produced in the steelmaking process, and the influence that modeling choices have on LCA results for different blended cement types commercialized in Brazil. Allocation by mass and by economic value, as well as system expansion, are examined for ordinary Portland cement (CP I-S-32, with industry standard 5% ggbfs) and two types of blended cements with higher ggbfs contents as clinker replacement (CP II-E-32 and CP III-32).

2. The challenge of handling multifunctional processes in LCA

Life cycle assessment (LCA) evaluates the potential environmental impacts and resources used throughout a product's lifecycle (ISO, 2006a,b), with records that begin with raw material acquisition and end with waste scenarios. In most LCA studies, no environmental burden is associated with waste production because it is considered to be unintentional generation (Chen et al., 2010). However, certain types of waste have been used as alternative raw material supply for other industry sectors, which has led to a paradigm shift. Interest in revising the status of waste is raised because it can not only generate pollution and incur in environmental management costs, but also become economically profitable if appropriate applications are found and well grounded in the marketplace. The European Directive 2008/98/EC notes that a waste can be considered to be a by-product (i) if its further use is certain, (ii) if it is produced as an integral part of a production process, (iii) if it can be used without any further processing other than normal industrial practice, and (iv) if its further use is lawful (European Union, 2008).

In LCA methodology, the key issue of waste recycling is the allocation procedure. Environmental impact allocation remains however as one of the most controversial methodological issues within the LCA community, as it can significantly influence the outcomes of a study (Frichknecht, 2000; Weidema, 2001; Ekvall and Finnveden, 2001; Reap et al., 2008; Sayagh et al., 2010).

ISO 14044 (ISO, 2006b) states that allocation should be avoided "*wherever possible*", either by dividing multifunctional processes into sub-processes or by expanding the product system to include the additional functions related to the by-products (Marvuglia et al., 2010). When allocation cannot be avoided, ISO 14044 (2006b) prescribes that system inputs and outputs should be divided based on the "*underlying physical relationships between them*". If those physical relationships are not easily identified to enable partitioning, then the inputs and outputs are to be attributed in a way that reflects other relationships between the products and functions, such as their economic value. This position is also strongly recommended by SETAC (Lundie et al., 2007). The ISO standard also states that when several allocation alternatives seem applicable, a sensitivity analysis should be conducted to illustrate the procedures' influence on the final results.

The ISO standard has been criticized for not taking into consideration the fact that different approaches for the allocation problem can result in different types of information and for failing to mention that there should be a correlation between the study's goals and the chosen approach (Yellishetty et al., 2009). The standard's allocation hierarchy can also be criticized for providing too much freedom (Marvuglia et al., 2010): for instance, how would one assure that allocation was avoided "*wherever possible*"?

No specific method is consensually appointed as correct in the reviewed published work on allocation. Many approaches have rather been suggested to avoid or minimize the influence of impact distribution on the LCA results. Weidema and Schmidt (2010) affirm that system expansion always ensures mass and energy balances, whereas allocation nearly always fails to do so. Contrastingly, three studies identified in bfs use in cement and concrete making literature have all applied some kind of allocation. Firstly, Sayagh et al. (2010) used mass allocation for sensitivity analysis of bfs recycled in concrete. Chen et al. (2010) state that allocation is generally preferable, since there is no global coherency across studies that define different system boundaries, and applied both mass and economic value allocation procedures in their study on LCA of mineral additions in concrete.

The major conceptual limitation of mass- and economic value-based allocation principles is probably their failure to capture the benefit of reinserting recycling in the process modeling as avoided primary material extraction and some sort of environmental or economic credit to the different parts involved. Habert (2013) then proposed an allocation method based on the European Union Greenhouse Gas Emission Trading System (EU-ETS), which attributes the same economic gains and losses to all of the industries involved in by-products trading within the cement manufacturing chain. Even though such proposal provided a pragmatic solution to encourage material loop closure across different industries, its application finds practical challenges in contexts not supported by an established emission trading system.