# Primary data priorities for the cycle inventory of construction products: Focus on foreground processes

**Fernanda Belizario Silva [1,2]; Daniel Costa Reis [1]; Yazmin Lisbeth Mack-Vergara [1,3,7]; Lucas Pessoto [1,2]; Haibo Feng [4]; Sérgio Almeida Pacca [5]; Sebastién Lasvaux [6]; Guillaume Habert [7]; Vanderley Moacyr John [1].**

[1] University of São Paulo, Polytechnic School, Department of Construction Engineering, Av. Prof. Almeida Prado, Trav. 2, 83, São Paulo, SP 05508-900, Brazil
[2] Institute for Technological Research of the State of São Paulo, Center for Technology of the Built Environment, Av. Prof. Almeida Prado, 532, São Paulo, SP 05508-901, Brazil
[3] Universidad Tecnológica de Panamá, Experimental Center for Engineering, Route to Tocumen Airport, Tocumen, Province of Panama, Panama
[4] University of British Columbia, School of Civil Engineering, V1V 1V7 Kelowna, Okanagan, Canada
[5] University of São Paulo, School of Arts, Sciences and Humanities, Rua Arlindo Bettio, 1000, São Paulo, SP 03828-000, Brazil
[6] University of Applied Sciences of Western Switzerland (HES-SO), School of Business and Management Vaud (Heig-vd), Laboratory of Solar Energetics and Building Physics (IGT-LESBAT), 1401 Yverdon-les-Bains, Switzerland
[7] Swiss Federal Institute of Technology in Zurich, Institute for Construction and Infrastructure Management, Chair of Sustainable Construction, Stefano-Franscini-Platz, 5, 8093 Zurich, Switzerland

**Corresponding author:** Fernanda Belizario Silva
E-mail: fernanda.belizario@lme.pcc.usp.br
Telephone: + 55 11 3767 4556

## Abstract

*Purpose* Life cycle assessment can support decisions for improving the environmental performance of construction products. However, the amount of data required for developing life cycle inventories limits the adoption of LCA. This work associates the interpretation of the impact results of construction products at the unit process level with a quantitative definition for the foreground and background system, for guiding primary data collection towards foreground processes that can be affected by decision-makers in the construction sector.

*Methods* A set of construction products commonly used in Brazil is selected and their cradle-to-gate life cycle inventories are modeled using the ecoinvent database (version 2). Life cycle impact assessment is performed using the ReCiPe Midpoint Hierarchist method. The contribution of each process during the life cycle of construction products for each impact category is quantified. These processes are associated with economic sectors, which are classified as belonging to the foreground or background system from the perspective of the construction industry. Foreground sectors are those controlled or influenced by the construction sector and are defined based on the production share consumed by the construction value chain. The elementary flows defining each impact category are also identified.

*Results and discussion* Foreground processes show significant contributions to most impact results of construction products. Global warming, fine particulate matter formation, ozone formation, acidification, human carcinogenic toxicity, and terrestrial ecotoxicity are mainly caused by direct emissions and fossil fuel combustion in manufacturing processes. Land occupation for production activities contributes to land use change, while the consumption of fuels, raw materials and water causes fossil and mineral resource scarcity and water consumption respectively. Freshwater and marine ecotoxicities and human non-carcinogenic toxicity have foreground contributions only for steel and copper products due to emissions from the landfilling of mining tails. Ionizing radiation and stratospheric ozone depletion are mostly driven by background processes. A reduced group of elementary flows covers a big share of the environmental impacts of most construction products.

*Conclusions* The results indicate priorities for life cycle inventory primary data collection of construction products, by focusing on foreground processes and the corresponding elementary flows that cause many of the potential embodied impacts of construction. Increasing the availability of primary data for these processes improves the reliability of LCA-based decisions in the construction sector, especially in countries which still lack local LCI databases.

KEYWORDS: data collection; life cycle assessment; unit process; foreground; background; construction.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the Swiss–Latin American cooperation program coordinated by the University of St. Gallen; the Foundation for Support of the Institute for Technological Research (FIPT); the Laboratory of Microstructure and Eco-efficiency of Materials (LME), the National Institute on Advanced Eco-Efficient Cement-Based Technologies (CEMtec), the São Paulo Research Foundation (FAPESP) (grant nº 2014/50948-3); the National Council for Scientific and Technological Development (CNPq) (grant nº465593/2014-3); the Technological University of Panama (UTP), Institute for Training and Development of Human Resources (IFARHU) of the Republic of Panama (fellowship nº. 08-2014-42); and the Swiss Government Excellence Scholarship for Foreign Scholars 2017/2018.

## 1 Introduction

Reducing anthropogenic impacts on the environment is an urgent task for all economic sectors (Berg 2018). This task is particularly challenging for the construction sector, as it must combine the reduction of resource use, energy consumption, waste generation and their corresponding impacts (Horvath 2004; Krausmann et al. 2009), with the provision of the built environment required by a growing world population and an increasing urbanization rate (Doyle and Havlick 2009; IPCC 2014; United Nations 2015). With the increase in the energy efficiency of buildings and the use of cleaner energy sources, the focus of measures for reducing the environmental impact of buildings is shifting to their embodied impact due to the intense use of materials in construction and its associated impacts (International Energy Agency and United Nations Environment Programme 2018).

Life Cycle Assessment (LCA) (ISO 2006a, b) is the most recommended method to assess the environmental performance of construction, because of its quantitative and comprehensive approach in terms of impact categories and life cycle stages, which is considered appropriate for complex and long-lasting products such as buildings (Finnveden et al. 2009; Hellweg and Mila i Canals 2014). Regarding the embodied impact of buildings, LCA is often applied to select the products with lowest impacts through comparison of functionally equivalent alternatives, and/or to identify hotspots for improving the environmental performance of specific construction products (Cabeza et al. 2014).

However, LCA requires a large amount of life cycle inventory data, which inhibits the use of primary data from the industry and causes LCA to be predominantly based on secondary data (Todd and Curran 1999; Soust-Verdaguer et al. 2016). Data demand is increased by a growing amount of impact categories, like in the new version of EN 15804 (DIN 2018) that requires assessing sixteen impact categories. Many of these categories are not familiar to construction stakeholders (WBCSD 2016a), which diminshes their willingness to collect data and to act on those impacts. This scenario poses a challenge for adopting LCA as a decision tool, especially in countries that still lack local, comprehensive LCI databases. It is thus necessary to set priorities for life cycle inventory primary data collection, by identifying the most relevant elementary and product flows for assessing the impacts of construction products.

Nevertheless, LCA studies usually analyze only the aggregated impact results, and often do not identify the specific unit processes and flows that cause these impacts, making it difficult to identify these priorities. Just to name a few examples of such LCA studies for construction products: Mohammadi and South (2017) indicate that cement and aggregates are the main drivers of ozone depletion of concrete; Almeida et al. (2016) identify packaging as the dominant process for eutrophication and human toxicity of ceramic tiles; Paleari et al. (2016) indicate the use of copper as the cause for acidification and eutrophication of building finishes and systems; and Corradini et al. (2019) present the production of the heating system of a wooden building as an important driver of freshwater ecotoxicity, human non-carcinogenic toxicity, and marine eutrophication. None of these studies explain how elementary or product flows relate to these impact categories. On the other hand, the identification of impact causes at the unit process level can be wrong, like attributing ionizing radiation to the mining of limestone (Condeixa et al. 2014) – the (possible) natural radioactivity of limestone is not accounted for in LCA. While some secondary LCA databases (like GaBi) generally disclose aggregated information and do not allow for analyzing unit processes, others (like ecoinvent) have thousands of unit processes within a life cycle inventory, making the analysis at the unit process level considerably difficult (Bourgault et al. 2012; Reinhard et al. 2016).

Moreover, when interpreting LCA results, there is hardly a distinction between impact causes that are under the influence of construction stakeholders – which can be more easily mitigated – and those that are not. In LCA, this is respectively called foreground and background systems and this classification is usually applied for defining the strategy for life cycle inventory data collection (European Commission 2010a). Primary data are required for the foreground system and secondary data are accepted for the background system (European Commission 2010b; Wernet et al. 2016). Although the division between the foreground and background systems is not entirely straightforward, this perspective is useful because it prioritizes primary data for modelling processes that can be more easily modified or influenced, and consequently improved, by agents from the construction sector (Bourgault et al. 2012; Van Hoof et al. 2013).

To the best of our knowledge, a systematic interpretation of LCA results of construction products associating the specific unit processes causing the various impacts with a clear classification for the foreground and background systems has not been carried out yet. It is of relevance, as more and more new LCIA indicators and methods are developed, with less understanding of whether they assess mostly foreground or background processes. Therefore, the objective of this work is to identify the processes belonging to the foreground system and the corresponding elementary flows that determine the impact results in the life cycle assessment of construction products. This can help researchers and LCA practitioners to set priorities for primary data collection for the life cycle inventory of construction products, by focusing on issues that can be more easily improved by stakeholders of the construction sector (including manufacturers, designers and policy makers) as a result of LCA studies.

This study focuses on the main construction products used in Brazil where there is a large construction demand for housing, infrastructure and other types of buildings and a lack of reliable LCI databases.

## 2 Method

To identify the foreground processes driving the environmental impacts of construction products, a systematic classification of foreground and background processes from the perspective of the Brazilian construction sector is carried out, followed by an analysis of contribution of the foreground and background processes to the life cycle impact assessment results and the identification of the main elementary flows contributing to each impact category. Figure 1 presents an overview of the method. The details of the method are presented in the following sections.

## 2.1 Life cycle inventory

This study analyses the main construction products used in Brazil, which are selected based on the specifications of a one-story detached house belonging to a social housing project for low-income families in Brazil. This house has one living room, one kitchen, one bathroom, and three bedrooms, with a total area of 66 m² (the detailed specifications are available in Tables S1 and S2 and the floor plan is shown in Figure S2—Electronic Supplementary Material). It is considered representative of a typical house in Brazil since the mass composition of the house is in agreement with the national bill of construction products compiled for the market-share analysis performed for foreground/background system classification (Table S7—Electronic Supplementary Material), which includes all types of buildings and infrastructure projects. The choice of using a typical Brazilian building is due to the level of detail of the life cycle inventories required for the following steps of analysis, which is not compatible with the more general information of national figures for consumption of construction products.

The system boundary considered for this study extends from the cradle to the factory gate. Although relevant environmental impacts may occur in other life cycle stages of constructed assets (e.g., in the final disposal of those products), we consider that the chosen system boundary is coherent with the aim of this work.

Life cycle inventories are modeled using the ecoinvent database version 2.2. This database is selected because it provides data as “unit processes”, which facilitates the understanding of the chain of activities within the product system and the identification of the key impact drivers, thus making it appropriate to the proposed analysis. The updated ecoinvent version 3.5 is structured along market activities, which makes the tracking of the upstream processes extremely difficult and dilutes the contribution of each process. Furthermore, most construction material production processes available in version 3 are similar or identical to those in version 2. However, once the main foreground processes have been identified, the results of this work can be applied to other and more recent databases.

The selection of ecoinvent also relies on the fact that ecoinvent provides meaningful and complete life cycle data, even though its applicability is limited to countries like Brazil (Silva et al. 2017). Datasets for representing the construction products used in the reference house project are chosen based on the analysis of the product specifications and production processes available in ecoinvent (Althaus et al. 2007; Hischier 2007; Kellenberger et al. 2007; Werner et al. 2007; Classen et al. 2009). In some cases, inventories are compiled based on the composition of the construction products, using existing ecoinvent datasets (Table S3—Electronic Supplementary Material). The inventory of the house along with the corresponding ecoinvent datasets is presented in Table S2 (Electronic Supplementary material).

## 2.2 Life cycle impact assessment

Life cycle impact assessment results are determined for one unit (kg, m, $m^2$ or $m^3$) of each construction product. Life cycle inventory compilation and impact assessment are carried out using Simapro (version 8.5.0.0) and the impact assessment method ReCiPe 2016 Midpoint, Hierarchist version (version 1.01). An adaptation is done in Simapro for the impact category "water consumption", excluding the "water, turbine use" and "water, cooling" from the characterization factors list in the software. The adaptation concerning "water, turbine use" is performed because ecoinvent version 2 presents data pertaining to only water withdrawal, without the corresponding water output flow (Pfister et al. 2016), resulting in an apparently higher water consumption level. In the case of "water, cooling", activities that use this flow are mostly performed in a closed-loop (Havey 2008; Lafarge 2011; Regucki et al. 2016), which means that the water is not actually consumed but continuously reused.

Considering the cut-off rules recommended by ISO 21930 (ISO 2017) that allow the exclusion of items that simultaneously contribute less than 1% to the cumulative mass or energy and all environmental impact results (while keeping at least 95% of these cumulative values), some materials are excluded from the subsequent analyses, as indicated in Table S2 (Electronic Supplementary Material). Infrastructure is excluded from the calculation of LCA results due to the high uncertainty associated with these flows (Weidema et al. 2013).

## 2.3 Analysis of the contribution of unit processes and elementary flows

For each product and each impact category, the "process contribution" is assessed, which refers to the individual contribution of each unit process within the system product to the impact result, due to the direct consumption of natural resources or emission of substances occurring in that unit process (Reinhard et al. 2016). This assessment allows identifying the specific processes along the supply chain of each product causing environmental impacts, considering the ecoinvent unit process modeling approach. Subsequently, these processes are assigned individually to the foreground or background system (details presented in

Section 2.4). The analysis of the process contribution is complemented with that of the impact networks, both of which extracted from Simapro. The individual cut-off level is adjusted to 1%, and the sum of all activities contributing less than 1% to the total impact is assigned to an “unclassified” category. In some cases, the share of the impact due to unclassified activities is quite high, which is a limitation of this study that is further discussed in the results section. An example of the process contribution analysis is given in Table 1. The corresponding network is available in the Electronic Supplementary Material (Figure S3).

The combustion of fuels and the corresponding emissions are sometimes modeled in ecoinvent via “heat datasets” or “combustion datasets” (e.g., “diesel, burned in building machine”), although in practice, these are direct emissions occurring in the processes that use these fuels. Such combustion/heat unit processes are used throughout the product systems, and by only extracting the process contribution from Simapro, it is not possible to identify the activities in which these unit processes are used. To overcome this problem, the “single product flow” function in Simapro is used, which allows tracking the activities that use a specific product flow and their corresponding shares (in absolute or percentage values). This approach applies only to the combustion datasets and not to the upstream processes of these combustion activities. An example is shown in Figures S4 and S5 (Electronic Supplementary Material).

For the “fossil resource scarcity” impact category, the contribution analysis is carried out differently. Due to the ecoinvent unit process structure, the extraction of natural fossil resources (crude oil, natural gas, coal, etc.) happens mainly in fuel production processes. However, fossil fuels (or resources, as for plastics) are only produced to be consumed by downstream processes; therefore, fossil resource scarcity cannot be attributed to fossil fuel production but rather to the processes that demand these fuels, and this is not reflected by the process contribution analysis. The contributions of the processes to fossil resource scarcity results are approximated by analyzing the cumulative impact networks until a certain upstream level and identifying the corresponding cumulative contribution from the cradle until that upstream level for each activity; this level of analysis is adjusted until a point at which fuel production activities are still upstream. Figure S6 (Electronic Supplementary Material) shows an example of this analysis.

One limitation faced in this study is that ecoinvent version 2.2 includes datasets that are available only as aggregated life cycle inventories (with only inputs and outputs from/to nature, called “system processes”), and not as unit processes. Thus, it is not possible to identify which upstream process might be related to the impact since this chain of activities does not exist for some products. This condition is observed for “titanium dioxide, chloride process, at plant/RER S”; “titanium dioxide at plant, sulphate process, at plant/RER S”; “esters of versatic acid, at plant/RER S”; “sodium perborate, tetrahydrate, powder, at plant/RER S”; and “feldspar, at plant/RER S”. In addition, the PVC and the nylon datasets are also modeled almost completely in the form of system processes since the only interactions with the technosphere are outputs of “waste to treatment activities”. These datasets affect the analysis of all impact results of the acrylic paint and the adhesive mortar and part of the results of the ceramic tile, the wooden door, and the PVC pipes.

To identify the prevailing elementary flows related to each impact category, the inputs and outputs from/to nature considering the cradle-to-gate system boundary are compiled, using the “inventory” function available in Simapro, with the “characterization” setup. This analysis is performed for each impact category and construction product, which allows identifying the substances that are causing the impacts (e.g., emissions of pollutants to air), thereby providing more detailed guidance for defining improvement actions and the corresponding primary data collection.

## 2.4 Classification of foreground and background processes

The definition of the foreground and background systems adopted in this study follows the ILCD management approach, which considers the ability of specific stakeholders to influence the processes (European Commission 2010a). The capacity of influence that the construction sector has over a certain industrial sector is assessed by the share of its total production that is consumed by the construction sector. If the construction value chain is an important client, that sector will possibly be more inclined to improve its environmental performance based on construction policies or demands of construction clients. In consequence, processes belonging to this sector would be considered as foreground from the perspective of the construction sector. Conversely, background processes are those belonging to industries that supply predominantly to other sectors and therefore are unlikely to be influenced by policies pertaining to the construction sector.

Note that a sectorial perspective is applied so that the recommendations derived from the analysis can be valid for the entire construction sector. This definition can be illustrated by the production of concrete: Ready-mix concrete producers control the amount of cement used in concrete, but cement manufacturers also belong to the construction sector and can be affected by policies proposed for this sector; therefore, cement production is considered a foreground process. Conversely, concrete producers cannot choose among different electricity supply options as there is usually only one national electricity grid; moreover, they cannot influence the electricity generation and transmission processes. Therefore, electricity production is considered a background process for the construction sector (there are some exceptions for companies that consume a large amount of electricity, but the classification is performed for the sector, not for specific products).

Table 2 provides the consumption share results and the classification of industrial sectors as belonging to the foreground or to the background system in Brazil. The consumption shares, in terms of mass or energy (not revenue), are based on a comprehensive evaluation of Brazilian sectorial reports and public data for the year 2015. We assume that foreground sectors are those whose share of production consumed by the construction sector is at least 20% (a sensitivity analysis on this threshold value is performed). The details concerning the calculation of the construction consumption shares are presented in the Electronic Supplementary Material (Tables S4, S5, and S6).

Each process extracted from the process contribution analysis is linked to the economic/industrial sector to which it belongs. For example, “hard coal, at mine” is classified as “fuels” since it is a fuel production process, while “hard coal, burned in power plant” is classified as “electricity” as it is an electrical power generation process. Combustion datasets are linked to the industrial sectors in which they occur. In this case, the foreground or background classification is based on the classification of the processes that use these combustion datasets. Table S8 (Electronic Supplementary Material) presents the list of all processes taken from the process contribution results (for all construction products and impact categories) and their corresponding classification.

Considering the classification of each process contributing to each impact category, the share of impact assessment results caused by foreground processes is calculated as shown in equations 1 and 2, for each of the construction products assessed in this study.

$$I_{i,j} = \sum\nolimits_k IP_{i,j,k} = \sum\nolimits_k \left(FIP_{i,j,k} + BIP_{i,j,k}\right) + \sum\nolimits_k UIP_{i,j,k} = 1{,}0 \qquad \text{(equation 1)}$$

$$FIS_{i,j} = \sum\nolimits_k FIP_{i,j,k} \qquad \text{(equation 2)}$$

Where $I_{i,j}$ is the total impact result for impact category “i” and product “j”; $IP_{i,j,k}$ is the fraction of the total impact result of each process “k” throughout the life cycle (for the considered impact category and product); $FIP_{i,j,k}$ is the fraction of each “k” foreground process; $BIP_{i,j,k}$ is the fraction of each “k” background process; and $\Sigma_k UIP_{i,j,k}$ is the fraction of all “k” unclassified processes (which is disclosed in Simapro as “remaining processes", i.e., the sum of all processes that contribute individually with less than 1% of the total impact result). $FIS_{i,j}$ is the foreground impact share of a product, for a certain impact category.

## 3 Results

Most construction material production sectors are considered foreground, except for those of aluminum, some metals, polymers, chemicals, and paper, for which most of the market is not construction-related, and agriculture that is clearly not related to the construction sector. Electricity and fuel production, transportation, and waste treatment are considered background since these economic sectors provide materials and services to many other industrial sectors. Most combustion processes are classified as foreground since they occur in processes belonging to the foreground system.

To illustrate and explain the process contribution analysis and the foreground/background classification carried out in this study, Table 1 presents an example for the product "cement-based mortar" and the impact category "terrestrial acidification". In this example, 67.7% of the impact is caused by foreground processes (55.0% alone by the clinker production process), 16.7% by background processes and 15.6% by unclassified processes; hence, acidification is predominantly caused by foreground processes for the mortar.

This analysis is performed in a similar manner for all construction products and all impact categories, and the results with the total foreground shares of impact results ($FIS_{i,j}$) are presented in Table 3. Table S9 (Electronic Supplementary Material) presents the share of unclassified impact results ($\Sigma UIP_{i,j,k}$), which are caused by processes with an individual contribution lower than the cut-off level of 1% of the impact result. The total unclassified share is mostly below 10%, which means that the biggest part of the impact can be understood and assigned to the foreground or background system; however, in specific cases, this share can reach values close to 30% because the impact is spread among many processes that make a small individual contribution.

The use of aggregated datasets to model the life cycle inventories of some construction products or their inputs – specifically acrylic paint, adhesive mortar, ceramic tile, wooden door, and PVC pipe – generates an inconsistent classification of the foreground and background processes because all elementary flows are attributed to the processes in which they are aggregated. For example, the production of titanium dioxide (used by the acrylic paint and, according to ecoinvent, by the adhesive mortar, although the latter is not true for Brazilian adhesive mortars) shows a direct emission of Radon-222 (an isotope with a half-life of less than 4 days), which probably comes from the upstream process of nuclear electricity production. Consequently, the uncertainty on the foreground impact shares of these products is high for all impact categories (except FRS). This inconsistency is also observed for the ceramic tile, the wooden door, and the PVC pipe. For a proper assessment of these materials, unit process data are required.

Tables 4, 5 and 6 present, respectively, the main air emissions, water emissions and raw material elementary flows contributing to each impact category, with their corresponding minimum and maximum contribution shares to each impact, among all construction products assessed (the detailed charts per product are presented in the Electronic Supplementary Material). This list comprises only the elementary flows that contribute at least to 10% of the total impact result for at least one impact category (there are substances that contribute to more than one impact category). This contribution is assessed regardless of if it comes from foreground, background or even unclassified processes.

Table 7 presents the main unit processes causing each of the impacts assessed (hotspot analysis), with the corresponding main elementary flows. This table allows for a deeper understanding of the main drivers of cradle-to-gate environmental impacts of construction products.

## 4 Discussion

Table 3 shows that for ten impact categories, the impact is predominantly caused by foreground processes (weighted foreground impact share higher than 50%), namely, global warming potential (GWP), fine particulate matter formation (FPMF), ozone formation—human health (OFHH), ozone formation—terrestrial ecosystems (OFTE), terrestrial acidification (TA), terrestrial ecotoxicity (TET), land use (LU), fossil resource scarcity (FRS), mineral resource scarcity (MRS), and water consumption (WC). Six impact categories have predominantly foreground contributions only for specific materials, including human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), freshwater ecotoxicity (FET), and marine ecotoxicity (MET) that are relevant for copper and steel products; and freshwater and marine eutrophication (FE and ME) that correspond to high foreground contributions only for copper products. It must be observed that steel and copper products have a relatively small mass in the house (1,34%) – 96,6% of the house mass is composed of only five construction products: concrete, ceramic block, mortar, gravel, and ceramic roof tile.

Table 7 allows for identifying which foreground processes are causing these impacts. The combustion of fossil fuels in various production processes generates emissions that are accounted for in global warming potential, fine particulate matter formation, ozone formation (human health and terrestrial ecosystems), acidification, and terrestrial ecotoxicity, while the consumption of these fossil fuels contributes to fossil resource scarcity. This finding is coherent with the high correlation between fossil energy demand and other impact categories assessed by Rydh and Sun (2005) and Huijbregts et al. (2006, 2010). Mining processes (including blasting and crushing) are a relevant cause of fine particulate matter formation, as observed by Ingrao et al. (2014) and Petek Gursel et al. (2014). Land occupation intensive processes (like forestry and mining) naturally count for land use. Processes that are intensive in the use of metallic substances contribute to mineral resource scarcity; however, this impact category does not account for bulk minerals extensively used in construction products (Habert et al. 2010), which represent 93,2% of the building's mass. The use of water in manufacturing processes is a major source of water consumption. The landfilling of sulfidic tailings of copper mining, as well as the disposal of waste, slag and sludge from steel production, cause emissions accounted for in human toxicity and ecotoxicity-related impact categories (except for terrestrial ecotoxicity) for copper and steel products, which is coherent with the results of Laurent et al. (2012). Emissions from landfilled sulfidic tailings are also the cause of freshwater and marine eutrophication for copper products (Laurent et al. 2012). This understanding at the unit process level allows for LCA to be used as a tool for process improvement, as suggested by Bourgault et al. (2012).

Regarding the contributions coming from background processes, the landfilling of lignite and coal tailings (used as fuel or in the fossil share of the electricity mix) is the cause for freshwater and marine eutrophication for products other than copper-based materials, and it also drives human non-carcinogenic toxicity, freshwater- and marine ecotoxicity for products other than copper and steel. Van Hoof et al. (2013) present similar findings, but for a totally different product system (a hand dishwashing product). It is worth mentioning that the share of coal in the Brazilian energy mix is of only 3,7% (EPE 2019) and the electricity supply has not been adapted in the ecoinvent datasets used in this study. Both stratospheric ozone depletion (SOD) and ionizing radiation (IR) do not have relevant foreground contributions for any material, except for those affected by aggregated datasets. They are caused by processes far back in the upstream product life cycle, such as radioactive emissions for uranium milling tailings (in the production of nuclear fuel used in nuclear electricity generation), and fugitive emissions of ozone depleting substances used as fire extinguishers and coolants in oil and gas production, respectively. Similar conclusions are presented by

Medeiros et al. (2018) for the cause of SOD in the cradle-to-gate LCA of an educational building located in Brazil, modeled with the ecoinvent database as well. SOD demonstrates non-negligible foreground contributions for gravel and the wood door though (28% for both), due to the combustion of fuels.

Concerning the elementary flows, it can be observed from Tables 4, 5 and 6 that a group of 49 flows – 19 air emissions, 9 water emissions, 16 natural resources, and 5 different types of area occupation – cause more than 95% of the impacts among all products for most impact categories, except for HCT (93%), HNCT (84%), TET (94%), LU (79%), and MRS (78%). 13 additional elementary flows allow for 95% impact coverage for all products and impact categories, except for the acrylic paint and the adhesive mortar for MRS, which have approximately 8% of their impact coming from substances with an individual contribution of less than 1%. This number of elementary flows (62) is significantly lower than the number of elementary flows present in the ReCiPe Midpoint list of characterization factors (more than 3,000).

Some elementary flows define various impact categories, including airborne emissions of $NO_x$ (accounted for in FPMF, OFHH, OFTE, and TA), of $SO_2$ (FMPF and TA), and of non-methane volatile organic compounds – NMVOC (OFHH and OFTE), all of them associated with the combustion of fossil fuels that drives the mentioned impact categories. Further elementary flows shared by different impact categories comprise emissions to water of zinc and vanadium (accounted for in HNCT, FET, and MET), and of chromium VI, copper, and nickel (FET and MET), which originate from leachates of sulfidic tailings and wastes from copper and steel production. On the other hand, some elementary flows are specific to given impact categories, such as the emission of fine particles (FPMF), the consumption of natural resources (mineral: MRS, fossil: FRS, and water: WC) and some direct air emissions (like $CO_2$ for GWP).

The fact that different impact categories are driven by the same processes is aligned to a certain extent with the correlations among impact results assessed by Lasvaux et al. (2016). These authors identified five uncorrelated components for describing the environmental impact of building products: 1) Fossil fuel consumption (related to global warming, acidification, photochemical ozone formation and, in some cases, eutrophication and human toxicity); 2) ecotoxicity (which in our case is explained by the landfilling of sulfidic tailings and waste from steel production); 3) ionizing radiation and ozone depletion (whose underlying causes may affect the impact of electricity production); 4) land use and 5) mineral resource consumption – these authors did not include "water consumption" in their analysis. Regarding the elementary flows, Lasvaux et al. (2014) also observed that, for construction products, a reduced set of substances allows for an accurate assessment of impact indicators.

The results of this study indicate that several impact categories are associated with foreground processes and corresponding elementary flows that the construction sector can act on. Therefore, in order to assess these foreground environmental aspects in a reliable way and monitor the effects of process improvement actions, primary data collection for construction products can be focused on specific processes and elementary flows, in addition to the product flows required for compiling the life cycle inventory, as summarized in Table 8. Nine air emissions ($CO_2$, $NO_x$, $SO_2$, PM2.5, Cu, Hg, Ni, V, and Zn), four types of land use, three main types of fossil resources, nine mineral resources, and two water flows (withdrawal and release) are the main elementary flows that require primary data for all products. For copper and steel products, seven additional flows of emissions to water need to be inventoried ($PO_4^{3-}$, $NO_3^-$, Zn, V, Ni, Cu, and Cr VI). Regarding the elementary flows required for assessing mineral resource scarcity, bulk minerals (e.g., limestone, sand, basalt, and granite) could eventually be included as well. Although ReCiPe does not account for these minerals because they are globally abundant, they can be locally scarce while their consumption levels are high, and this represents an environmental concern for the construction sector (Habert et al. 2010).

Conclusions could be different if the threshold level of minimum material consumption by the construction sector used to define the foreground processes were modified: If the level were reduced to 10%, not only would other industrial sectors become foreground (aluminum, thermoplastic, and zinc production), but the fuel production sector would also be classified as foreground; in this case, all impact categories would have significant contributions from foreground processes (especially considering the fuels used for electricity production). In contrast, if the threshold level were increased to 30% (with copper classified as background) or even 40% (with steel and lime classified as background), there would be no significant differences in the weighted average of the foreground impact shares. The results of this sensitivity analysis are presented in Table 9.

The findings of this study are valid for the cradle-to-gate system boundary and for the construction technology assessed, which is the dominant in Brazil and many developing countries, although these results should be analyzed with caution since the life cycle inventories are extracted from a European LCI database. The consideration of other construction technologies, such as lightweight structural materials or insulation products, may introduce flows associated with different impact categories, thereby changing the foreground and background impact shares, and eventually adding flows to the primary data demand. If other life cycle stages such as building use and end-of-life are included in the study, the results will also be affected, since stages such as landfilling of construction waste will introduce different elementary flows to be inventoried. Moreover, other LCI data sources might not consider the same processes and elementary flows. Finally, conclusions could be different for other LCIA methods, especially regarding the decision of elementary flows to be inventoried.

Despite these limitations, this study indicates relevant priorities for primary data collection for the life cycle inventory of construction products commonly used in Brazil and developing countries. Focusing primary data on the foreground processes can reduce the resources required for LCA studies while keeping the reliability of the main LCA results used by construction stakeholders for their decisions. Background processes and processes with a minor contribution to the impact of construction products can be modeled with secondary data, as they are not the focus of improvement measures. This is particularly important for countries that still lack local LCI databases. In this sense, the outcomes of this study can be regarded as an input for defining streamlined LCA approaches for the construction sector of developing countries, aiming at increasing the adoption of LCA as a decision support tool by facilitating the access to this method.

Furthermore, the proposed method of analysis – a process contribution analysis linked to a quantitative definition for the foreground and background systems – can be adapted to any geographic region or economic sector, using commonly available data concerning market shares.

## 5 Conclusion

The proposed interpretation of the LCA results for construction products, with the identification of the specific unit processes along the cradle-to-gate boundary that present the elementary flows related to the different potential environmental impacts, allows for a more detailed understanding of the causes of environmental impacts on the manufacturing of construction products. By assigning these processes to clearly defined foreground and background systems, it is possible to differentiate processes that can be modified by decision-makers and by policies targeting the construction sector from processes that cannot be easily influenced by construction sector agents. Furthermore, by understanding which impact categories are predominantly driven by foreground processes, one can define which indicators are more useful for the eco-design of construction products. This in turn indicates priorities for the collection of primary data for the life cycle inventory of construction products, aiming to support effective decisions and facilitate the development of local LCI databases.

Considering the construction products assessed in this study, airborne emissions from the combustion of fossil fuels are the main cause of global warming, fine particulate matter and ozone formation, terrestrial acidification and terrestrial ecotoxicity, while particles' emissions from mining activities also contribute to particulate matter formation. Land occupation for minerals and wood extraction causes land use. The consumption of water, mineral resources (especially metals) and fossil fuels respectively cause water, mineral and fossil resource scarcity. Emissions of pollutants to water from the disposal of wastes from metal mining and refining are the cause of human- and ecotoxicity related impacts for copper and steel products, as well as of eutrophication for copper products; background processes drive these impacts for other construction products. Ionizing radiation and stratospheric ozone depletion are mostly caused by background processes. A total of 49 elementary flows describe the majority of the environmental impacts associated with foreground processes for the construction products evaluated. Therefore these flows need to be measured among different building material producers so that their distinct environmental impact potentials are accurately assessed.

## 6 References

ABAL (2017) 2017 Abal Statistical Yearbook. São Paulo

ABCOBRE (2017) Brazilian Copper Yearbook 2017. São Paulo

ABIPLAST (2016) Indústria brasileira de transformação e reciclagem de material plástico - Perfil 2016

ABIQUIM (2016) O Desempenho da Indústria Química Brasileira em 2016

ABRAFATI (2018) Associação Brasilera dos Fabricantes de Tintas. http://www.abrafati.com.br/en/. Accessed 5 Nov 2018

ACR (2016) Anuário Estatístico de Base Florestal para o Estado de Santa Catarina 2016 (ano base 2015). Lages

Almeida MI, Dias AC, Demertzi M, Arroja L (2016) Environmental profile of ceramic tiles and their potential for improvement. J Clean Prod 131:583–593. https://doi.org/10.1016/j.jclepro.2016.04.131

Althaus H-J, Hischier R, Osses M, et al (2007) Life cycle inventories of chemicals. ecoinvent report n. 8. Dübendorf

ANA (2018) Brazilian Water Resources Report 2017. Brasília

Berg J (2018) Tomorrow's earth. Science 360:1379. https://doi.org/10.1126/science.aau5515

Bleiwas D (2011) Estimates of electricity requirements for the recovery of mineral commodities, with examples applied to sub-Saharan Africa. https://doi.org/https://doi.org/10.3133/ofr20111253

Bourgault G, Lesage P, Samson R (2012) Systematic disaggregation: a hybrid LCI computation algorithm enhancing interpretation phase in LCA. Int J Life Cycle Assess 17:774–786. https://doi.org/10.1007/s11367-012-0418-7

Cabeza LF, Rincón L, Vilariño V, et al (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew Sustain Energy Rev 29:394–416. https://doi.org/10.1016/j.rser.2013.08.037

CEFIC (2017) Facts & Figures 2017 of the European Chemical Industry

Classen M, Althaus H-J, Blaser S, et al (2009) Life cycle inventories of metals. ecoinvent report n. 10. Dübendorf

Condeixa K, Haddad A, Boer D (2014) Life Cycle Impact Assessment of masonry system as inner walls: A case study in Brazil. Constr Build Mater 70:141–147. https://doi.org/10.1016/j.conbuildmat.2014.07.113

Corradini G, Pierobon F, Zanetti M (2019) Product environmental footprint of a cross-laminated timber system: a case study in Italy. Int J Life Cycle Assess 24:975–988. https://doi.org/10.1007/s11367-018-1541-x

DIN (2018) EN 15804:2012+A1:2013/prA2:2018 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (draft). 80

DNPM (2018) Sumário Mineral 2016. Brasília

DNPM (2016) Anuário mineral brasileiro - principais substâncias metálicas. Brasília

Doyle MW, Havlick DG (2009) Infrastructure and the Environment. Annu Rev Environ Resour 34:349–373. https://doi.org/10.1146/annurev.environ.022108.180216

EPE (2019) Balanço energético nacional 2019: ano base 2018. Rio de Janeiro

EPE (2016) Balanço Energético Nacional 2016: Ano base 2015. Rio de Janeiro

European Commission (2010a) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed Guidance, 1st edn. Publications Office of the European Union, Luxembourg

European Commission (2010b) International Reference Life Cycle Data System (ILCD) Handbook : Specific guide for Life Cycle Inventory data sets. Publications Office of the European Union, Luxembourg

FAO (2017) Yearbook of Forest Products 2015. Food and Agriculture Organization of the United Nations, Rome

Finnveden G, Hauschild MZ, Ekvall T, et al (2009) Recent developments in Life Cycle Assessment. J Environ Manage 91:1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Habert G, Bouzidi Y, Chen C, Jullien A (2010) Development of a depletion indicator for natural resources used in concrete. Resour Conserv Recycl 54:364–376. https://doi.org/10.1016/j.resconrec.2009.09.002

Havey T (2008) California’s coastal power plants: alternative cooling system analysis. Oakland

Hellweg S, Mila i Canals L (2014) Emerging approaches, challenges and opportunities in life cycle assessment. Science 344:1109–1113. https://doi.org/10.1126/science.1248361

Hischier R (2007) Life cycle inventories of packagings and graphical paper. ecoinvent report n. 11. Dübendorf

Horvath A (2004) Construction Materials and the Environment. Annu Rev Environ Resour 29:181–204. https://doi.org/10.1146/annurev.energy.29.062403.102215

Huijbregts MAJ, Hellweg S, Frischknecht R, et al (2010) Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production. Environ Sci Technol 44:2189–2196. https://doi.org/10.1021/es902870s

Huijbregts MAJJ, Rombouts LJAA, Hellweg S, et al (2006) Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? Environ Sci Technol 40:641–648. https://doi.org/10.1021/es051689g

IABR (2018) Relatório de Sustentabilidade 2018. Rio de Janeiro

Ingrao C, Lo Giudice A, Tricase C, et al (2014) The use of basalt aggregates in the production of concrete for the prefabrication industry: Environmental impact assessment, interpretation and improvement. J Clean Prod 75:195–204. https://doi.org/10.1016/j.jclepro.2014.04.002

Instituto Brasileiro do PVC (2015) Brasil recicla 17,1% de PVC pós-consumo - outubro 2015. https://pvc.org.br/imprensa/releases/brasil-recicla-171-de-pvc-pos-consumo-outubro-2015. Accessed 5 Nov 2018

International Energy Agency, United Nations Environment Programme (2018) 2018 Global Status Report: towards a zero‑emission, efficient and resilient buildings and construction sector

IPCC (2014) Climate change 2014: Synthesis Report. Contribution of Working Groups I ,II and III to the Fifth Assessment Report of the Intergovernamental Panel on Climate Change. IPCC, Geneva

ISO (2006a) ISO 14040 - Environmental management - Life cycle assessment - Principles and framework. 20

ISO (2006b) ISO 14044 - Environmental management - Life cycle assessment - Requirements and guidelines. 46

ISO (2017) ISO 21930 - Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services. 80

Kellenberger D, Althaus H-J, Künninger T, et al (2007) Life Cycle Inventories of Building Products. ecoinvent report n. 7. Dübendorf

Krausmann F, Gingrich S, Eisenmenger N, et al (2009) Growth in global materials use, GDP and population during the 20th century. Ecol Econ 68:2696–2705. https://doi.org/10.1016/j.ecolecon.2009.05.007

Lafarge (2011) Sustainability 11th Report. Paris

Lasvaux S, Achim F, Garat P, et al (2016) Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: What matters? Ecol Indic 67:174–182. https://doi.org/10.1016/j.ecolind.2016.01.056

Lasvaux S, Schiopu N, Habert G, et al (2014) Influence of simplification of life cycle inventories on the accuracy of impact assessment: application to construction products. J Clean Prod 79:142–151. https://doi.org/10.1016/j.jclepro.2014.06.003

Laurent A, Olsen SI, Hauschild MZ, et al (2012) Limitations of carbon footprint as indicator of environmental sustainability. Environ Sci Technol 46:4100–4108. https://doi.org/10.1021/es204163f

Medeiros LM, Durante LC, Callejas IJA (2018) Contribuição para a avaliação de ciclo de vida na quantificação de impactos ambientais de sistemas construtivos. Ambient Construído 18:365–385. https://doi.org/http://dx.doi.org/10.1590/s1678

MME (2009) Perfil de argilas para cerâmica vermelha

MME (2017) Anuário estatístico do setor de transformação de não metálicos

MME (2010) Perfil do Titânio

Mohammadi J, South W (2017) Life cycle assessment (LCA) of benchmark concrete products in Australia. Int J Life Cycle Assess 22:1588–1608. https://doi.org/10.1007/s11367-017-1266-2

Paleari M, Lavagna M, Campioli A (2016) The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of a multifamily building in Italy. Int J Life Cycle Assess 21:1667–1690. https://doi.org/10.1007/s11367-016-1133-6

Petek Gursel A, Masanet E, Horvath A, Stadel A (2014) Life-cycle inventory analysis of concrete production: A critical review. Cem Concr Compos 51:38–48. https://doi.org/10.1016/j.cemconcomp.2014.03.005

Pfister S, Vionnet S, Levova T, Humbert S (2016) Ecoinvent 3: assessing water use in LCA and facilitating water footprinting. Int J Life Cycle Assess 21:1349–1360. https://doi.org/10.1007/s11367-015-0937-0

Regucki P, Engler B, Szeliga Z (2016) Analysis of water management at a closed cooling system of a power plant. J Phys Conf Ser 760:012026. https://doi.org/10.1088/1742-6596/760/1/012026

Reinhard J, Mutel CL, Wernet G, et al (2016) Contribution-based prioritization of LCI database improvements: Method design, demonstration, and evaluation. Environ Model Softw 86:204–218. https://doi.org/10.1016/j.envsoft.2016.09.018

Reis DC, Mack‐Vergara Y, John VM (2019) Material flow analysis and material use efficiency of Brazil's mortar and concrete supply chain. J Ind Ecol 23:1396–1409. https://doi.org/10.1111/jiec.12929

Rydh CJ, Sun M (2005) Life cycle inventory data for materials grouped according to environmental and material properties. J Clean Prod 13:1258–1268. https://doi.org/10.1016/j.jclepro.2005.05.012

Silva FB, Arduin RH, Diestelkamp ED, et al (2017) The importance of primary data for Life Cycle Assessment of construction products in Brazil. In: VII International Conference on Life Cycle Assessment in Latin America. Medellín, p 6

SNIC (2015) Consumo aparente de cimento por regiões e estados (t) 2015. http://snic.org.br/assets/pdf/numeros/cr2015.pdf. Accessed 3 Aug 2019

Soust-Verdaguer B, Llatas C, García-Martínez A (2016) Simplification in life cycle assessment of single-family houses: A review of recent developments. Build Environ 103:215–227. https://doi.org/10.1016/j.buildenv.2016.04.014

Tavares SF (2006) Metodologia de análise do ciclo de vida energético de edificações residenciais brasileiras. Universidade Federal de Santa Catarina

Todd JA, Curran MA (1999) Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup

UN Environment, International Resource Panel (2018) Global materials flow database. https://www.resourcepanel.org/global-material-flows-database. Accessed 5 Nov 2018

United Nations (2015) World Population Prospects 2015 - Data Booklet (ST/ESA/SER.A/377)

USGS (2016) Mineral Commodity Summaries 2016. https://doi.org/http://dx.doi.org/10.3133/70140094

Van Hoof G, Vieira M, Gausman M, Weisbrod A (2013) Indicator selection in life cycle assessment to enable decision making: issues and solutions. Int J Life Cycle Assess 18:1568–1580. https://doi.org/10.1007/s11367-013-0595-z

WBCSD (2016a) The Business Case for the Use of Life Cycle Metrics in Construction & Real Estate. Geneva

WBCSD (2016b) GNR Project Reporting CO2 - Total production volumes of cement - grey and white cement - Brazil. http://www.wbcsdcement.org/GNR-2016/Brazil/GNR-Indicator_21TGWcm-Brazil.html. Accessed 12 Dec 2017

Weidema BP, Bauer C, Hischier R, et al (2013) Overview and methodology - Data quality guideline for the ecoinvent database version 3. St. Gallen

Werner F, Althaus H-J, Künninger T, et al (2007) Life cycle inventories of wood as fuel and construction material. ecoinvent report n. 9. Dübendorf

Wernet G, Bauer C, Steubing B, et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230. https://doi.org/10.1007/s11367-016-1087-8

## Figures

(see separate file – Fig1.tiff)
Figure 1 – Overview of the research methodology used in this study.

# Tables

Table 1 – Example of unit process contribution analysis, presenting the classification of the unit processes into economic/industrial sectors, the corresponding foreground/background classification, and the total foreground/ background/ unclassified impact shares for the impact category “terrestrial acidification” of the product “cement-based mortar” (named “base plaster” in ecoinvent v2).

| **Process** | **Relative contribution ($IP_k$) (%)** | **Economic / industrial sector** | **Classification** |
|---|---|---|---|
| Clinker, at plant/CH U | 55.0 | Cement production | Foreground |
| Natural gas, sour, burned in production flare/MJ/GLO U | 4.8 | Fuel production | Background |
| Operation, lorry 20–28 t, fleet average/CH U | 4.4 | Transportation | Background |
| Light fuel oil, burned in industrial furnace 1 MW, non-modulating/CH U | 4.3 | Light fuel oil combustion (industrial furnace) | Foreground |
| Diesel, burned in building machine/GLO U | 3.5 | Diesel combustion (machinery) | Foreground |
| Quicklime, in pieces, loose, at plant/CH U | 3.1 | Lime production | Foreground |
| Operation, transoceanic tanker/OCE U | 2.7 | Transportation | Background |
| Blasting/RER U | 1.8 | Bulk mineral extraction | Foreground |
| Heavy fuel oil, burned in refinery furnace/MJ/RER U | 1.4 | Fuel production | Background |
| Natural gas, sweet, burned in production flare/MJ/GLO U | 1.2 | Fuel production | Background |
| Hard coal, burned in power plant/ES U | 1.2 | Electricity production | Background |
| Heavy fuel oil, burned in power plant/IT U | 1.1 | Electricity production | Background |
| Remaining processes | 15.6 | Generic | Not classifiable |
| **Foreground impact share (Σ FIP)** | **67.7** | | |
| **Background impact share (Σ BIP)** | **16.7** | | |
| **Unclassified impact share (Σ UIP)** | **15.6** | | |

Table 2 - Classification of foreground and background industrial sectors considering the mass/ energy share consumed by the construction sector.

| Economic / industrial sector | Construction consumption share (%) | Classification | Main references |
|---|---|---|---|
| Cement production | 100% | Foreground | (SNIC 2015; WBCSD 2016b) |
| Bulk mineral production [i] | ± 100% | Foreground | (Reis et al. 2019) and estimates |
| Ceramic production [ii] | 100% | Foreground | (MME 2009, 2017) |
| Gypsum production [iii] | 80% | Foreground | (USGS 2016; WBCSD 2016b; DNPM 2018) |
| Lime production [iv] | 39% | Foreground | (USGS 2016; MME 2017) |
| Wood production [v] | 81% | Foreground | (ACR 2016; FAO 2017) |
| Steel production | 40% | Foreground | (EPE 2016; IABR 2018) |
| Aluminum production | 15% | Background | (EPE 2016; ABAL 2017) |
| Copper production | 27% | Foreground | (EPE 2016; ABCOBRE 2017) |
| PVC production [vi] | 65% | Foreground | (Instituto Brasileiro do PVC 2015; ABIPLAST 2016) |
| Thermoplastic production [vii] | 16% | Background | |
| Zinc production | 11% | Background | (EPE 2016; DNPM 2018) |
| Paint production | 84% | Foreground | (MME 2010; ABRAFATI 2018; DNPM 2018) |
| Chemical production [viii] | <7% | Background | (ABIQUIM 2016; CEFIC 2017) |
| Other metal production [ix] | <5% | Background | (DNPM 2016; USGS 2016) |
| Paper production | ~3% | Background | Estimate |
| Agriculture | ~ 0% | Background | - |
| Electricity production | 8% | Background | (Bleiwas 2011; EPE 2016) |
| Fuel production | 13% | Background | (Tavares 2006; EPE 2016) |
| Transportation | 6% | Background | (Tavares 2006) |
| Water production | ~ 2% | Background | (ANA 2018) |
| Generic waste treatment [x] | no data | Background | - |

[i] Official figures on aggregate production indicate that the supply is not sufficient to satisfy the cementitious material demand, as estimated after cement production and typical formulations of materials, consistent with the observation that most aggregates are provided by the informal market. According to the International Resource Panel, approximately 95% of non-metallic minerals are consumed by the construction industry (UN Environment and International Resource Panel 2018).

[ii] Includes ceramic tiles, bricks and sanitaryware. Refractories are not included.

[iii] Includes gypsum used in cement production and the calcinated fraction used for wallboards and plaster products.

[iv] Includes lime used to produce mortar and the fraction consumed in steel production.

[v] Wood used in cellulose production and fuels is not included. Only round wood, sawn wood and wood-based boards are accounted for.

[vi] Since PVC is the most valuable thermoplastic consumed in construction industry, it was considered separately.

[vii] Thermoplastics include PP, HDPE, LDPE, LLDPE, PET, PS, EPS, EVA and nylon.

[viii] Chemicals include substances such as acetic acid, adipic acid, ammonia, benzene, butyl acrylate, chlorine, epoxy resin, esters of versatic acid, hydrogen cyanide, nitric acid, paraffin, sodium perborate, urea and urea formaldehyde resin.

[ix] Other metals include lead, nickel and tin.

[x] Generic waste treatment refers to the incineration or landfilling of municipal or average residues. Process specific residues such as mining spoils are assigned to the corresponding production activity.

Table 3 - Share of the impact result caused by foreground processes for the ReCiPe Midpoint Hierarchist impact categories, presented for each construction product (assessment of 1 kg, m, m² or m³ according to the product) and for the house (bold values in the last row, which correspond to the weighted average of the foreground impact shares of each product by mass). The greener the color of the cell, the higher the foreground impact share.

| Construction product "j" | Mass in reference house (%) | Impact categories "i" - Foreground Impact Share - FISi,j (%) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mineral resource scarcity | Land use | Fossil resource scarcity | Global warming potential | Ozone formation - Human Health | Ozone formation - Terrestrial ecosystem | Fine particulate matter formation | Terrestrial acidification | Water consumption | Terrestrial ecotoxicity | Human carcinogenic toxicity | Human non-carcinogenic toxicity | Stratospheric ozone depletion | Marine ecotoxicity | Freshwater ecotoxicity | Marine eutrophication | Freshwater eutrophication | Ionizing radiation |
| | | MRS | LU | FRS | GWP | OFHH | OFTE | FPMF | TA | WC | TET | HCT | HNCT | SOD | MET | FET | ME | FE | IR |
| Concrete | 47,3 | 96 | 81 | 92 | 91 | 81 | 81 | 76 | 77 | 83 | 74 | 12 | 16 | 12 | 6 | 1 | 2 | 0 | 0 |
| Cement-based mortar | 14,4 | 95 | 97 | 86 | 87 | 74 | 73 | 66 | 68 | 74 | 85 | 9 | 20 | 9 | 15 | 4 | 2 | 0 | 0 |
| Cement-based adhesive mortar* | 0,5 | 84 | 92 | 68 | 49 | 35 | 35 | 45 | 45 | 34 | 51 | 63 | 48 | 33 | 53 | 52 | 41 | 49 | 42 |
| Ceramic block | 21,6 | 100 | 96 | 78 | 79 | 76 | 76 | 59 | 56 | 23 | 19 | 37 | 0 | 6 | 0 | 0 | 0 | 0 | 0 |
| Ceramic roof tile | 4,4 | 100 | 91 | 78 | 78 | 75 | 75 | 56 | 53 | 15 | 14 | 38 | 0 | 4 | 0 | 0 | 0 | 0 | 0 |
| Ceramic tile* | 1,0 | 72 | 83 | 74 | 60 | 46 | 46 | 95 | 37 | 42 | 8 | 22 | 9 | 27 | 15 | 15 | 16 | 22 | 12 |
| Gravel | 8,9 | 18 | 98 | 63 | 48 | 82 | 82 | 57 | 47 | 96 | 26 | 44 | 4 | 28 | 5 | 5 | 0 | 0 | 0 |
| Wooden door* | 0,1 | 40 | 98 | 58 | 18 | 40 | 41 | 37 | 21 | 16 | 33 | 45 | 19 | 28 | 12 | 22 | 1 | 5 | 3 |
| Acrylic paint* | 0,2 | 80 | 83 | 88 | 56 | 58 | 57 | 60 | 60 | 46 | 73 | 72 | 61 | 64 | 66 | 66 | 54 | 54 | 52 |
| PVC pipe* | 0,1 | 71 | 98 | 91 | 86 | 90 | 90 | 77 | 79 | 79 | 85 | 4 | 10 | 82 | 8 | 6 | 69 | 2 | 0 |
| Steel rebar | 0,7 | 70 | 9 | 80 | 62 | 39 | 39 | 52 | 39 | 76 | 67 | 96 | 37 | 3 | 51 | 51 | 0 | 21 | 0 |
| Light steel frame profile | 0,6 | 22 | 24 | 82 | 49 | 41 | 40 | 64 | 79 | 47 | 5 | 87 | 45 | 4 | 12 | 14 | 7 | 9 | 0 |
| Copper pipe | 0,01 | 94 | 93 | 77 | 31 | 79 | 79 | 91 | 92 | 73 | 99 | 90 | 97 | 2 | 98 | 99 | 88 | 97 | 0 |
| Bronze pipe fitting | 0,002 | 73 | 64 | 64 | 34 | 83 | 83 | 82 | 81 | 37 | 99 | 91 | 97 | 5 | 98 | 99 | 88 | 98 | 0 |
| Copper cable with PVC insulation | 0,02 | 94 | 93 | 100 | 16 | 66 | 65 | 88 | 87 | 71 | 99 | 91 | 97 | 3 | 98 | 99 | 89 | 98 | 0 |
| Copper ground rod | 0,01 | 94 | 93 | 87 | 38 | 82 | 81 | 92 | 93 | 79 | 99 | 94 | 97 | 3 | 98 | 99 | 91 | 98 | 0 |
| Aluminum door | 0,03 | 0 | 68 | 92 | 12 | 10 | 10 | 2 | 4 | 0 | 74 | 0 | 2 | 3 | 2 | 0 | 0 | 0 | 0 |
| Aluminum window frame | 0,1 | 0 | 75 | 86 | 13 | 10 | 9 | 2 | 4 | 0 | 60 | 1 | 1 | 1 | 13 | 12 | 0 | 4 | 0 |
| **Weighted average FIS of ref. house** | | **88** | **87** | **84** | **81** | **77** | **77** | **68** | **65** | **65** | **55** | **22** | **11** | **11** | **6** | **2** | **1** | **0** | **0** |

* (Dashed cells) Products whose foreground shares are affected by datasets modeled as “system processes” in ecoinvent. In the calculation of the weighted average of the foreground impact share for each impact category, these values were not included; however, this does not significantly change the weighted average results.

Table 4 – Contribution of prevailing airborne emissions to the impact results of construction products, by impact category. The values presented are the minimum and maximum relative contributions among the studied construction products. Only elementary flows with a maximum contribution larger than 10% are considered.

| **Flow** | **GWP** | | **FPMF** | | **OFHH** | | **OFTE** | | **TA** | | **HCT** | | **HNCT** | | **TET** | | **MET** | | **IR** | | **SOD** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** |
| Ammonia | - | - | - | 40 | - | - | - | - | - | 72 | - | - | - | - | - | - | - | - | - | - | - | - |
| $CO_2$ (fossil) | 78 | 97 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Copper (Cu) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 10 | 83 | - | 11 | - | - | - | - |
| $N_2O$ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 35 | 96 |
| Formaldehyde | - | - | - | - | - | - | - | - | - | - | - | 38 | - | - | - | - | - | - | - | - | - | - |
| Mercury (Hg) | - | - | - | - | - | - | - | - | - | - | - | - | - | 2 | - | 28 | - | - | - | - | - | - |
| $CH_4$ (fossil) | 3 | 14 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| CFC-10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 16 |
| CFC-14 | - | 14 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Halon 1211 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 2 | 50 |
| Halon 1301 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 2 | 47 |
| Nickel (Ni) | - | - | - | - | - | - | - | - | - | - | - | 8 | - | - | 1 | 28 | - | 1 | - | - | - | - |
| $NO_x$ | - | - | 1 | 44 | 82 | 98 | 74 | 96 | 6 | 51 | - | - | - | - | - | - | - | - | - | - | - | - |
| NMVOC | - | - | - | - | 2 | 17 | 3 | 25 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PM < 2.5 µm | - | - | 12 | 94 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Radon-222 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 95 | 96 | - | - |
| $SO_2$ | - | - | 4 | 69 | - | - | - | - | 22 | 88 | - | - | - | - | - | - | - | - | - | - | - | - |
| Vanadium (V) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 26 | - | 1 | - | - | - | - |
| Zinc (Zn) | - | - | - | - | - | - | - | - | - | - | - | - | - | 31 | 3 | 78 | - | 12 | - | - | - | - |

Table 5 – Contribution of prevailing emissions to water to the impact results of construction products, by impact category. The values presented are the minimum and maximum relative contributions among the studied construction products. Only elementary flows with a maximum contribution larger than 10% are considered.

| **Flow** | **FE** | | **ME** | | **HCT** | | **HNCT** | | **FET** | | **MET** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** |
| Ammonium ion | - | - | - | 42 | - | - | - | - | - | - | - | - |
| Chromium VI | - | - | - | - | 59 | 100 | - | - | - | 26 | - | 27 |
| Copper (Cu) | - | - | - | - | - | - | - | - | 5 | 24 | 4 | 21 |
| Nickel (Ni) | - | - | - | - | - | 3 | - | - | - | 14 | - | 13 |
| Nitrate ($NO_3^-$) | - | - | 33 | 99 | - | - | - | - | - | - | - | - |
| Nitrogen | - | - | - | 25 | - | - | - | - | - | - | - | - |
| Phosphate ($PO_4^{3-}$) | 98 | 100 | - | - | - | - | - | - | - | - | - | - |
| Vanadium (V) | - | - | - | - | - | - | - | 8 | - | 41 | - | 41 |
| Zinc (Zn) | - | - | - | - | - | - | 59 | 94 | 36 | 88 | 35 | 86 |

Table 6 – Contribution of prevailing raw materials and land occupation flows to the impact results of construction products, by impact category. The values presented are the minimum and maximum relative contributions among the studied construction products. Only elementary flows with a maximum contribution larger than 10% are considered.

| **Flow** | **LU** | | **FRS** | | **MRS** | | **WC** | |
|---|---|---|---|---|---|---|---|---|
| | **min** | **max** | **min** | **max** | **min** | **max** | **min** | **max** |
| Aluminum | - | - | - | - | - | 99 | - | - |
| Clay | - | - | - | - | - | 100 | - | - |
| Coal, brown | - | - | 2 | 13 | - | - | - | - |
| Coal, hard | - | - | 4 | 65 | - | - | - | - |
| Copper 1,18% in sulfide | - | - | - | - | - | 24 | - | - |
| Copper 2,19% in sulfide | - | - | - | - | - | 31 | - | - |
| Natural gas | - | - | 8 | 77 | - | - | - | - |
| Iron | - | - | - | - | - | 70 | - | - |
| Lead | - | - | - | - | - | 11 | - | - |
| Molybdenum, 0,010% in sulfide | - | - | - | - | - | 17 | - | - |
| Nickel 1,98% in silicates, 1,04% in crude ore | - | - | - | - | - | 63 | - | - |
| Occupation, dump site | - | 89 | - | - | - | - | - | - |
| Occupation, forest, intensive | - | 54 | - | - | - | - | - | - |
| Occupation, forest, intensive, normal | 1 | 96 | - | - | - | - | - | - |
| Occupation, industrial area | - | 16 | - | - | - | - | - | - |
| Occupation, mineral extraction site | - | 98 | - | - | - | - | - | - |
| Crude oil | - | - | 8 | 66 | - | - | - | - |
| Tin | - | - | - | - | - | 23 | - | - |
| Uranium | - | - | - | - | - | 54 | - | - |
| Water | - | - | - | - | - | - | 100 | 100 |
| Zinc | - | - | - | - | - | 11 | - | - |

Table 7 – Overview of the most impactful foreground unit processes and of the corresponding main elementary flows.

| Impact category | Most impactful foreground processes | Main elementary flows |
|---|---|---|
| Mineral resource scarcity (MRS) | Cementitious and ceramic products (including ceramic tile): consumption of clay as raw material.<br>Steel products: consumption of iron ore and ferronickel.<br>Copper products: consumption of copper concentrate.<br>Wooden door and gravel: consumption of iron ore and ferronickel (contained in parts of door kits and in steel parts of gravel production equipment). | Consumption of aluminum, clay, copper, iron, lead, molybdenum, nickel, tin and zinc (depending on product composition). Consumption of uranium for nuclear electricity generation. |
| Land use (LU) | Cementitious products: occupation of area for wood production for the mortar, and for gravel extraction for concrete production.<br>Ceramic products: occupation of area for wood production and clay extraction.<br>Gravel: occupation of area for gravel extraction.<br>Wood door: occupation of area for wood production.<br>Copper products: occupation of area for disposal of sulfidic tailings from copper mining.<br>Steel products: occupation of area for wood production.<br>Aluminum products: occupation of area for wood production.<br>Although wood production is classified as a foreground process, in all cases except for that of the wood door, wood is used as fuel (which actually pertains to a background process). | Occupation of dumpsite, forest, industrial area, and mineral extraction site (all products, with varied contributions among the area types). |
| Fossil resource scarcity (FRS) | Overall high foreground impact shares, mainly due to the consumption of fossil resources as fuels used in the production processes. | Consumption of crude oil, natural gas, and coal (all products). |
| Global warming potential (GWP) | Cementitious products (mortar and concrete): direct emissions in clinker production (decomposition of calcium carbonate and emissions from fossil fuel combustion).<br>Ceramic products (block, roof tile): direct emissions in clay firing (natural gas combustion).<br>Gravel: emissions from the combustion of fossil fuels in the gravel extraction process.<br>Steel products (rebar and light steel frame profile): direct emissions in pig iron production and sintering (reduction of iron oxide and emissions from fossil fuel combustion).<br>Copper products (bronze fitting, cable, pipe and ground rod), wood door and aluminum products (door and window): emissions from fossil fuel combustion in production processes.<br>Highest shares of unclassifiable processes among all impact categories, probably due to the high importance of GWP, causing more inventories to report greenhouse gas flows. | Emission of $CO_2$ to air (all products)<br>Minor contributions of emissions of $CH_4$ (all products) and CFC-14 (aluminum products) to air. |
| Ozone formation, human health (OFHH) and ozone formation, | Cementitious products: direct emissions in clinker production.<br>Ceramic products (including ceramic tile): direct emissions in clay firing.<br>Gravel: emissions from the combustion of diesel in the gravel extraction process.<br>Wood door: emissions from combustion of wood chips in production processes. | Emission of $NO_x$ to air (all products). |

| Impact category | Most impactful foreground processes | Main elementary flows |
|---|---|---|
| terrestrial ecosystems (OFTE) | Steel products: direct emissions in blasting (in iron ore mining), iron sintering and diesel combustion in production processes.<br>Copper products: direct emissions in blasting (for copper mining). | Minor contributions of emissions of NMVOC to air (all products, especially for PVC). |
| Fine particulate matter formation (FPMF) | Cementitious products: direct emissions in clinker production.<br>Ceramic products (including ceramic tile): direct emissions in clay firing and ceramic tile production.<br>Gravel: emissions from the combustion of fossil fuels in the gravel extraction process.<br>Wood door: emission from combustion of wood chips in production processes.<br>Steel products: direct emissions in the mining of iron ore and iron sintering for the steel rebar; direct emissions in the application of zinc coat for galvanized steel frame profile.<br>Copper products: direct emissions in the refining of primary copper and production of copper concentrate. | Emission of $SO_2$, particulates ≤ 2,5 µm and $NO_x$ to air (all products).<br>Emission of $NH_3$ to air (galvanized steel frame profile due to the zinc coating process). |
| Terrestrial acidification (TA) | Cementitious products: direct emissions in clinker production.<br>Ceramic products: direct emissions in clay firing.<br>Steel products: direct emissions in iron sintering (for the rebar) and zinc coating (for galvanized steel frame profile).<br>Gravel: emissions from the combustion of diesel in the gravel extraction process.<br>Copper products: direct emissions in copper refining.<br>Wood door: emissions from the combustion of fossil fuels and wood chips in production processes. | Emission of $SO_2$ and $NO_x$ to air (all products).<br>Minor contributions of emissions of $NH_3$ to air (copper and steel products, more for galvanized steel frame profile due to the zinc coating process). |
| Water consumption (WC) | Cementitious products: consumption of water in the production of sand, gravel, and clinker.<br>Ceramic products: consumption of water in the block and roof tile production processes.<br>Gravel: consumption of water in the gravel production process.<br>Steel products: consumption of water for pig iron production, steel production, and steel hot rolling.<br>Copper products: consumption of water in the production of copper concentrate. | Consumption of water and water evaporation. |
| Terrestrial ecotoxicity (TET) | Cementitious products: emissions from light fuel oil combustion in industrial furnaces and from clinker production.<br>Ceramic products: combustion of fossil fuels in production processes.<br>Gravel: emissions from the combustion of fossil fuels in the gravel extraction process.<br>Wood door: emissions from combustion of wood chips, and light and heavy fuel oils in production processes.<br>Steel products: direct emissions from electric arc furnace steel production (rebar).<br>Copper products: direct emissions from primary copper production.<br>Aluminum products: emissions from light fuel oil combustion in industrial furnace in production processes. | Emissions of copper, zinc, vanadium, nickel, and mercury to air (all products, with varied contributions among these substances). |
| Human carcinogenic toxicity (HCT) | Ceramic products: direct emissions in clay firing.<br>Steel products: direct emissions from waste disposal (slag and sludges) of steel production and steel rolling.<br>Gravel: direct emissions from waste disposal of steel production (replacement parts for gravel production equipment). | Emissions of chromium VI to water (all products).<br>Emissions of formaldehyde to air (ceramic block and roof tile). |

| Impact category | Most impactful foreground processes | Main elementary flows |
|---|---|---|
| | Copper products: direct emissions from the landfilling of sulfidic tailings generated in copper mining and direct emissions in primary copper production.<br>Wood door: direct emissions from waste disposal of steel production (steel parts of door kits).<br>For cementitious materials, the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities; for aluminum products, the impact is mainly caused by emissions from disposal of red mud from the bauxite digestion process (background). | Minor contribution of emissions of nickel to air (copper products). |
| Human non-carcinogenic toxicity (HNCT) | Cementitious products: direct emissions in clinker production and fossil fuel combustion in production processes.<br>Wood door: emissions from the disposal of wood ash and from wood chip combustion in production processes.<br>Steel products: direct emissions from steel production and emissions from waste disposal of steel production.<br>Copper products: direct emissions from the landfilling of sulfidic tailings generated in copper mining and direct emissions in primary copper production.<br>For other materials, the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities (background). | Emissions of zinc to water (all products).<br>Minor contributions of emissions of zinc to air (steel products). |
| Stratospheric ozone depletion (SOD) | No significant foreground impact shares (except for products that contain datasets modeled as system processes).<br>Wood door: foreground contribution from emissions from wood chip combustion.<br>Gravel: foreground contribution from emissions from diesel combustion.<br>The impact is caused mainly by fugitive emissions from fire extinguishers and cooling systems present in installations for crude oil production and natural gas production and direct emissions from nitric acid production (background). | Emissions of $N_2O$, Halon 1211 and Halon 1301 to air, with a minor contribution of CFC-10 to air (all products). |
| Marine ecotoxicity (MET) | Steel products: direct emissions from waste disposal (slag and sludges) of steel production.<br>Copper products: emissions from the landfilling of sulfidic tailings generated in copper mining.<br>For other materials, the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities (background). | Emissions of zinc to water (all products).<br>Minor contributions of emissions of vanadium, nickel, copper and chromium VI to water. |
| Freshwater ecotoxicity (FET) | Steel products: direct emissions from waste disposal (slag and sludges) of steel production.<br>Copper products: emissions from the landfilling of sulfidic tailings generated in copper mining.<br>Wood door: disposal of steel slags (from the production of steel parts) and wood ash.<br>For other materials, the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities (background). | Emissions of zinc to water (all products).<br>Minor contributions of emissions of vanadium, nickel, copper and chromium VI to water. |
| Marine eutrophication (ME) | Copper products: direct emissions from the disposal of sulfidic tailings generated in copper mining in landfills.<br>For other materials, the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities (background). | Emissions of nitrate to water (all products). |

| Impact category | Most impactful foreground processes | Main elementary flows |
|---|---|---|
| Freshwater eutrophication (FE) | Steel: direct emissions from the landfilling of basic oxygen furnace waste.<br>Copper products: direct emissions from the disposal of sulfidic tailings generated in copper mining in landfills.<br>For other materials (and for the remaining impact of steel products), the impact is caused by emissions from the disposal of spoils of lignite and hard coal mining, related to fuel production activities (background). | Emissions of phosphate to water (all products). |
| Ionizing radiation (IR) | No significant foreground impact shares (except for products that contain datasets modeled as system processes).<br>The impact is mainly caused by air emissions from uranium tailings generated in uranium milling, required for nuclear electricity production (background). | Emission of Radon-222 to air (all products). |

Table 8 – Main foreground unit processes and elementary flows for construction products and the associated impact categories.

| Main foreground processes | Main elementary flows | MRS | LU | WC | FRS | GWP | OFHH | OFTE | FPMF | TA | TET | HCT | HNCT | MET | FET | ME | FE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Consumption of primary raw materials | aluminum, clay, copper, iron, lead, molybdenum, nickel, tin, zinc | ■ | | | | | | | | | | | | | | | |
| Occupation of land for production processes | dumpsite, forest, mineral extraction site, industrial area | | ■ | | | | | | | | | | | | | | |
| Water consumption for production processes | input and output of water flows | | | ■ | | | | | | | | | | | | | |
| Fuel consumption for thermal energy used in production processes | coal, natural gas, crude oil | | | | ■ | | | | | | | | | | | | |
| Direct emissions and fossil fuel combustion | $CO_2$ to air | | | | | ■ | | | | | | | | | | | |
| | $SO_2$ to air | | | | | | | | ■ | ■ | | | | | | | |
| | Cu to air | | | | | | | | | | ■ | | | ■ | | | |
| | Ni to air | | | | | | | | | | ■ | ■ | | | | | |
| | V to air | | | | | | | | | | ■ | | | | | | |
| | Hg to air | | | | | | | | | | ■ | | | | | | |
| | Zn to air | | | | | | | | | | ■ | | ■ | ■ | | | |
| Fossil fuel combustion and blasting | $NO_x$ to air | | | | | | ■ | ■ | ■ | ■ | | | | | | | |
| Blasting, grinding and fossil fuel combustion | PM 2.5 µm to air | | | | | | | | ■ | | | | | | | | |
| Landfilling of sulfidic tailings and waste from steel production (foreground only for copper and steel) | V to water | | | | | | | | | | | | ■ | ■ | ■ | | |
| | Zn to water | | | | | | | | | | | | ■ | ■ | ■ | | |
| | Cr (VI) to water | | | | | | | | | | | ■ | | ■ | ■ | | |
| | Ni to water | | | | | | | | | | | | | ■ | ■ | | |
| | Cu to water | | | | | | | | | | | | | ■ | ■ | | |
| | $PO_4^{3-}$ to water | | | | | | | | | | | | | | | | ■ |
| Landfilling of sulfidic tailings (foreground only for copper) | $NO_3^-$ to water | | | | | | | | | | | | | | | ■ | |

Table 9 – Analysis of the sensitivity of varying the minimum consumption share on classifying a sector as foreground and the corresponding effect on the weighted average foreground impact shares by impact category. The greener the color of the cell, the higher the foreground impact share.

| Impact category | | Minimum consumption share for foreground sectors | | | |
|---|---|---|---|---|---|
| | | 10% | **20%** | 30% | 40% |
| Mineral resource scarcity | MRS | 90 | 88 | 88 | 86 |
| Land use | LU | 95 | 87 | 87 | 87 |
| Fossil resource scarcity | FRS | 84 | 84 | 84 | 84 |
| Global warming potential | GWP | 84 | 81 | 81 | 80 |
| Ozone formation - Human Health | OFHH | 80 | 77 | 77 | 77 |
| Ozone formation - Terrestrial ecossystem | OFTE | 80 | 77 | 77 | 76 |
| Fine particulate matter formation | FPMF | 74 | 68 | 68 | 67 |
| Terrestrial acidification | TA | 73 | 65 | 65 | 64 |
| Water consumption | WC | 71 | 65 | 65 | 64 |
| Terrestrial ecotoxicity | TET | 69 | 55 | 55 | 54 |
| Human carcinogenic toxicity | HCT | 85 | 22 | 22 | 12 |
| Human non-carcinogenic toxicity | HNCT | 90 | 11 | 11 | 10 |
| Stratospheric ozone depletion | SOD | 59 | 11 | 11 | 11 |
| Marine ecotoxicity | MET | 85 | 6 | 6 | 5 |
| Freshwater Ecotoxicity | FET | 86 | 2 | 2 | 1 |
| Marine eutrophication | ME | 86 | 1 | 1 | 1 |
| Freshwater Eutrophication | FE | 97 | 0 | 0 | 0 |
| Ionizing radiation | IR | 96 | 0 | 0 | 0 |