FERNANDA BELIZARIO SILVA

Proposal of life cycle-based environmental performance indicators for decision-making in construction

São Paulo
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Revised version

Thesis presented to the Polytechnic School of the University of São Paulo to obtain the degree of Doctor of Science.

Concentration area: Civil and Urban Construction Engineering

Advisor: Prof. Dr. Vanderley John

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This work is dedicated to Prof. Dr Mércia Barros,

representing all professors who made a difference in my life

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“*It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience.*”
(Albert Einstein, 1933)

“*Everything should be made as simple as possible, but not simpler.*”
(Roger Sessions, 1950, simplifying what Einstein said).

ABSTRACT

BELIZARIO-SILVA, F. Proposal of life cycle-based environmental performance indicators for decision-making in construction. Thesis (Doctor of Science) – Polytechnic School, University of São Paulo, São Paulo, 2022.

Humanity must drastically reduce the impacts caused on the environment, especially global warming, and the construction sector contributes significantly to many environmental impacts. Therefore, improving the environmental performance throughout the life cycle of buildings is essential, especially because there is still much to build. Despite this, most decisions in this sector do not consider environmental criteria. This work aims to propose a set of indicators to measure the environmental performance throughout the life cycle of buildings in a practical and accessible way so that these indicators can be used for decision-making. To this end, the characteristics that can increase the probability of using environmental performance indicators for decision making are identified: indicators must be focused on priority environmental aspects, reliable, comparable, and easy to measure and understand. Life Cycle Assessment (LCA) is the most recommended method for assessing the environmental performance of construction. Therefore, a cradle-to-grave LCA study of a typical Brazilian building is performed to understand the meaning of each impact result. It is concluded that LCA indicators cover too many impact categories, some caused by processes that the construction sector can hardly influence. Also, LCA indicators are difficult to measure and understand. Thus, a simplification of LCA is proposed, resulting in five indicators to assess the environmental performance over the construction life cycle: material demand, energy demand, water demand, land occupation and CO_2 emission. These indicators present low correlation among themselves, assess priority environmental aspects that the construction sector can influence, and can be easily measured and understood. This proposal is expected to increase the use of life-cycle based environmental performance indicators to guide decisions and reduce the environmental impacts caused by the construction sector.

Keywords: Life Cycle Assessment. Environmental Performance. Sustainable Construction. Decision-Making.

RESUMO

BELIZARIO-SILVA, F. Proposta de indicadores de desempenho ambiental baseados em ciclo de vida para tomada de decisão na construção. Tese (Doutorado) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2022.

A humanidade precisa reduzir drasticamente os impactos causados sobre o meio ambiente, em especial o aquecimento global, e o setor da construção contribui de forma significativa para muitos impactos ambientais. Portanto, é fundamental melhorar o desempenho ambiental ao longo do ciclo de vida das edificações, sobretudo porque ainda há muito a construir. Apesar disso, a maior parte das decisões tomadas nesse setor não considera critérios ambientais. Esse trabalho tem como objetivo propor um conjunto de indicadores para medir o desempenho ambiental ao longo do ciclo de vida das construções, de forma prática e acessível, para que estes indicadores possam ser utilizados na tomada de decisão. Para isso, identificaram-se as características que aumentam a probabilidade de indicadores de desempenho ambiental serem adotados pelos agentes do setor: eles devem ser focados em aspectos ambientais prioritários, confiáveis, comparáveis, fáceis de medir e de entender. Como a Avaliação do Ciclo de Vida (ACV) é o método mais indicado para avaliar o desempenho ambiental da construção, realizou-se um estudo de ACV de uma edificação típica brasileira, para compreender o significado de cada um dos resultados de potencial de impacto ambiental. Conclui-se que os indicadores da ACV cobrem muitas categorias de impacto, sendo que algumas dessas categorias são difíceis serem influenciadas pelo setor da construção. Além disso, os indicadores de ACV são difíceis de medir e compreender. Sendo assim, propõe-se uma simplificação da ACV, que resulta em cinco indicadores para avaliar o desempenho ambiental do ciclo de vida da construção: demanda de material, demanda de energia, demanda de água, ocupação do solo e emissão de CO_2. Esses indicadores apresentam baixa correlação entre si, avaliam aspectos ambientais prioritários e que podem ser influenciados pelo setor da construção, podem ser facilmente medidos e compreendidos. Espera-se que essa proposta contribua para aumentar o uso de indicadores de desempenho ambiental baseados em ciclo de vida para orientar decisões e assim reduzir os impactos ambientais causados pelo setor da construção.

Palavras-chave: Avaliação do Ciclo de Vida. Desempenho Ambiental. Construção Sustentável. Tomada de Decisão.

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1 INTRODUCTION

Human activities are causing environmental impacts so high that a new geological area is ongoing – the Anthropocene (CRUTZEN, 2002). The concentration of carbon dioxide (CO_2) in the atmosphere skyrocketed since the industrial revolution, reaching an unprecedented level of more than 400 ppm (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, 2022) and causing an increase of 1,07°C in the global mean temperature above pre-industrial levels, the highest temperature in at least 2000 years (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021b). Human-induced climate change has severe consequences for the environment, such as sea-level rise, ocean acidification, and more frequent and exacerbated extreme weather events, including heatwaves, heavy precipitation, and droughts (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021b), with far-reaching economic and social impacts. Fighting climate change is the greatest and most urgent environmental challenge that society faces today.

This scenario results mainly from the increasing consumption of fossil fuels to produce the energy required by manufacturing processes, transportation, and buildings. The annual mass of materials and fuels used today is comparable to the total amount of biomass produced by nature over one year (KRAUSMANN *et al.*, 2009). In addition to global warming, the extraction and processing of materials cause many other environmental impacts, such as landscape degradation, habitat loss, waste generation, and pollution (OLIVETTI; CULLEN, 2018). Water scarcity is also an environmental concern, as global water use has increased more than twice the population growth rate over the last century, putting increasing pressure on limited available water resources, exacerbated by climate change (UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION; UN-WATER, 2020). Construction is responsible for a significant share of resource consumption and corresponding environmental impacts. The construction and operation of buildings correspond to 35% of the energy consumption and 38% of the energy-related CO_2 emissions globally (UNITED NATIONS ENVIRONMENT PROGRAMME, 2021). Construction consumes at least 50% of all resources extracted from nature, especially bulk minerals such as sand and gravel (MIATTO *et al.*, 2017). Although agriculture determines most water withdrawal at the global level (UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION; UN-WATER, 2020), domestic water use in buildings represents the highest share of water withdrawal in many watersheds near urban areas (AGÊNCIA NACIONAL DE ÁGUAS (BRASIL), 2019). Land occupation by buildings is also increasing due to population growth, increasing urbanization, and declining land-use efficiency in recent years, leading to losses of agricultural land and natural habitat (GÜNERALP *et al.*, 2020).

Engaging the construction value chain is crucial to reduce the environmental impacts caused over buildings' life cycle and to meet sustainable development goals. Building less is not an option, considering that the world population, currently at 7,7 billion people, is expected to grow by more than 3 billion people by 2100, mostly in developing countries (UNITED NATIONS, 2019). Furthermore, it is necessary to provide infrastructure for a large share of the world's population that still lives under unacceptable conditions: 2 billion people still lack safely managed drinking water, 3,6 billion people lack safely managed sanitation, 759 million people lack access to electricity, and more than 1 billion people live in slums (UNITED NATIONS, 2020). The challenge that lies ahead for the construction industry is enormous, as it is necessary to build more while causing less harm to the environment. In other words, it is necessary to decouple construction growth from environmental impacts.

Therefore, environmental criteria must be integrated into decision-making throughout the construction value chain for all kinds of buildings and infrastructure works and not just for a few "green buildings". Moreover, all decisions have the potential to reduce environmental impacts (FAVA, 2019), whether by optimizing building design (ZHU *et al.*, 2019), selecting a material supplier with a lower impact (OLIVEIRA; PACCA; JOHN, 2016; SILVA, *et al.*, 2019), operating a building more efficiently (ZOU *et al.*, 2018), among other examples. Measuring the environmental performance of construction is essential to inform such decisions, which requires appropriate environmental performance indicators. These indicators must be practical to be implemented on a large scale, allowing the development of environmental performance benchmarks. Benchmarks give an understanding of the current situation and support the definition of environmental performance targets (LYDENBERG; ROGERS; WOOD, 2010).

There are methods for producing environmental performance indicators for construction, with Life Cycle Assessment (LCA) being the most recommended (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2016). LCA quantifies all mass and energy flows that enter and leave the processes that occur throughout the life cycle of products and then converts these flows into indicators of potential environmental impacts, which are expressed in relation to a functional unit that describes the product's performance in a quantitative way (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a, b). LCA is a data-intensive method because it requires considering the whole life cycle of products, which is challenging for complex and long-lasting products like buildings. Furthermore, the more impact categories to assess, the more flows must be quantified throughout the product's life cycle. For instance, the latest version of the European standard for issuing LCA-based environmental performance declarations for construction products requires assessing 16 impact categories (DEUTSCHES INSTITUT FÜR NORMUNG, 2020), which in turn requires inventorying thousands of substances (EUROPEAN COMMISSION; JOINT RESEARCH CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2011; FANTKE *et al.*, 2017; GUINÉE *et al.*, 2004; HUIJBREGTS, *et al.*, 2016). As a result of the high complexity, the use of LCA in the construction sector remains limited (OLINZOCK *et al.*, 2015; SAUNDERS *et al.*, 2013), and so does its contribution to improving the environmental performance of construction.

There is a general understanding that LCA must be simplified (WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016), and many studies propose simplification strategies (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020; GRADIN; BJÖRKLUND, 2021; TODD; CURRAN, 1999), including in the construction sector (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). However, most strategies rely on secondary LCA data (HESTER *et al.*, 2018; MALMQVIST *et al.*, 2011; TECCHIO *et al.*, 2019; ZABALZA BRIBIÁN; ARANDA USÓN; SCARPELLINI, 2009) and do not simplify the process of collecting primary inventory data, which is essential to inform decisions. Even studies that propose reducing the number of inventory flows only allow for minor simplification, as they seek to get similar results compared to conventional LCA (LASVAUX *et al.*, 2014; LEWANDOWSKA *et al.*, 2015). Studies about correlations among LCA indicators reveal that more significant simplification can be achieved by focusing on uncorrelated environmental aspects (LASVAUX *et al.*, 2016; MARSH, 2016), but they do not question whether all aspects are relevant for decision-making.

Furthermore, LCA simplification approaches hardly address practical aspects, such as the cost of measuring inventory data (SCHALTEGGER, 1996). Reducing the LCA scope, such as excluding impact categories, is often rejected as it would affect the completeness of the assessment (FREIDBERG, 2015), even if completeness is achieved through the use of secondary data, often unrepresentative, to fill inventory data gaps (REAP *et al.*, 2008a). Consequently, the wide scope established by construction LCA standards is perpetuated, although many impact categories are not part of the environmental agenda of construction (SEIDEL, 2016; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016). Proposals to simplify LCA have not led to a significant increase in its adoption for decision-making.

The life cycle approach is appropriate for measuring the environmental performance of construction. However, a set of life cycle-based indicators that can be calculated using primary data to support daily decision-making is still missing. This research addresses this knowledge gap by combining the characteristics that can increase the adoption of indicators with the environmental priorities of the construction sector. This analysis is complemented with a detailed interpretation of the LCA results of a typical Brazilian building. Based on these elements, a set of life cycle-based environmental performance indicators for construction is proposed. The proposal aims to increase the use of environmental performance indicators for decision-making by construction sector stakeholders.

1.1 Aim of the study

This study aims to **propose a set of environmental performance indicators for construction** that facilitates the collection of primary inventory data and supports decision-making toward improving the environmental performance of construction.

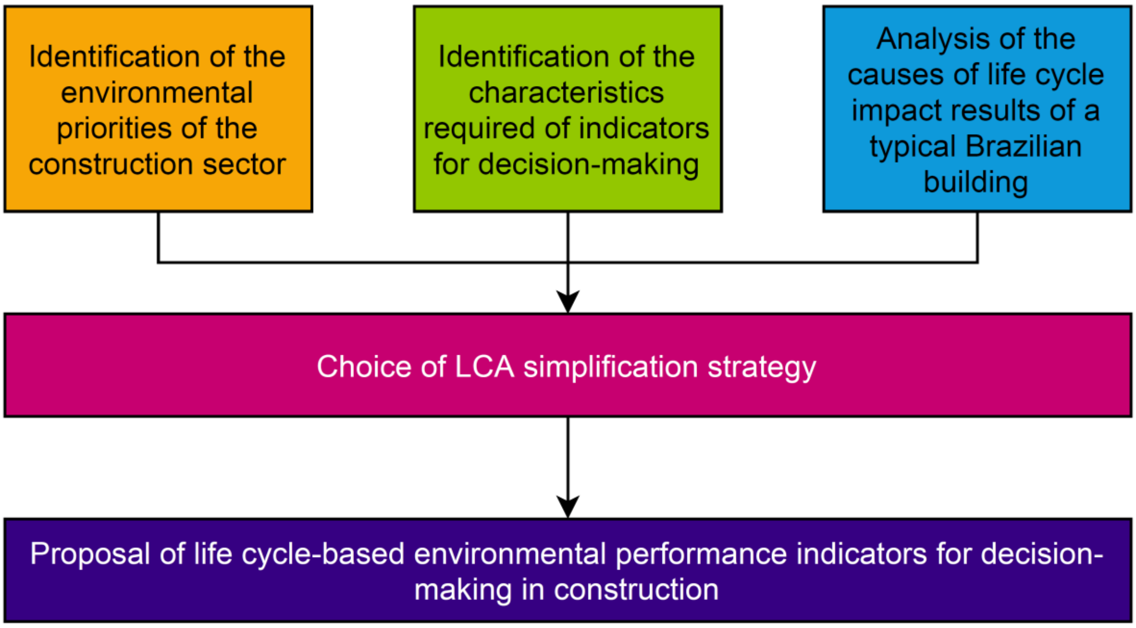
1.2 Method

This study combines findings from the environmental and life cycle management fields with the detailed interpretation of LCA results of a typical Brazilian building. These elements are used to propose a set of indicators for decision-making in construction focused on the sector’s environmental priorities (Figure 1). The study builds on the researcher’s background on LCA applied to construction. The following activities were carried out:

a) literature review to understand the environmental priorities of the construction sector, complemented by a survey among Brazilian construction stakeholders;

b) literature review to identify the characteristics required of environmental performance indicators to increase the probability of their adoption for decision-making;
c) LCA study of a typical Brazilian building and interpretation of the results at the elementary process level to identify which processes and substances are causing each environmental impact required by construction LCA standards;
d) review of LCA simplification strategies and choice of the strategy to be applied in this study;
e) proposal of construction environmental performance indicators, based on a simplification of the LCA method, considering the environmental priorities of the construction sector and the characteristics required of effective indicators for decision-making.

Figure 1 - Overview of the research method.



Source: the author.

1.3 Structure of the thesis

This thesis comprises five chapters, including the introduction (Chapter 01).

Chapter 02 presents the main environmental concerns of the construction sector stakeholders based on a literature review of international references and the findings of a local stakeholder survey. Reducing carbon emissions and resource consumption (including materials, energy, and water) and increasing circularity are the highest environmental priorities of the sector. It also presents the characteristics that can increase the adoption of environmental performance indicators for decision-making: priority, measurability, reliability, comparability, and comprehensibility. It becomes clear that current LCA indicators do not meet these characteristics, thereby confirming that some degree of simplification is required to increase the adoption of life cycle-based environmental performance indicators in construction.

Chapter 03 presents the analysis of the LCA results of a typical Brazilian building. The specific processes and substances causing each of the 16 impact results of the building are identified. Different environmental impacts are caused by the same processes and sometimes even by the same substances, showing that some indicators provide redundant information for decision-making. Moreover, while some impacts are directly associated with construction activities, others are caused by background processes that are much more difficult to influence. The magnitude of the inventory flows causing the impacts is also discussed because it reflects their measurability. This detailed interpretation of LCA results at the elementary process level indicates that simplifications are possible.

Chapter 04 presents a review of LCA simplification strategies and the choice of the simplification approach adopted in this study, namely the exclusion of correlated life cycle impact categories. Starting from the analysis of the LCA results presented in Chapter 03, the proposal of a reduced set of life cycle-based construction environmental performance indicators is developed. The five selected inventory indicators are described: material demand, energy demand, water demand, land occupation, and CO_2 emission. These indicators are coherent with the environmental priorities of the construction sector. A comparison between the proposed set of indicators and LCA is presented, demonstrating that the risk of ignoring relevant environmental aspects (the so-called unintended burden shifting) is low, and this risk is outweighed by the greater likelihood of adopting the proposed environmental performance indicators.

Chapter 05 presents the general conclusions and recommendations for future research.

The references are presented as one final bibliography at the end of the thesis.

2 INCREASING THE USE OF ENVIRONMENTAL PERFORMANCE INDICATORS FOR DECISION-MAKING

Measuring the environmental performance of construction is complex because buildings have many interactions with the environment over their life cycle. Whereas some of these interactions are local, such as the contamination of a water body due to the uncontrolled release of pollutants from a factory producing construction materials, other interactions have global effects, such as greenhouse gases emitted during the operation of buildings. These environmental aspects of construction are of varying complexity and require different indicators to be measured and actions to be controlled. However, measuring all possible environmental aspects of construction is neither possible nor feasible. Thomas Graedel, an early advocate of streamlined LCA approaches to support decision-making, states that "*if no limitations to time, expense, data availability, and analytical approach existed, a comprehensive LCA would provide the ideal advice for improving the environmental performance. In practice, however, these limitations are always present"* (GRAEDEL, 1998).

Furthermore, providing too many indicators for decision-makers can be confusing, especially because most decision-makers are not used to environmental issues (LYYTIMÄKI *et al.*, 2013; SCHALTEGGER, 1996). Therefore, choosing which environmental aspects to address is crucial if environmental performance indicators are to be used in practice (LYDENBERG; ROGERS; WOOD, 2010). It helps reducing the burden of inventory data collection and focusing on the most relevant environmental issues (SCHALTEGGER, 1996).

Some environmental aspects of the construction life cycle have higher priority than others. The clearest example is global warming: all sectors of the economy, including the construction sector, are taking action to achieve net-zero emissions by 2050. However, fighting climate change is not the only environmental challenge of construction. Therefore, this chapter presents an overview of the environmental priorities of the construction sector, based on a literature review complemented by a survey conducted among Brazilian construction stakeholders.

Furthermore, to increase the use of environmental performance indicators for decision-making in construction, these indicators must meet the expectations of decision-makers. Some of these expectations are given by best practices for designing effective environmental performance indicators. Therefore, after presenting the environmental priorities of construction, this chapter presents the main characteristics that can increase the adoption of environmental performance indicators for decision-making.

2.1 Environmental priorities of the construction sector

2.1.1 Global scenario

Many documents allow us to understand the environmental priorities of construction on a global scale. One important reference is the "*Global Status Report for Buildings and Construction*", issued by the Global Alliance for Buildings and Construction and the United Nations Environment Programme (UNITED NATIONS ENVIRONMENT PROGRAMME, 2021). The 2021 version focuses on CO_2 emissions due to the urgency to fight climate change. Since 73% of the sector's CO_2 emissions are associated with energy consumption in buildings, energy efficiency is a relevant concern. According to the report, in 2019, 80 countries had mandatory or voluntary building energy codes. However, as building operation becomes more efficient, the focus is gradually shifting to embodied carbon emissions. According to the report "*Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities*" issued by the Rocky Mountain Institute (RMI), embodied carbon is expected to represent approximately 50% of global building-sector emissions between now and 2050 (JUNGCLAUS *et al.*, 2021).

Therefore, net-zero carbon buildings are a hot topic these days. The World Business Council for Sustainable Development (WBCSD) and the design company Arup have recently released a report entitled "*Net-zero buildings: where do we stand?*" (WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT; ARUP, 2021), which included the following key messages: committing to LCA on all projects, developing consistent and transparent carbon intensity and benchmark data, defining explicit carbon targets, defining the concept of net-zero buildings, and establishing wider collaboration across the value chain. Also, the World Green Building Council has released a "*Net-zero carbon buildings commitment*", which requires that "*by 2030 existing buildings reduce their energy consumption and eliminate emissions from energy and refrigerants removing fossil fuel use as fast as practicable*" and "*new developments and major renovations are built to be highly efficient, powered by renewables, with a maximum reduction in embodied carbon and compensation of all residual upfront emissions*" (WORLD GREEN BUILDING COUNCIL, 2021).

Regarding embodied carbon, the WBCSD has released another report entitled "*Decarbonizing construction: guidance for investors and developers to reduce embodied carbon*" that gives recommendations on reducing greenhouse gas emissions associated with materials production and building construction, including creating a carbon policy, setting targets for projects, prioritizing circularity, optimizing the design, and low-carbon procurement (WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2021a). Similarly, the RMI report gives recommendations to reduce embodied carbon in buildings in the United States, demonstrating that "*midsized commercial building projects can reduce embodied carbon by up to 46% at less than 1% cost premium using materials that are widely available today*" (JUNGCLAUS *et al.*, 2021).

Circularity is another critical topic for construction since this sector consumes more than 50% of natural resources and generates a significant amount of waste. According to the WBCSD report "*The business case for circular buildings: exploring the economic, environmental and social value*" (WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2021b), a circular building "*optimizes the use of resources while minimizing waste throughout its whole life cycle*". By applying the circular economy principles, it is possible to design out waste, increase resource productivity and maintain resource use within planetary boundaries. Circularity is also regarded as a means to fight climate change, as it also reduces the consumption of materials that are intensive in CO_2. The Ellen Macarthur Foundation and Arup have developed a Circular Buildings Toolkit, considering four main strategies: build nothing (reuse existing buildings), build for long-term value (increase space utilization, longevity, adaptability, and disassembly), build efficiently (material efficiency), and build with the right materials (reduce virgin materials, reduce carbon-intensive materials, and design out hazardous and polluting materials) (ELLEN MACARTHUR FOUNDATION; ARUP, 2021).

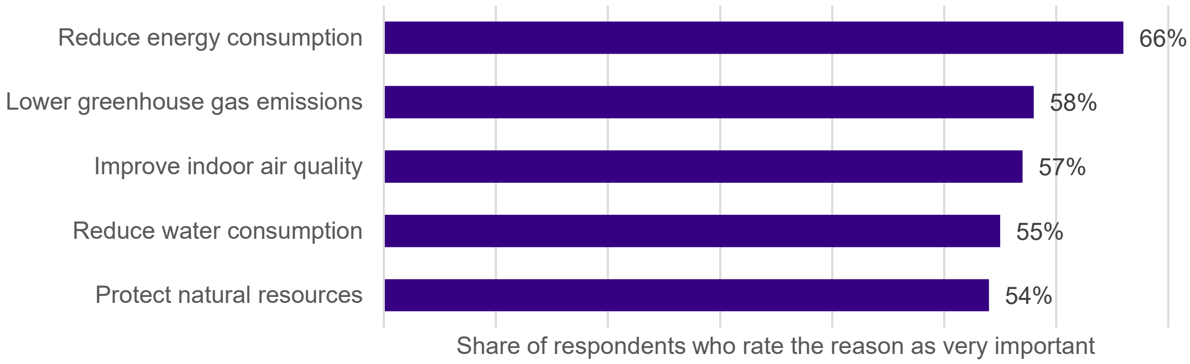
Green building rating systems also offer insight into the environmental priorities of the construction sector. However, they apply to a reduced share of buildings worldwide. The following certification systems are considered: Leadership in Energy and Environmental Design (LEED) (U. S. GREEN BUILDING COUNCIL, 2019), Building Research Establishment's Environmental Assessment Method (BREEAM) (BRE GLOBAL, 2016), *Deutsches Gesellschaft für Nachhaltiges Bauen* (DGNB) (DEUTSCHE GESELLSCHAFT FÜR NACHHALTIGES BAUEN, 2020), *Haute Qualité*

Environementale (HQE) (HQE; CERWAY, 2014), Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (JAPAN SUSTAINABLE BUILDING COUNCIL, 2014), and the Brazilian *Selo Casa Azul*+ (CAIXA, 2020). All systems cover the following environmental aspects: global warming (sometimes presented as carbon emissions or use of fossil fuels), energy, materials, water, waste, outdoor pollution, and indoor air quality. Some environmental aspects are mentioned indirectly: for instance, promoting bicycles and public transportation contributes to reducing energy use and global warming. The use of hazardous or toxic products, biodiversity, and land use are also frequently mentioned. The environmental aspects covered by each system are presented in the Electronic Supplementary Material to this thesis (available at: http://dx.doi.org/10.17632/k4mnt33tyc.2).

In general, energy is the topic with the highest importance in green building rating systems. Reducing carbon emissions also appears often, although only DGNB and CASBEE require reporting life cycle CO_2 emissions. LEED has recently launched a new certificate called “LEED Zero”, which acknowledges zero-carbon, zero-energy, zero-water, or zero-waste buildings during the operational phase (U. S. GREEN BUILDING COUNCIL, 2020). Materials consumption, waste generation, and recycling are also prioritized by all systems. These topics are aligned with the principles of circular economy and other aspects, such as durability, maintainability, and flexibility of spaces. In addition to environmental aspects, green building rating systems cover other topics such as comfort, well-being, accessibility, and social impacts.

The priorities of green building rating systems are aligned with the findings of the World Green Building Trends Report (DODGE CONSTRUCTION NETWORK, 2021). Based on an online survey among construction stakeholders with 1207 respondents from 79 countries, the main reasons for building green include reducing energy consumption, lowering greenhouse gas emissions, improving indoor air quality, reducing water consumption, and protecting natural resources (Figure 2). The main strategies for building green are net-zero/net-positive buildings, controlling embodied carbon, increasing resiliency, passive buildings, prefabrication and modular construction, and design for disassembly and recovery. Note that the last two strategies are connected with circular economy principles.

Figure 2 - Top environmental reasons for building green according to the World Green Building Trends Report.



Source: adapted from DODGE CONSTRUCTION NETWORK (2021).

LCA standards for construction also offer a list of environmental aspects to be covered, with the corresponding indicators. Table 1 presents the environmental indicators required by three construction LCA standards: ISO 21930 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017) and EN 15804 (DEUTSCHES INSTITUT FÜR NORMUNG, 2020), which set the rules for Environmental Product Declarations of construction products, and EN 15978 (DEUTSCHES INSTITUT FÜR NORMUNG, 2012), which applies LCA for assessing the environmental performance of buildings. European standards are included because they are often used outside Europe too. The indicators required by construction LCA standards include more environmental aspects than those covered by green building rating systems. For instance, acidification, eutrophication, photochemical oxidation, freshwater ecotoxicity, and ionizing radiation are not explicitly mentioned by any of the analyzed green building systems or the reviewed reports about sustainable construction.

Table 1 – Environmental indicators required by construction LCA standards.

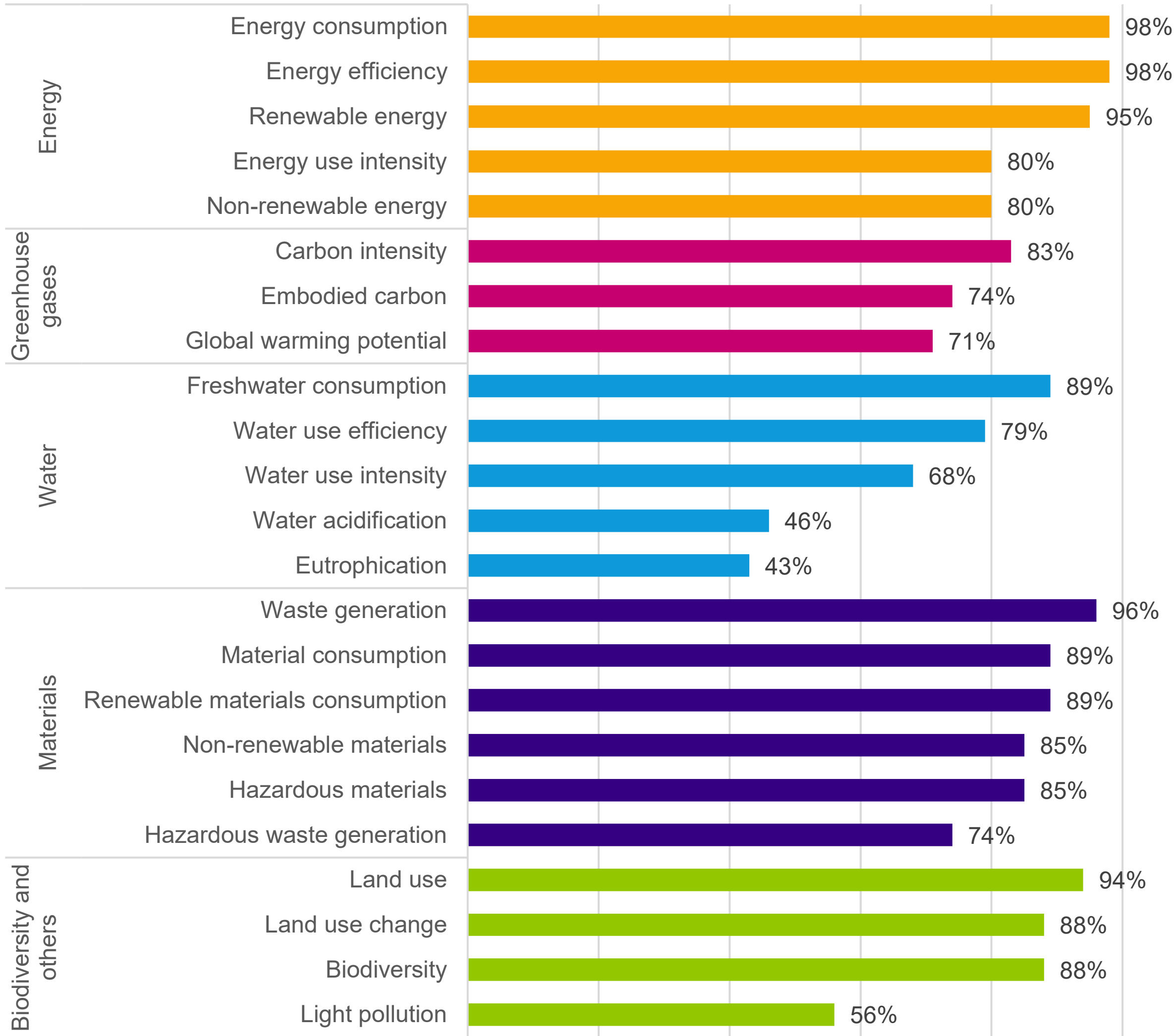
Environmental indicators	ISO 21930	EN 15804	EN 15978
Impact indicators			
Global warming	mandatory	mandatory [b]	mandatory
Ozone depletion	mandatory	mandatory	mandatory
Freshwater eutrophication	mandatory	mandatory	mandatory
Marine eutrophication	-	mandatory	-
Terrestrial eutrophication	-	mandatory	-
Acidification	mandatory	mandatory	mandatory
Photochemical oxidation	mandatory	mandatory	mandatory
Abiotic depletion of minerals	optional	mandatory	mandatory
Abiotic depletion of fossil fuels	-	mandatory	mandatory
Water use	-	mandatory	-
Land use	optional	optional	-
Human carcinogenic toxicity	optional	optional	-
Human non-carcinogenic toxicity	optional	optional	-
Freshwater ecotoxicity	optional	optional	-
Particulate matter emissions	-	optional	-
Ionizing radiation	-	optional	-
Inventory indicators			
Use of primary renewable resources as energy	mandatory	mandatory	mandatory
Use of primary renewable resources as material [a]	mandatory	mandatory	mandatory
Use of primary non-renewable resources as energy	mandatory	mandatory	mandatory
Use of primary non-renewable resources as material [a]	mandatory	mandatory	mandatory
Use of secondary materials	mandatory	mandatory	mandatory
Use of renewable secondary fuels	mandatory	mandatory	mandatory
Use of non-renewable secondary fuels	mandatory	mandatory	mandatory
Use of recovered energy	mandatory	-	-
Use of freshwater	mandatory	mandatory	mandatory
Hazardous waste disposed	mandatory	mandatory	mandatory
Non-hazardous waste disposed	mandatory	mandatory	mandatory
Radioactive waste disposed	mandatory	mandatory	mandatory
Component for reuse	mandatory	mandatory	mandatory
Materials for recycling	mandatory	mandatory	mandatory
Materials for energy recovery	mandatory	mandatory	mandatory
Recovered energy exported	mandatory	mandatory	mandatory

a) Only resources with energy content
b) Disaggregated into fossil, biogenic, land use and land-use change

Source: DEUTSCHES INSTITUT FÜR NORMUNG (2020, 2012); INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (2017).

The WBCSD has conducted a stakeholder survey about life cycle metrics in construction, which shows that the indicators required by construction LCA standards have varying importance (Figure 3) (WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016). Based on the survey results, the WBCSD recommends using the following life cycle metrics to ensure materiality and avoid burden-shifting: energy, greenhouse gas emissions, water, and materials.

Figure 3 - Importance of life cycle metrics according to construction stakeholders.



Source: adapted from WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT (2016).

2.1.2 Local stakeholder consultation

The stakeholder consultation was conducted among professionals of academic and industry associations engaged in sustainable construction initiatives in Brazil. Based on the indicators required by construction LCA standards, they were asked to provide their opinion about the willingness to control a list of environmental indicators. No explanation about the indicators was provided, as the aim was to assess their opinion based on their existing knowledge. They were also asked to provide the number of environmental performance indicators they consider appropriate for daily decision-making.

The survey was held online between July and November 2021, using Microsoft Forms®. A total of 75 responses were obtained. Although this number of responses does not configure a statistically representative sample of the Brazilian construction value chain, it includes the opinion of relevant decision-makers (Table 2). For comparison, the WBCSD survey about life cycle metrics obtained 69 valid responses globally. The survey form is presented in the Electronic Supplementary Material (http://dx.doi.org/10.17632/k4mnt33tyc.2).

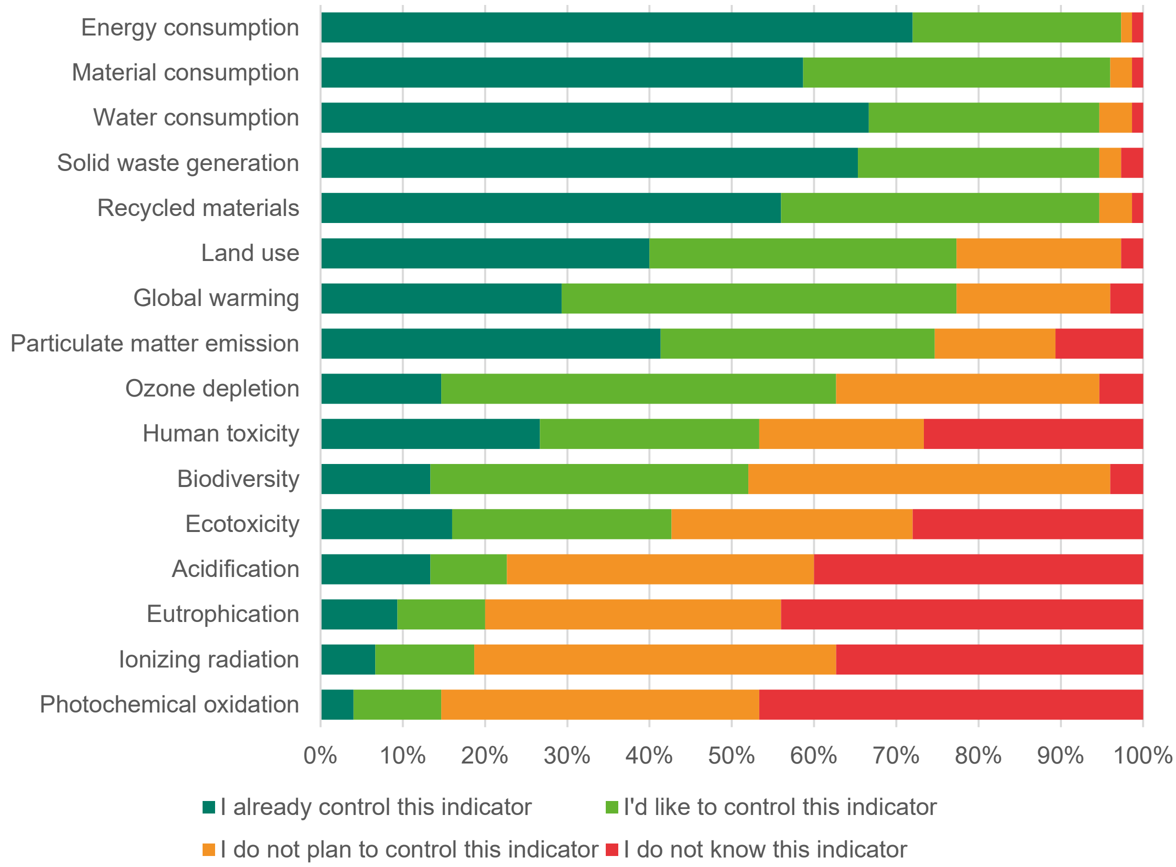
Table 2 – Stakeholder groups that took part in the survey.

Stakeholder group	**Number of respondents**
National Association of Built Environment Technology (ANTAC)	9
Brazilian Association of Building Material Manufacturers (ABRAMAT)	14
Construction Industry Union of the North of Paraná (Sinduscon Paraná Norte)	7
Brazilian Association of Architectural Firms (ASBEA)	2
Brazilian Sustainable Construction Council (CBCS)	2
Advisory Committee for the Construction Environmental Performance Information System Project (SIDAC)	20
Innovation and Digital Construction Hub (HUBIC)	21

Source: the author.

Figure 4 presents the stakeholders' opinions about the willingness to control environmental indicators. Figure 5 shows the profile of the respondents.

Figure 4 - Willingness to control environmental performance indicators indicated by stakeholders from the Brazilian construction sector.



Source: the author.

Figure 5 - Profile of respondents of the stakeholder consultation, with the absolute number of responses per stakeholder group.

Source: the author.

The results of the stakeholder consultation show different priority levels among environmental performance indicators. More than 95% of the respondents already control or wish to control energy consumption, material consumption, water consumption, solid waste generation, and recycled materials. There is a second group of indicators that 75% to 77% of the respondents already control or would like to control: land use, global warming, and particulate matter emission.

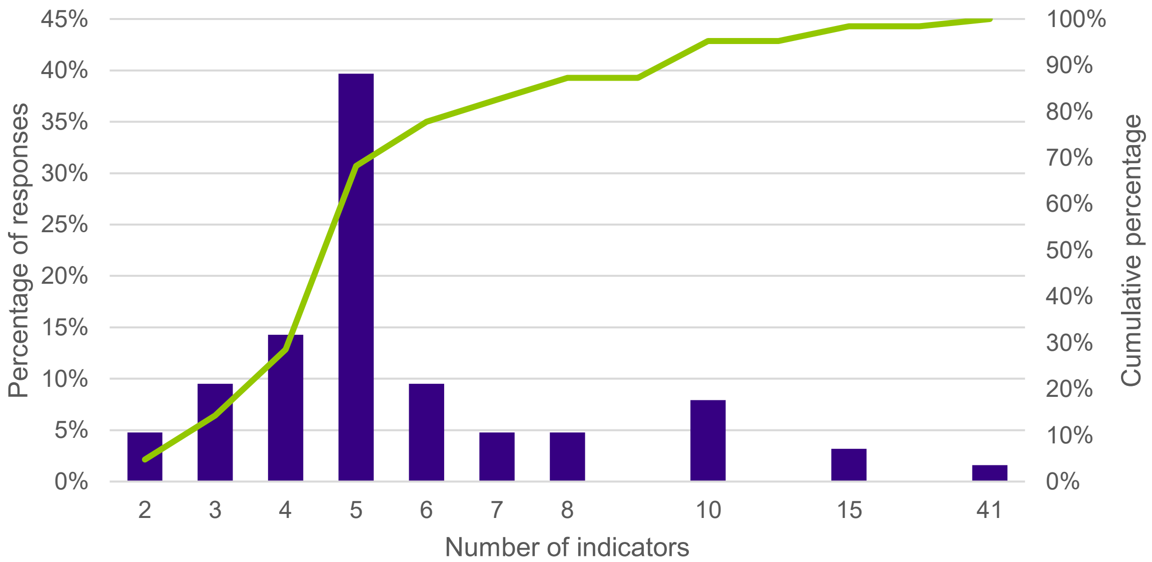
Unlike the global scenario, global warming is not among the top priorities of Brazilian stakeholders. A possible reason for this result is that, as Brazil's greenhouse gas emissions are mainly caused by deforestation and agriculture (POTENZA *et al.*, 2021), construction stakeholders do not consider limiting global warming as their task. Another possibility is that respondents did not understand the term global warming, as in the WBCSD survey, 12% more respondents considered carbon intensity as important than global warming.

A third group of indicators, formed by ozone depletion, human toxicity, biodiversity, and ecotoxicity, are likely to be controlled by 43% to 63% of the respondents. Four indicators show a low level of priority: acidification, eutrophication, ionizing radiation, and photochemical oxidation. Many respondents do not yet know the meaning of the least prioritized indicators, except for biodiversity. Some of these least prioritized indicators are among the mandatory indicators required by construction LCA standards.

Decision-makers are the majority of survey respondents (63%), mainly due to the contribution of construction product manufacturers, who represent 41% of respondents alone. Researchers were not considered decision-makers because they do not take daily decisions that affect the environmental performance of the built environment, even though they might influence these decisions through their research works, teaching, and, in some cases, consulting services.

The number of environmental indicators considered most appropriate by construction stakeholders is 5, as shown in Figure 6, for all stakeholder groups. 70% of respondents answered five or fewer indicators, and only a few preferred more indicators. Considering the priorities shown in Figure 4, the five priority indicators for the construction value chain are energy consumption, materials consumption, water consumption, solid waste generation, and recycled materials.

Figure 6 - Number of environmental indicators for decision support indicated by the Brazilian construction sector stakeholders.



Source: the author.

2.2 Characteristics of indicators for decision-making

The sole existence of environmental performance indicators does not ensure that they will be used for decision-making (LYYTIMÄKI *et al.*, 2013). To be effectively adopted, indicators must meet the expectations of the decision-makers (MOLDAN; DAHL, 2007). Some of these expectations are common and can be considered good practice for designing environmental performance indicators (SILVA; NUZUM; SCHALTEGGER, 2019). The following subsections present the main characteristics required of indicators intended to be used for decision-making based on a literature review covering environmental performance and life cycle management references and guidelines.

2.2.1 Priority

An increasing amount of information faces decision-makers who need to manage demands other than reducing environmental impacts (LYDENBERG; ROGERS; WOOD, 2010). Furthermore, businesses and government agencies have limited resources to address environmental concerns (UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a; WHITEHEAD, 2017). Therefore, it is advisable to keep the total number of environmental performance indicators to a minimum by prioritizing the most relevant environmental aspects (LYDENBERG; ROGERS; WOOD, 2010; MOLDAN; DAHL, 2007; SILVA; NUZUM; SCHALTEGGER, 2019).

Priority is a principle recommended by several sustainability standards and guidelines for designing successful environmental indicators (ASTM INTERNATIONAL, 2018; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2021; ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2011; UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2019; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016). Priority aspects are also known as “material topics” (GLOBAL REPORTING INITIATIVE, 2022) or “hotspots” (UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b). Priority environmental aspects are considered key by stakeholders, can be influenced, and, if omitted or wrong, can result in misleading decisions (GLOBAL REPORTING INITIATIVE, 2022; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a, b).

Identifying key environmental performance indicators should not be based only on scientific assessment but also on stakeholder views on priorities and opportunities for action (SILVA; NUZUM; SCHALTEGGER, 2019). No matter how comprehensive or correct environmental indicators are: if decision-makers do not use them, they are not useful (FULLANA I PALMER *et al.*, 2011; SEIDEL, 2016). On the other hand, stakeholders may not know about environmental impacts and their relationship with construction activities, which is why a scientific basis is needed (ASTM INTERNATIONAL, 2018; BAULER *et al.*, 2007; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b). Experts can also counterbalance the political interests of stakeholders (UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b).

Some guidelines recommend identifying key environmental aspects at the company level (GLOBAL REPORTING INITIATIVE; UNITED NATIONS GLOBAL COMPACT; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2019; PRICEWATERHOUSECOOPERS, 2007). However, some level of agreement is needed at the value chain level; otherwise, the exchange of environmental performance information becomes too difficult, making the environmental performance assessment incomplete (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2019). For example, to account for a building's greenhouse gas (GHG) emissions, the GHG of the materials composing the building must be known, requiring material producers and contractors to report GHG emissions. Therefore, to ensure consistency, it is recommended to identify the key environmental aspects at the value chain level (LYDENBERG; ROGERS; WOOD, 2010; UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2019), as presented in section 2.1.

2.2.2 Measurability

For environmental performance indicators to be used in day-to-day management, they should be based on information that is easy to measure (MOLDAN; DAHL, 2007; UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2019). Measurement should be accessible to small enterprises and independent professionals (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2011; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b), an essential part of the construction value chain. Making environmental performance assessment accessible increases stakeholder engagement (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2019; UNITED NATIONS ENVIRONMENT PROGRAMME, 2008). It also allows directing resources towards improving environmental performance rather than measuring it (GLOBAL REPORTING INITIATIVE; UNITED NATIONS GLOBAL COMPACT; WORLD

BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2019; MOLDAN; DAHL, 2007; SCHALTEGGER, 1996).

Therefore, the feasibility of collecting the data required for calculating environmental performance indicators must be considered, including technical aspects, such as data availability and measurement accuracy, and practical aspects, such as the cost and time of measurement (ASTM INTERNATIONAL, 2018; UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2004). As general guidance, environmental performance indicators should be based as far as possible on existing data (BAULER *et al.*, 2007). Using existing information ensures measurability and allows stakeholders to start managing and improving their environmental performance immediately, with little extra cost and effort (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2011).

Ultimately, environmental performance assessment can be integrated into company design and management systems, such as Building Information Modelling (BIM) (RÖCK *et al.*, 2018) and Enterprise Resource Planning (ERP) (MEINRENKEN *et al.*, 2012). This integration allows data collection to be automated and environmental performance information to be produced in real-time, leading to faster and better decisions (MEINRENKEN *et al.*, 2012). The use of digital systems will increase with the advances in technology and concepts such as Industry 4.0 and the Internet of Things (IoT). Therefore, environmental performance assessment systems should follow the same trend (FERRARI *et al.*, 2021; RAIHANIAN MASHHADI; BEHDAD, 2018).

2.2.3 Reliability

Decision-makers must trust environmental performance indicators to use them (MOLDAN; DAHL, 2007; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a, b). This trust involves trusting the indicators themselves and the process used to generate them, especially when indicators are used to formulate public policies that impact the interests of various stakeholders (BRAS-KLAPWIJK, 1998; SEIDEL, 2016). Therefore, reliability and transparency are essential features of environmental performance indicators.

The reliability of indicators is inherently limited by the reliability of the data used to calculate them. Therefore, data must be of good quality and represent the physical system they refer to (MOLDAN; DAHL, 2007; SCHALTEGGER, 1996; UNITED

NATIONS, 2020). For instance, environmental performance indicators that intend to represent an average performance of a product should be based on data collected from a statistically representative sample; otherwise, they cannot be considered actual averages. Data should also be accurate and up-to-date (ASTM INTERNATIONAL, 2018; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2019; LYYTIMÄKI *et al.*, 2013; UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2004). Accuracy depends on the measurement method for collecting the data; therefore, reliability and measurability are connected.

Indicators must be able to be verified and reproduced (ASTM INTERNATIONAL, 2018; BAULER *et al.*, 2007; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2019; UNITED NATIONS ENVIRONMENT PROGRAMME, 2008). Indicators should be based on well-defined and transparent data collection and calculation methods, preferably using existing scientific guidelines (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2019). Transparency should also guide the disclosure of environmental performance indicators by clearly presenting the data sources, premises, results, and limitations (BRAS-KLAPWIJK, 1998; LYDENBERG; ROGERS; WOOD, 2010; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b). The uncertainty associated with the environmental performance indicators should be declared (HOFSTETTER; METTIER, 2003); otherwise, decision-makers will lack a relevant part of the information (SEIDEL, 2016).

2.2.4 Comparability

Many decisions that can improve the environmental performance of construction consist of comparing alternatives, for instance, building design options, material suppliers, and technological alternatives. Peer comparison, also known as benchmarking, is widely recognized as an important driver for improvement (INTERNATIONAL ENERGY AGENCY, 2019; LYDENBERG; ROGERS; WOOD, 2010; PRICEWATERHOUSECOOPERS, 2007). Monitoring the effect of improvement measures requires comparing environmental performance over time (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2011; ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2011). Therefore, environmental performance indicators should be comparable (ASTM INTERNATIONAL, 2018; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2019).

Herein, the life cycle approach can contribute to increased comparability because it requires considering environmental loads throughout a product's life cycle, thereby reducing the risk of shifting environmental burdens between life cycle stages (FINNVEDEN *et al.*, 2009; ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2011). Also, a life cycle approach prevents sub-optimal solutions that can result from isolated analyses (SCHALTEGGER, 1996; SEIDEL, 2016). For example, choosing a product that causes less impact to be produced but is not durable and requires frequent repairing, or choosing a local product with a low impact for transportation but a high impact during manufacturing.

Comparable indicators should be expressed using a common basis (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2021; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a). One example is the "functional unit" concept of LCA, defined as the "quantified performance of a product system to be used as a reference unit" (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). If the functional unit is defined appropriately, it allows comparing alternatives of equivalent performance. Note that the definition of a functional unit requires considering the whole life cycle of products, which can be challenging for complex, multifunctional, and long-lasting products such as buildings.

If indicators allow the development of benchmarks, benchmarks, in turn, add context to indicators (MOLDAN; DAHL, 2007). Benchmarks are vital for environmental performance indicators because many construction professionals and researchers are unfamiliar with those numbers. Benchmarks can provide a range of values that can be reasonably expected based on current technology (SCHLEGL *et al.*, 2019; TRIGAUX; ALLACKER; DEBACKER, 2021; UNITED NATIONS ENVIRONMENT PROGRAMME, 2008). However, developing benchmarks requires more than comparable indicators: it also requires a broad data collection from the industry to represent the expected variation of environmental performance among possible options (LYDENBERG; ROGERS; WOOD, 2010; TRIGAUX; ALLACKER; DEBACKER, 2021). Increasing data collection, in turn, requires data to be collected in a practical way.

2.2.5 Comprehensibility

Decision-makers with many different profiles must understand environmental performance indicators, from production workers to strategic managers (ASTM INTERNATIONAL, 2018; FAVA, 2019; SCHALTEGGER, 1996). More importantly, decision-makers must be able to understand how they can improve these indicators. Therefore, environmental performance indicators must be easily comprehended by stakeholders with reasonable knowledge about the environmental aspects of construction (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2004; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016). Focusing on the environmental aspects prioritized by these stakeholders helps to keep indicators comprehensible by considering their background. Also, it avoids confusing decision-makers with excessive information (LYDENBERG; ROGERS; WOOD, 2010; PRICEWATERHOUSECOOPERS, 2007).

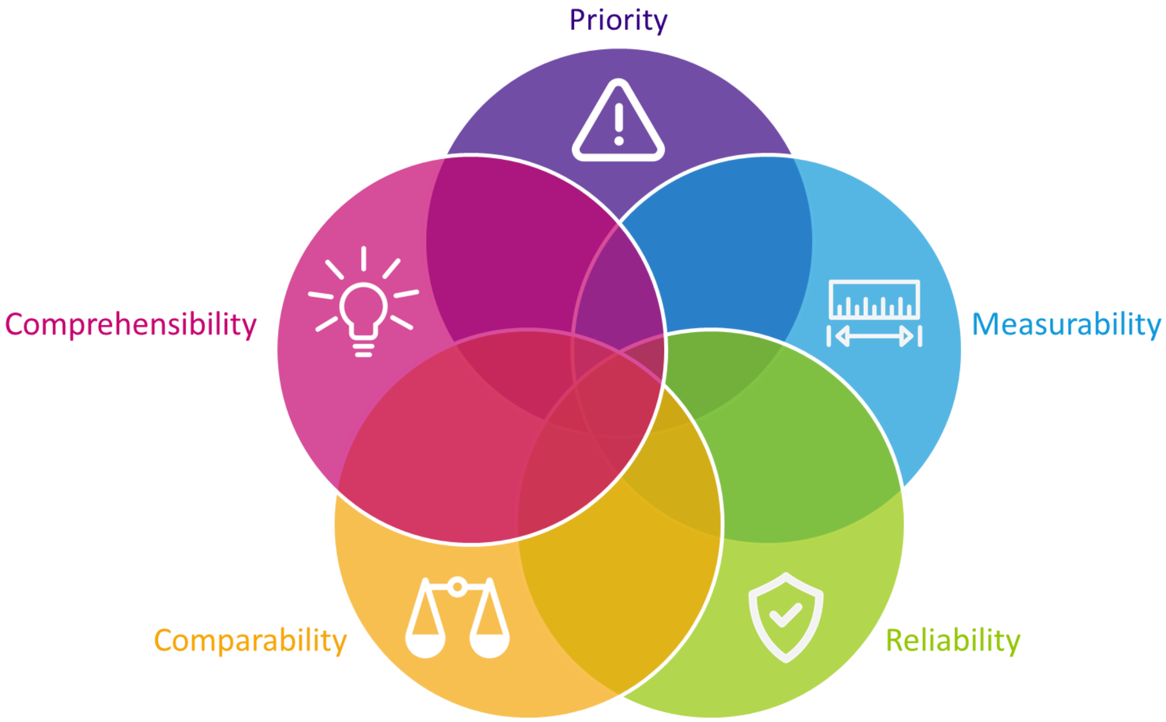
Environmental performance indicators should be clear and concise (UNITED NATIONS ENVIRONMENT PROGRAMME, 2017a). Technical terms, acronyms, jargon, and other content likely to be unfamiliar to the intended audience should be avoided (SEIDEL, 2016). The level of detail of the indicators should be adjusted to the needs of stakeholders: while the general public may prefer simple indicators, managers and policymakers might need more granular information to identify opportunities for action (MOLDAN; DAHL, 2007; UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b).

The format and language used to present indicators are also important. A business-to-consumer (B2C) communication might require a different, more user-friendly format than a business-to-business (B2B) communication (UNITED NATIONS ENVIRONMENT PROGRAMME, 2008). Graphical representations and dashboards may help users interpret indicators (HOLLBERG *et al.*, 2021) and visualize hotspots (UNITED NATIONS ENVIRONMENT PROGRAMME, 2017b). Graphical comparison to benchmarks also enhances the interpretation of environmental performance indicators (UNITED NATIONS ENVIRONMENT PROGRAMME, 2008).

One particular challenge is the communication of the uncertainty associated with environmental performance indicators. There is no single guidance on communicating uncertainty to stakeholders, especially considering the audience's wide range of scientific and mathematical expertise (SPIEGELHALTER; PEARSON; SHORT, 2011). Numerical information accurately conveys uncertainty but may not be understood by the general public (INSTITUTE OF MEDICINE, 2013). Graphic presentations may be more appealing, but choosing the right graphic can be tricky (INSTITUTE OF MEDICINE, 2013; LLOYD; RIES, 2008; SPIEGELHALTER; PEARSON; SHORT, 2011). Regardless of the format, it is recommended to focus the communication of uncertainty on those aspects that can influence decisions (FISCHHOFF; DAVIS, 2014).

Figure 7 synthesizes the characteristics required for environmental performance indicators to support decisions.

Figure 7 - Required characteristics of environmental performance indicators for decision-making



Source: the author.

2.3 Conclusion

This chapter presented the most important environmental aspects of the construction industry and the characteristics required of environmental performance indicators designed to support decisions. The objective is to establish the foundations for proposing a set of environmental performance indicators that can be effectively used for decision-making in the construction sector.

At the global level, construction's most important environmental concern is reducing greenhouse gas emissions over the life cycle of buildings due to the urgency to fight climate change. Associated with that, increasing energy efficiency and reducing embodied carbon are frequently mentioned by stakeholders as key sustainability strategies. Increasing circularity is also a priority, which requires reducing the consumption of virgin materials and reducing waste generation. Reducing water consumption, improving indoor air quality, avoiding the use of hazardous substances, and safeguarding biodiversity are other important environmental issues for construction.

The survey results among Brazilian stakeholders show similar environmental concerns, namely energy, water, materials, and waste. Global warming has received a lower priority level compared to international surveys. Most respondents consider the ideal number of five environmental performance indicators to support daily decisions. The results are similar to the WBCSD survey's findings about using life cycle metrics in construction, which recommends using the following four indicators: energy, greenhouse gas emissions, water, and materials. This number of indicators is much lower than the number required by construction LCA standards, which varies between 21 and 25 mandatory indicators, considering both inventory and impact indicators.

Best practices for designing effective indicators to support decision-making recommends focusing on priority environmental aspects. Priority aspects are relevant aspects that may be targeted for improvement actions, potentially leading to wrong decisions if omitted. Indicators should also be easy to measure, using existing information as far as possible. They must also be reliable, which requires well-defined and transparent methods for data collection and indicators' calculation. Indicators must also be comparable, as most decisions involve comparing alternatives. Finally, indicators should be comprehensible to decision-makers, including non-experts in environmental performance assessment.

3 ENVIRONMENTAL IMPACTS OVER THE CONSTRUCTION LIFE CYCLE

The previous chapter has shown the characteristics required of environmental performance indicators for decision-making in the construction sector. One of the requirements is to prioritize key environmental performance indicators. The results of the stakeholder consultation reveal the most significant aspects from their perspective. However, it is also necessary to assess the relevance of environmental aspects from a scientific viewpoint.

LCA is the method indicated by international standards to assess the environmental performance of construction (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2011, 2017, 2016). LCA quantifies all materials and energy flows that enter and leave the processes required for producing a product and then converts these flows into indicators that express the potential environmental impacts caused by them. These indicators are expressed relative to a functional unit, which quantitatively describes the product’s performance (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a, b). Construction LCA standards indicate the list of environmental impact categories to be assessed (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017). Therefore, LCA is used here to analyze the environmental impacts of the construction life cycle.

An LCA study of a typical social housing project in Brazil is performed, covering from the cradle to the grave, i.e., from extracting raw materials to demolishing the house. A design service life of 50 years is considered. LCA results are analyzed to understand the meaning of each impact result by identifying the specific processes and elementary flows causing those impacts. Also, it is analyzed whether these processes can be influenced or acted upon by construction stakeholders and what it means to measure the elementary flows required to calculate LCA indicators.

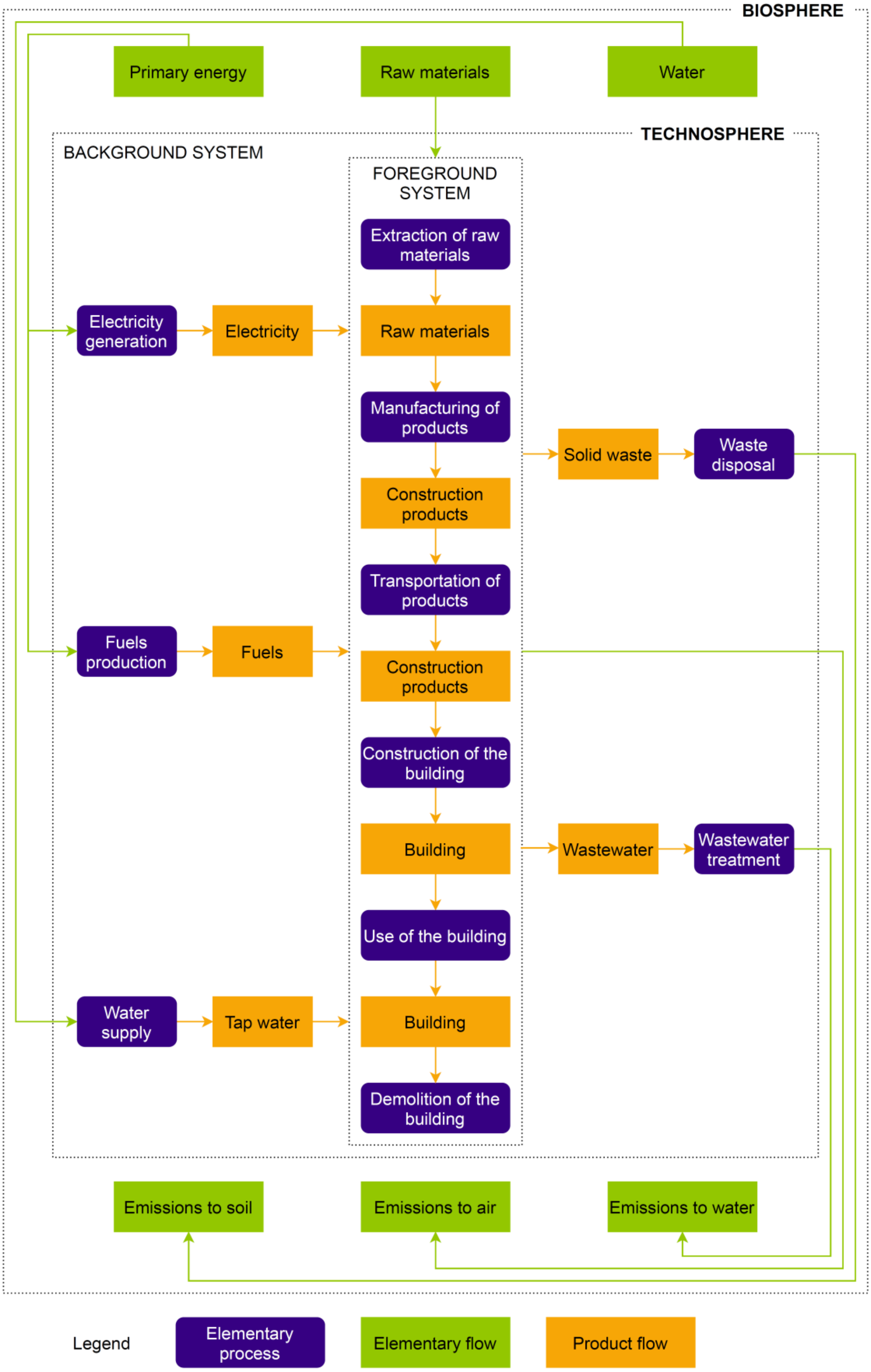
3.1 Fundamentals of LCA

LCA is the compilation and evaluation of a product system's input, output, and potential environmental impacts throughout its life cycle (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). The product system is a set of elementary processes, with elementary and product flows, performing one or more functions, which describes a product’s life cycle. Elementary flows are flows from or to nature, such as sand extracted from a quarry or the emission of CO_2. Product flows are originated at or destined to other product systems, such as the consumption of concrete or the production of steel (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). The system boundary defines which processes and flows belong to the product system. Figure 8 illustrates the product system of a building, considering the cradle-to-grave system boundary, i.e., from the extraction of raw materials until the building's end of life.

The functional unit expresses the quantified performance of the product system (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). For a building, the functional unit can be one m^2.year of building, meeting the minimum performance requirements for residential buildings for a service life of 50 years. The reference flow measures the output of a product system required to perform the function expressed by the functional unit (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). For example, a concrete building requires a particular volume of concrete, whereas a wooden building requires a different volume of wood for the same functional unit of 1 m^2.year. Note that the definition of the functional unit is critical to ensure comparability among the alternatives.

The definition of the product system and the corresponding functional unit depends on the goal and scope of the LCA study. For example, suppose the goal is to compare a concrete and a wooden building. In that case, the LCA scope should include the building's envelope and all life cycle stages. On the other hand, if the goal is to compare different concrete suppliers of the same type of concrete type, a cradle-to-gate LCA study is sufficient. The choice of the environmental impact categories also influences the definition of the product system. For instance, if the scope of the study focuses only on global warming potential, the only airborne emissions that must be included in the product system are greenhouse gases. On the other hand, more elementary flows must be considered if the scope includes other impact categories, meaning that more data must be collected.

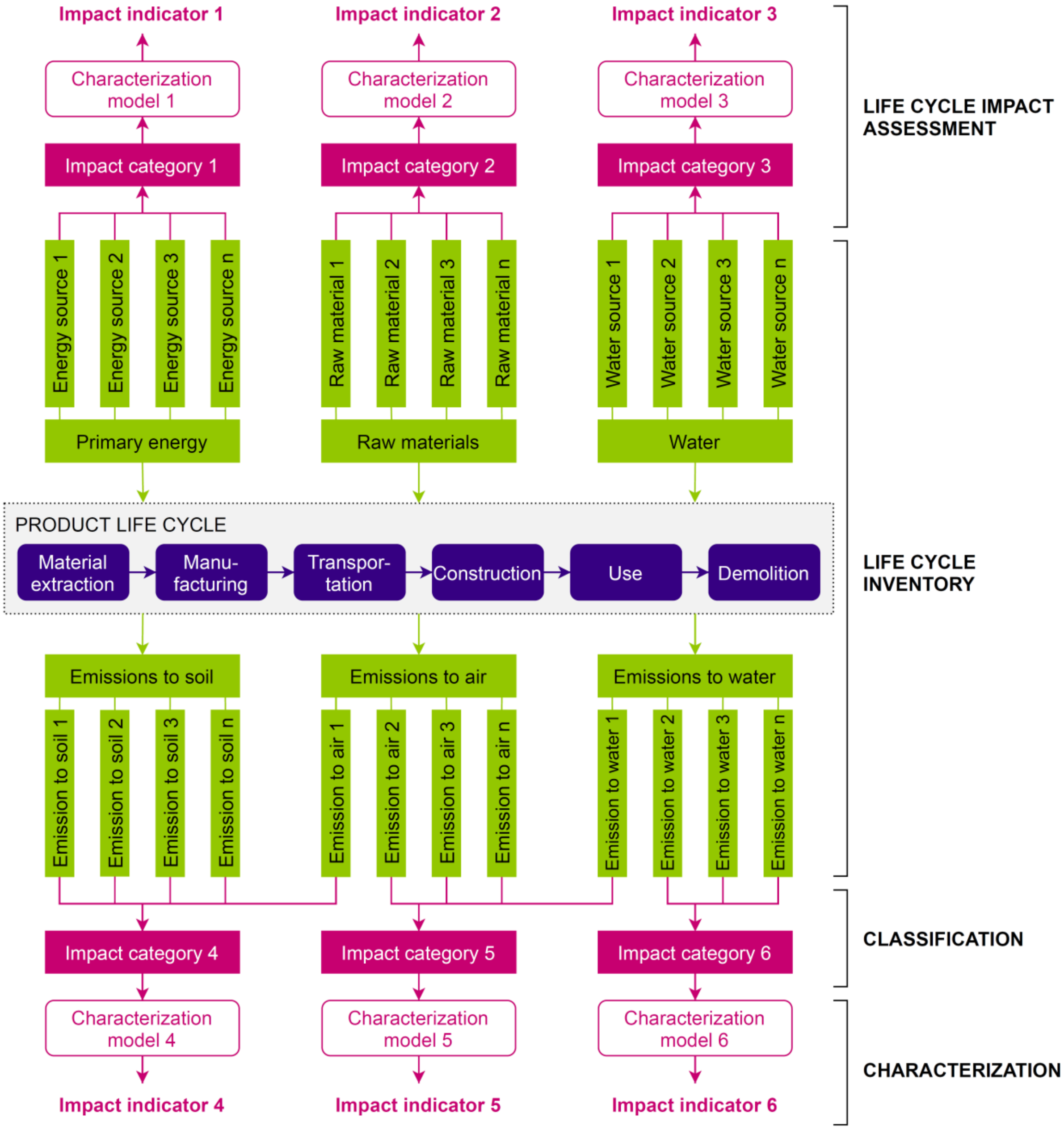
Figure 8 - Cradle-to-grave product system of a building composed of elementary processes, elementary flows, and product flows. Elementary processes might belong to the foreground (main) or background systems.



Source: the author.

All inventory flows of the product system must be quantified for one functional unit of the product. This quantification is called life cycle inventory (LCI). In the case of multifunctional processes, i.e., processes that produce more than one product, flows must be allocated to the different products using allocation factors. Elementary flows are then correlated with the environmental impact categories included in the LCA scope, a step called classification. For instance, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are greenhouse gases and, therefore, they are classified to the global warming potential indicator. Finally, impact results are calculated by multiplying the classified inventory flows by corresponding characterization factors according to predefined cause-effect models (characterization models). For example, global warming potential indicator with 100 years timeframe (GWP-100), expressed in kg CO_2 equivalent/functional unit, has the following characterization factors: 1 for CO_2, 28 for CH_4 and 265 for N_2O, according to the characterization model of the Intergovernmental Panel on Climate Change (IPCC) (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2014). This last stage of LCA is called life cycle impact assessment (LCIA) (Figure 9).

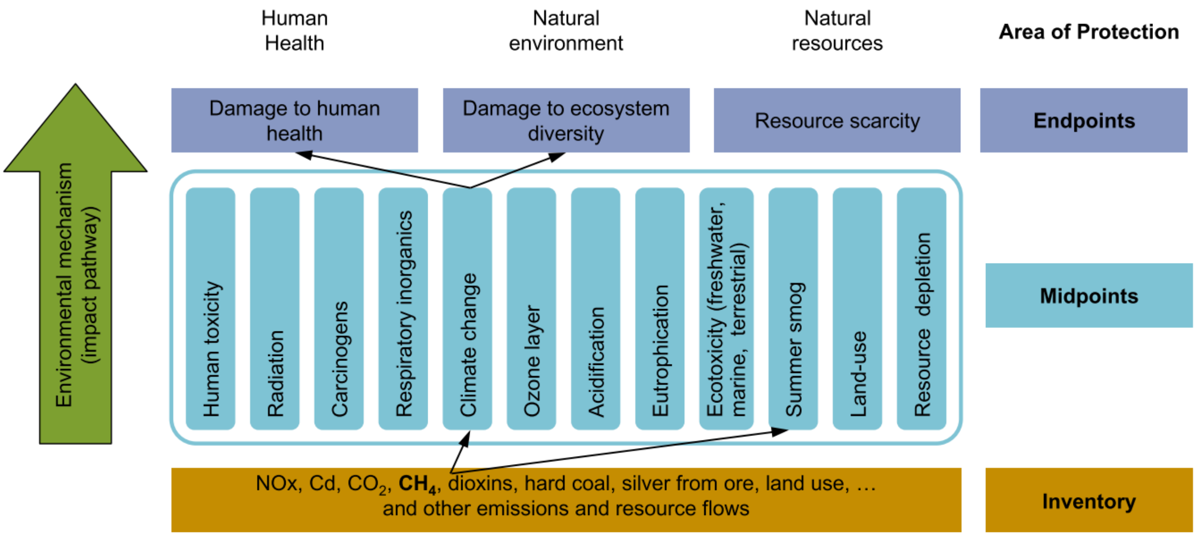
Figure 9 - Schematic representation of the LCIA steps, including the compilation of the cradle-to-grave LCI, the classification of elementary flows into impact categories, and the application of characterization models to calculate the potential impact indicators.



Source: the author.

There are two types of life cycle impact indicators: midpoint and endpoint (Figure 10). Midpoint impact indicators represent environmental impacts at an intermediate stage in the cause-effect chain. For example, the global warming potential quantifies the radiative forcing caused by the emission of greenhouse gases to the atmosphere relative to the radiative forcing of CO_2. Endpoint indicators represent the effect of impacts on the environment, considering the following areas of protection: human health, natural environment, and natural resources. Global warming (or climate change) causes damage to human health and the natural environment. Endpoint indicators are fewer than midpoint indicators, for which more than a dozen impact categories exist; however, they are more uncertain than midpoint indicators (EUROPEAN COMMISSION; JOINT RESEARCH CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2010).

Figure 10 - LCIA from life cycle inventory to category midpoints and endpoints.



Source: EUROPEAN COMMISSION; JOINT RESEARCH CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY (2010).

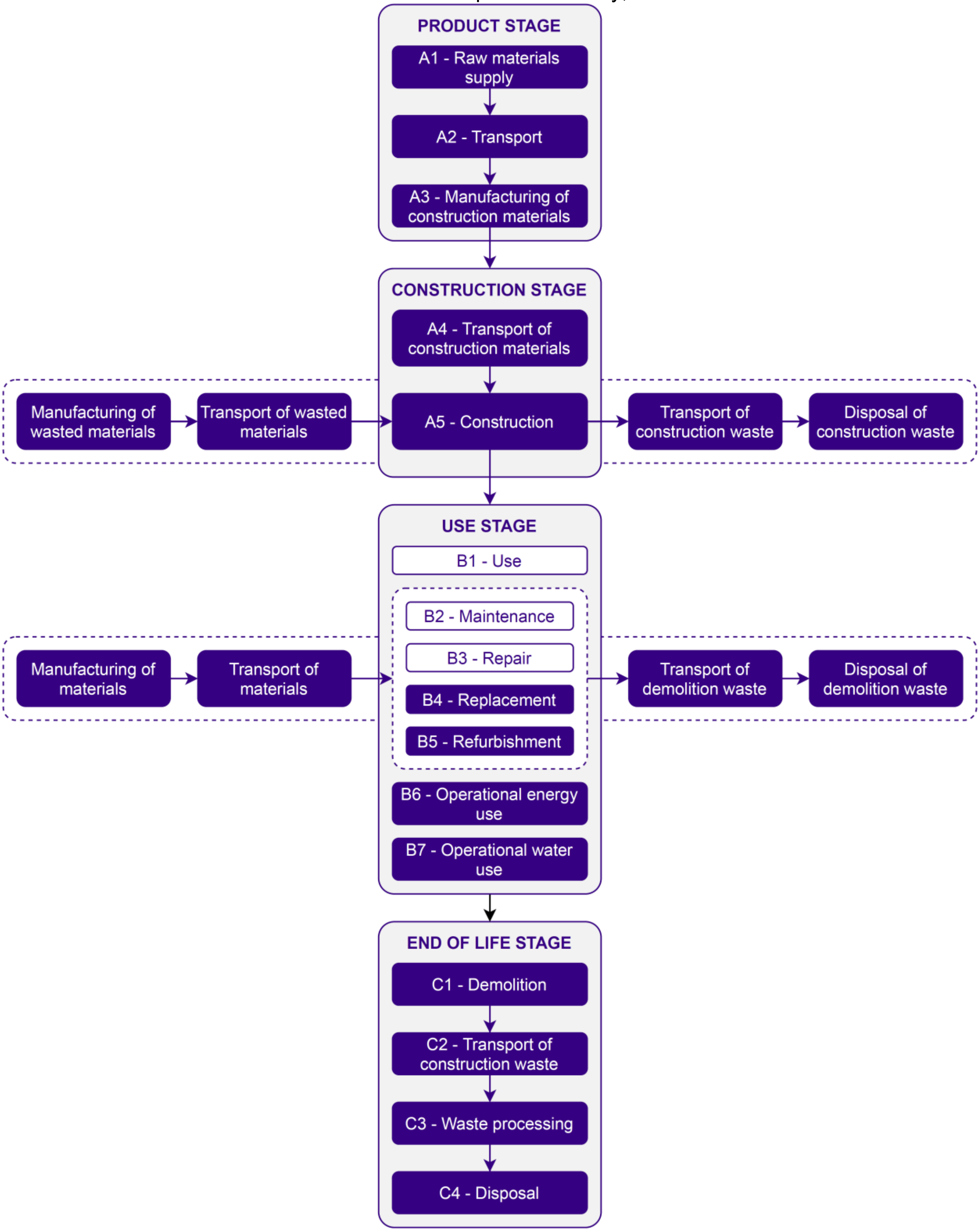
After calculating the life cycle impact results, it is possible to normalize the indicators relative to a reference, e.g., the impact results caused by an average inhabitant of a particular region over a year. The normalization gives an idea about the relative magnitude of the different environmental impact indicators by eliminating different units. Finally, these normalized impact results can be grouped and weighed to calculate a single impact score. However, normalization, grouping, and weighing require subjective judgment. Therefore, they are optional elements of an LCA, which should be avoided in comparative LCA studies disclosed to the public (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a).

3.2 Method

3.2.1 Goal and scope of the LCA

The goal of the LCA is to analyze the environmental impacts associated with the life cycle of a typical Brazilian building. The analysis considers the environmental impact categories assessed by current construction LCA standards, particularly the new version of EN 15804 (DEUTSCHES INSTITUT FÜR NORMUNG, 2020). The system boundary covers the whole life cycle of the building, from the extraction of raw materials to the disposal of the demolition waste after the building's end-of-life[1]. Figure 11 shows the information modules included in the LCA scope.

Figure 11 - Building's life cycle stages according to the nomenclature established by EN 15978. Filled information modules are included in the LCA scope of this study, and the unfilled ones are excluded.



Source: the author.

[1] This LCA study goes beyond the cradle-to-gate LCA developed by the author and colleagues and published in the International Journal of Life Cycle Assessment (SILVA *et al.*, 2020).

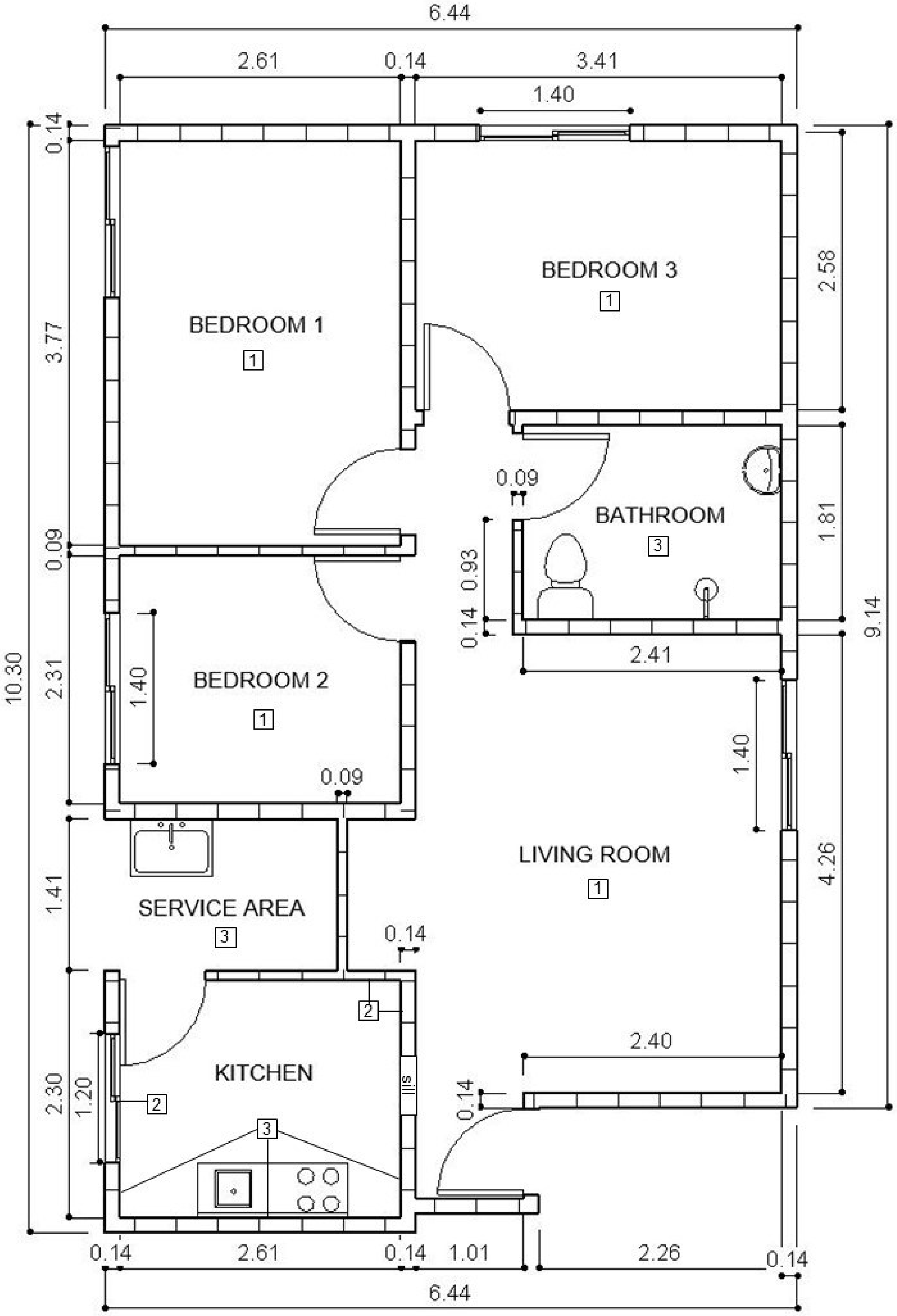
All house materials were included in the scope of the product stage, meaning that no cut-off was applied in advance. The construction stage considers materials’ wastage, including the production, transport, and disposal of the wasted materials and water consumption for materials’ preparation on-site (e.g., mortar). Energy use at the construction site was not accounted for because it was considered negligible compared to the energy consumed during the rest of the house's life cycle. Direct emissions of particulate matter (dust) in the construction site were not considered due to a lack of data and the difficulty of collecting primary data as required in LCA (which requires estimating the total amount of particulate matter in kg per functional unit).

The use phase considers the operational energy use, including lighting, ventilation/air-conditioning, and hot water production. Domestic appliances were not considered following the recommendation of EN 15978 (DEUTSCHES INSTITUT FÜR NORMUNG, 2012). Operational water use and the corresponding wastewater generation were considered. The use phase also includes replacing materials over the house's life cycle because of the expiration of their service life or renewal (e.g., replacing ceramic tiles). The production and transportation of the replaced materials and the disposal of the demolished ones were also considered. The end-of-life stage considers the demolition of the whole building, the transportation of the demolition waste to the sorting and disposal facilities, and their final disposal.

3.2.2 Description of the analyzed building

The analyzed building is a one-story detached house belonging to a social housing program in São Paulo (Brazil), with a net floor area of 58,3 m² (Figure 12 and Figure 13). Table 3 presents the specification of the house. This house is considered representative of typical construction in Brazil since its mass composition agrees with the national bill of construction materials (Table 4). The choice of using a typical Brazilian building was due to the level of detail of the life cycle inventories required for the following steps of the analysis.

Figure 12 - Floor plan of the reference house and principal dimensions. The numbers in squares indicate the wall coverings: 1) 8 mm-thick rendering mortar; 2) 15 mm-thick rendering mortar; 3) ceramic tiles over 15 mm-thick rendering mortar.



Source: *Companhia de Desenvolvimento Habitacional e Urbano do Estado de São Paulo (CDHU).*

Figure 13 - Picture of the house adopted as a reference for this study.

Source: CDHU.

Table 3 - Specifications of the reference house.

Construction element	Specification
Foundation	Slab-on-grade: 10 cm-thick reinforced concrete slab over a 4-cm thick gravel bed
Structure	Structural masonry walls with 14 cm-thick ceramic blocks Beam-and-block slab: 7,5 cm-thick prefabricated concrete beams and ceramic blocks with 4,5 cm-thick concrete topping
Roof	Ceramic roof tiles over a wooden structure made of untreated native wood
Coverings	Walls: cement-based mortar rendering, 8 mm-thick (bedrooms and living room), 1,5 cm-thick (bathroom, service area and kitchen), and 2,0 cm-thick (external walls)
Finishing	Walls: acrylic paint, ceramic tiles in the kitchen and the bathroom Ceiling: acrylic painting over the slab Floor: ceramic tiles
Coldwater supply	PVC pipes and polyethene water reservoir
Hot water supply	Copper pipes
Gas supply	Copper pipes
Electrical installation	Electric cables made of copper with plastic insulation Copper grounding bar (copper wire)
Doors	Internal wooden doors, external aluminium doors
Windows	Aluminium profile frame with 4 mm-thick glass

Source: the author.

Table 4 – Mass composition of the reference house and mass of construction materials consumed in Brazil. Detailed information is available in the Electronic Supplementary Material.

	House		Brazil	
Material	**Mass (t)**	**Mass (%)**	**Mass (t) [a]**	**Mass (%)**
Sand and gravel	49,9	60	306.722.000 [b]	54
Clay	23,4	28	148.195.000 [c]	26
Cement	7,74	9,2	58.160.313 [d]	10
Wood	1,17	1,4	33.827.220 [e]	6,0
Steel	0,596	0,71	9.480.000 [f]	1,7
Lime	0,288	0,34	3.237.000 [g]	0,57
Other chemicals	0,173	0,21	no data	-
PVC	0,140	0,17	744.100 [h]	0,13
Paint	0,135	0,16	1.279.000 [i]	0,23
Glass	0,079	0,095	1.452.032 [j]	0,26
Aluminium	0,074	0,088	196.350 [k]	0,035
Ornamental stone	0,026	0,031	3.038.000 [l]	0,54
Copper	0,016	0,019	113.130 [m]	0,020
Other thermoplastics	0,010	0,012	920.000 [n]	0,16
Total	**83,7**	**100**	**567.364.145**	**100**

a) Construction sector only
b) COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO (2018); SCRIVENER; JOHN; GARTNER (2018)
c) BRASIL (2017a, 2009)
d) SINDICATO NACIONAL DA INDÚSTRIA DO CIMENTO (2017)
e) ASSOCIAÇÃO CATARINENSE DE EMPRESAS FLORESTAIS (2016); FOOD AND AGRICULTURE ORGANIZATION (2017)
f) BRASIL (2017b); INSTITUTO AÇO BRASIL (2018); WORLD STEEL ASSOCIATION (2016)
g) BRASIL (2018b); UNITED STATES GEOLOGICAL SERVICE (2016)
h) ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO PLÁSTICO (2016); INSTITUTO BRASILEIRO DO PVC (2018)
i) ASSOCIAÇÃO BRASILEIRA DOS FABRICANTES DE TINTAS (2022)
j) ZAMPELLI (2017)
k) ASSOCIAÇÃO BRASILEIRA DO ALUMÍNIO (2017); BRASIL (2017b)
l) ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DE ROCHAS ORNAMENTAIS (2022)
m) ASSOCIAÇÃO BRASILEIRA DO COBRE (2017); BRASIL (2017b)
n) ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO PLÁSTICO (2016)

Source: the author, based on the Electronic Supplementary Material of SILVA *et al.* (2020).

3.2.3 Life cycle inventory

The ecoinvent database was chosen as the data source for the life cycle inventories because it provides data as elementary processes (“unit processes”) or disaggregated. This data structure allows understanding the chain of interlinked processes within the product system and identifying the specific processes causing the environmental impacts. Moreover, as ecoinvent is designed to match any LCIA method, its datasets cover an extensive list of elementary flows. Such detailed information is not available in Brazil, which explains why ecoinvent was used here despite its unrepresentativeness, which is a limitation of this study. The only ecoinvent dataset that refers specifically to Brazil is the electricity dataset that considers the national electricity mix. All other datasets (including upstream electricity generation datasets) are based on foreign, predominantly European data.

Version 2 of ecoinvent was used instead of the updated version 3 because the latter is structured in terms of global market activities, diluting individual processes' contribution in different locations, making the analysis at the elementary process level extremely difficult. Furthermore, most datasets available in version 3 are similar or identical to those in version 2 – only 8 of the 46 datasets used to model the cradle-to-grave life cycle inventory of the house have had their elementary processes individually updated. However, all electricity datasets were updated in version 3. Since electricity is used in almost every elementary process, different results can be expected if updated information is used. A sensitivity analysis is carried out to assess this difference, presented in Appendix A.

Datasets for representing the materials used in the house were chosen based on the house design documents and ecoinvent documentation (CLASSEN *et al.*, 2009; KELLENBERGER *et al.*, 2007; WERNER *et al.*, 2007). Average transportation distances from factories to the construction site were estimated using Google Maps®, considering that the building is in São Paulo city. The same procedure was adopted to estimate the average distance from the construction site to waste sorting facilities and inert landfills. Road transportation was considered for all materials because it is the dominant transport mode, with a EURO3-class lorry corresponding to the highest share of Brazil's circulating fleet (BRASIL, 2014).

Materials wastage rates during construction were based on Brazilian construction bidding estimates (PINI, 2008). The values are consistent with measurements carried out on Brazilian construction sites (FORMOSO *et al.*, 2002). The production, transport, and disposal of the wasted materials were accounted for in the construction stage. This stage also considered water consumption for preparing mortars, considering a water content of 20% of the dry mass. Electricity use for construction equipment and other water uses (e.g., cleaning) was not considered because they are negligible compared to the other life cycle stages.

The operational energy use was based on the national average for electricity consumption and the share of electricity consumed for lighting, air conditioning, and hot water production (EMPRESA DE PESQUISA ENERGÉTICA (BRASIL), 2020a, b). Natural gas consumption was accounted for based on the total national consumption of households in 2019 (EMPRESA DE PESQUISA ENERGÉTICA (BRASIL), 2020b) divided by the estimated Brazilian population (211 million inhabitants). 40% of the residential natural gas consumption and 10% of the national LPG consumption go for hot water production, whereas the remaining share is used for cooking (Maia, 2021, personal information)[2]. However, because no LPG combustion dataset was available in ecoinvent, all gas consumption was converted to natural gas. Water consumption was estimated at 116 L/(capita.day) (GUIMARÃES, 2020), and the same value was considered for wastewater generation. An average occupation of 2,9 persons/house was considered based on national statistics (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2019). The period of use of the building is 50 years, according to the minimum design service life required in Brazil (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013). Replacement rates of building materials over the design service life are presented in the Electronic Supplementary Material, based on expert opinion.

Land use by the house considers only the area of the lot (180 m²) occupied over one year during the construction and 50 years during the use stage. Indirect land occupation (e.g., for infrastructure and roads) was not accounted for, following the recommendation of EN 15978 (DEUTSCHES INSTITUT FÜR NORMUNG, 2012).

Only the transport and disposal of demolition waste were considered for the end-of-life stage. The energy consumption by demolition equipment was not accounted for because it is deemed negligible compared to the energy consumed throughout the rest of the life cycle. Although relevant, particulate matter emissions were not considered due to a lack of data. Only copper and aluminium are assumed to be recycled; the rest is either disposed of in landfills or incinerated.

The detailed life cycle inventory of the house, with the corresponding ecoinvent datasets, is presented in the Electronic Supplementary Material of this thesis (http://dx.doi.org/10.17632/k4mnt33tyc.2).

3.2.4 Life cycle impact assessment

Life cycle inventory compilation and impact assessment were carried out using Simapro (version 8.5.2.0) and the impact assessment methods identified in Table 5, based on the methods recommended by EN 15804 (DEUTSCHES INSTITUT FÜR NORMUNG, 2020) and the available methods implemented in the software: CML baseline (GUINÉE *et al.*, 2004), ReCiPe Midpoint (Hierarchist Version) (HUIJBREGTS *et al.*, 2016), ILCD 2011 Midpoint (EUROPEAN COMMISSION; JOINT RESEARCH

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[2] MAIA, A. C. B. *Gás residencial*. Addressee: Roberto Lamberts. [Brasília], 13th May 2021 [e-mail].

CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2011), USETox (FANTKE *et al.*, 2017), and AWARE (BOULAY *et al.*, 2018). Infrastructure is excluded from the calculation due to the high uncertainty associated with these flows (SILVA *et al.*, 2018).

Table 5 – List of the impact categories assessed in this study, with the corresponding characterization models, their description, and units.

Impact category	Model	Description	Unit
Mineral resource depletion	CML baseline	Consumption of a mineral resource relative to its availability, considering antimony as the reference mineral. The availability of minerals is based on the ultimate reserves, i.e., the amount of minerals available in the Earth's upper crust that is recoverable and corresponding extraction rates.	kg Sb eq.
Fossil resource depletion	CML baseline	Consumption of fossil fuels converted to energy considering the Lower Heating Value (LHV)	MJ eq.
Global warming	IPCC	Additional radiative forcing integrated over 100 years caused by the emission of greenhouse gases, relative to the radiative forcing integrated over the same time horizon caused by the release of 1 kg of CO_2.	Kg CO_2 eq.
Ozone depletion	WMO	Amount of stratospheric ozone a substance can deplete relatively to the ozone depletion caused by 1 kg of CFC-11 for a specific time horizon, considering the substance's chemical composition (number of chlorine and bromine groups) and its atmospheric lifetime.	kg CFC-11 eq.
Photochemical ozone creation	LOTOS-EUROS (ReCiPe)	Ozone is formed by photochemical reactions of NO_x and non-methane volatile organic compounds (NMVOC) with air in the presence of sunlight. The characterization factor is calculated by dividing the intake fraction of a precursor substance for ozone formation by the emission-weighted world average intake fraction of NO_x. Inhalation of ozone can cause respiratory diseases in humans and harm photosynthesis.	kg NO_x eq.[a]
Acidification	Accumulated Exceedance (ILCD)	The acidification potential quantifies the soil acidity increase caused by a substance relative to the increase caused by a mol of H+. Atmospheric deposition of sulphates and nitrates can cause a change in the acidity of the soil, resulting in damage to plants.	mol H+ eq.
Fine particulate matter formation	ReCiPe [b]	Particulate matter formation potential is calculated by dividing the intake fraction of fine particulate matter or a precursor substance by the emission-weighted world average intake fraction of particulate matter with a maximum diameter of 2,5 µm. Inhalation of fine particulate matter can cause respiratory diseases.	kg PM 2,5 eq.

(continues)

(continuation)

<table>
<tr><th>Impact category</th><th>Model</th><th>Description</th><th>Unit</th></tr>
<tr><td>Terrestrial eutrophication</td><td>Accumulated Exceedance (ILCD)</td><td rowspan="3">The eutrophication potential quantifies the increase in nutrients caused by a substance relative to the increase caused by phosphorus (freshwater) and nitrogen (land and sea). The rise in nutrient levels (phosphorus and nitrogen) causes the increase of cyanobacteria and algae that deplete oxygen from water bodies, leading to the loss of aquatic species. It can also cause an imbalance of terrestrial ecosystems.</td><td>mol N eq.</td></tr>
<tr><td>Freshwater eutrophication</td><td>EUTREND (ReCiPe)</td><td>kg P eq.</td></tr>
<tr><td>Marine eutrophication</td><td>EUTREND (ReCiPe)</td><td>kg N eq.</td></tr>
<tr><td>Human carcinogenic toxicity</td><td rowspan="3">USETox</td><td rowspan="3">The characterization factor of a substance considers its effect, the exposure to it and its fate in the environment. The effect factor for human toxicity is based on toxicity data for cancer and non-cancer effects derived from laboratory studies with animals. The exposure factor considers different transfer mechanisms according to the substance (e.g., inhalation, ingestion, absorption through the skin). For ecotoxicity, the effect factor considers the relation between a substance’s concentration in freshwater and species’ morbidity. The exposure equals the dissolved fraction of the substance.</td><td>CTUh</td></tr>
<tr><td>Human non-carcinogenic toxicity</td><td>CTUh</td></tr>
<tr><td>Freshwater ecotoxicity</td><td>CTUe</td></tr>
<tr><td>Ionizing radiation</td><td>Frischknecht et al. 2000 (ILCD)</td><td>Damage caused by exposure to and the effect of a radionuclide relative to the damage caused by airborne uranium-235. Exposure to ionizing radiation may cause cancer and adverse hereditary effects.</td><td>kBq U235 eq.</td></tr>
<tr><td>Water use</td><td>AWARE</td><td>The characterization factors of the AWARE model (an acronym for Available Water Remaining) assess the potential of water deprivation, considering the availability of water relative to water consumption in the region. Water consumption considers water that is evaporated, incorporated into products, transferred into other watersheds, or disposed of into the sea.</td><td>m^3 eq.</td></tr>
<tr><td>Land use</td><td>ReCiPe [b]</td><td>The land use characterization factor is based on the relative species loss caused by a specific land-use type proportionate to the relative species loss resulting from annual crop production. The species richness of the current anthropogenic land use is compared with the natural reference, not accounting for any other anthropogenic land uses that may have been in place before the current land use.</td><td>m^2a crop eq.</td></tr>
</table>

a) According to the ReCiPe Midpoint impact assessment method, as implemented in Simapro, the unit of the photochemical ozone creation potential is kg NO_x eq., and not kg ethene eq. as required by EN 15804.
b) The models recommended by EN 15804 were not implemented in the version of Simapro used in this study; therefore, these impact categories were assessed using the characterization models of the ReCiPe Midpoint (Hierarchist Version) impact assessment method.

Source: the author.

No regionalization is considered for the life cycle impact assessment due to the lack of regionalized life cycle inventory data and corresponding characterization factors.

3.2.5 Interpretation of LCA results

For each impact category, the contribution of each elementary process and elementary flow to the impact result of the house was quantified. The contribution of elementary processes allowed identifying the specific processes within the system boundary that cause the environmental impact assessed (REINHARD *et al.*, 2016). The contribution of elementary flows allowed identifying which substances (natural resources consumed or substances emitted to the environment) cause the impact. This disaggregated analysis made it possible to understand the meaning of each impact result associated with the house's life cycle.

The "process contribution" function of Simapro was used, with the "characterization" setup, to quantify the contribution of elementary processes to each impact result. The cut-off level was adjusted to cover at least 80% of the impact of the house in the contribution analysis. For the "heat datasets" and "combustion datasets", the "single product flow" function was used, which allows for tracking the processes that use a specific product flow and their corresponding shares (in absolute or percentage values). This procedure was applied to the following datasets: "Diesel, burned in building machine/GLO U", "Natural gas, burned in industrial furnace >100Kw/RER U", and "Light fuel oil, burned in boiler 100Kw, non-modulating/CH U". The single product flow analysis was also applied for the datasets "Blasting/RER U", which describes the use of explosives for mining processes, and "Tap water, at user/RER U", which describes the supply of water from the public network.

To quantify the contribution of elementary flows to the impact results, the "inventory" function of Simapro was used with the "characterization" setup for each impact category. In addition, the total mass of each elementary flow entering or leaving the cradle-to-grave product system was quantified to analyze their measurability. For that, the life cycle inventory of the house was extracted from Simapro, also using the "inventory" function with default units.

3.3 Results

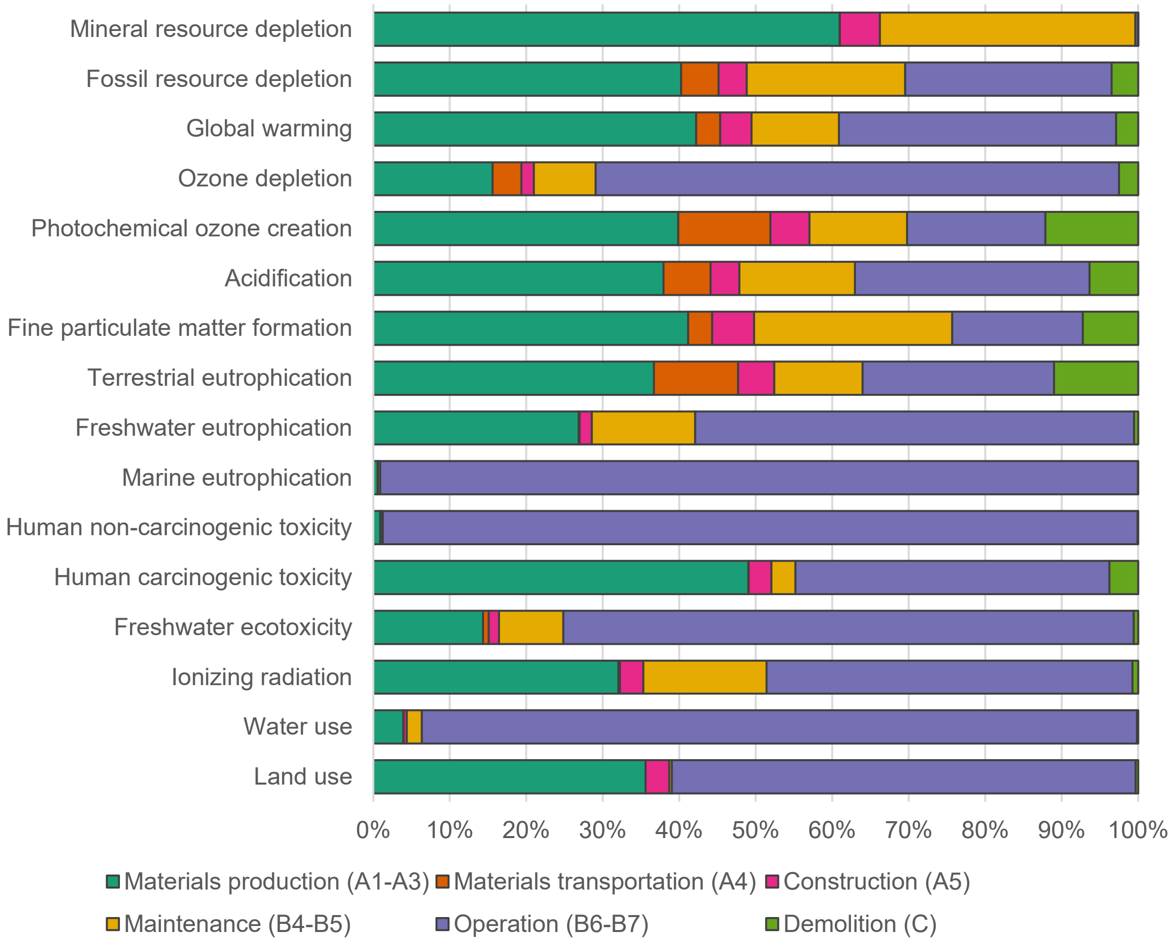
Table 6 summarizes the LCA results of the house. Figure 14 shows the relative contribution of different life cycle stages to the total impact results of the house. The production of materials (stages A1-A3) and the operation of the house (stages B6-B7) are the major contributors to half of the impact categories. The third most important stage is maintenance, which corresponds to the production of materials for replacement over the house service life. Materials transportation, construction, and demolition show relatively small contributions to the total impact results compared to the other life cycle stages.

Table 6 – Life cycle impact results of the house, presented for one house, for 1 m², and 1 m².a, considering a reference study period of 50 years.

Impact category	**Unit**	**Impact result per functional unit**		
		1 house	**1 m²**	**1 m².a**
Mineral resource depletion	kg Sb eq.	0,069	0,0012	$2,4.10^{-5}$
Fossil resource depletion	MJ eq.	336.113	5.764	115
Global warming potential	kg CO_2 eq.	39.753	682	13,6
Ozone depletion	kg CFC-11 eq.	0,019	$3,2.10^{-4}$	$6,4.10^{-6}$
Photochemical ozone creation	kg NO_x eq.	81	1,4	0,028
Acidification	mol H+ eq.	137	2,3	0,047
Fine particulate matter formation	kg PM 2,5 eq.	49	0,84	0,017
Terrestrial eutrophication	mol N eq.	372	6,4	0,13
Freshwater eutrophication	kg P eq.	14	0,24	0,0048
Marine eutrophication	kg N eq.	37	0,63	0,013
Human non-carcinogenic toxicity	CTUh	$1,3.10^{-5}$	$2,3.10^{-7}$	$4,6.10^{-9}$
Human carcinogenic toxicity	CTUh	$1,3.10^{-5}$	$2,2.10^{-7}$	$4,4.10^{-9}$
Freshwater ecotoxicity	CTUe	211	3,6	0,072
Ionizing radiation	kBq U-235 eq.	7.472	128	2,6
Water use	m³ eq.	326.167	5.594	112
Land use	m²a eq.	11.294	194	3,9

Source: the author.

Figure 14 – Relative contribution of life cycle stages to the life cycle impact results of the house.



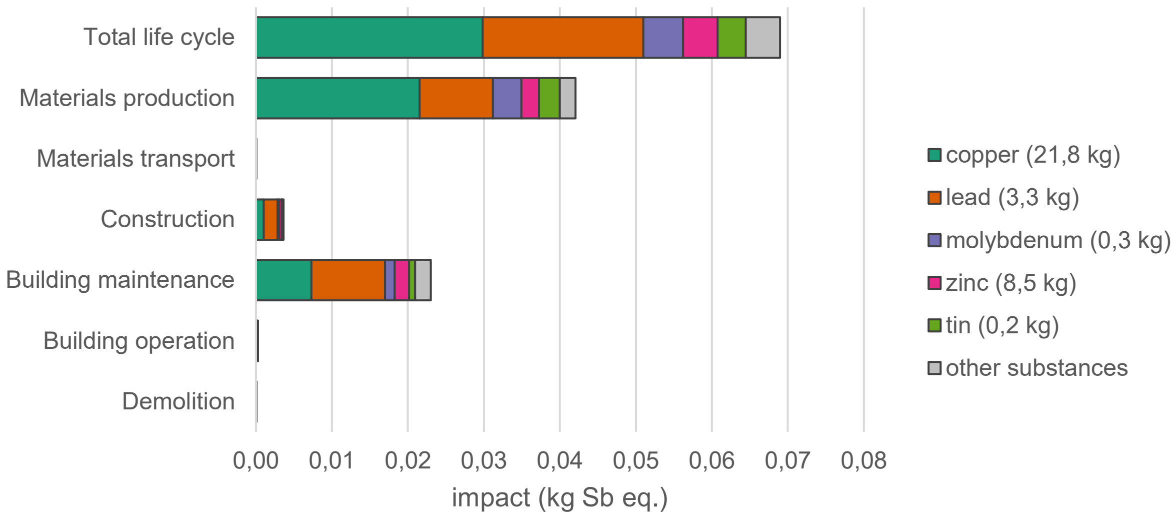
Source: the author.

However, these aggregated LCA results do not allow an understanding of the causes of each environmental impact. Therefore, the following sections present a more detailed analysis of the LCA result, identifying the elementary processes and flows that most contribute to each impact category.

3.3.1 Mineral resource depletion

The mineral resource depletion potential is 69 g of antimony equivalent. This impact is caused by the consumption of metallic substances for producing the materials used to build and maintain the house. The main metallic substances are copper and molybdenum contained in copper pipes used for gas supply and in electric cables, lead and zinc contained in the frit used for glazing the ceramic tiles (KELLENBERGER *et al.*, 2007), and tin contained in the bronze connections of the hydraulic system (Figure 15).

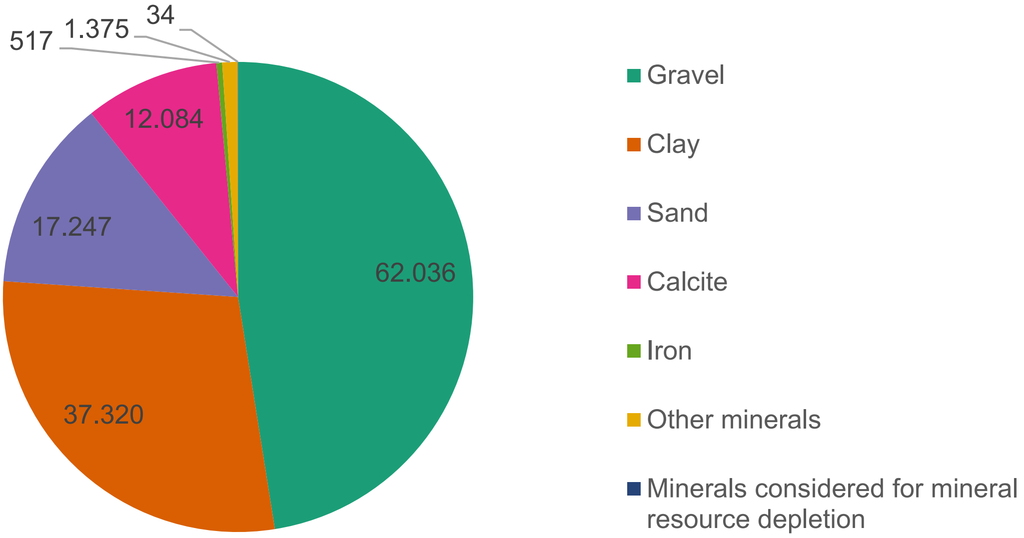
Figure 15 – Contribution of elementary flows to the impact result of depletion of abiotic resources – mineral elements. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Although these metallic substances represent 93% of the mineral abiotic depletion potential of the house, they correspond to a mass of 34,1 kg, which represents only 0,03% of the minerals that enter the product system (130.614 kg). Construction minerals are not accounted for in this impact category, despite representing the main share of raw materials, as shown in Figure 16. Even iron, the primary metallic substance in the house (517 kg), does not figure among the substances that significantly contribute to the impact results. Construction minerals do not contribute to the abiotic depletion potential of minerals because their ultimate global reserves are considered very large or infinite; therefore, their characterization factors are almost zero or zero, according to the selected LCIA method.

Figure 16 – Construction minerals entering the cradle-to-gate product system of the house. Values in kilograms. The slice referring to the minerals considered in the mineral resource depletion indicator is not visible in the chart because it corresponds to only 0,03% of the mass of the house.



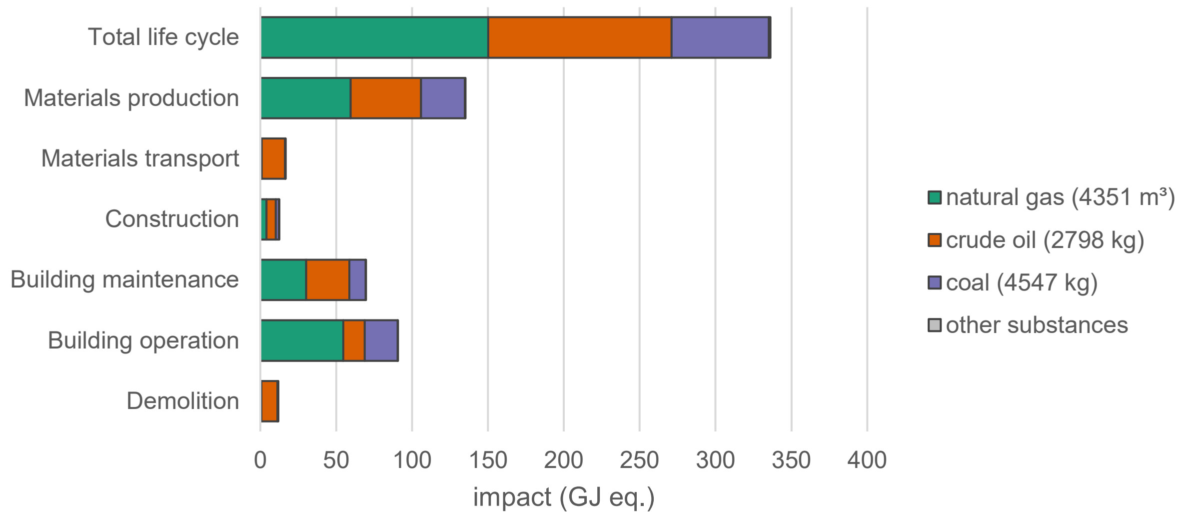
Source: the author.

3.3.2 Fossil resource depletion

The fossil resource depletion potential is 336 GJ equivalent. The leading causes are the consumption of fossil fuels for manufacturing construction products and operating the house for 50 years, including the consumption of natural gas for hot water production and crude oil and coal for electricity generation in thermal power plants (Figure 17). Fossil fuel consumption in industrial processes includes natural gas used in clay firing, petroleum coke used in the clinker kiln, and coal used in the blast furnace for pig iron production. For the use phase, the ecoinvent dataset used to represent the Brazilian electricity mix[3] considers that 9,9% of the electricity is generated by power plants that consume fossil fuels. In contrast, national statistics indicate a share of 14,6% for 2019 (Table 7). Fossil fuels are also consumed for materials transportation and landfilling.

[3] No adaptation of the electricity mix was performed in the datasets used to represent the production of materials.

Figure 17 – Contribution of elementary flows to the impact result of depletion of abiotic resources – fossil fuels. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Table 7 – Brazilian electricity mix according to ecoinvent version 2 and to the National Energy Balance 2020.

Energy source	Participation in the electricity mix	
	ecoinvent v2	**National Energy Balance 2020**
Hydropower (reservoir power plant)	84%	65%
Thermal power plant (natural gas)	4,8%	9,3%
Cogeneration (sugarcane bagasse)	4,0%	8,4% [a]
Nuclear power plant	2,3%	2,5%
Thermal power plant (coal)	1,9%	3,3%
Cogeneration (diesel)	1,9%	2,0% [b]
Thermal power plant (oil)	0,7%	
Thermal power plant (industrial gas)	0,6%	-
Wind	0,0%	8,6%
Solar	-	1,0%

a) Biomass includes firewood, sugarcane bagasse, and leachate
b) Petroleum products

Source: the author, based on the ecoinvent database (version 2) and (EMPRESA DE PESQUISA ENERGÉTICA (BRASIL) (2021).

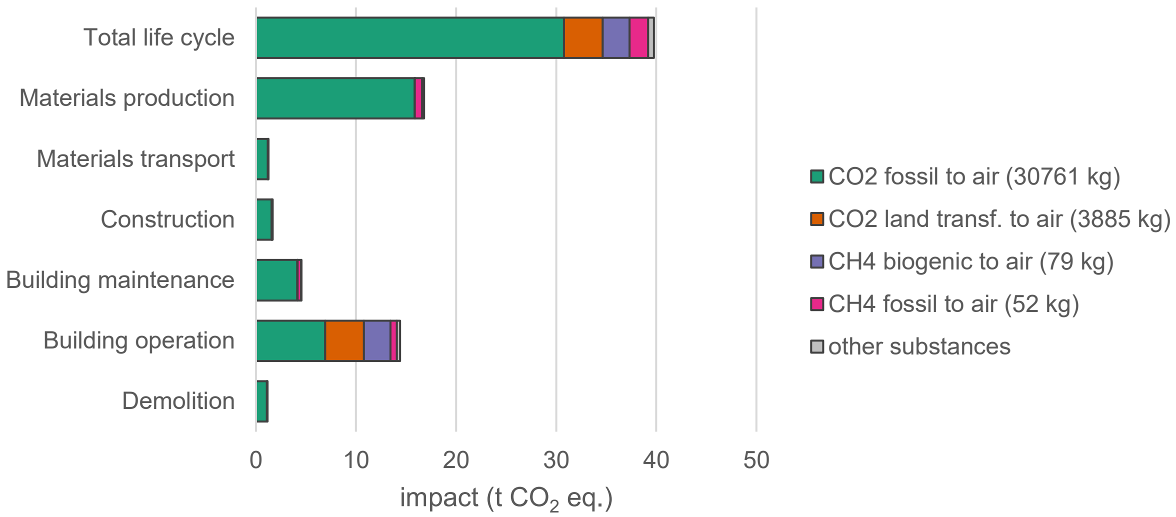
3.3.3 Global warming

The global warming potential is 39,8 t CO_2 equivalent. This impact is caused by the emission of greenhouse gases, mainly CO_2 (Figure 18). The main process causing this impact is the production of clinker, the primary raw material of cement, which corresponds to 17% of the total global warming potential of the house (Figure 19). Clinker is produced in an energy-intensive process that consumes fossil fuels (petroleum coke) and emits CO_2. It also emits CO_2 from the chemical reaction for decomposing calcium carbonate (Equation 1) (HANLE *et al.*, 2006).

$$CaCO_3 \rightarrow CaO + CO_2$$ Equation 1

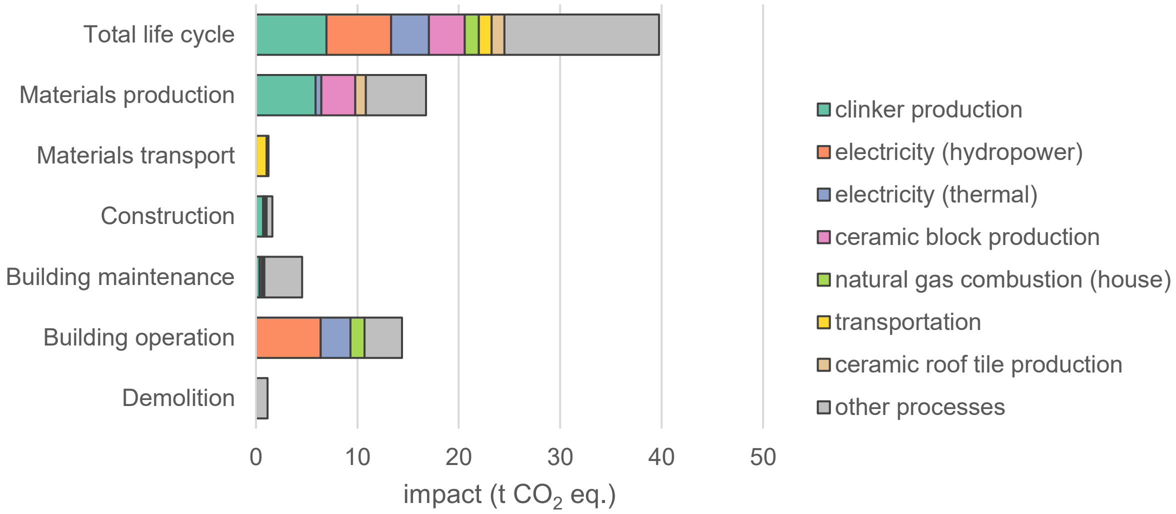
The second and the third most contributing processes are associated with electricity generation, accounting together for 25% of the GWP of the house. Electricity is mainly consumed during the use phase of the building. The reservoirs of hydropower plants emit CO_2 from land transformation and CH_4 from the decomposition of submerged organic matter. Hydropower is the principal energy source for generating electricity in Brazil. In the dataset “Electricity mix/BR U” considered in the life cycle inventory, the hydropower share is 84%, whereas recent national statistics indicate a share of 65% in the electricity mix (Table 7). Note that the ecoinvent dataset for hydropower energy says that the emissions of CO_2 from land transformation and CH_4 from reservoirs are highly uncertain estimates. The generation of electricity in thermal power plants is another source of CO_2. The current share of thermal power plants using fossil fuels in Brazil (14,6%) is higher than the share considered by the ecoinvent dataset (9,9%) (Table 7).

Figure 18 – Contribution of elementary flows to the impact result of global warming. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 19 – Contribution of elementary processes to the impact result of global warming.



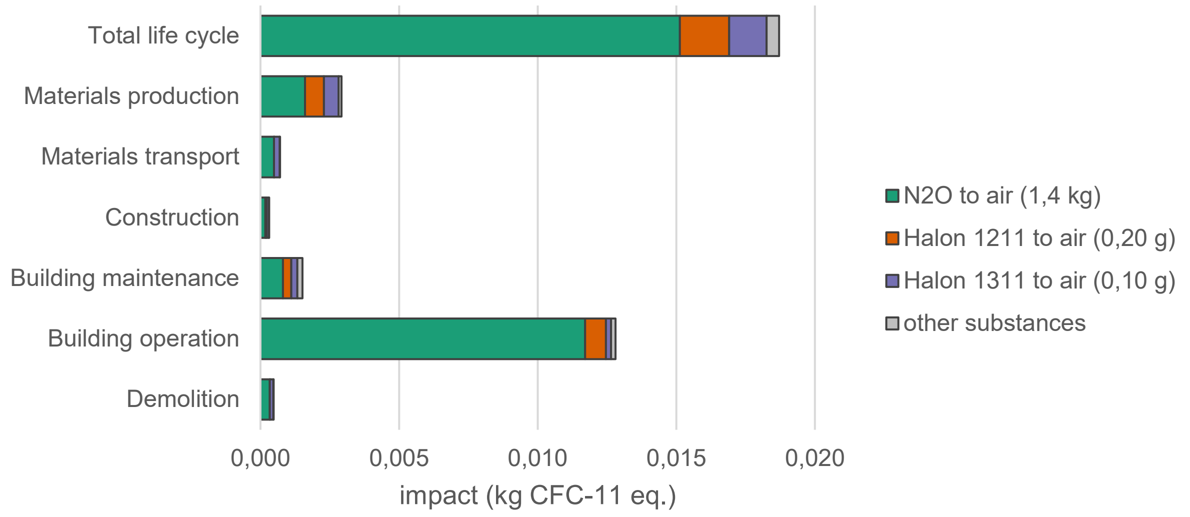
Source: the author.

The production of ceramic blocks and roof tiles corresponds to 12% of the global warming potential. According to the ecoinvent datasets used in this study, these products are fired in kilns that consume natural gas. Other processes that consume fossil fuels and emit CO_2 are the transportation of materials and the combustion of natural gas for hot water production. Natural gas consumption represents 14% of the energy demand for operating the house and 4% of its global warming potential. There are also greenhouse gas emissions from producing natural gas.

3.3.4 Ozone depletion

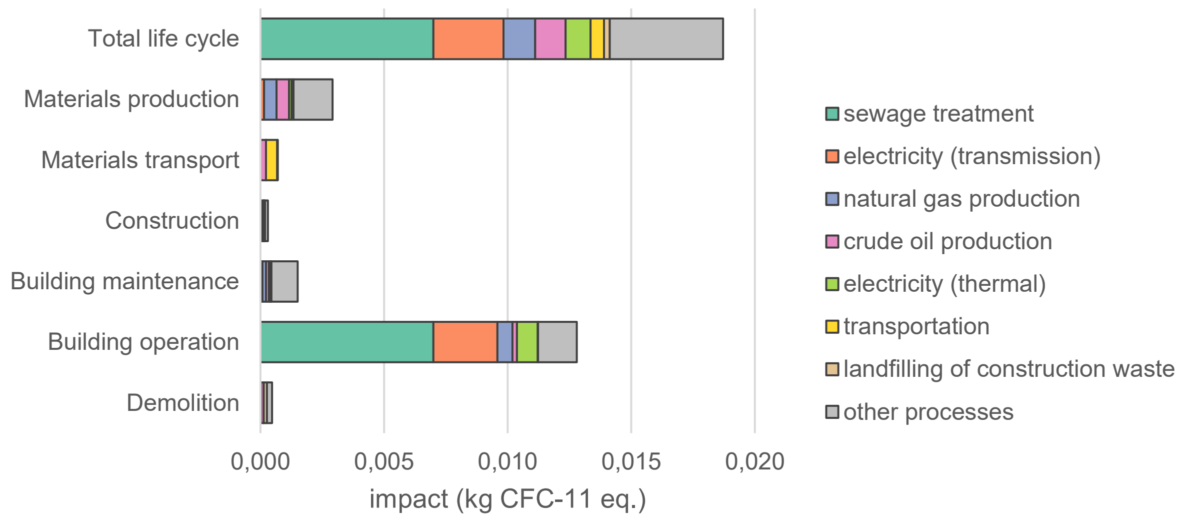
The ozone depletion potential is 19 g CFC-11 equivalent. The leading cause of ozone depletion is the emission of dinitrogen monoxide (N_2O) into the air, which represents 81% of the ozone depletion potential (Figure 20). N_2O is emitted mainly from wastewater treatment plants, contributing to 37% of the ozone depletion potential (Figure 21). According to ecoinvent, N_2O is emitted through sludge incineration associated with the wastewater treatment service, the amount of emission being 10 mg of N_2O/m^3 of wastewater treated (DOKA, 2009b). Note that the dataset used for wastewater treatment is not representative of Brazil, where it is not common to incinerate the sludge from wastewater treatment plants (BATISTA, 2018). N_2O is also formed by ionising the air surrounding high voltage transmission lines, known as the “corona effect” (DONES *et al.*, 2007). It is also emitted from fossil fuel combustion in thermal power plants, thereby explaining the contribution of electricity to 21% of this impact (Figure 21).

Figure 20 – Contribution of elementary flows to the impact result of ozone depletion. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 21 – Contribution of elementary processes to the impact result of ozone depletion.



Source: the author.

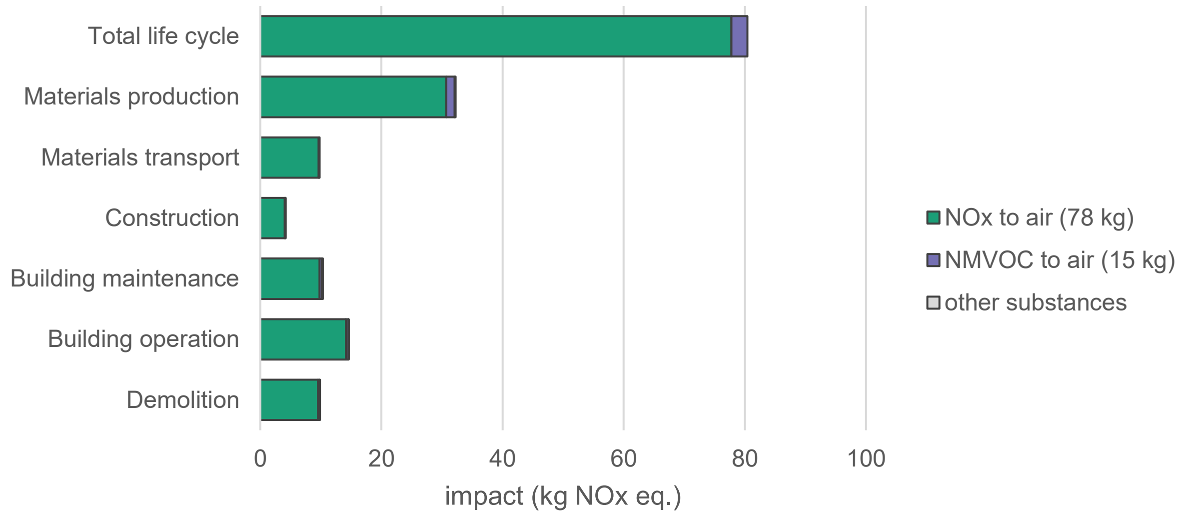
As for the halogenated compounds – Halon 1211 (CF_2BrCl) and Halon 1301 (CF_3Br) – these are fugitive emissions from fire extinguishers and cooling systems present in installations for crude oil production (JUNGBLUTH, 2007) and natural gas transportation (FAIST EMMENEGGER *et al.*, 2007).

Altogether, the total amount of ozone-depleting substances emitted over the house's life cycle is extremely low: only 1,4 kg. It is worth mentioning that these emissions are calculated based on rough estimates (DONES *et al.*, 2007; FAIST EMMENEGGER *et al.*, 2007; JUNGBLUTH, 2007). Moreover, Halon-1211 and Halon-1301 were phased out by the Montreal Protocol in 2010, with exemptions only for essential use (UNITED NATIONS ENVIRONMENT PROGRAMME, 2019a).

3.3.5 Photochemical ozone creation

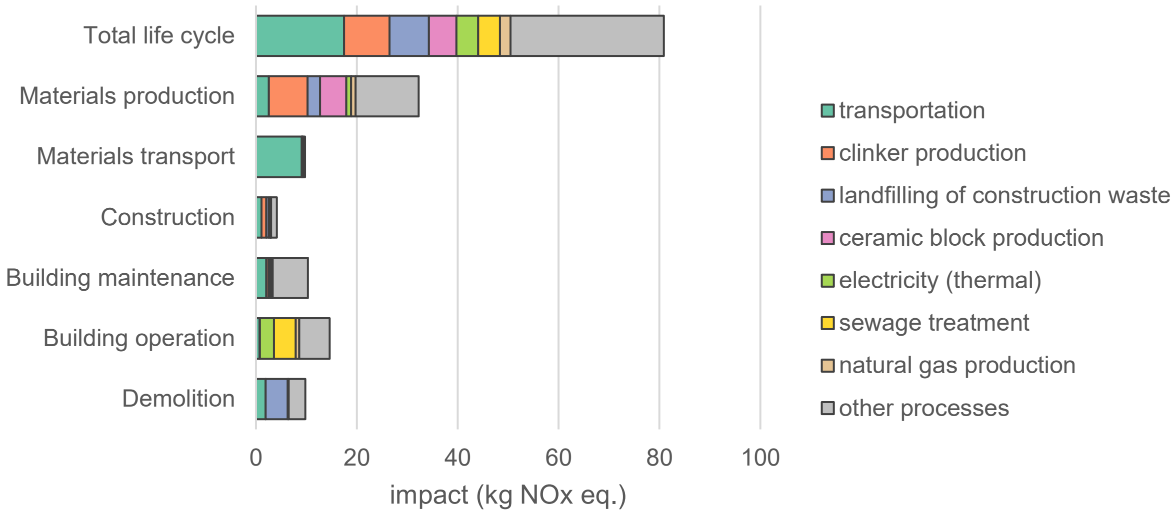
The photochemical ozone creation potential is 81 kg NO_x equivalent. The leading cause is the emission of nitrogen oxides (NO_x) (Figure 22). 78 kg of NO_x are emitted throughout the product system primarily because of the oxidation of nitrogen contained in the air during the combustion of fuels. The elementary processes that contribute to direct NO_x emissions are those intensive in fuels, such as the transportation of materials, the production of clinker, and the landfilling of construction and demolition waste (Figure 21). Sewage treatment contributes 5% to the photochemical ozone creation potential because of the oxidation of the nitrogen contained in the sewage. As many elementary processes consume fuels and emit NO_x, the share of the impact attributed to processes that contribute less than 1% of the impact ("other processes") becomes considerably high (38%).

Figure 22 – Contribution of elementary flows to the impact result of photochemical ozone creation. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 23 – Contribution of elementary processes to the impact result of photochemical ozone creation.

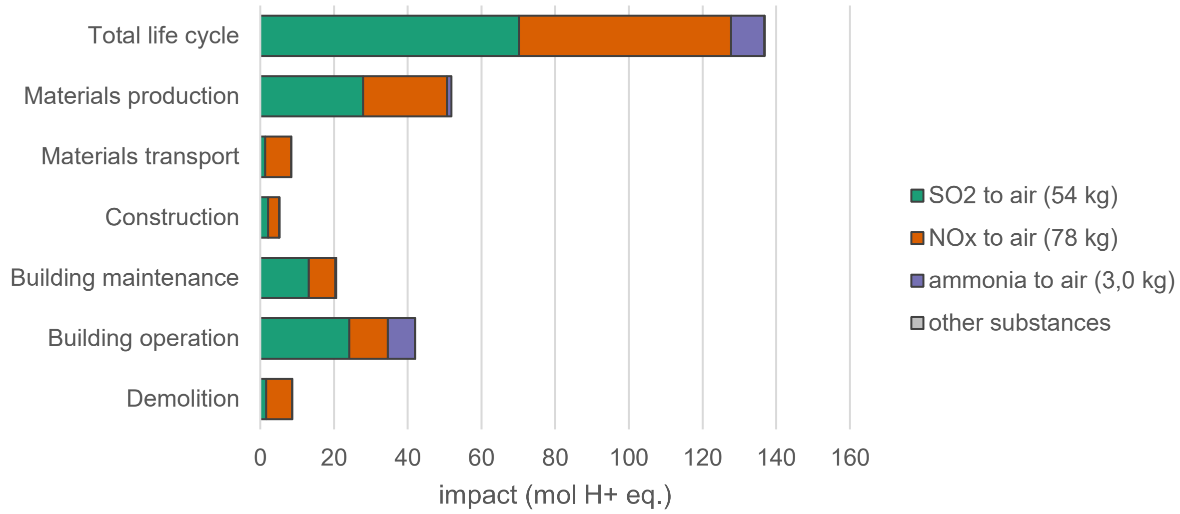


Source: the author.

3.3.6 Acidification

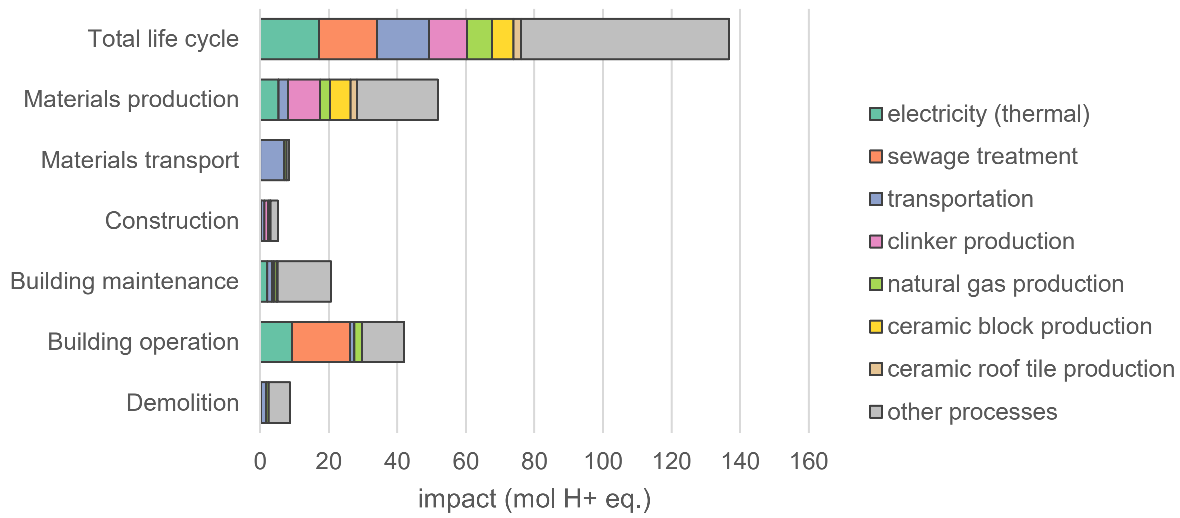
The acidification potential is 137 mol H+ equivalent. Acidification is caused chiefly by airborne emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) (Figure 24), which can react with water forming acid rain. SO_2 is emitted mainly from the oxidation of fuels containing sulfur. Therefore, processes intensive in these fuels contribute to this impact, such as electricity generation in power plants, transportation, and clinker production (Figure 25). Over the house's life cycle, 54 kg of SO_2 is emitted into the atmosphere. NO_x is also emitted from the combustion of fuels and the sewage treatment process, as discussed for the impact category of photochemical ozone creation—this explains why these impact categories share the same elementary processes.

Figure 24 – Contribution of elementary flows to the impact result of acidification. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 25 – Contribution of elementary processes to the impact result of acidification.



Source: the author.

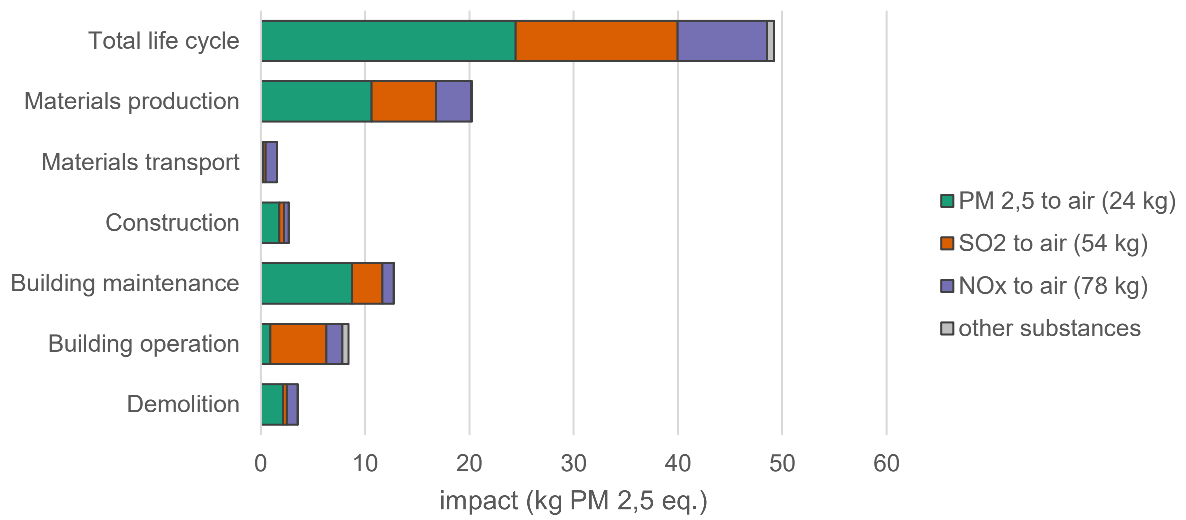
3.3.7 Fine particulate matter formation

The fine particulate matter formation potential is 49 kg PM 2,5 equivalent. This impact is caused by direct emissions from particles with a maximum diameter of 2,5 μm (PM 2,5), SO_2, and NO_x (Figure 26). The process that most contributes to this impact is ceramic tiles production, representing 33% of the total fine particulate matter potential (Figure 27). According to ecoinvent, the ceramic tiles production emits 8,7 g PM 2,5/kg of tiles, based on an EPA emission factor for comminution and ceramic glass spray booth (KELLENBERGER; ALTHAUS, 2009). As one replacement of the ceramic tiles is expected to happen during the use phase, this explains the contribution of the maintenance stage to the total impact over the life cycle.

Emission of PM 2,5 also happens in other mining and comminution processes, including the production of cement, aggregates, and clay. Estimating particulate matter emission factors (kg PM/kg product) for open mining and grinding processes is not straightforward. To the best of our knowledge, no clear guidance exists for converting the concentration of particulate matter in the air (kg PM/m³) to emission factors in open systems. Most ecoinvent datasets rely on emission factors provided by other sources, like EPA. Particulate matter is also emitted during construction and demolition, but these emissions were not considered due to a lack of data. The contribution of these life cycle stages is explained here by other processes, including materials production to compensate for wastage and fossil fuel consumption for transporting and disposing of the waste. Fine particulate matter is also emitted from the combustion of fossil fuels. Over the house's life cycle, 24 kg of PM 2,5 is emitted.

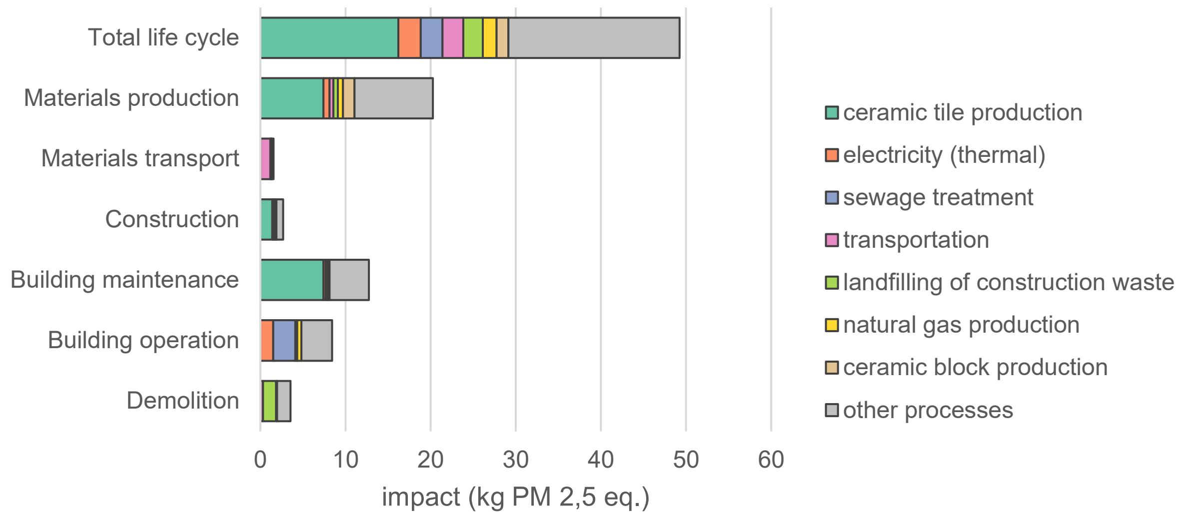
SO_2 and NO_x emissions have already been discussed. These substances may react and form fine particles that remain suspended in the air and can be inhaled, causing respiratory diseases (EUROPEAN ENVIRONMENT AGENCY, 2013). Since SO_2 and NO_x emissions are mostly related to the combustion of fuels, this explains the contribution of fuel-intensive processes such as electricity generation, transportation, waste landfilling, and the production of some materials to the fine particulate matter formation potential results.

Figure 26 – Contribution of elementary flows to the impact result of fine particulate matter formation. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 27 – Contribution of elementary processes to the impact result of fine particulate matter formation.



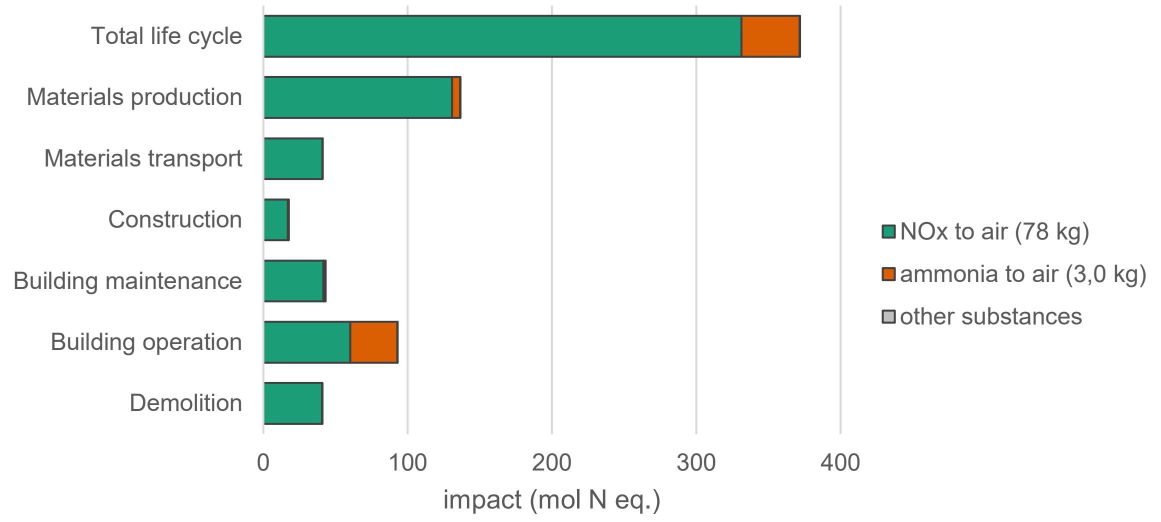
Source: the author.

The emission of fine particulate matter during construction was not considered. The EPA informs an emission factor of total suspended particles (TSP) of 2,69 Mg/(ha.month) for heavy construction activities, a conservative estimate that dates back to 1974 (U.S. ENVIRONMENTAL PROTECTION AGENCY, 1995). Although the EPA emission factor does not apply to house construction, a calculation is done for sensitivity purposes. Applying the EPA emission factor to the analyzed building, considering a plot area of 180 m² and 12 months of construction, results in a total particulate matter emission of 581 kg. Although this number is much higher than the 24 kg quantified in the house life cycle inventory, no information is provided about the share of fine particles within this estimate.

3.3.8 Terrestrial eutrophication

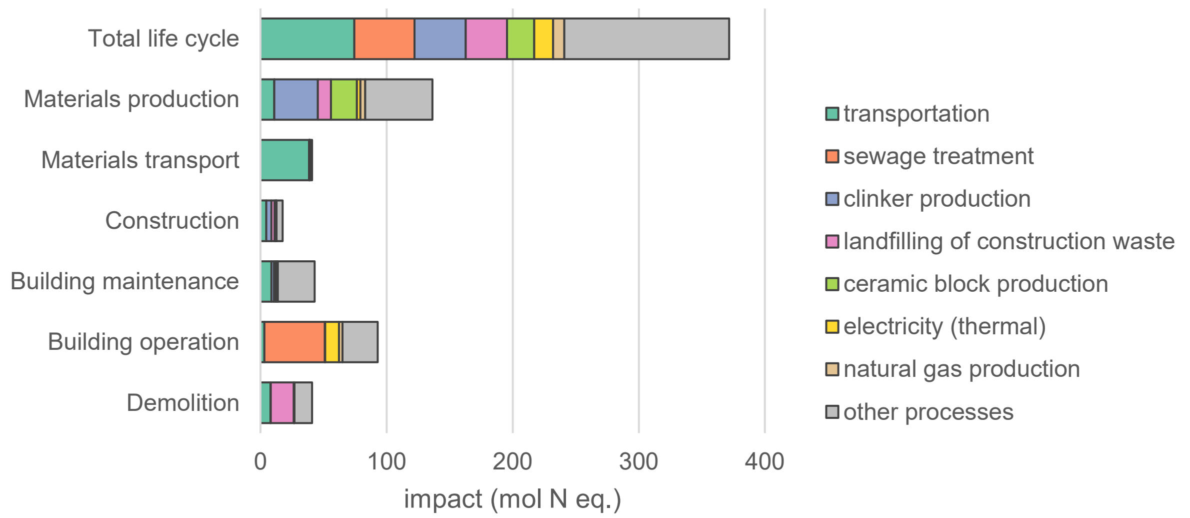
The terrestrial eutrophication potential is 372 mol nitrogen equivalent. It is caused by airborne emissions of nitrogen oxides (Figure 28), which contain nitrogen that increases the concentration of nutrients that characterise the eutrophication phenomenon when deposited in the soil. As discussed previously (sections 3.3.5, 3.3.6, and 3.3.7), NO_x is emitted from fossil fuel combustion in several processes and sewage treatment plants (Figure 29).

Figure 28 – Contribution of elementary flows to the impact result of terrestrial eutrophication. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 29 – Contribution of elementary processes to the impact result of terrestrial eutrophication.



Source: the author.

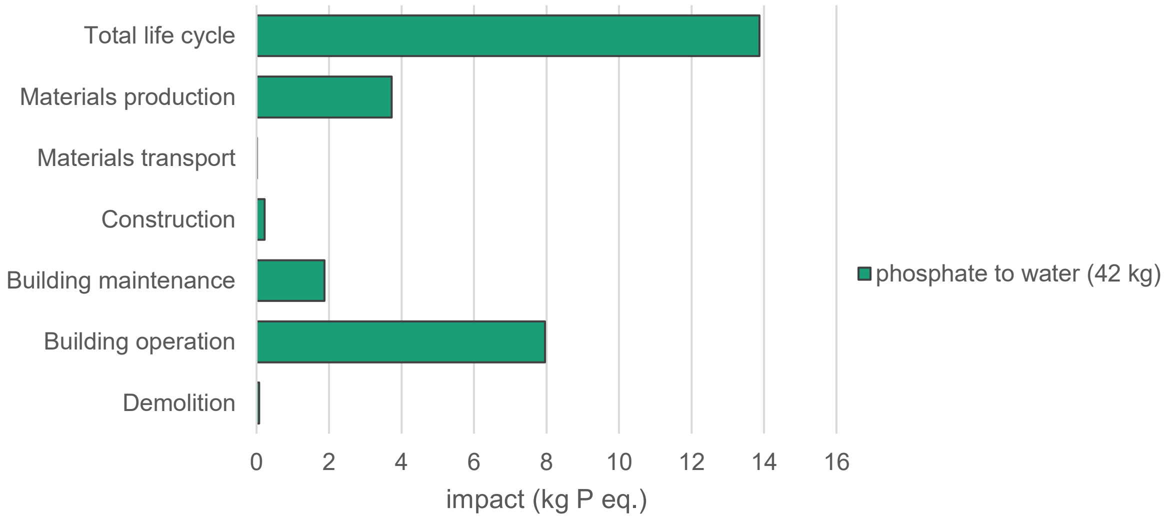
3.3.9 Freshwater eutrophication

The freshwater eutrophication potential is 14 kg phosphorus equivalent. The emission of phosphate into water causes this impact– 42 kg of phosphate are emitted over the house’s life cycle (Figure 30). Phosphate can be emitted from sewage treatment, contributing 42% to the impact result (Figure 31). Note that the dataset used to represent this process considers a phosphate precipitation step to reduce its concentration in the effluent (DOKA, 2009b). This step is not common in Brazilian wastewater treatment plants (AGÊNCIA NACIONAL DE ÁGUAS (BRASIL), 2017).

Therefore, a higher relative contribution from wastewater treatment could be expected if local data were used.

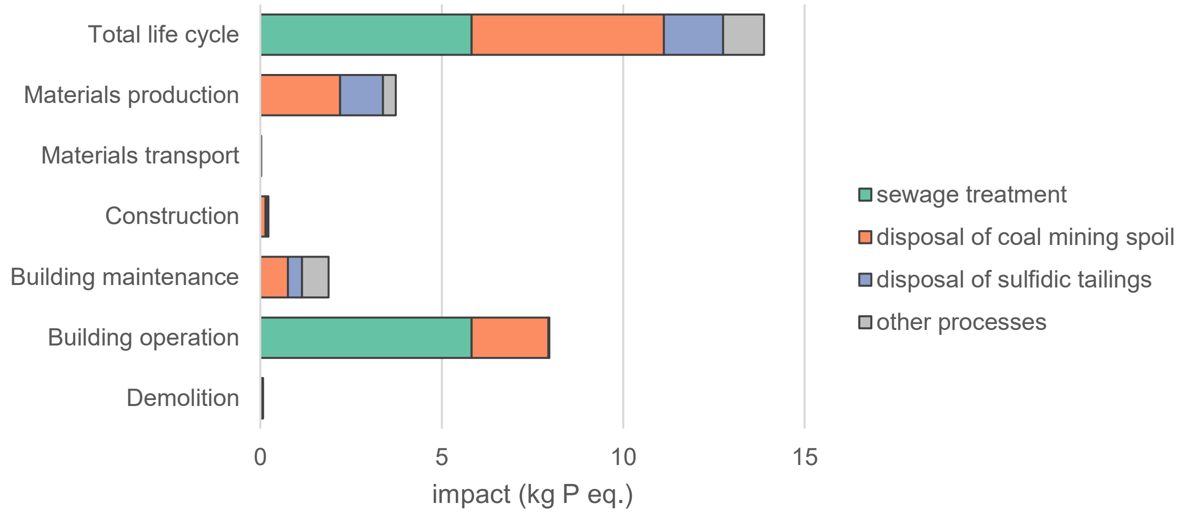
Phosphate is also contained in leachates from landfills of coal mining spoils (38% of the impact) and sulfidic tailings (12% of the impact) (Figure 31). Ecoinvent estimates this emission based on a leaching model with global average values and transfer coefficients of substances from landfills to the environment over 60.000 years (CLASSEN *et al.*, 2009; DOKA, 2009a). Therefore, it is a highly uncertain estimate. Coal (including lignite) is used mainly for electricity production and in some material production processes. Sulfidic tailings are produced during copper refining (CLASSEN *et al.*, 2009).

Figure 30 – Contribution of elementary flows to the impact result of freshwater eutrophication. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 31 – Contribution of elementary processes to the impact result of freshwater eutrophication.

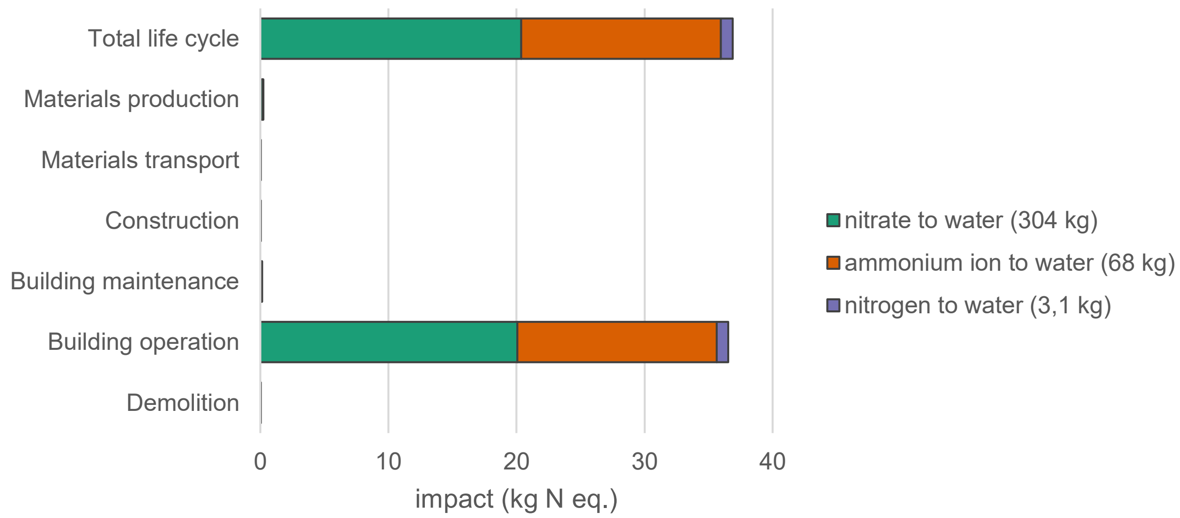


Source: the author.

3.3.10 Marine eutrophication

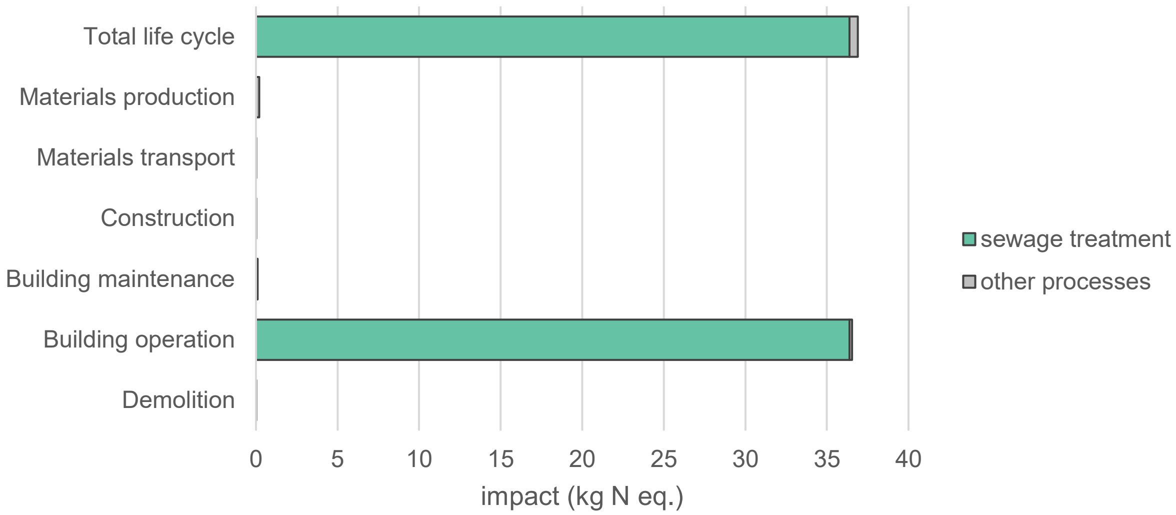
The marine eutrophication potential is 37 kg nitrogen equivalent. This impact is caused mainly by the emission of nitrate and ammonium to water from sewage treatment (Figure 32 and Figure 33). The sewage treatment process considered in the life cycle inventory is aerobic (DOKA, 2009b), forming more nitrogen compounds than the anaerobic processes commonly used in Brazil (AGÊNCIA NACIONAL DE ÁGUAS (BRASIL), 2017). Nevertheless, the contribution of this process is so high compared to other processes that the results of the contribution analysis should not change much if national data were used.

Figure 32 – Contribution of elementary flows to the impact result of marine eutrophication. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 33 – Contribution of elementary processes to the impact result of marine eutrophication.



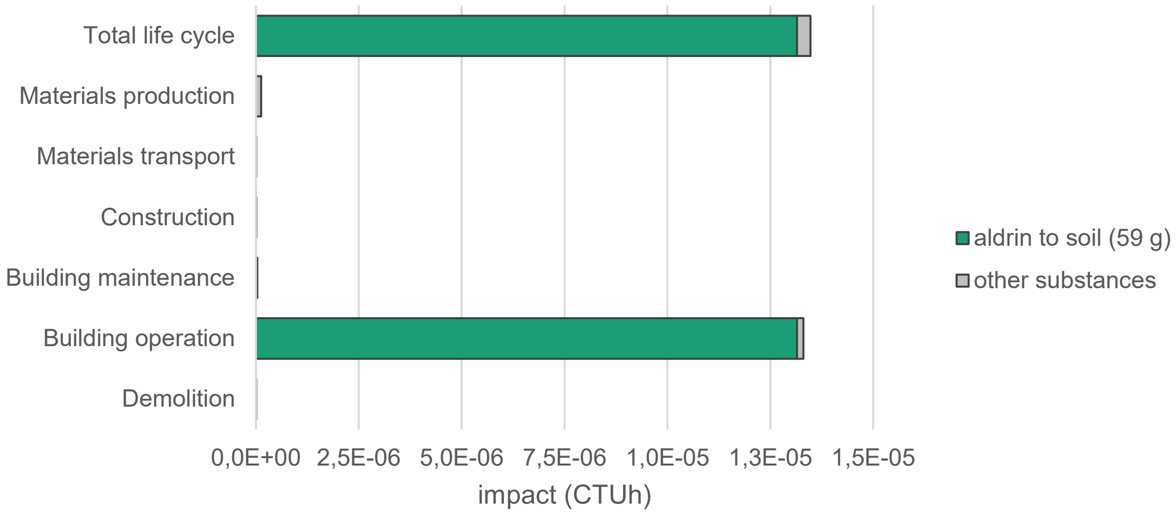
Source: the author.

3.3.11 Human non-carcinogenic toxicity

The human non-carcinogenic toxicity potential is $1{,}3.10^{-5}$ Comparative Toxic Units for human toxicity (CTUh). The leading cause is the emission of a highly toxic organochlorine pesticide called aldrin (HONEYCUTT; SHIRLEY, 2014) (Figure 34) into the soil during sugarcane production (Figure 35) (3,6 mg/kg of sugarcane). Sugarcane is fermented to produce ethanol (a biofuel); the sugarcane bagasse is burned to generate steam for the fermentation plant, and it also generates electricity as a byproduct. Economic allocation is applied by ecoinvent for this multifunctional process, resulting in an allocation factor of 99,45% for ethanol (the main product) and 0,55% for electricity (JUNGBLUTH *et al.*, 2007). Sugarcane fermentation generates 4,0% of the electricity (Table 7) consumed during the whole life cycle of the house, according to the electricity dataset used in the life cycle inventory, which explains how sugarcane is connected to the analyzed product system.

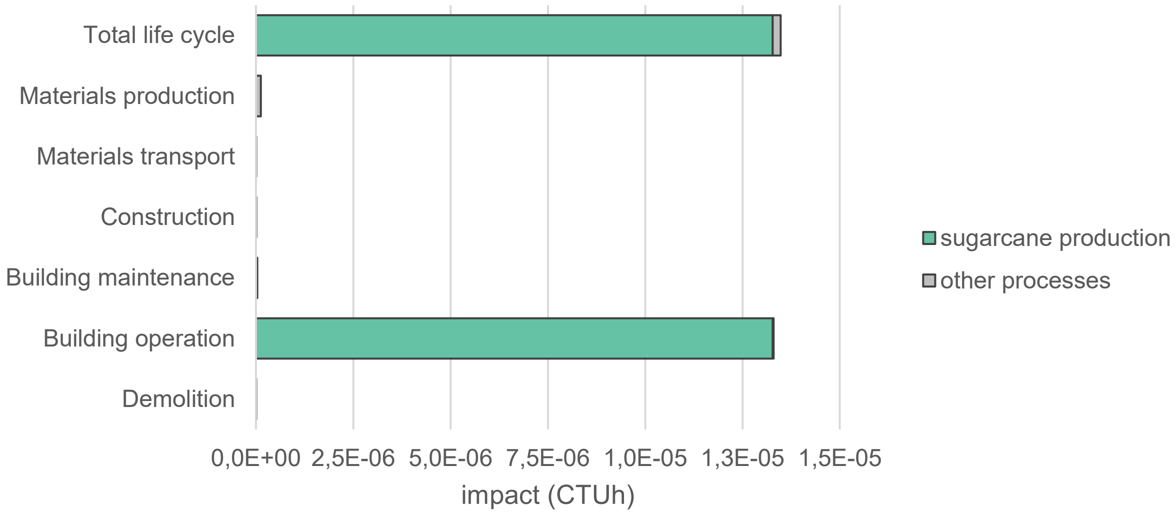
However, rather than raising a potential concern for human non-carcinogenic toxicity, this result indicates that there are no significant non-carcinogenic toxic emissions over the house's life cycle, as the impact is dominated by emissions from a background process far upstream in the supply chain. Moreover, aldrin is listed among the substances that should be eliminated according to the Stockholm Convention for Persistent Organic Pollutants (POPs), which was adopted in 2001 (UNITED NATIONS ENVIRONMENT PROGRAMME, [*s. d.*]).

Figure 34 – Contribution of elementary flows to the impact result of human non-carcinogenic toxicity. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 35 – Contribution of elementary processes to the impact result of human non-carcinogenic toxicity.



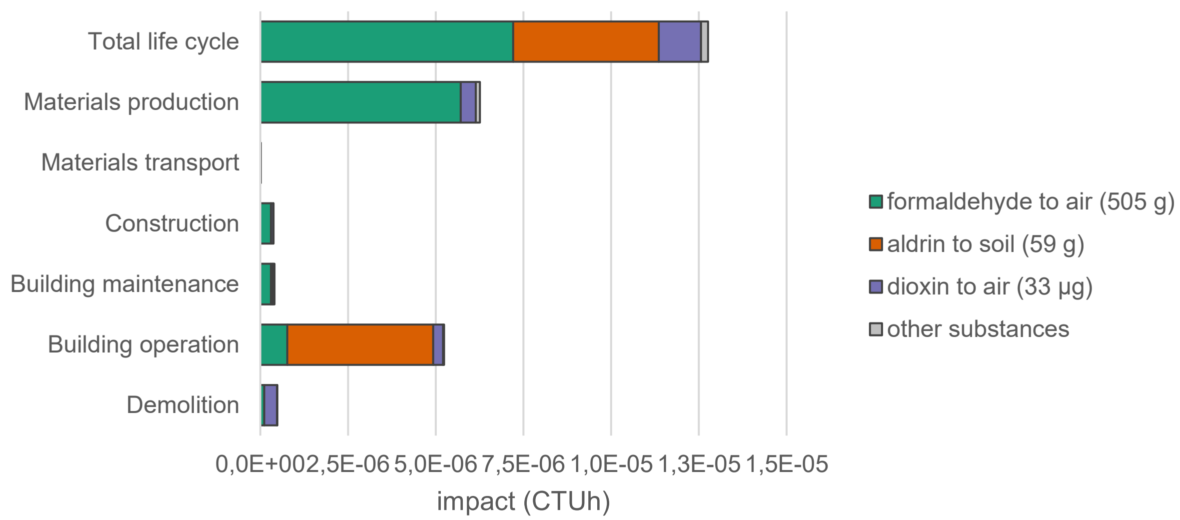
Source: the author.

3.3.12 Human carcinogenic toxicity

The human carcinogenic toxicity potential is $1{,}3.10^{-5}$ Comparative Toxic Units for human toxicity (CTUh). The leading cause is the emission of formaldehyde to air during the production of ceramic blocks (16,4 mg/kg of block) and roof tiles (24,6 mg/kg of roof tile); a total of 505 g of formaldehyde is emitted throughout the life cycle of the house (Figure 36 and Figure 37). The ecoinvent dataset for “brick production”, which represents the ceramic block, is based on data provided by 12 German factories, of which only one provided data for formaldehyde emission. The ecoinvent dataset for "roof tile production" is extrapolated from brick production by multiplying fuel consumption and the corresponding emissions by a factor of 1,5 (KELLENBERGER *et al.*, 2007). Therefore, these flows have high uncertainty.

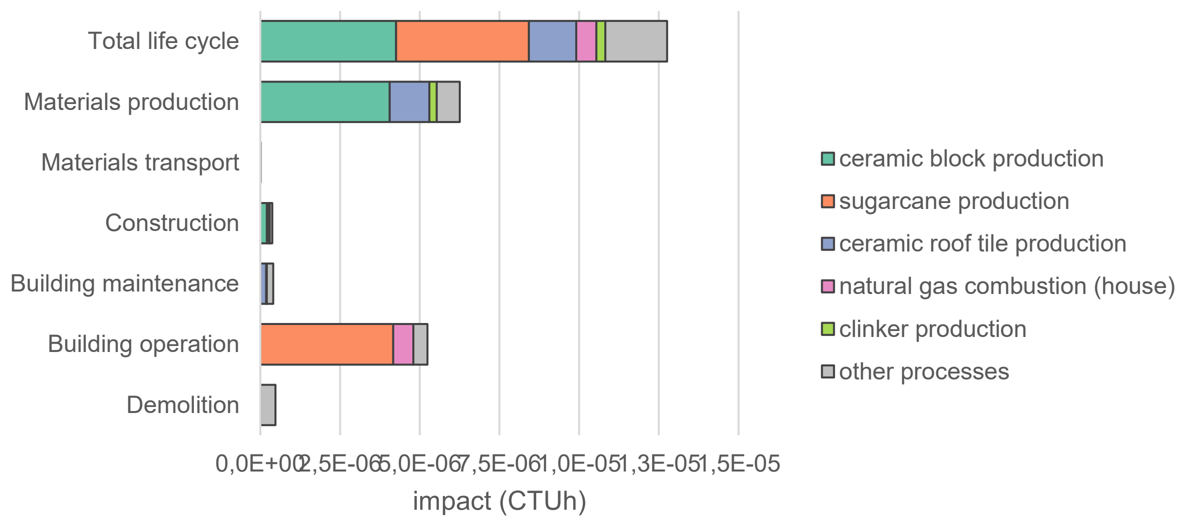
The second most important substance contributing to this impact is the emission of aldrin to the soil from sugarcane production, as already discussed for the human non-carcinogenic toxicity impact category. Dioxin, which contributes 9% of human carcinogenic toxicity (Figure 36), is emitted during clinker production, but in a minimal concentration – the total amount of dioxins released to the air for the whole life cycle of the house is 33 µg.

Figure 36 – Contribution of elementary flows to the impact result of human non-carcinogenic toxicity. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle



Source: the author.

Figure 37 – Contribution of elementary processes to the impact result of human non-carcinogenic toxicity.



Source: the author.

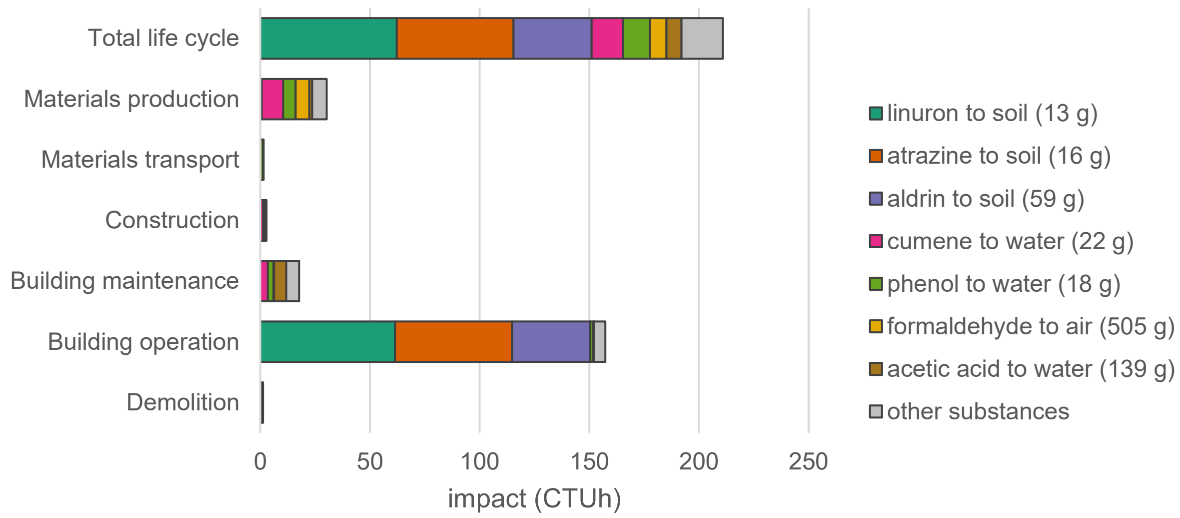
3.3.13 Freshwater ecotoxicity

The freshwater ecotoxicity potential is 211 Comparative Toxic Units for ecotoxicity (CTUe). The main contribution to this impact category comes from the emission of chemicals to soil (Figure 38) from sugarcane production (Figure 39): linuron (13 g throughout the life cycle of the house), atrazine (16 g), and aldrin (59 g). Aldrin emission has already been discussed in sections 3.3.11 and 3.3.12. Linuron and atrazine are herbicides that are toxic to aquatic animals (CHEN, 2014; LIU, 2014).

There is also a contribution from the emission of cumene and phenol to water, from the production of phenol used in wooden pallets, doors, and chemical admixtures contained in adhesive mortars (a generic organic chemical is used as a proxy). Phenol is also emitted from the discharge of water produced in petroleum platforms. These emissions to water are based on rough estimates according to ecoinvent. Formaldehyde emission to air during the production of ceramic blocks contributes 15% to this impact category.

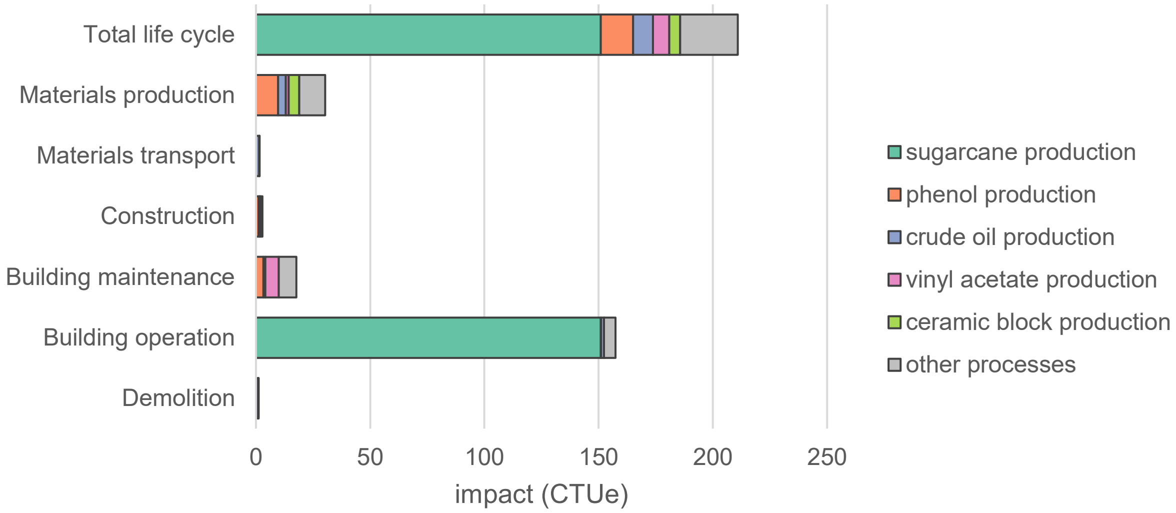
Again, these results indicate no significant emissions that contribute to freshwater ecotoxicity within the product system, as most of the impact is caused by minor emissions that stem from background processes.

Figure 38 – Contribution of elementary flows to the impact result of freshwater ecotoxicity. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 39 – Contribution of elementary processes to the impact result of freshwater ecotoxicity.

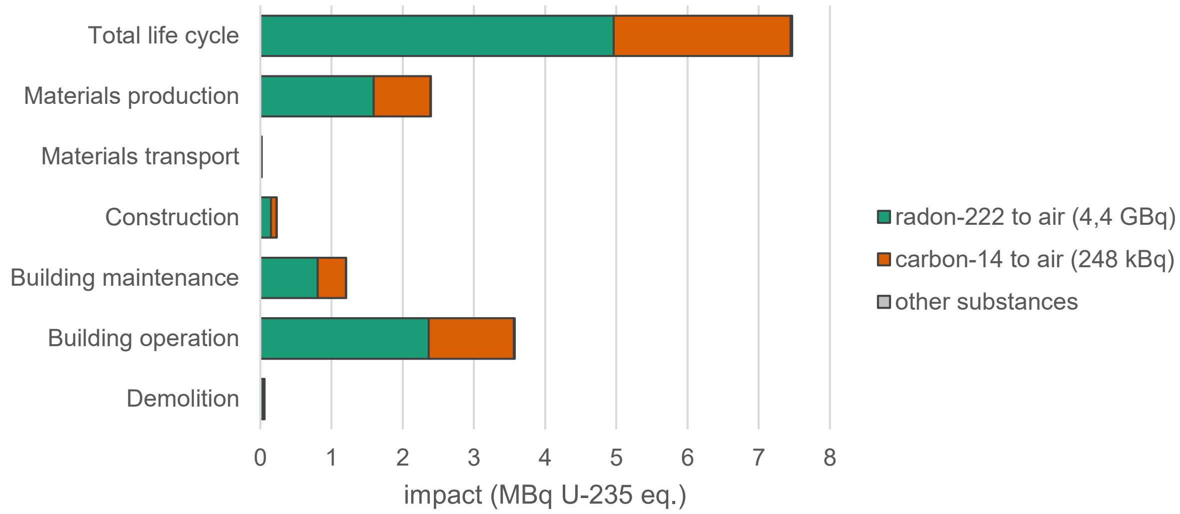


Source: the author.

3.3.14 Ionizing radiation

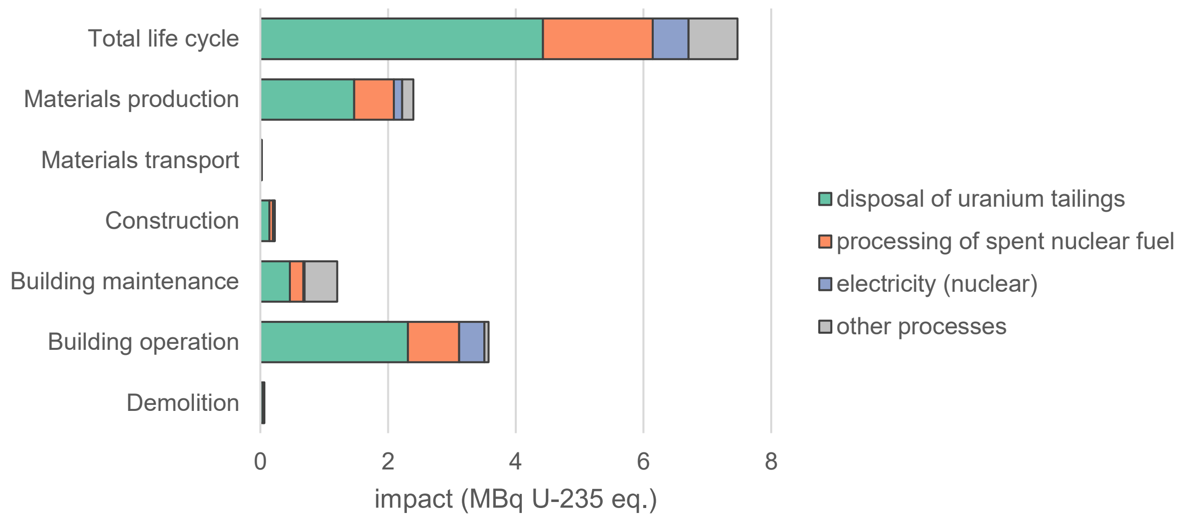
The ionizing radiation potential is 7,5 MBq Uranium-235 equivalent. It is caused by the airborne emission of Radon-222 (Figure 40) from uranium mill tailings disposed of in piles (Figure 41). Another cause is the airborne emission of Carbon-14 (Figure 40) from the reprocessing of spent nuclear fuels and radioactive waste temporarily stored at the nuclear power plant (Figure 41). These processes are part of the nuclear electricity production chain, representing 2,5% of the Brazilian electricity mix according to the dataset used (Table 7). Although the Brazilian electricity mix was considered in the operational phase of the house, no adaptations were performed for the electricity used in the production of construction materials, which is based on European datasets. As Brazil has a smaller share of nuclear power than Europe, the life cycle stages of materials production and building maintenance would be expected to contribute less to this impact category if national data were used for production processes.

Figure 40 – Contribution of elementary flows to the impact result of ionizing radiation. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle



Source: the author.

Figure 41 – Contribution of elementary processes to the impact result of ionizing radiation.



Source: the author.

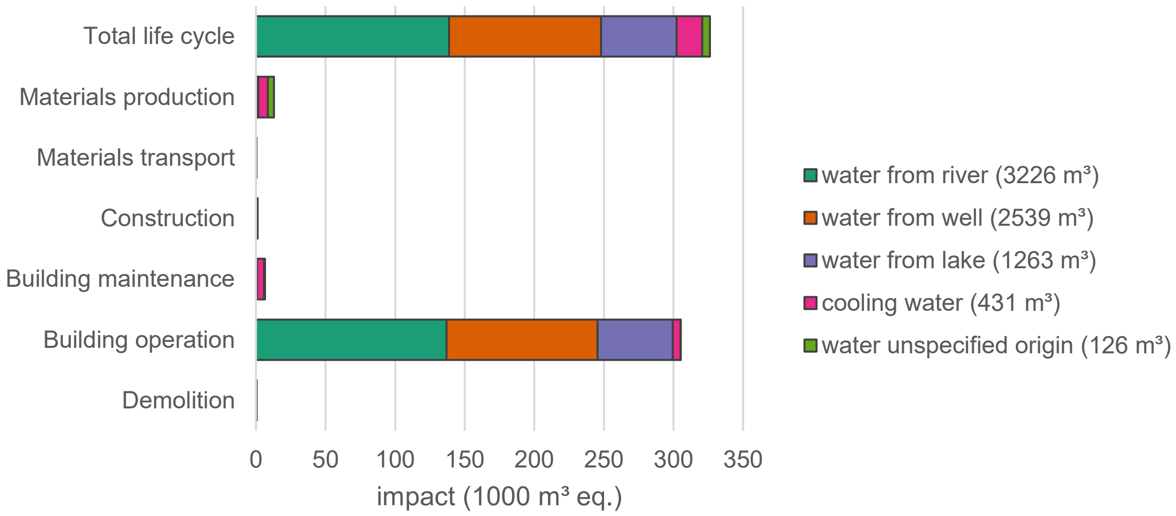
The ionizing radiation results do not include radon emitted from the soil to the interior of buildings, nor naturally occurring radioactive substances, for instance, contained in natural stones used as aggregates (usually in trace concentrations) (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2021). However, these radiation sources are not relevant for naturally ventilated buildings like the one analyzed here, as radioactive substances do not accumulate inside them (UNITED NATIONS ENVIRONMENT PROGRAMME, 2016b). According to measurements made in Brazil, the radon concentration in the indoor air is typically below 100 Bq/m³ (LARA, 2017; SILVA, 2005). Considering the volume of the analyzed building (approximately

160 m³), the total quantity of radon in the indoor air would be 16 kBq. No clear guidance exists on how to consider the total amount of radon over the house life cycle, as required in LCA; however, the result is many orders of magnitude lower than the elementary flows emitted from radioactive waste.

3.3.15 Water use

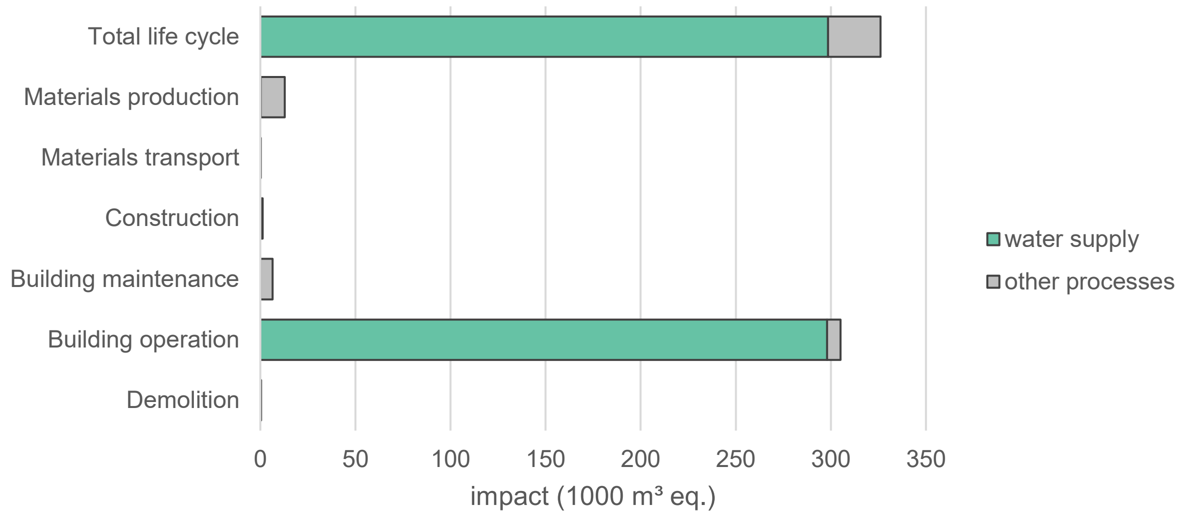
The water use potential of the house is 326.167 m³ equivalent. This result considers the water consumption in the product system (7602 m³ in total, Figure 42) multiplied by the characterization factor of the impact assessment method. Note that ecoinvent version 2 does not provide regionalized water flows, which would allow considering the local water availability. The main water use is water consumption during the 50 years of house use, corresponding to 91% of the total water use (Figure 43). The remaining impact share is mostly associated with water used for cooling in industrial processes.

Figure 42 – Contribution of elementary flows to the impact result of water use. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 43 – Contribution of elementary processes to the impact result of water use.

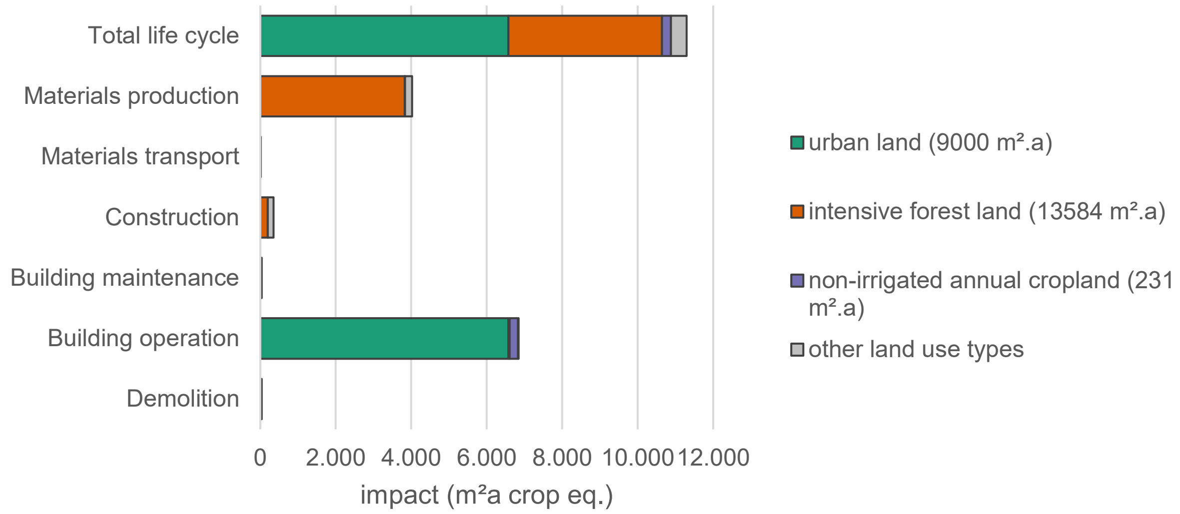


Source: the author.

3.3.16 Land use

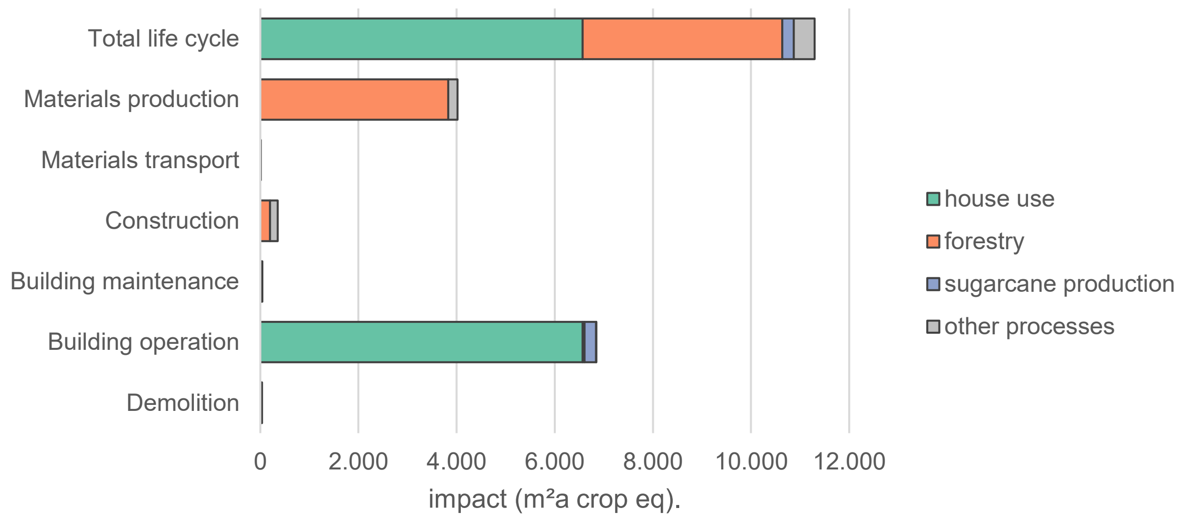
The land use potential is 11.294 m².a crop equivalent. The main driver for land use (58% of the potential impact) is the occupation of land by the house itself: 180 m² occupied over 51 years (one year of construction plus 50 years of use). The second most important cause is the area occupied for forestry to produce wood, which corresponds to 36% of the land use (Figure 45). The ecoinvent dataset for hardwood considers a yield of 14,1 m²/m³ of softwood (including bark) and a time of 150 years for forest use, resulting in 2115 m².a/m³ (WERNER *et al.*, 2007). In Brazil, forestry conditions are different (trees grow faster, extraction rates are different), but the inventory was not adapted. There is also a contribution of sugarcane production of 2% to the total land use associated with the share of electricity that comes from biomass, as discussed in previous items.

Figure 44 – Contribution of elementary flows to the impact result of land use. The numbers in the parenthesis refer to the quantity of the elementary flow over the building life cycle.



Source: the author.

Figure 45 – Contribution of elementary processes to the impact result of land use.



Source: the author.

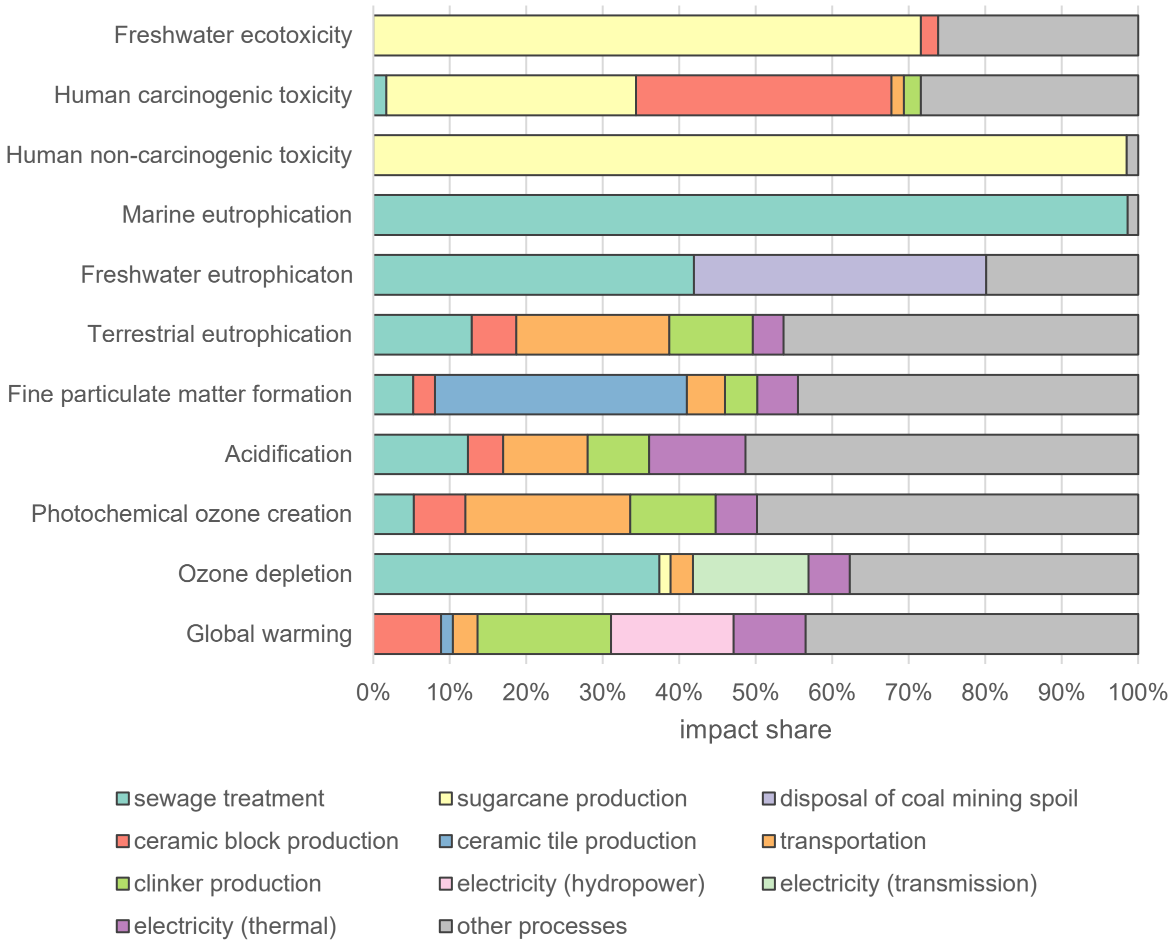
3.4 Discussion

The following discussion analyzes all LCA results together, identifying common causes behind the life cycle impact results in section 3.4.1, evaluating the influence level that construction stakeholders can exert on those causes in section 3.4.2, and analyzing the measurability of elementary flows in section 3.4.3. Environmental aspects associated with the construction life cycle and not addressed by LCA indicators are discussed in section 0. A synthesis of the discussion is shown in section 3.4.5, and section 3.4.6 discusses the limitations of the LCA study.

3.4.1 Common causes of environmental impacts

The first issue that stands out from the results is that the same elementary processes cause many impacts. Fossil fuel-intensive processes contribute significantly to global warming, ozone depletion, photochemical ozone creation, acidification, particulate matter formation, terrestrial eutrophication, and human carcinogenic toxicity. Sewage treatment contributes significantly to freshwater eutrophication, marine eutrophication, and ozone depletion, and it has smaller contributions to other impact categories. Sugarcane production is the leading cause of human non-carcinogenic toxicity and freshwater ecotoxicity and contributes to human carcinogenic toxicity. The ten most contributing elementary processes shown in Figure 46 explain between 49% and 99% of the impact results for the eleven impact categories that share common underlying causes. The remaining impact categories (mineral resource depletion, ionizing radiation, water use, and land use) do not present common causes in terms of contributing elementary processes.

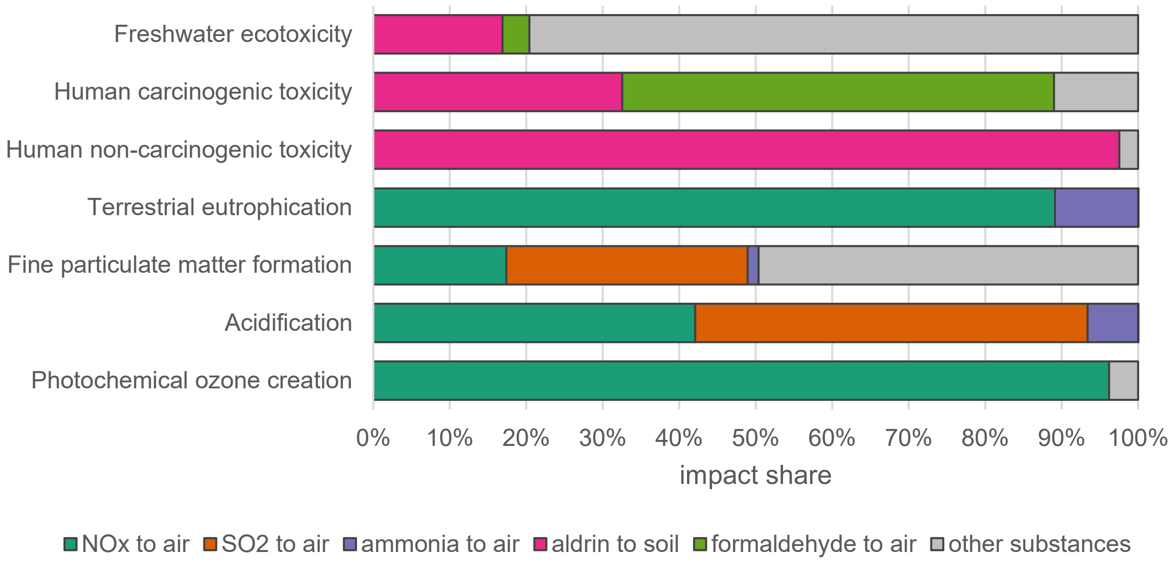
Figure 46 – Relative contribution to the impact results of the ten most contributing elementary processes to different impact categories.



Source: the author.

Furthermore, some impacts are caused by the same elementary flows (Figure 47). NO_x contributes to the creation of photochemical ozone, acidification, fine particulate matter, and terrestrial eutrophication, and SO_2 contributes to acidification and fine particulate matter formation. The emission of aldrin to soil contributes to human carcinogenic and non-carcinogenic toxicity and freshwater ecotoxicity. In some cases, the same substance can contribute to more than one impact; for instance, aldrin can be ingested by fish that can be ingested by humans, thereby causing both ecotoxicity and human toxicity. However, in other situations, this may configure double counting; for example, a molecule of NO_x that reacts to form tropospheric ozone cannot react with water to form acid rain.

Figure 47 – Relative contribution to the impact results of elementary flows shared by different impact categories.



Source: the author.

These results indicate that some life cycle impact indicators are determined by the same cause, meaning that they provide redundant information for decision-makers. For example, suppose a decision is taken to reduce the emission of nitrogen oxides from a particular process. In that case, the results of photochemical ozone creation, acidification, fine particulate matter formation, and terrestrial eutrophication will decrease, as they are all determined by NO_x emissions. Three groups of impact categories share common underlying causes:

a) Impacts caused by the consumption of fossil fuels and corresponding airborne emissions: fossil resource depletion, global warming, photochemical ozone creation, acidification, fine particulate matter formation, terrestrial eutrophication, and, to a lesser extent, human carcinogenic toxicity;
b) Impacts caused by the emission of toxic substances from pesticides (during sugarcane production for electricity generation): human non-carcinogenic toxicity, freshwater ecotoxicity and, to a lesser extent, human carcinogenic toxicity;
c) Impacts caused by emissions to water from wastewater treatment: freshwater and marine eutrophication.

Lasvaux et al. (2016) also observed correlations among impact categories based on cradle-to-gate LCA results for 98 construction products (LASVAUX *et al.*, 2016). These authors applied Principal Component Analysis (PCA), identifying five components, i.e., five groups of correlated impact results: 1) abiotic depletion of fossil fuels, global warming, photochemical ozone creation, acidification, and eutrophication; 2) freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, and human toxicity; 3) ionizing radiation and ozone depletion; 4) land use; 5) abiotic depletion of elements (no impact category associated with water use was considered in this analysis). Note that the first two groups agree with the results of this study. Steinmann et al. (2016) also applied PCA to 976 products (including, but not limited to, construction products) and 135 impact indicators from the ecoinvent database. These authors found six indicators that together explain 92,3% of the total variance: climate change, land use, ozone depletion, acidification (and eutrophication), marine toxicity, and terrestrial ecotoxicity. These authors also investigated the correlations with footprint indicators, with fossil energy consumption explaining the highest share of environmental impacts (92,3%). Huijbregts et al. (2006) also observed that fossil energy demand is strongly correlated with resource depletion, global warming, acidification, eutrophication, and photochemical ozone creation; there is also a moderate correlation with stratospheric ozone depletion and human toxicity (HUIJBREGTS *et al.*, 2006).

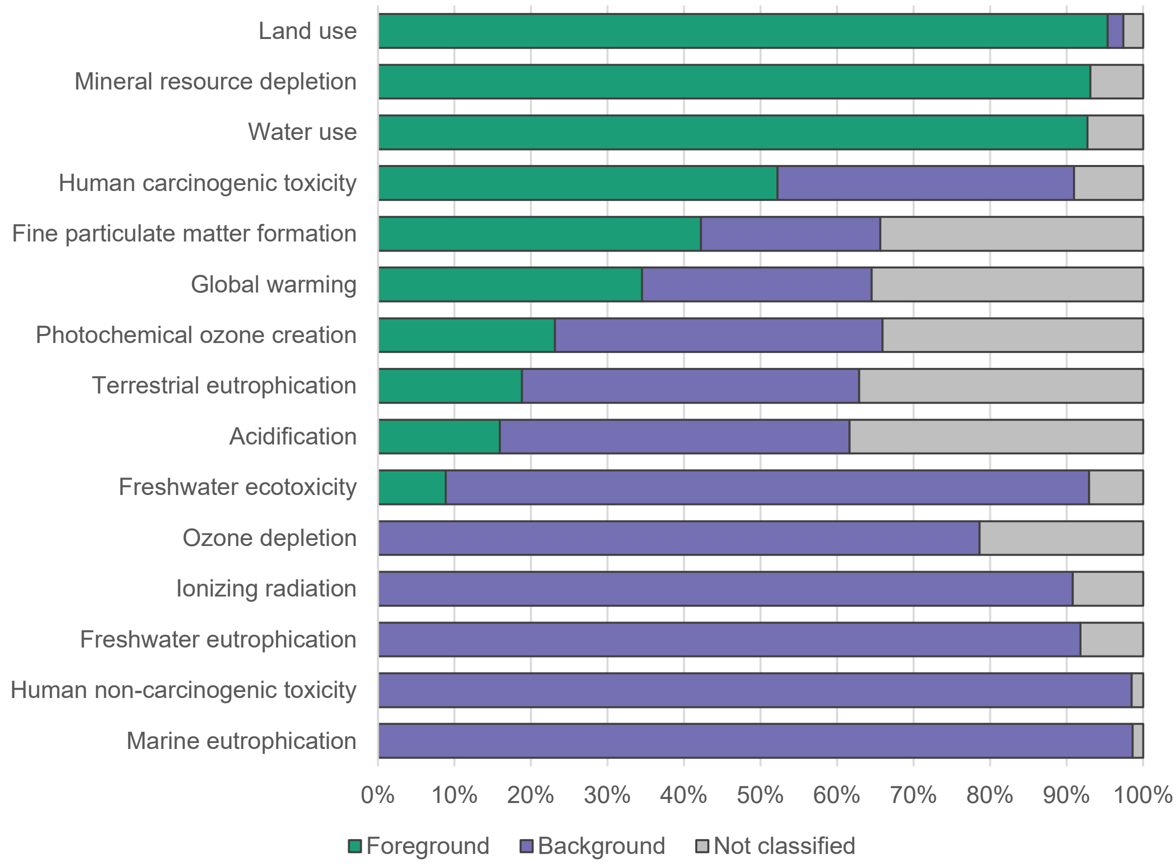
3.4.2 Level of influence on environmental impacts

Another aspect that deserves analysis is the possibility of influencing processes causing environmental impacts, as it is one of the criteria that define a key environmental performance indicator. Construction stakeholders can directly influence some processes, such as reducing the emission of CO_2 in clinker production, increasing the efficiency of energy and water use during building operation, or increasing the efficiency of land use for construction. However, other processes are more difficult to change. For instance, human non-carcinogenic toxicity and freshwater ecotoxicity are caused chiefly by sugarcane production emissions, a process far upstream in the electricity supply chain. Therefore, to reduce the impact caused by this process, construction stakeholders must reduce electricity consumption, meaning that this impact can only be indirectly influenced.

Other impact categories whose causes are hard to influence are: 1) ionizing radiation, caused by processes associated with nuclear electricity generation; 2) ozone depletion, caused mostly by emissions from sewage treatment and the transmission of electricity in high voltage lines; 3) freshwater eutrophication, caused by sewage treatment and the landfilling of coal mining spoils and of sulfidic tailings; and 4) marine eutrophication, caused by sewage treatment.

Figure 48 synthesizes the share of each impact result caused by processes belonging to either the foreground or the background system to illustrate the influence construction stakeholders have on the different impact categories. LCA guidelines define the foreground system as being formed by processes under the control or influence of construction stakeholders, whereas the background system consists of processes that they cannot influence (at least not directly) (EUROPEAN COMMISSION; JOINT RESEARCH CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2010). The following processes are part of the background system: electricity generation and transmission (as well as preceding activities, such as nuclear fuel or sugarcane production), fuel production, transportation (the operation of vehicles, since customers can usually only influence the transportation distance), sewage treatment, and landfilling.

Figure 48 – Share of impact results caused by processes belonging to the foreground or the background system. Processes that contribute less than 1% to the total impact result were considered "not classified".

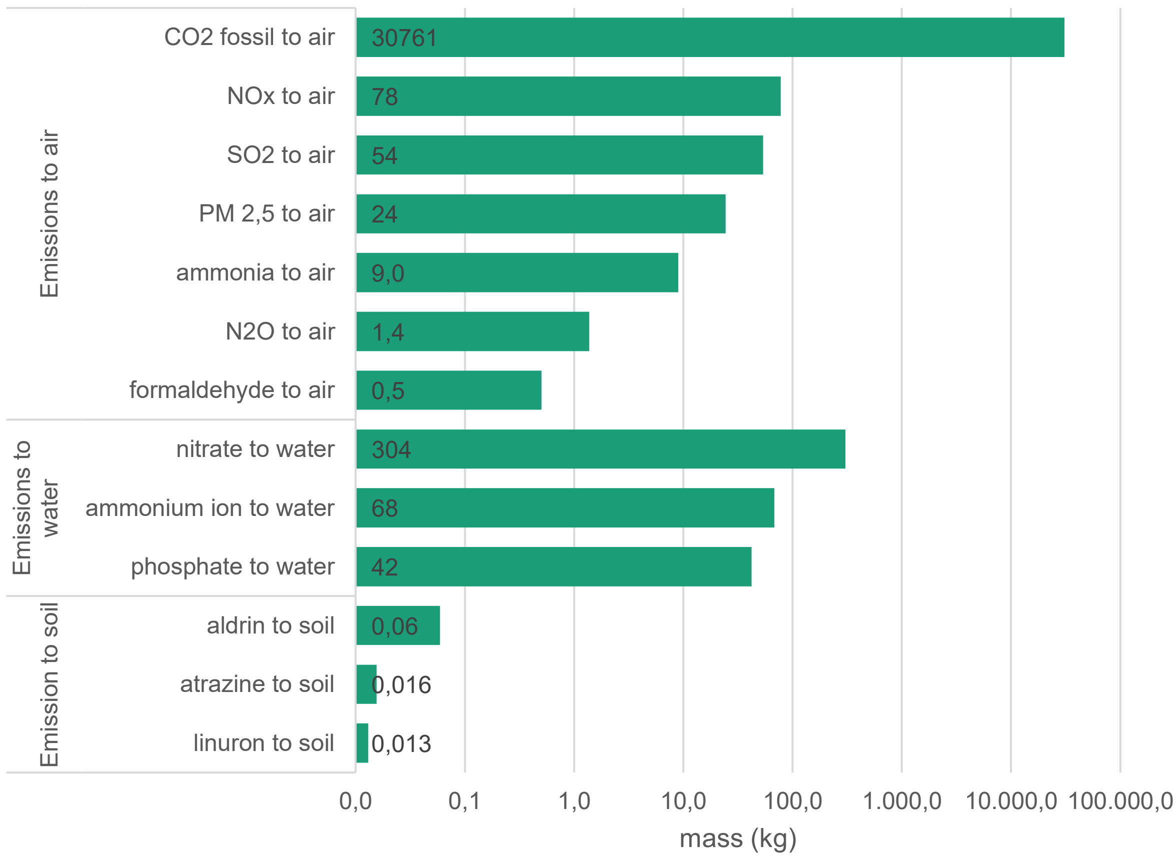


Source: the author.

3.4.3 Elementary flows magnitude

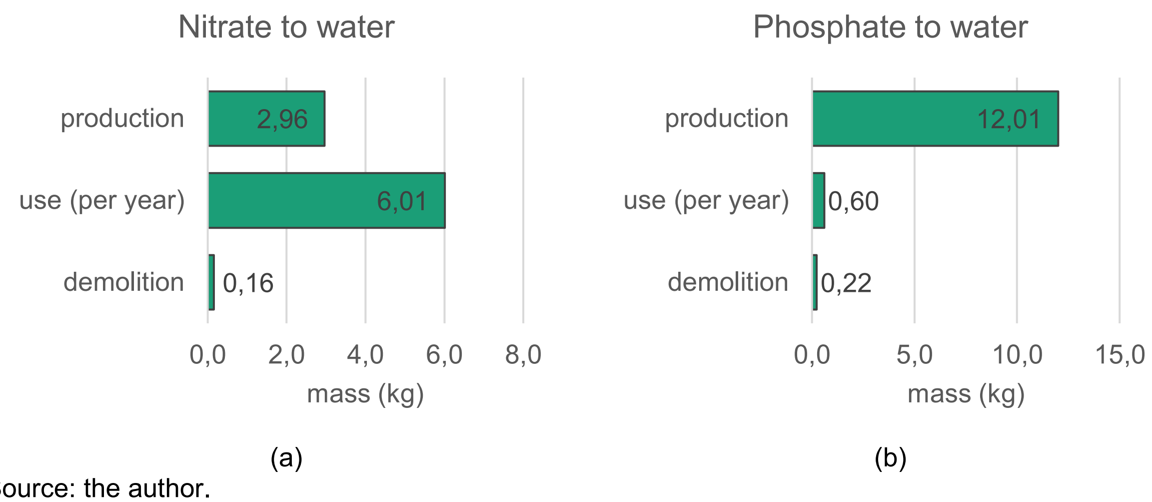
There are substantial differences in the magnitude of the elementary flows that determine impact results. Figure 49 presents the mass of all emissions that contribute significantly to the impact results of the house. While some emissions correspond to a high mass, such as CO_2 (30,7 t), others correspond to less than 1 kg throughout the 50 years life cycle of the house, such as formaldehyde. Furthermore, their quantities become even smaller when emissions are distributed over the use phase (as measured and controlled). Figure 50 illustrates this distribution for two emissions to water that mostly happen during the use phase. For example, although 304 kg of nitrate are emitted over the life cycle, only 6,0 kg are emitted per year during the use phase, or 16 g/day – to compare, CO_2 emission during the use phase is approximately 0,6 kg/day. In general, the lower the magnitude of an elementary flow, the more difficult it is to measure it and the more uncertain it becomes.

Figure 49 – Mass of the main elementary flows (emissions only) throughout the house's life cycle. Only emissions contributing to at least 10% of at least one impact category are presented. Note that the scale of the chart is logarithmic



Source: the author.

Figure 50 – Mass of emissions distributed over the life cycle, with the emissions of the use phase disclosed by year and over 50 years: a) nitrate emitted to water; b) phosphate to water. Emissions from operation and maintenance are distributed equally over the use phase.



Source: the author.

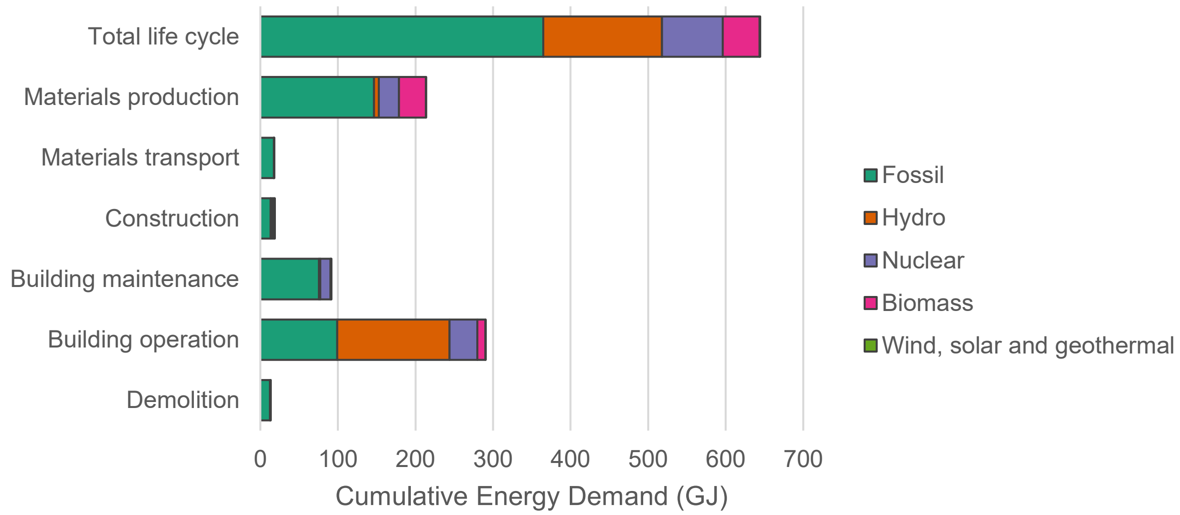
3.4.4 Environmental aspects not addressed in LCA

There are relevant environmental aspects associated with the construction life cycle that are not addressed in LCA. For example, construction minerals are not considered, albeit corresponding to a mass of 128 t over the building's life cycle. Construction minerals represent at least 50% of the global material footprint (SCHANDL *et al.*, 2018). The consumption of bulk minerals is not an environmental impact per se because these minerals are abundant globally. However, these minerals can be locally scarce (IOANNIDOU *et al.*, 2017). Furthermore, their extraction is associated with negative environmental and social impacts that should also be minimized (MIATTO *et al.*, 2017; UNITED NATIONS ENVIRONMENT PROGRAMME, 2019b).

Likewise, conventional LCA indicators do not detect solid waste generation, even considering that the house's mass (87 t) becomes waste when demolished. Neglecting solid waste generation happens because the majority is inert waste (OSMANI; VILLORIA-SÁEZ, 2019), and emissions from inert landfills do not cause environmental impacts such as eutrophication or toxicity. However, construction and demolition waste (CDW) corresponds to approximately 35% of the total waste generated in the European Union and 30% to 40% of the waste generated in China (OSMANI; VILLORIA-SÁEZ, 2019), to illustrate their importance. Recycling and backfilling rates are low in many parts of the world, where much of CDW goes to inert landfills (OSMANI; VILLORIA-SÁEZ, 2019) or ends up in illegal dump sites (ZAINUN; RAHMAN; ROTHMAN, 2016), with negative environmental and social impacts.

The LCA results also do not fully represent energy consumption over the house's life cycle. The share of fossil resources in the total primary energy demand is 57% (Figure 51). Although fossil resource depletion is required by LCA standards, running out of fossil resources is not a primary environmental concern. In fact, to limit global warming, a significant share of fossil resource reserves must remain unused (MCGLADE; EKINS, 2015). It is essential to consider energy consumption from renewable sources as they are not free of environmental, economic and social impacts (DAVIS *et al.*, 2018). Moreover, encouraging energy efficiency in the construction sector makes shifting to renewable energy sources easier as less energy needs to be generated.

Figure 51 – Contribution of different primary energy resources to the cumulative energy demand of the house.



Source: the author.

Furthermore, although many LCA indicators deal with pollutants and their impacts, not all types of pollution are covered. One example is indoor air pollution, a concern present in many green building labels (BRE GLOBAL, 2016; DEUTSCHE GESELLSCHAFT FÜR NACHHALTIGES BAUEN, 2018b; HQE; CERWAY, 2014; U. S. GREEN BUILDING COUNCIL, 2019) because of the emission of volatile organic compounds (VOCs) from building products such as paints and adhesives. Another example is water pollution by pathogens (e.g., faecal coliforms), caused mainly by untreated domestic sewage, estimated to cause 3,4 million deaths yearly (UNITED NATIONS ENVIRONMENT PROGRAMME, 2016a). Hence, the comprehensiveness of LCA in terms of environmental impact categories does not make LCA a panacea.

3.4.5 Synthesis

Table 8 presents a synthesis of the discussion, covering all impact categories analyzed for the house's life cycle.

Table 8 – Summary of the analysis of the impact categories assessed in the LCA of the house.

Impact category	**Main elementary flows causing the impacts**	**Main processes causing the impacts**
Depletion of mineral elements	Consumption of copper and lead	Consumption of metallic minerals
Depletion of fossil fuels	Consumption of natural gas, crude oil, and coal	Consumption and combustion of fossil fuels
Global warming	Emission of CO_2 into the air	
Photochemical ozone creation	Emission of NO_x into the air	
Acidification	Emission of SO_2 and NO_x into the air	
Fine particulate matter formation	Emission of PM 2.5 µm, SO_2, and NO_x into the air	
Terrestrial eutrophication	Emission of NO_x into the air	
Freshwater eutrophication	Emission of phosphate into the water	
Marine eutrophication	Emission of nitrate and ammonium ion into the water	Sewage treatment
Ozone depletion	Emission of N_2O into the air	Electricity transmission
Human non-carcinogenic toxicity	Emission of aldrin into the soil	Sugarcane production (for electricity)
Freshwater ecotoxicity	Emission of linuron, atrazine, and aldrin into the soil	
Human carcinogenic toxicity	Emission of aldrin into the soil and of formaldehyde into the air	Combustion of fossil fuels
Ionizing radiation	Emission of Radon-222 and carbon-14 into the air	Nuclear electricity production
Water use	Water consumption	Water consumption during the use phase
Land use	Urban area occupation and forest area occupation	Land occupation by the house and forestry

Source: the author.

3.4.6 Limitations

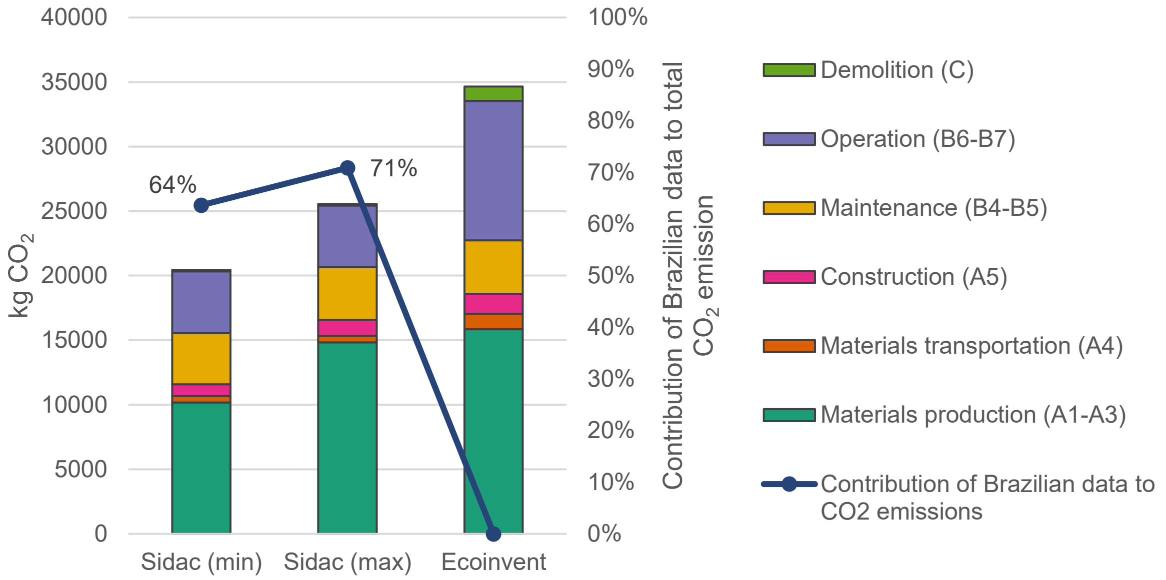
One of the limitations of this study is considering a single specification for the house. If other materials were considered, the causes of environmental impacts would probably be different. For example, considering a light steel framing system instead of masonry could increase the contribution of metal mining and beneficiation processes to some impact categories, such as freshwater eutrophication, which is partly determined by leached substances from metallic mining spoils. It could also increase the share of foreground processes contributing to mineral resource depletion. Also, considering wood treated with preservatives against termite attack could affect the toxicity-related impact indicators. Nevertheless, the materials used in the house agree with Brazil's national bill of construction materials, which is unlikely to change soon. However, the results do not apply to other countries that use different construction systems as the primary form of construction.

Also, the use phase was modelled using average data for energy and water consumption and Brazil's average share of energy sources. Specific buildings and use patterns may yield different results, especially for the impact categories mostly determined by operational energy and water use. For example, buildings with air conditioning consume more electricity, increasing the relative contribution of electricity to environmental impacts. If refrigerant gas leaks during maintenance are considered, the contribution to ozone depletion or global warming may increase significantly (depending on the substance used as a refrigerant). However, since the use phase considers average Brazilian data, the findings are consistent at the country level.

Another limitation of this LCA study is using foreign secondary inventory data from the ecoinvent database. Ideally, the analyses should be conducted using national data representing the foreground and the background systems. However, these data are unavailable for Brazil, especially in the detail level required for the analyses conducted here for elementary processes and flows. Collecting national data covering all elementary flows required would be unfeasible for this study – for instance, modelling the leaching of substances from landfills or collecting airborne emission data for all material production processes. Therefore, the results should be regarded with caution, and the values for potential impact results presented in Table 6 should not be taken as a reference or benchmark for Brazilian buildings.

A new calculation was performed to estimate the potential deviation between indicators caused by using Brazilian data. Ecoinvent datasets were replaced with CO_2 emission data from the Information System for Environmental Performance in Construction (Sidac) (MINISTÉRIO DE MINAS E ENERGIA; CONSELHO BRASILEIRO DE CONSTRUÇÃO SUSTENTÁVEL, 2022), the official Brazilian system for construction products' life cycle data. Minimum and maximum CO_2 emissions per declared unit are available for some materials (concrete, mortar, gravel, clay block, clay roof tile, rebar, and wood) and some basic inputs (electricity, fuels, water, and transportation). The rest of the datasets were kept as ecoinvent data. Figure 52 shows the results of this comparison.

Figure 52 - Comparison of CO_2 emission results calculated using Brazilian data from Sidac and ecoinvent data.



Source: the author.

The CO_2 emission results calculated using Brazilian data are 28% to 43% lower than those calculated using ecoinvent data. The main difference occurs in the operational phase, mainly related to electricity. Sidac considers an emission factor of 0,07 kg CO_2/kWh, including only emissions from fossil fuel combustion in thermal power plants. In contrast, ecoinvent considers an emission factor of 0,21 kg CO_2/kWh, of which 0,10 kg CO_2/kWh is associated with land transformation for constructing hydropower reservoirs. This difference also reflects in other life cycle stages since most processes consume electricity. Also, ecoinvent data overestimate the impact of materials production, as the total CO_2 emission is higher than the maximum value assessed using Sidac. Brazilian data contribute to 64% to 71% of the total CO_2 emissions, meaning that a high representativeness level is achieved for this indicator, even considering the limited number of datasets available in Sidac compared to ecoinvent.

Despite these differences, the main conclusions regarding the most important elementary processes and flows remain valid. The analysis allows understanding each impact indicator's meaning as it is assessed today, predominantly based on foreign, secondary data. The limitation of secondary data also explains why other building typologies, construction systems, and use patterns were not investigated in this study. Performing such analyses would further increase the use of unrepresentative secondary data, and the uncertainties would limit the contribution of these additional analyses to the purpose of this work.

Regarding the use of ecoinvent version 2 data instead of the updated version 3, the sensitivity analysis presented in the appendix of this thesis shows that, despite the differences in the total LCA results, the main conclusions derived from the analysis at the elementary process level remain valid.

3.5 Conclusion

This chapter presented an in-depth analysis of the LCA results for the entire life cycle of a typical Brazilian building, using the conventional LCA methodology and an international LCI database. The sixteen impact categories required by the new version of EN 15804 were analyzed. The specific processes and elementary flows causing the impacts were identified. This type of analysis is not usual. Most LCA studies tend to focus on aggregated results, failing to understand the real meaning of impact results in the interpretation phase.

The LCA results show that some impacts are caused by the same processes and sometimes even by the same elementary flows. This result is confirmed by correlations found in the literature. These correlated LCA indicators provide redundant information for decision-makers, as a single action can improve the results of different indicators. For instance, reducing the consumption of fossil fuels can decrease multiple impact results determined by airborne emissions from fossil fuels, including global warming, photochemical ozone creation, acidification, fine particulate matter formation, and terrestrial eutrophication (except if a specific pollutant is to be abated, but that is generally not the case for LCA-based analyses).

Another finding is that whereas some impacts are caused by processes that construction stakeholders can control, others are caused by background activities that are very difficult to influence. For example, the use of pesticides in the production of sugarcane that generates the bagasse used for electricity production is the leading cause of human non-carcinogenic toxicity and freshwater ecotoxicity of the house. On the other hand, current LCA indicators do not reflect relevant environmental aspects for construction, such as the consumption of construction minerals and the generation of solid waste.

Furthermore, the results show that the elementary flows causing the impacts are very different in magnitude. For example, the emission of CO_2 over the building's life cycle is 30,7 t, versus 1,4 kg of ozone-depleting substances or 88 g of pesticides. Moreover, elementary flows are not equally easy to measure, and some of them refer to fugitive emissions that can only be estimated with high uncertainty.

Therefore, life cycle impact indicators do not meet all characteristics of effective environmental performance indicators presented in chapter 2. The high number of indicators – 16 impact categories – lacks priority. Besides reporting indicators with common underlying causes, LCA includes impacts that construction stakeholders can hardly influence. Furthermore, some elementary flows required to calculate LCA results can be challenging to measure or estimate, reducing indicators' measurability, reliability, and comparability. The results confirm that LCA requires simplification to deliver effective construction environmental performance indicators for decision support.

4 PROPOSAL OF LIFE CYCLE-BASED ENVIRONMENTAL PERFORMANCE INDICATORS FOR DECISION-MAKING IN CONSTRUCTION

The analysis of the LCA results of a typical Brazilian building reveals that the full set of indicators required by LCA standards do not meet the characteristics of effective environmental performance indicators for decision-making. Furthermore, many indicators are not among the main environmental concerns of the construction sector. LCA is a data-intensive process and could only be executed in this study using secondary life cycle inventory data unrepresentative of Brazilian construction products and background processes. The difficulty of measuring life cycle inventory flows makes it hard to work with primary data. Consequently, it reduces the reliability of impact assessment results. The number of life cycle impact categories (16 according to EN 15804) surpasses the number of indicators considered appropriate by construction stakeholders (five indicators according to the survey). Furthermore, some impacts are caused by processes that do not belong to the construction value chain, making it difficult for the construction sector to influence them. On the other hand, environmental aspects important for construction are underrepresented in LCA.

Previous surveys with stakeholders have already indicated these limitations of LCA (COOPER; FAVA, 2006; FREIDBERG, 2015; TESTA *et al.*, 2016), including surveys conducted in the construction sector (BALOUKTSI *et al.*, 2020; OLINZOCK *et al.*, 2015; SAUNDERS *et al.*, 2013). The high data collection workload is considered a significant barrier for LCA (GRAEDEL, 1998; TODD; CURRAN, 1999) and prevents the development of market benchmarks (SCHALTEGGER, 1996). Secondary data are frequently used to work around this difficulty (OSSÉS DE EICKER *et al.*, 2010; SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016), but these data are usually unrepresentative of the actual life cycle inventory flows. Unrepresentative LCI data undermine the reliability of LCA results and, consequently, the confidence in them to support decisions (OLINZOCK *et al.*, 2015; SAUNDERS *et al.*, 2013).

Despite the positive features of LCA, it needs simplification to enable its use for day-to-day decision-making. Many studies agree that LCA must be simplified (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020; GRAEDEL, 1998; KELLENBERGER; ALTHAUS, 2009; LASVAUX *et al.*, 2016, 2014; LEWANDOWSKA *et al.*, 2015; OLINZOCK *et al.*, 2015; SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016; TECCHIO *et al.*, 2019; TODD; CURRAN, 1999; WORLD

BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2016; ZABALZA BRIBIÁN; ARANDA USÓN; SCARPELLINI, 2009). In this chapter, the LCA scope recommended by international construction LCA standards is the starting point for proposing a set of life cycle-based construction environmental performance indicators that meet the requirements of effective indicators for decision support.

4.1 Simplification strategies for LCA

The idea of simplifying LCA has been discussed since the 1990s, with a task group of SETAC North America releasing a report discussing strategies to streamline LCA (TODD; CURRAN, 1999) and the publication of the book "*Streamlined Life-Cycle Assessment*" by Thomas Graedel (GRAEDEL, 1998). Both publications reflect the concern of making LCA useful for decision-making. Since then, many studies have discussed the simplification or streamlining of LCA (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020; GRADIN; BJÖRKLUND, 2021), including in the construction sector (HESTER *et al.*, 2018; KELLENBERGER; ALTHAUS, 2009; LASVAUX *et al.*, 2014; LEWANDOWSKA *et al.*, 2015; MALMQVIST *et al.*, 2011; SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016; ZABALZA BRIBIÁN; ARANDA USÓN; SCARPELLINI, 2009). Here, the terminology proposed by Beemsterboer, Baumann and Wallbaum (2020) is used to describe LCA simplification strategies.

4.1.1 Inventory data substitution

LCA simplifications are often motivated by a lack of data (GRADIN; BJÖRKLUND, 2021). Therefore, multiple strategies exist to reduce the effort of compiling the life cycle inventory (Figure 53 represents the data required for a cradle-to-grave LCA of a building). The most widespread strategy is substituting inventory data using secondary data from LCA databases (Figure 54). This strategy is so common that many LCA studies do not even recognise it as a simplification (GRADIN; BJÖRKLUND, 2021).

Although secondary data are usually needed to model the background system, because of the difficulty of collecting primary data for these processes, they are often used to model the foreground system (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). The selection of secondary data is generally based on similarities between processes, usually a rough approximation that can be misleading. Furthermore, not all countries have comprehensive LCA databases, leading to the use of foreign databases (OSSÉS DE EICKER *et al.*, 2010). Despite the widespread practice, secondary or proxy data may increase the uncertainty of LCA results significantly (HESTER *et al.*, 2018; REAP *et al.*, 2008b; SILVA *et al.*, 2017). There is also a risk of cherry-picking LCA data to achieve more favourable results.

4.1.2 Inventory parts exclusion

Another strategy is to exclude parts of the life cycle inventory, such as life cycle stages or processes (Figure 55). Lewandowska et al*.* (2015) conclude that considering only the materials production and use stages allows sufficient accuracy of buildings' LCA results. Also, Zabalza Bribián, Aranda Usón and Scarpellini (2009) consider only material production and operational energy use because these life cycle stages contribute most to energy consumption and CO_2 emission. DGNB takes a similar approach and requires considering materials production (including maintenance and replacement over the lifetime), operational energy and water use, and the building's end-of-life (DEUTSCHE GESELLSCHAFT FÜR NACHHALTIGES BAUEN, 2018a). However, the LCA results presented in chapter 3 show that excluding the construction stage would omit a non-negligible amount of materials wastage on the construction site.

Regarding the exclusion of processes, many LCA studies consider only the foundation, structure, and envelope of the building for calculating the embodied environmental impacts, ignoring other building parts such as electrical and hydraulic installation (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016; ZABALZA BRIBIÁN; ARANDA USÓN; SCARPELLINI, 2009). Herein, cutting off products or processes with a negligible contribution in terms of mass, energy, or environmental impacts is a common simplification strategy (GRADIN; BJÖRKLUND, 2021). However, Kellenberger and Althaus (2009) show that ancillary materials usually cut-off from LCA studies, such as nails used in wooden structures, present a non-negligible contribution to LCA results depending on the impact category. Therefore, the decision to exclude certain processes or life cycle stages from the LCA scope is context-specific and hard to generalize.

4.1.3 Impact category exclusion

A different simplification strategy consists of excluding some impact categories, using fewer indicators (Figure 56). Each impact indicator requires a set of elementary flows to be calculated, which sometimes can reach thousands of substances (ROSENBAUM *et al.*, 2008). Therefore, reducing the number of impact categories reduces the demand for life cycle inventory data. Many construction LCA studies prioritize specific impact categories, with cumulative energy demand and global warming being more frequently assessed than other environmental impact categories (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). However, LCA specialists often criticise this strategy because omitted impacts can increase without being noticed by decision-makers, which is known as unintended burden shifting (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020). Nevertheless, this criticism ignores that some impact categories are correlated (HUIJBREGTS *et al.*, 2006; LASVAUX *et al.*, 2016). Furthermore, today most decisions taken in the construction sector do not consider environmental performance at all.

4.1.4 Qualitative expert judgement

There are other alternatives to reduce the data collection effort. One is to use qualitative expert judgement (Figure 57), such as the matrix approach proposed by (GRAEDEL, 1998). In this matrix, the life cycle stages are represented in the rows and the environmental stressors in the columns. Each cell receives a score linking life cycle stages and stressors. For example, in concrete production, the life cycle stage “clinker production” would receive a bad score for the environmental stressor “gaseous residues” because of the high direct CO_2 emission and a good score for “solid residues” because it does not generate solid waste. The matrix can be useful for identifying hotspots for action within a company. However, this procedure does not allow for a consistent exchange of environmental performance information across the supply chain because it is not a quantitative assessment. Furthermore, scores are given based on subjective judgement (HOCHSCHORNER; FINNVEDEN, 2003), which reduces reliability and comparability. Therefore, qualitative expert judgment is considered here an alternative to LCA rather than a simplification of LCA, as it does not allow for measuring the environmental performance of products.

4.1.5 Standardization and automation

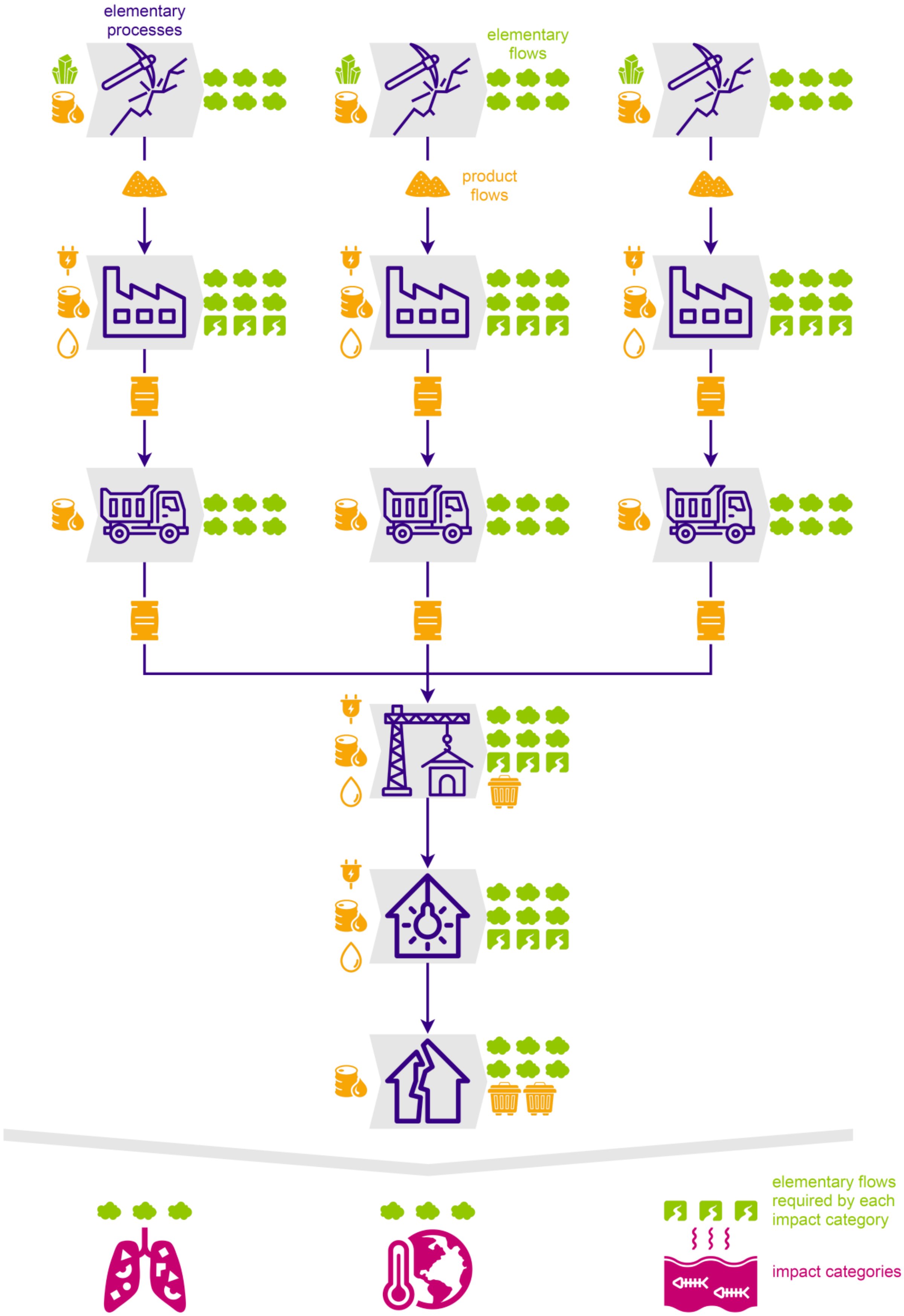
Standardization saves the LCA developer from making decisions by providing predefined criteria, such as the system boundary, cut-off criteria, and impact categories. Automation (Figure 58) accelerates LCA by making it easier to compile the life cycle inventory and calculate impact results (BEEMSTERBOER; BAUMANN;

WALLBAUM, 2020). For instance, the integration between LCA and ERP systems allows for automatizing the collection of life cycle inventory data (MEINRENKEN *et al.*, 2012). If connected with sensors, LCA-ERP integration can ultimately lead to real-time environmental performance indicators (FERRARI *et al.*, 2021). Another example of automation is the integration between LCA and BIM for collecting building inventory data such as material quantities (RÖCK *et al.*, 2018). However, neither standardization nor automation reduces the demand for data unless combined with other strategies, such as using LCA software to access secondary LCA databases.

4.1.6 Normalization and weighing

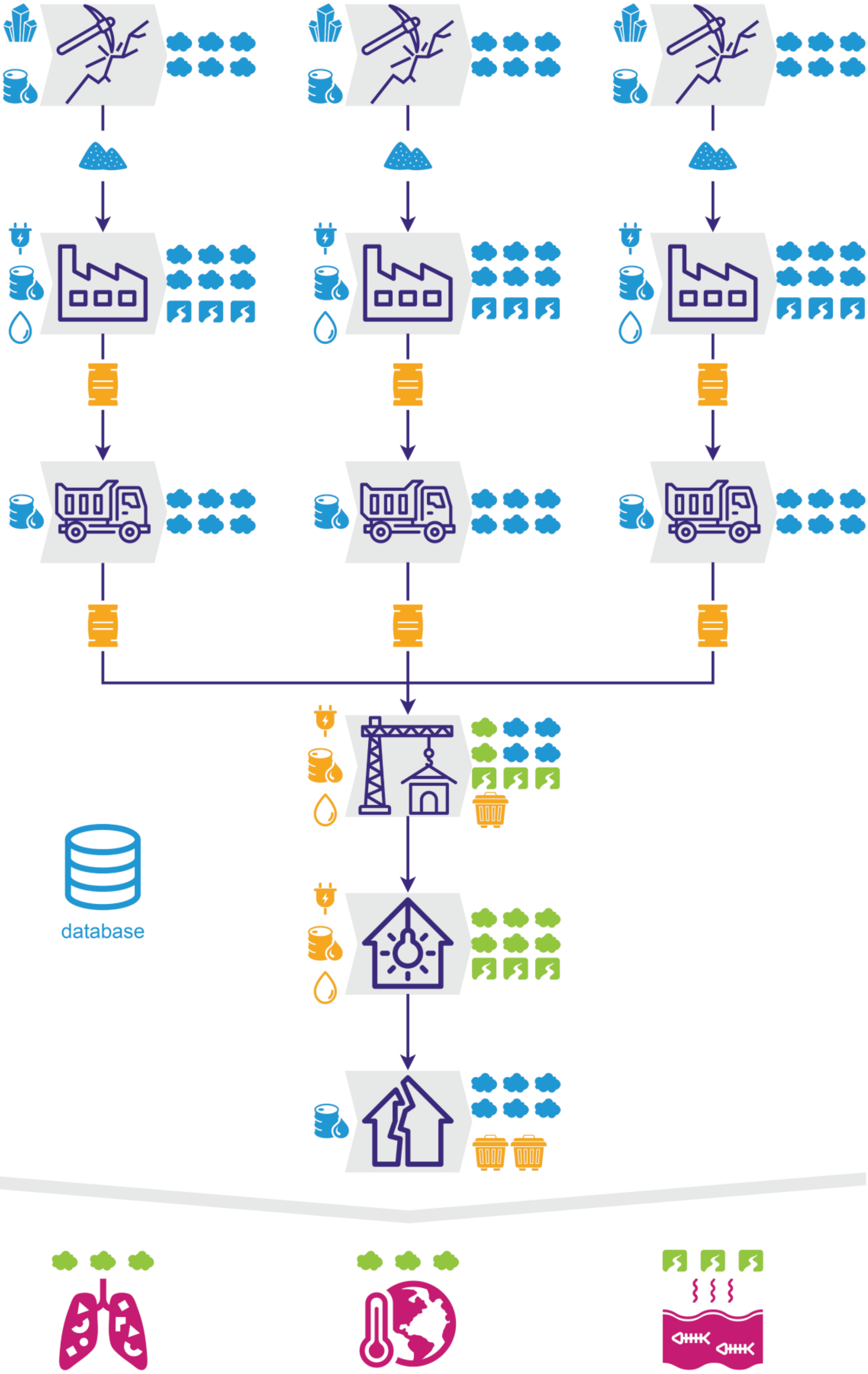
A further strategy to simplify LCA results is reducing the number of indicators by consolidating them into fewer indicators or even a single score (Figure 59). Expressing different indicators using the same unit requires normalizing LCA results using a standard reference (e.g., the average impact of a person). The normalized indicators can then be merged into fewer indicators by applying weighing factors (FINNVEDEN *et al.*, 2009). However, this strategy does not reduce the inventory data demand. Furthermore, the data required for normalizing LCA results have considerable uncertainty (STEINMANN *et al.*, 2016; VAN HOOF *et al.*, 2013), and weighing is difficult to agree upon (HOFSTETTER; METTIER, 2003). Although single scores can be easier to communicate to a broader audience, they prevent decision-makers from understanding the causes of the different environmental impacts and identifying opportunities for action (BAITZ *et al.*, 2013; HOFSTETTER; METTIER, 2003).

Figure 53 – Schematic representation of a cradle-to-grave LCA for a building.



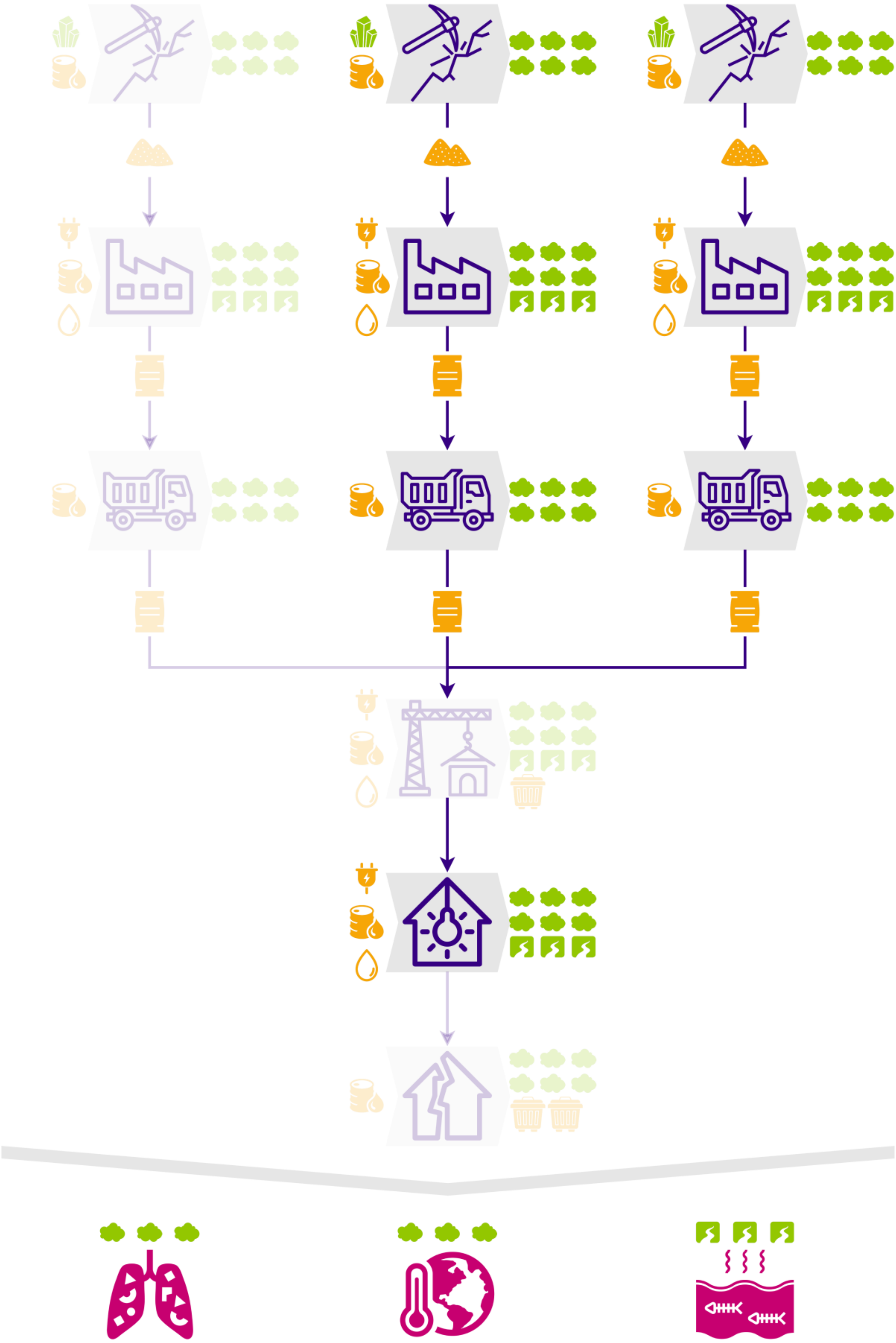
Source: the author.

Figure 54 – Schematic representation of the LCA simplification strategy of inventory data substitution. Substituted flows are represented in blue.



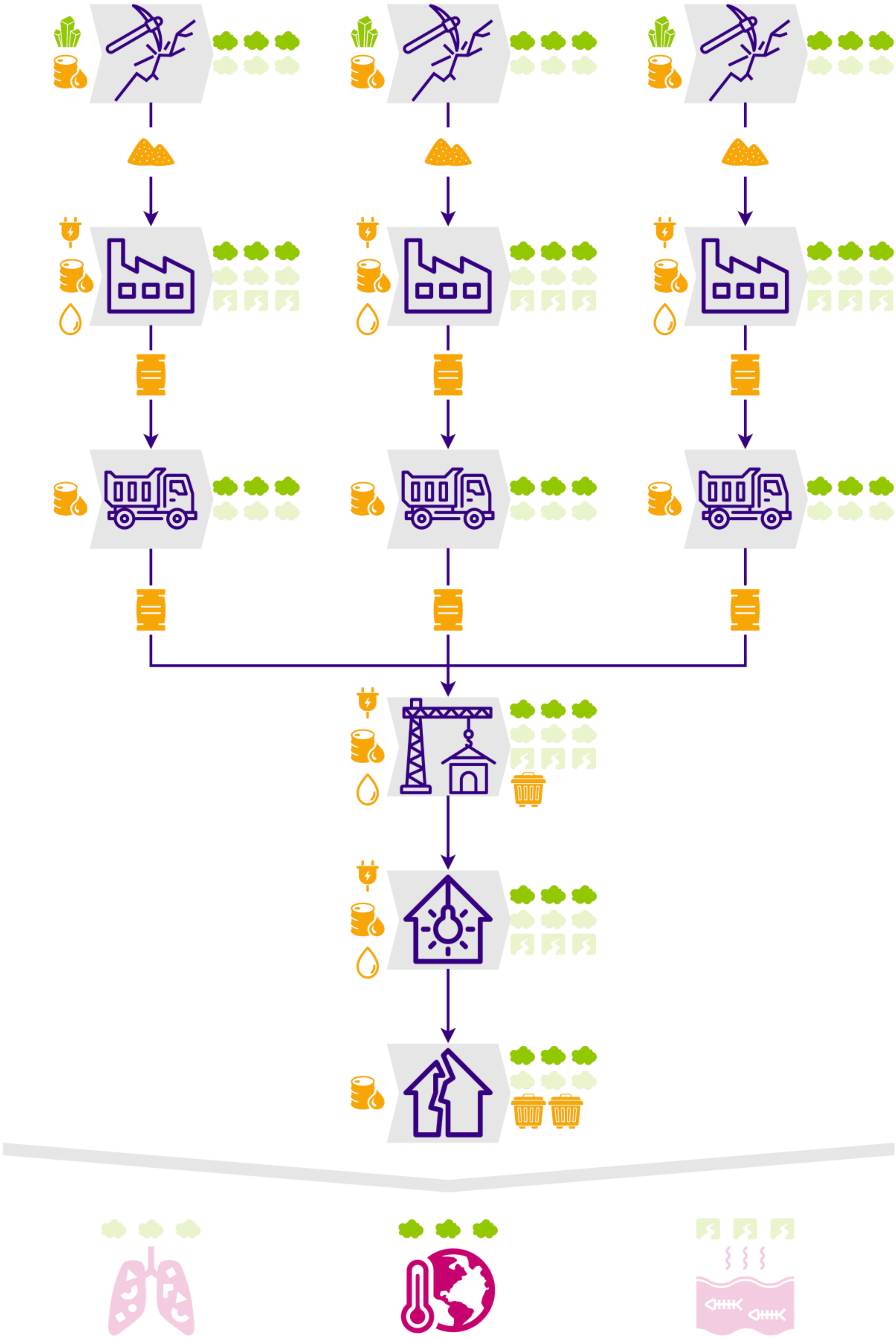
Source: the author.

Figure 55 – Schematic representation of the LCA simplification strategy of inventory parts exclusion. Excluded elementary processes and life cycle stages are shaded



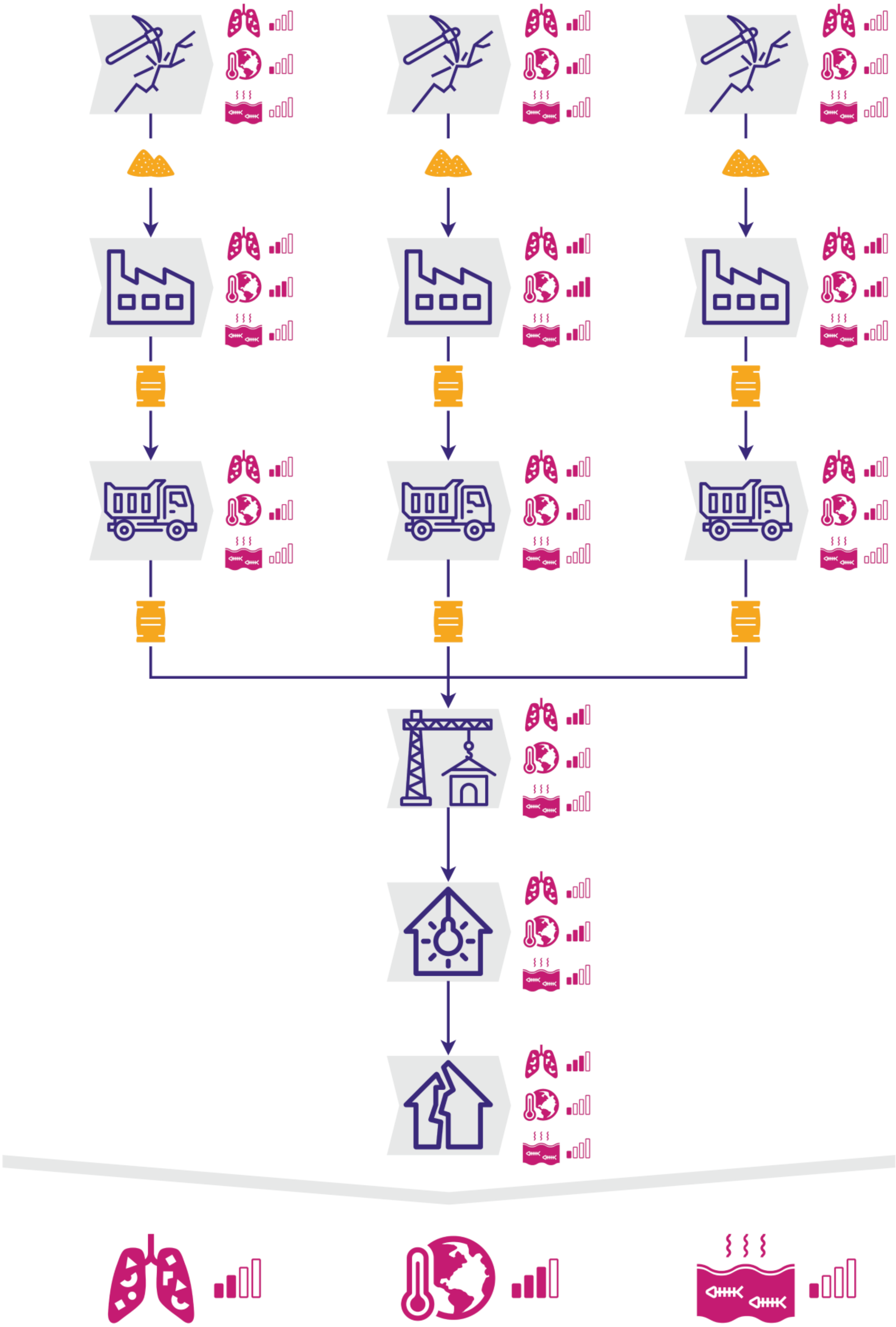
Source: the author.

Figure 56 – Schematic representation of the LCA simplification strategy of impact category exclusion. Excluded impact categories and corresponding elementary flows are shaded.



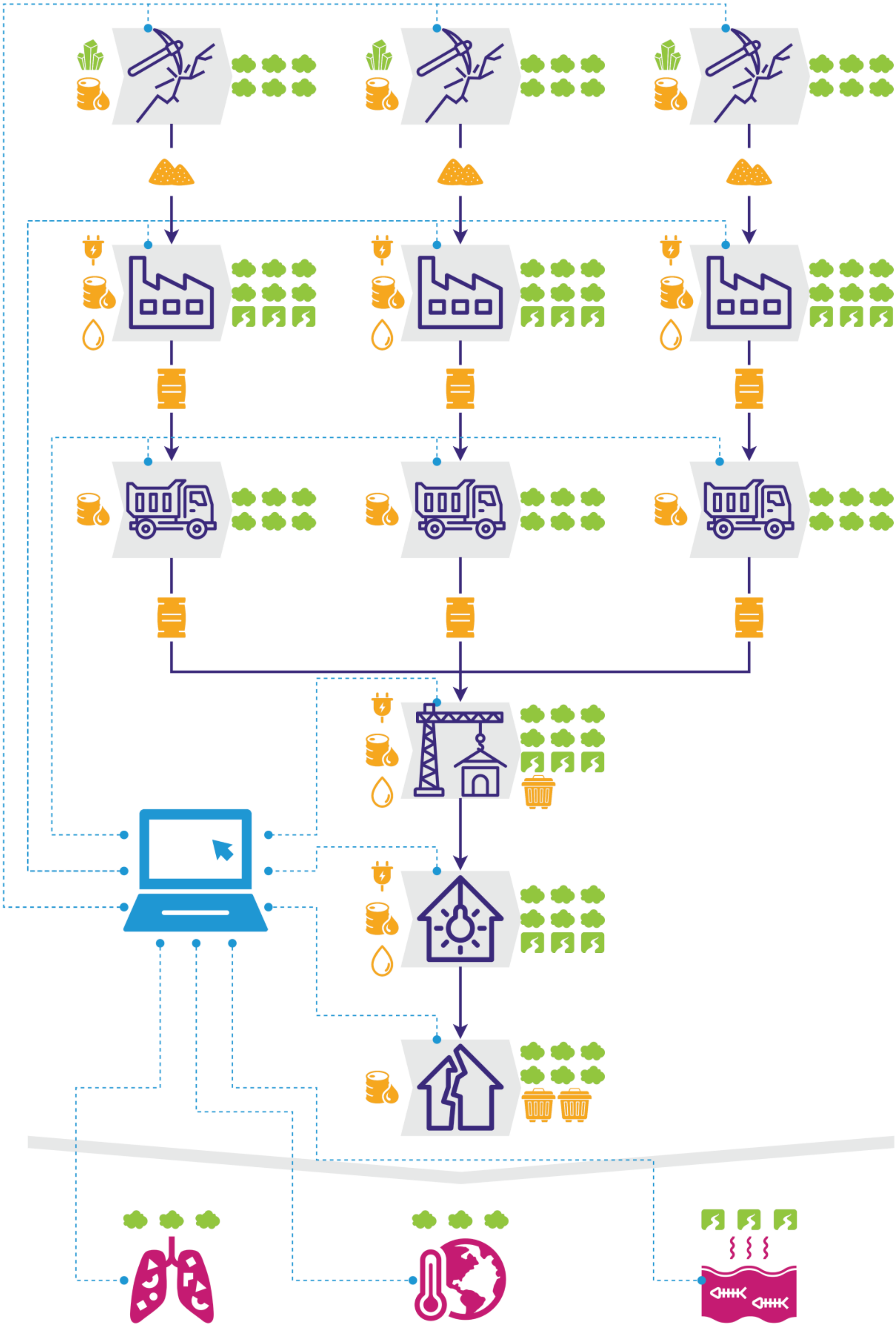
Source: the author.

Figure 57 – Schematic representation of the LCA simplification strategy of qualitative expert judgement. The intensity scale represents expert judgment with scores for each impact category.



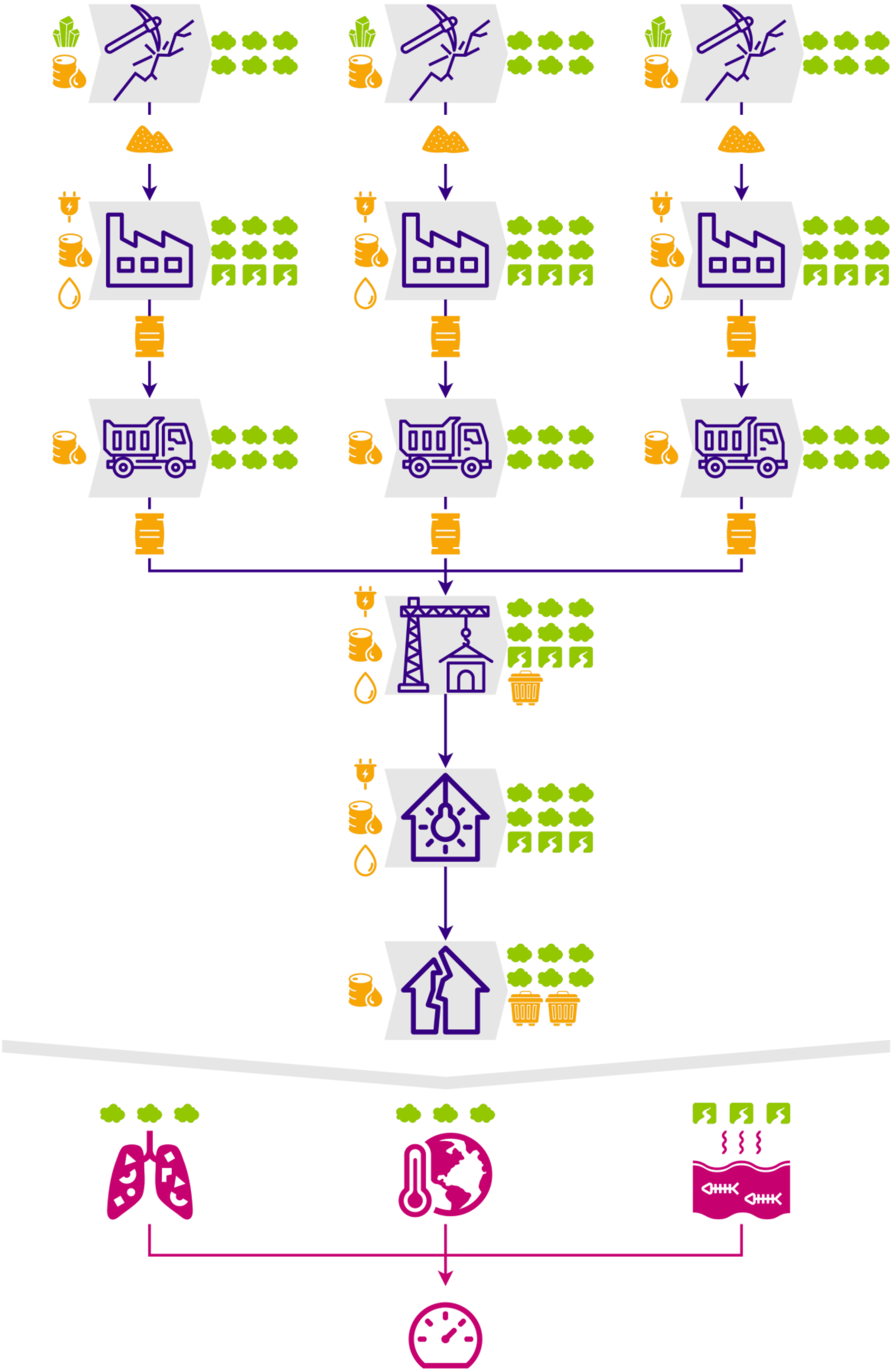
Source: the author.

Figure 58 – Schematic representation of the LCA simplification strategy of automation. Inventory flows and impact results are automatically compiled and calculated using LCA software.



Source: the author.

Figure 59 – Schematic representation of the LCA simplification strategy of normalization and weighing to calculate a single indicator.



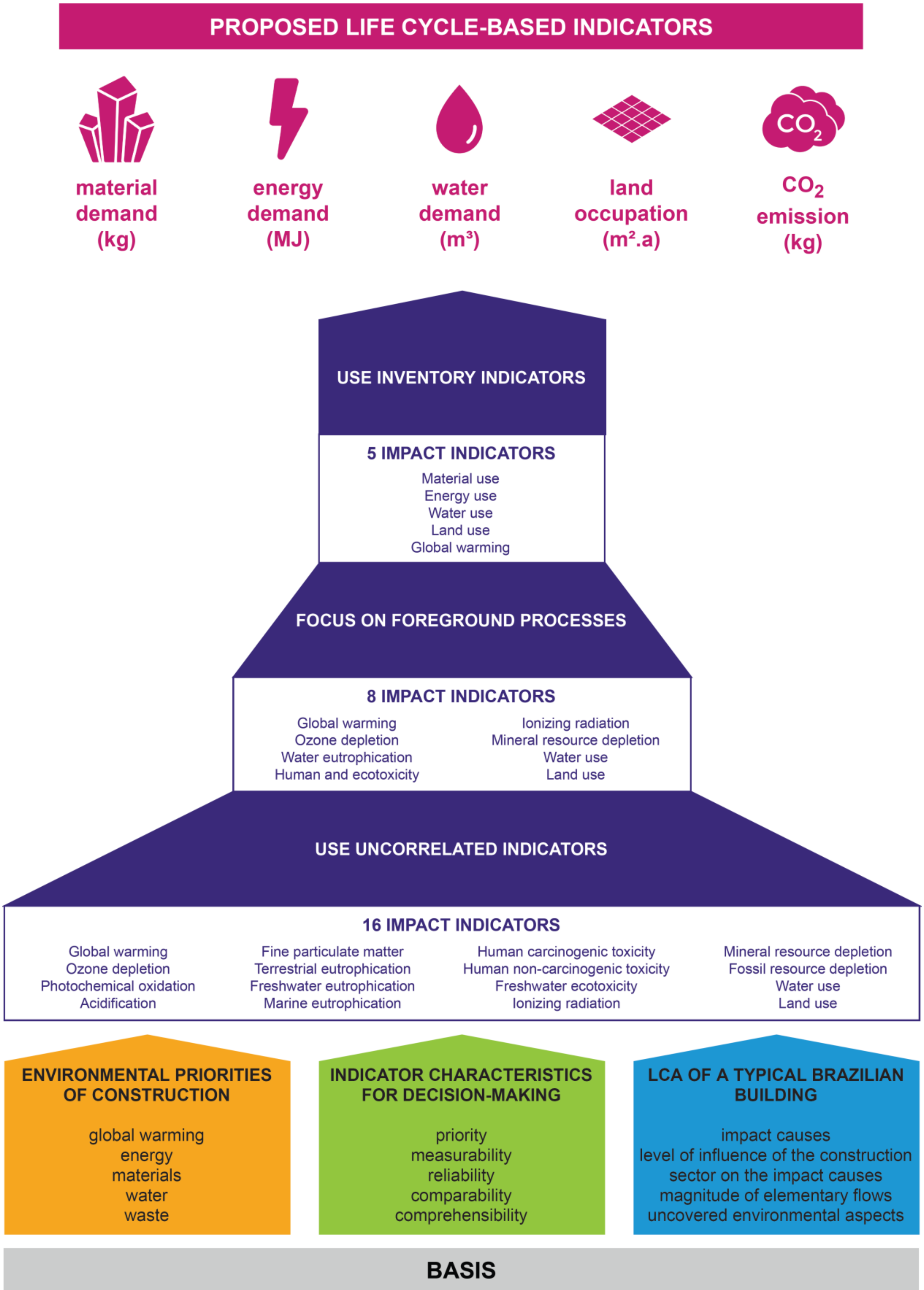
Source: the author..

4.2 Selection of an indicator set

The simplification strategies that reduce the demand for life cycle inventory data are 1) substituting inventory data, 2) excluding life cycle stages or processes from the inventory, and 3) excluding impact categories. Considering the objective of measuring the environmental performance of construction, it makes no sense to recommend substituting inventory data with secondary data (except for background processes). Also, excluding life cycle stages or processes is not recommended because it would be difficult to propose exclusion rules valid for the whole construction value chain. Moreover, it would exclude stakeholders from the environmental performance improvement effort, which is incompatible with the magnitude of impact reductions that must be achieved.

The remaining strategy of excluding impact categories deserves further analysis because not all impact categories assessed in LCA studies are a priority for measuring the environmental performance of construction. As discussed, some impact categories are correlated, while others are determined mainly by background processes. Therefore, this strategy is applied here to propose a reduced set of priority environmental performance indicators for construction, starting from the scope recommended by construction LCA standards (Figure 60). Each step of the analysis is discussed in the following sections.

Figure 60 – Strategy for proposing a reduced set of life cycle-based environmental performance indicators for construction.



Source: the author.

4.2.1 Use uncorrelated indicators

At first sight, the exclusion of impact categories seems to reduce the environmental comprehensiveness of the assessment and increase the risk of unintended burden shifting. However, some environmental impacts have common underlying causes and are correlated, providing redundant information for decision-makers. These correlations can be explored to reduce the number of indicators without necessarily increasing the risk of burden-shifting (STEINMANN *et al.*, 2016).

The LCA results of a typical Brazilian building presented in chapter 3 show that the 16 original impact categories can be grouped as follows, according to their cause:

a) Impacts caused predominantly by fossil fuel consumption and corresponding airborne emissions:
   - fossil resource depletion;
   - global warming;
   - photochemical ozone creation;
   - acidification;
   - fine particulate matter formation;
   - terrestrial eutrophication;
   - human carcinogenic toxicity.

b) Impacts caused predominantly by the emission of toxic substances from the use of pesticides for sugarcane production used in electricity generation:
   - human non-carcinogenic toxicity;
   - freshwater ecotoxicity.

c) Impacts caused predominantly by the emission of nutrients to water from wastewater treatment:
   - freshwater eutrophication;
   - marine eutrophication.

d) Stratospheric ozone depletion: caused by the emission of ozone-depleting substances (mostly N_2O) from electricity transmission and sewage treatment;

e) Ionizing radiation: caused by the emission of radioactive substances into the air during nuclear electricity production;

f) Mineral resource depletion: caused by the consumption of metallic substances;

g) Water use: caused by water consumption during the use of buildings;

h) Land use: caused by forestry and the occupation of land during the use of buildings.

Choosing one indicator to represent a set of correlated impacts allows for focusing on the common cause and reducing the number of indicators for decision-makers (STEINMANN *et al.*, 2016). For instance, among the fossil fuel-related impacts, global warming can be prioritized over the other five impacts of that group, given the urgency to control climate change (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2022). Furthermore, the magnitude of the CO_2 emission is much higher than the other pollutants from fossil fuel combustion (NO_x, SO_x, particulate matter), making it easier to measure. Hence, the number of indicators can be halved by exploring correlations, from 16 to eight indicators.

4.2.2 Focus on foreground processes

Another recommendation for effective indicators is prioritising issues that construction stakeholders can measure, manage, and improve. Therefore, indicators determined mainly by foreground processes (from the perspective of the construction sector) should be prioritized (SILVA *et al.*, 2020). Considering the eight uncorrelated environmental issues associated with the construction life cycle, the ones predominantly caused by foreground processes include:

a) Global warming: the production of construction materials is intensive in fossil fuels, and fossil fuels are consumed during building operation (e.g., for electricity production, hot water supply, and heating). Also, CO_2 is emitted from decarbonation and reduction reactions occurring in cement and steel production;
b) Mineral resource depletion: metallic minerals are used to produce construction materials;
c) Water use: building operation is intensive in water use;
d) Land use: the production of wood for construction, and the occupation of land by the house itself, are intensive in land use.

On the other hand, human non-carcinogenic toxicity, freshwater ecotoxicity, stratospheric ozone depletion, ionizing radiation, and freshwater and marine eutrophication are predominantly caused by background processes. These impacts are unlikely to be improved by actions undertaken by construction stakeholders, except for indirect measures, such as reducing electricity consumption to reduce toxicity indicators. However, even these indirect measures are more likely to be driven by indicators referring to the foreground system. For instance, increasing water use efficiency reduces the amount of sewage, consequently reducing eutrophication caused by sewage treatment. Prioritizing environmental impacts that construction stakeholders can manage allows for further reducing the number of indicators from eight to four.

However, these four impact categories do not cover environmental aspects considered relevant by construction stakeholders and to which construction contributes significantly:

a) Materials consumption, including bulk minerals and biomass (wood), and not only metals;
b) Energy consumption because it is not entirely considered by the fossil resource depletion indicator, which does not account for renewable energy sources.

Solid waste generation is also important for construction and is not accounted for in LCA. However, solid waste generation is correlated with materials consumption because all materials that enter a product system are converted into either products or waste. Moreover, when considering the whole life cycle of products, the product itself becomes waste unless recycled. The amount of materials consumed is more straightforward to measure than waste. Waste is hardly sorted appropriately or weighed, and volume-based measures must account for voids. Thus, the materials indicator can be prioritized over the waste indicator.

Environmental Product Declaration (EPD) standards require energy and materials consumption indicators for construction products as additional information (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017). This only confirms the importance given by construction stakeholders to these environmental aspects. However, only the consumption of materials with energy content is accounted for in EPDs, excluding bulk minerals.

By adding those environmental aspects that are currently not reflected in the LCA results to the list of uncorrelated, foreground environmental performance indicators, five impacts are considered:

a) Global warming;
b) Materials use (including bulk minerals and wood);
c) Water use;

d) Land use;
e) Energy use (including renewable energy sources).

4.2.3 Use inventory flows as indicators

The analysis can be further simplified if performed at the inventory level (STEINMANN *et al.*, 2017). For instance, calculating the global warming potential requires not only a robust characterization model (in this case, provided by the IPCC) but also collecting data for all greenhouse gases. CO_2 represents more than 80% of the global warming potential of most construction products (LASVAUX *et al.*, 2014; SILVA *et al.*, 2020) and is relatively easy to calculate using emission factors (GÓMEZ *et al.*, 2006; WALDRON *et al.*, 2006). In contrast, other greenhouse gases are more challenging to estimate. Emission factors for other greenhouse gases such as CH_4 and N_2O are highly uncertain (GÓMEZ *et al.*, 2006; WALDRON *et al.*, 2006). Reducing this uncertainty requires measuring emissions at production facilities, which represents an extra cost not justified by the quality gain for the assessment.

Other indicators can also be simplified to inventory indicators. Measuring the mass of raw materials consumed is relatively simple; however, developing characterization factors that account for the local scarcity of construction minerals requires extra information (IOANNIDOU *et al.*, 2017). Similarly, water consumption and land occupation are easy to measure, but characterization factors to account for local water scarcity and land use equivalents are not readily available (PFISTER; OBERSCHELP; SONDEREGGER, 2020). Depending on the impact category, the uncertainty of characterization factors may reach several orders of magnitude (EUROPEAN COMMISSION; JOINT RESEARCH CENTRE; INSTITUTE FOR ENVIRONMENT AND SUSTAINABILITY, 2011; REAP *et al.*, 2008b). Furthermore, for some impact categories, these uncertainties are not even estimated.

Inventory indicators are also more easily comprehended. For example, the consumption of 130 t of raw materials over the house's life cycle is easier to understand than the mineral resource depletion of 69 g of antimony equivalents. Inventory indicators also allow benchmarking environmental performance more efficiently than impact indicators. For instance, the water consumption of different factories can be compared using inventory indicators (e.g., m^3/functional or declared unit). In contrast, impact indicators like water scarcity are influenced by characterization factors that do not depend on manufacturers. Moreover, impact indicators may change due to changing characterization factors (e.g., change of water availability over time), even if no process changes are performed. In this sense, inventory indicators are closer to the raw process data (GILJUM *et al.*, 2011), informing management decisions better.

However, excluding the life cycle impact assessment stage means that the assessment no longer qualifies as an LCA according to ISO 14040 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2006a). However, life cycle inventory indicators keep the life cycle perspective and the orientation towards a functional unit, thereby ensuring performance-based comparability and the possibility of developing environmental performance benchmarks while preserving measurability, reliability, and comprehensibility.

As a result of the previous analyses, the suggested list of priority indicators for assessing the environmental performance of construction is composed of:

a) Material Demand (kg);
b) Energy Demand (MJ);
c) Water Demand (m^3);
d) Land Occupation (m^2.year);
e) CO_2 Emission (kg).

These indicators do not assess potential environmental impacts but the associated environmental aspects. For example, consuming materials is not an environmental problem per se, but extracting materials causes many (local) impacts. Energy, water, and land occupation are also associated with different environmental impacts. The CO2 emission indicator measures the emission of the most important greenhouse gas, so it is a partial assessment of global warming.

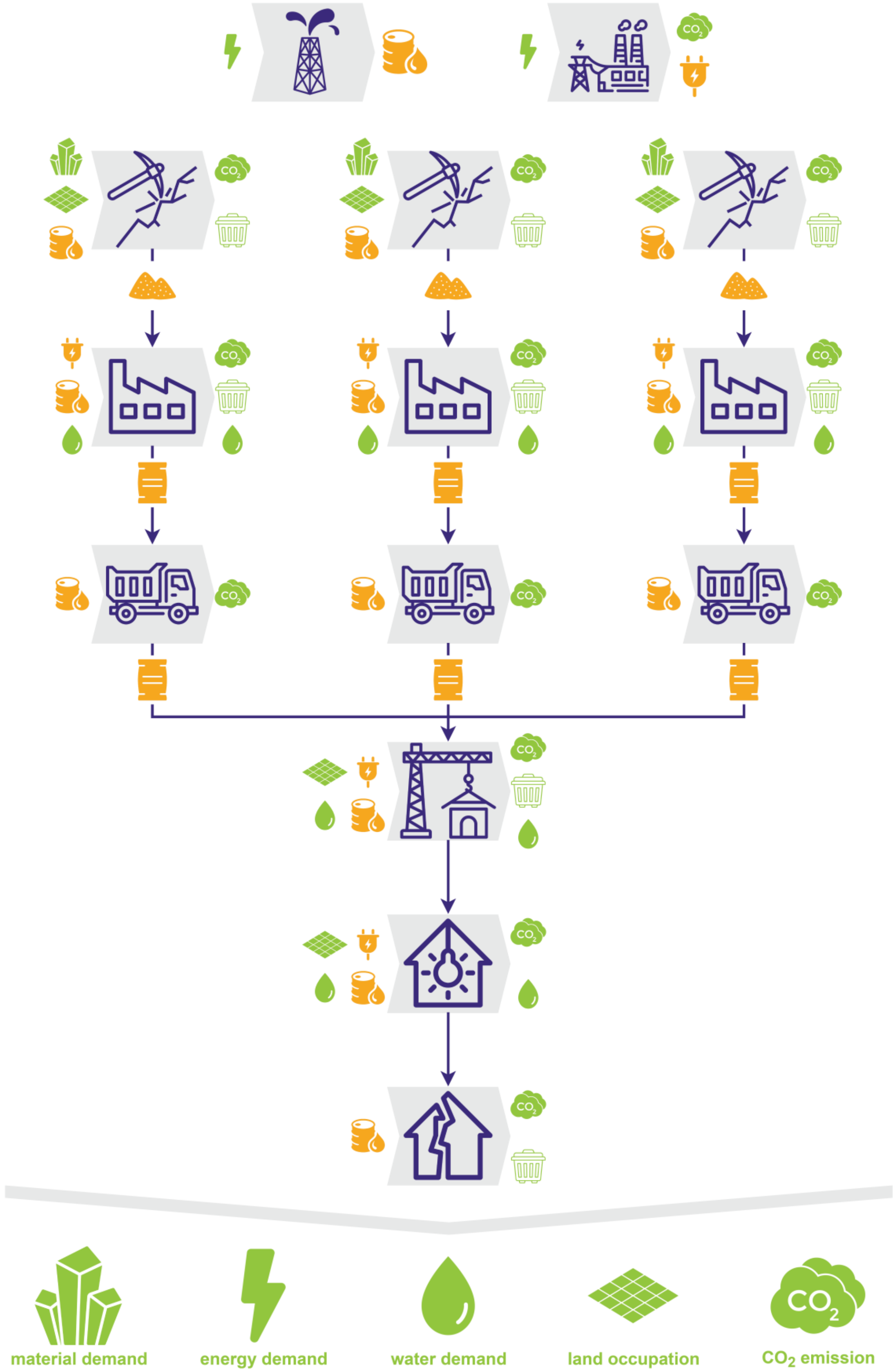
4.3 Description of the proposed indicators

The basis for the proposed construction environmental performance indicators is the life cycle approach, which ensures the reliability and comparability required to support robust decisions. Therefore, the main concepts of LCA remain valid and are applied here, up to the life cycle inventory phase. However, it should be clear that **it is a life cycle-based method, not a Life Cycle Assessment**.

The indicators are calculated considering the product's life cycle. The results are expressed relative to a functional unit, which quantitatively describes the product's function. For instance, the functional unit of a building can be one square meter of net floor area occupied during one year (m^2.a), which allows comparing buildings of different designs. If the product's function cannot be determined, such as when conducting a cradle-to-gate assessment, then the term "declared unit" is used instead (for example, kg of product) (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017).

The product's life cycle is modelled through the "product system", the set of elementary processes, with elementary and product flows required to fulfil the product's function. Elementary flows are flows from or to the biosphere (nature). Product flows are flows from or to the technosphere (human activities, represented by elementary processes). The system boundary defines the processes and flows that belong to the product system. All product and elementary flows are quantified throughout the product life cycle and then scaled up to the reference flow corresponding to the functional unit. The proposed indicators consist of sums of elementary flows: materials, energy, water, land occupation on the input side, and CO_2 emission on the output side. Figure 61 shows a schematic representation of this logic. The calculation of the indicators is further described in the following subsections.

Figure 61 – Schematic representation of the lifecycle-based environmental performance indicators for construction. Elementary flows are represented in green, and product flows are represented in orange. Indicators are also represented in green because they result from the sum of elementary flows throughout the product's life cycle.



Source: the author.

Since the LCA principles are maintained, it is possible to apply the mathematical formulation of LCA for calculating the proposed indicators using the matrix-based approach proposed by (HEIJUNGS; SUH, 2002). Equation 2 shows how the matrix approach solves the problem of scaling up all product and inventory flows to the reference flow that expresses the functional unit. Equation 3 shows the conversion of these flows to impact results using the characterization matrix in LCA.

The proposed method does not calculate potential impact results but inventory indicators. Therefore, the characterization matrix Q is renamed “conversion matrix” C, which simply correlates elementary flows and indicators with zeros and ones (Equation 4). Since fewer indicators are contemplated, and these indicators depend on a reduced list of elementary flows, matrix B has fewer rows than when used for LCA. Similarly, matrix C has fewer rows and columns than matrix Q of LCA. Table 10 shows an example of the conversion matrix, considering a non-exhaustive list of elementary flows – the calculation of each indicator is explained in the following subsections.

$$g = B.A^{-1}.f$$ Equation 2

$$h = Q.g$$ Equation 3

$$r = C.g$$ Equation 4

Table 9 – Symbols of the vectors and matrices presented in Equation 2, Equation 3 and Equation 4.

Symbol	Name	Rows	Columns
g	Inventory results	Elementary flows	1
B	Intervention matrix	Elementary flows	Elementary processes
A	Technology matrix	Product flows	Elementary processes
f	Final demand vector	Product flows	1
h [a]	Characterization results	Impact categories	1
Q [a]	Characterization matrix	Impact categories	Elementary flows
r	Indicator results	Indicators	1
C	Conversion matrix	Indicators	Elementary flows
a) Only applies to LCA			

Source: the author.

Using the matrix formulation allows applying uncertainty propagation algorithms developed for LCA (GROEN *et al.*, 2014) to propagate the variability of inventory flows (e.g., when using generic data) to the proposed indicators. It also allows using other instruments, such as sensitivity analysis (HEIJUNGS, 2010), to discover the most influential parameters for the environmental performance of products and buildings (BELIZARIO-SILVA *et al.*, 2021). Moreover, it facilitates the integration between the proposed method and LCA: users may develop a simplified life cycle inventory to calculate the construction environmental performance indicators, and if they want to perform an LCA, they only need to complement the inventory with the missing elementary flows and associate it with a characterization matrix, typically using LCA software (and secondary LCA databases). This integration is further discussed in section 4.4.2. Secondary energy and materials are modelled as elementary flows to facilitate the calculation using the matrix approach.

Table 10 – Conversion matrix to convert the elementary flows into the environmental performance indicators. Note that the list of elementary flows is non-exhaustive.

	Elementary flows																	
Indicators	**Limestone (kg)**	**Sand (kg)**	**Recycled aggregate (kg)**	**Wood (planted) (kg)**	**Primary fossil energy (MJ)**	**Recovered fossil energy (MJ)**	**Hydro energy (MJ)**	**Solar energy (MJ)**	**Surface water (m^3)**	**Ground water (m^3)**	**Harvested rainwater (m^3)**	**Reuse water (m^3)**	**Forest land occupation (m^2.a)**	**Agricultural land occupation (m^2.a)**	**Urban land occupation (m^2.a)**	**Fossil CO_2 emission (kg)**	**Process CO_2 emission (kg)**	**Non-ren. biomass CO_2 emission (kg)**
Material demand (kg)	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Primary material demand (kg)	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary material demand (kg)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Renewable material demand (kg)	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Non-renewable material demand (kg)	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy demand (MJ)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Primary energy demand (MJ)	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
Secondary energy demand (MJ)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Renewable energy demand (MJ)	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Non-renewable energy demand (MJ)	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Water demand (m^3)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
Land occupation (m^2.a)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
CO_2 emission (kg)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

Source: the author

4.3.1 Material demand

The material demand indicator is based on the cumulative raw material demand indicator, described by the VDI 4800 standard (VEREIN DEUTSCHER INGENIEURE, 2018). It consists of the sum of all raw materials that enter a product system, divided by the functional or declared unit of the product (Equation 5 and Figure 62). Raw materials include abiotic materials (e.g., minerals such as sand and gravel) and biotic materials (e.g., wood).

$$M_{total} = \frac{\sum_i m_i}{FU}$$ Equation 5

- M_{total}: total material demand (kg/functional unit)
- m_i: material "i" (kg) – only if used as raw material, excluding water
- FU: functional unit (or declared unit)

All materials entering the product system must be considered, including the unused extraction, i.e., extracted and not further processed. That includes, for instance, mining overburden that remains in the quarry area, residues from wood harvesting that remain in the forest, and excavation soil from construction works. Since these flows do not leave the production areas, they are sometimes called "hidden flows" (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2008). Therefore, they might be difficult to inventory since companies are not required to measure them. Nevertheless, unused extraction is an integral part of materials consumption that should not go on ignored: for example, for each kilogram of logs extracted from the Amazon Forest, 1,8 kilograms of biomass residues (on average) remain in the forest and decompose into CO_2 (CAMPOS; PUNHAGUI; JOHN, 2021). The recent collapse of mining dams in Brazil has raised attention to the enormous amount of waste generated by mining activities (CORNWALL, 2020). However, until it becomes possible to collect data about the unused extraction consistently, this part of the material demand can be reported separately, as recommended by VDI 4800 (VEREIN DEUTSCHER INGENIEURE, 2018) (Equation 6).

$$M_{total} = M_{used} + M_{unused}$$ Equation 6

- M_{total}: total material demand (kg/functional unit)
- M_{used}: material demand of used resources (kg/functional unit)
- M_{unused}: material demand of unused resources (kg/functional unit)

An important difference between the material demand indicator proposed here and other material indicators (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2008; RITTHOFF; ROHN; LIEDTKE, 2002; VEREIN DEUTSCHER INGENIEURE, 2018) is that only materials used for non-energetic purposes are considered. This procedure excludes materials used as energy sources (e.g., coal, petroleum, firewood) so that the material demand indicator refers specifically to the material efficiency of construction. It also avoids double-counting since the energy demand indicator (described in section 4.3.2) considers materials used as energy sources. Water is also excluded from this indicator, even if used as a raw material (e.g., water used in concrete production), because it is considered in a specific indicator.

Another difference is that the material demand considers the consumption of secondary raw materials, whereas VDI 4800 (VEREIN DEUTSCHER INGENIEURE, 2018) and other material indicators (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2008; RITTHOFF; ROHN; LIEDTKE, 2002) only account for primary raw materials. On the other hand, construction EPD standards require reporting the consumption of secondary materials (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017).

There is an increasing interest in using secondary materials encouraged by the Circular Economy movement (ELLEN MACARTHUR FOUNDATION; ANSYS GRANTA, 2019). Measuring the consumption of secondary raw materials is thus required. Moreover, secondary raw materials should not be an excuse for material inefficiency, not least because some secondary materials are scarce. For instance, there is insufficient granulated blast furnace slag to replace clinker in cement production (SCRIVENER; JOHN; GARTNER, 2016). Furthermore, knowing the total material demand is essential for developing material intensity benchmarks, for instance, to compare different design options (DE WOLF *et al.*, 2020). Therefore, the total material demand comprises primary and secondary raw materials, as expressed in Equation 7.

$$M_{total} = M_{pri} + M_{sec}$$ Equation 7

- M_{total}: total material demand (kg/functional unit)
- M_{pri}: primary material demand (kg/functional unit)
- M_{sec}: secondary material demand (kg/functional unit)

The total material demand can also be disaggregated into materials sourced from renewable and non-renewable sources (Equation 8). Renewable materials comprise cultivated or native biomass from sustainably managed areas, i.e., forestry operations undertaken at an intensity that allows the forest biomass to recover. Non-renewable materials include metallic and non-metallic minerals, crude oil (used as feedstock for plastic production), and native biomass from unsustainably managed areas, i.e., areas managed with a harvesting intensity higher than that required for forest recovery.

$$M_{total} = M_{ren} + M_{nren}$$ Equation 8

- M_{total}: total material demand (kg/functional unit)
- M_{ren}: renewable material demand (kg/functional unit)
- M_{nren}: non-renewable material demand (kg/functional unit)

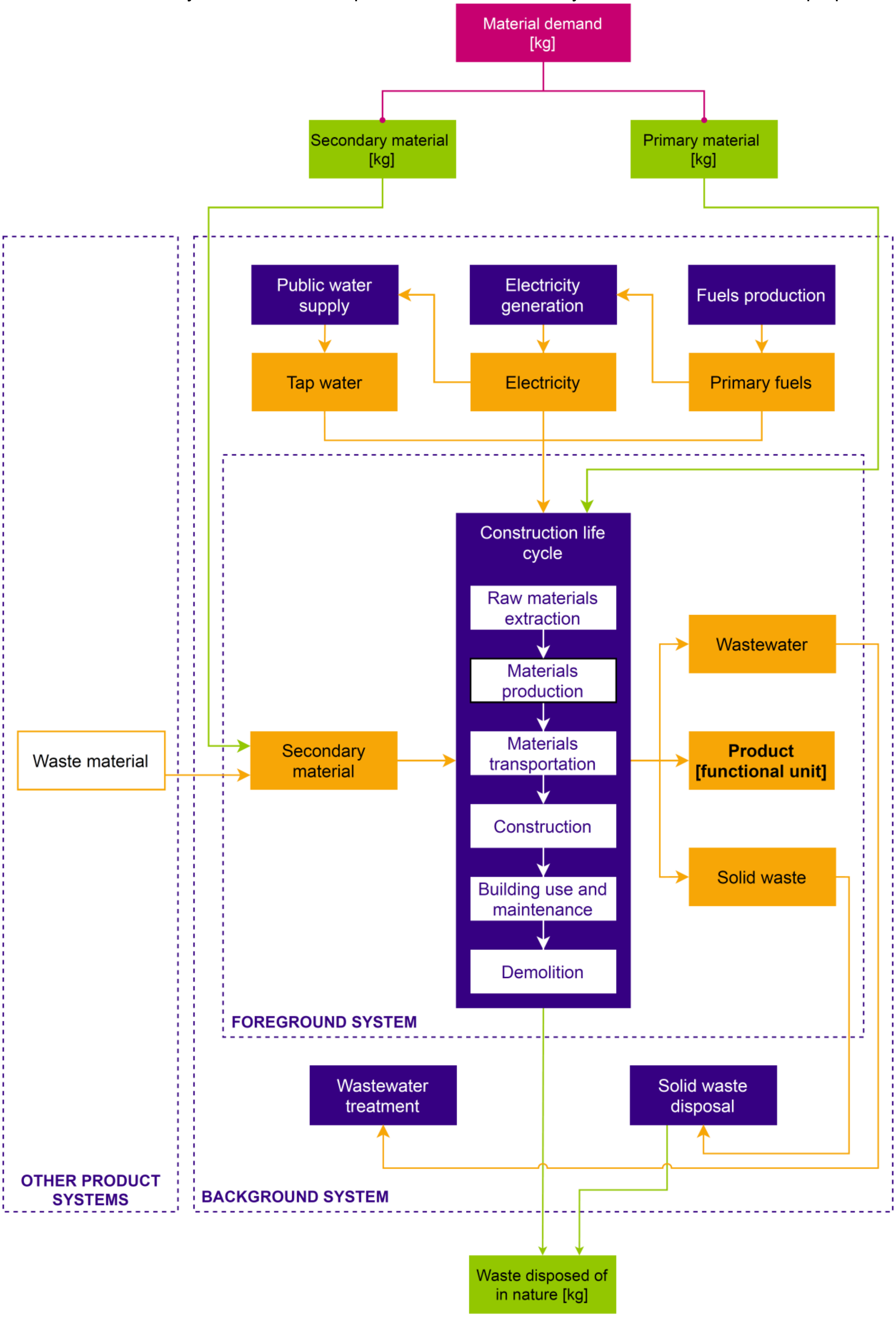
Both primary and secondary raw materials can be renewable or non-renewable. For example, sand and gravel are non-renewable primary materials, whereas recycled aggregates are non-renewable secondary materials. Wood from planted forests is a renewable primary material, whereas wood waste from deforestation is a non-renewable secondary material. Equation 7 and Equation 8 can thus be combined into Equation 9.

$$M_{total} = \left(M_{ren,pri} + M_{ren,sec}\right) + \left(M_{nren,pri} + M_{nren,sec}\right)$$ Equation 9

When calculating the material demand indicator, the mass balance throughout the product system must be observed, i.e., all materials that enter the system must leave it as products or waste. That also holds for the unused materials extraction since they are disposed of as waste at the same site. In some cases, emissions must be considered in the mass balance, such as in the calcination reaction to produce cement (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2008). Note that in a cradle-to-grave analysis of a physical product, the product itself becomes waste unless reused or recycled in a subsequent life cycle (RITTHOFF; ROHN; LIEDTKE, 2002).

Material demand occurs at the sourcing of raw materials at the beginning of the construction life cycle, such as in the extraction of aggregates, iron ore, and limestone. Materials wastage during manufacturing and construction also contributes to the material demand and the extraction of excavation soil from the construction site. The materials required for repair and replacement throughout the construction life cycle must also be accounted for, based on scenarios of replacement and service life estimates.

Figure 62 – Schematic representation of the material demand indicator and corresponding elementary flows. The elementary flow of "waste disposed of in nature" is only shown for mass balance purposes.



Source: the author.

4.3.2 *Energy demand*

The energy demand indicator is based on the Cumulative Energy Demand (CED) indicator, described by the VDI 4600 standard (VEREIN DEUTSCHER INGENIEURE, 2012). It is the sum of all primary energy that enters a product system, divided by the functional unit (or declared unit). Primary energy is the "*energy content of energy carriers that are found in nature and have not yet been converted through technical means*" (VEREIN DEUTSCHER INGENIEURE, 2012). All primary energy sources must be considered, including fossil fuels, renewable fuels (e.g., biomass), nuclear, solar, wind, hydropower, and geothermal energy (Equation 10 and Figure 63).

$$E_{total} = \frac{\sum_i e_i}{FU}$$ Equation 10

- E_{total}: total (primary) energy demand (MJ/functional unit)
- e_i: primary energy from source "i" (MJ) – only if used for energetic purposes
- FU: functional unit (or declared unit)

All energy consumption throughout the product life cycle must be considered, as well as the conversion efficiency from primary energy to final energy (energy that is effectively available for consumption). Energy consumption includes electricity from the public supply network or autogenerated (for instance, by solar panels), the consumption of fuels, and the intentional consumption of thermal energy, such as solar energy for hot water production or geothermal energy for heating or cooling. Natural lighting or space heating from the sun should not be considered.
The primary energy from fuels can be calculated by multiplying the amount of fuel consumed by its lower heating value (LHV) (Equation 11).

$$e_{fuel} = x_{fuel}.LHV_{fuel}$$ Equation 11

- e_{fuel}: primary energy from a specific fuel (MJ)
- x_{fuel}: the amount of fuel consumed (unit of fuel)
- LHV_{fuel}: the lower heating value of fuel (in MJ/unit of fuel)

Ideally, the life cycle of fuels should also be considered, meaning the primary energy demand for extracting, processing, and distributing the fuels. However, these data might be hard to obtain. If they are not readily available, it is recommended to consider only the lower heating value for all fuels to ensure consistency. Heating values can be found in literature and official publications (EMPRESA DE PESQUISA ENERGÉTICA (BRASIL), 2020b) or determined through testing. For nuclear fuels, the energy extracted from them should be considered.

The conversion of the final energy delivered by renewable energy sources other than fuels (such as hydro, solar, wind and geothermal power) into primary energy considers a factor of 1:1, meaning that any inefficiency of the conversion is disregarded, following the “energy harvested approach” proposed by Frischknecht *et al.* (2015). This approach is considered appropriate because it simplifies the calculation. Moreover, although higher efficiency in the conversion is desirable, wasting solar, kinetic, or hydraulic energy is not an environmental problem (at least not a relevant one). These conversion rules must also be observed for calculating the primary energy demand from the public electricity supply since the electricity mix is made of different primary energy sources, including fuels used in thermal power plants.

A difference between the proposed energy demand indicator and the recommendations of VDI 4600 (VEREIN DEUTSCHER INGENIEURE, 2012) and other standards such as ISO 21930 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017) and EN 15804 (DEUTSCHES INSTITUT FÜR NORMUNG, 2020) is that it considers only energy carriers used for energetic purposes. The standards require considering all inputs with energy content, even if they are not used as energy sources, including combustible materials (e.g., plastics) and biomass (e.g., wood used as material). However, by doing so, the energy demand indicator would not refer specifically to the energy efficiency but also the material efficiency, thereby mixing two different issues. For example, a building made of Cross Laminated Timber (CLT) would have a high energy demand because of the massive use of wood in walls and slabs, no matter how energy efficient that building would be. The material demand indicator already accounts for the consumption of materials, including those with energy content.

Another difference is that the energy demand indicator considers the primary energy recovered from waste. VDI does not consider the energy recovered from waste to avoid double counting of energy, which is also the recommendation of Frischknecht *et al.* (2015). However, double counting does not occur here because the energetic content of raw materials is not considered due to the exclusion of energy sources used as feedstock. It is important to account for the energy extracted from waste because it should not be an excuse for energy inefficiency. Burning waste also generates other environmental impacts. Also, knowing the total energy demands is essential for developing energy efficiency benchmarks.

The total energy demand can be disaggregated into renewable and non-renewable sources (Equation 12), as increasing the share of renewable energy is a relevant sustainability strategy. Reporting the use of renewable energy sources is required by construction LCA standards (DEUTSCHES INSTITUT FÜR NORMUNG, 2020, 2012; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017, 2016) and green building rating schemes (BRE GLOBAL, 2016; CAIXA, 2020; DEUTSCHE GESELLSCHAFT FÜR NACHHALTIGES BAUEN, 2018a; HQE; CERWAY, 2014; JAPAN SUSTAINABLE BUILDING COUNCIL, 2014; U. S. GREEN BUILDING COUNCIL, 2019). Renewable energy sources include hydropower, solar, wind, geothermal, and renewable biomass (cultivated or from sustainably managed areas). Non-renewable energy sources include fossil fuels, nuclear power, and non-renewable biomass.

$$E_{total} = E_{ren} + E_{nren} \quad \text{Equation 12}$$

- E_{total}: total primary energy demand (MJ/functional unit)
- E_{ren}: primary energy demand from renewable energy sources (MJ/functional unit)
- E_{nren}: primary energy demand from non-renewable energy sources (MJ/functional unit)

The primary energy demand can also be disaggregated into primary and secondary sources (Equation 13). Secondary energy sources include secondary fuels (e.g., coprocessing waste in cement plants) and energy recovered from processes outside the system boundary (e.g., heat from municipal waste incineration). Construction LCA standards require reporting the use of secondary fuels and recovered energy separately (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017).

$$E_{total} = E_{pri} + E_{sec}$$ Equation 13

- E_{total}: total primary energy demand (MJ/functional unit)
- E_{pri}: primary energy demand from primary energy sources (MJ/functional unit)
- E_{sec}: primary energy demand from secondary energy sources (MJ/functional unit)

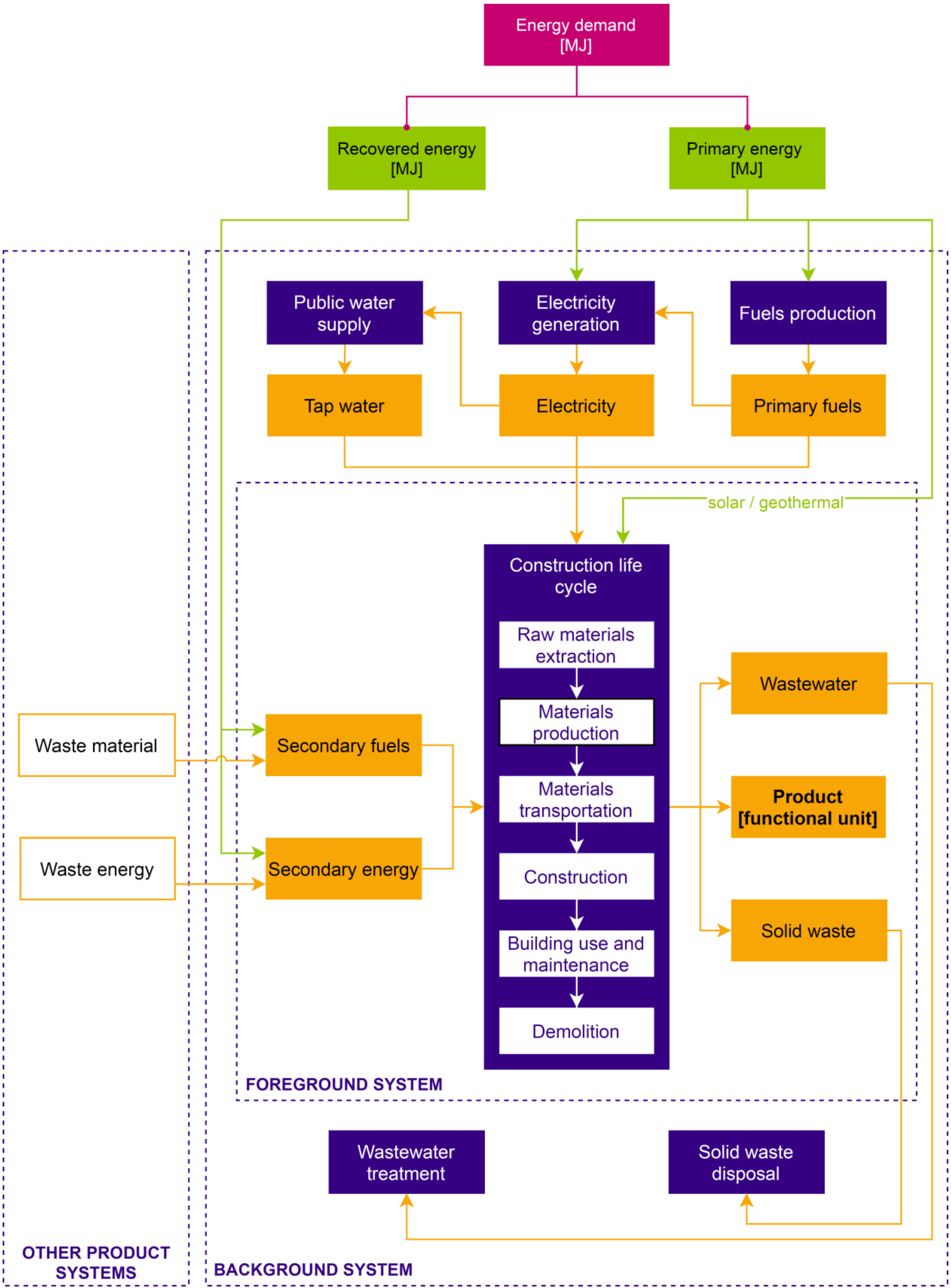
Both primary and secondary energy sources may be renewable or non-renewable. For instance, firewood is a renewable primary energy source, and wood waste used as an energy source is a renewable secondary energy source (considering wood from planted forests). Fuel oil is a non-renewable primary energy source, and waste oil is a non-renewable secondary energy source. Equation 14 combines the two concepts.

$$E_{total} = \left(E_{ren,pri} + E_{ren,sec}\right) + \left(E_{nren,pri} + E_{nren,sec}\right)$$ Equation 14

Energy is consumed throughout the whole life cycle of buildings and infrastructure works. Fossil-fueled mining and forestry equipment are used to extract raw materials from nature. Fuels and electricity are consumed in manufacturing processes. Transportation of materials (and waste) is made by vehicles that consume fuels or electricity. Construction machinery, such as cranes, consumes electricity and fuels during the erection of the building. The use and operation of the building consume electricity and fuels (e.g., for heating and hot water production) over decades. The production and transportation of materials for maintenance and repair works also contribute to energy consumption during the use stage. Finally, demolition equipment, waste transportation and disposal contribute to the energy demand at the building's end of life.

The energy consumption during the use stage should only account for the energy use of building-integrated technical systems, such as heating, cooling, lighting, water supply, internal transport (e.g., lifts and escalators), automation, communication, and fire safety. Appliances that are not building-related, such as entertainment electronics, washing machines, refrigerators, cooking appliances, and electronics, should not be considered (DEUTSCHES INSTITUT FÜR NORMUNG, 2012). Estimating the energy demand associated with operational energy use requires assumptions about user behaviour and scenarios about future primary energy sources, as many countries plan to increase the share of renewable energy.

Figure 63 – Schematic representation of the energy demand indicator and corresponding elementary flows.



Source: the author.

4.3.3 Water demand

The water demand indicator is based on the indicator proposed by Mack-Vergara (2019). It represents the volume of water removed from and not immediately returned to nature with the same (or better) quality because of evaporation, incorporation into products, or release back into water bodies with lower quality (Equation 15 and Figure 64).

$$W_{total} = \frac{\sum_i w_i - w_{clean}}{FU} = \frac{w_{evap} + w_{inc} + w_{low}}{FU} \quad \text{Equation 15}$$

- W_{total}: water demand (m³/functional unit)
- W_i: water withdrawal from source "i" (m³)
- $W_{eff,clean}$: water returned to water bodies with the same or better quality (m³)
- W_{evap}: water evaporated (m³)
- W_{inc}: water incorporated into products (m³)
- $W_{eff,pol}$: water returned to water bodies with lower quality (m³)
- FU: functional unit (or declared unit)

The water sources considered in this indicator include surface water, groundwater, harvested rainwater, and reuse water. The reused water is included for the same reason for including secondary materials and recovered energy: reusing water should not be an excuse for water use inefficiency. Furthermore, since the total water volume on earth is considered stable, it could be argued that all water is reused somehow – the only difference is the time frame between the discharge and the subsequent use. Instream water use is not considered, such as the water that goes through turbines for hydropower production (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2014), because this water is available for immediate use. Seawater is not considered, as it is an abundant water resource.

Water from the public supply network should be traced back to natural sources. Water losses in the distribution network should be considered. In Brazil, for example, losses in the public supply network vary between 13% and 70% (BRASIL, 2020). Reporting the losses in the network can stimulate water companies to operate more efficiently. On the other hand, water evaporation from reservoirs of the public supply system should not be included because the water demand indicator aims to assess water use efficiency, not to account for all possible water flows. Furthermore, many reservoirs are natural, so evaporation cannot be easily assigned to anthropogenic activities.

Only rainwater harvested for use is considered, which does not include rainwater diverted from infiltrating into the soil or incorporated by biomass, for instance, in forestry operations or as moisture in aggregates. Despite the interference that sites made impervious to rainwater penetration might have on natural water flows, it is not related to water use efficiency in product systems. As for rainwater absorption by biomass, it can hardly be determined whether the managed environment has a significantly different water consumption than the natural environment (LAUNIAINEN *et al.*, 2014). For the same reason, evapotranspiration from biomass products should not be considered (LAUNIAINEN *et al.*, 2014).

Regarding water discharges, water that returns to the water body with the same or better water quality is considered "clean water". However, the definition proposed by Mack-Vergara (2019) requires comparing water quality parameters between withdrawal and discharge to check whether they have improved or worsened. A practical rule is suggested to avoid this complexity. If activities that operate legally are allowed to discharge their effluents into a water body without treating them, the effluent is clean; otherwise, the effluent is of lower quality. Thus, if companies discharge effluents into water bodies without any control, or if any treatment is required, including industrial wastewater treatment on-site or domestic sewage treatment in public wastewater treatment plants, the effluent is of lower quality.

This rule is justified because standards that set parameters for discharging effluents into water bodies require the concentration of pollutants to be below the concentration accepted for the receiving water body and not below the concentration of the originally sourced water. Furthermore, at least in Brazil, the standard for effluent discharge allows pollutants to be in higher concentrations than the concentration of pollutants used to classify the quality of the water body (BRASIL, 2011). Therefore, effluents tend to be of lower quality than water withdrawn and only achieve comparable quality after sufficient dilution. One might argue that the proposed rule treats illegal discharge and wastewater treatment as equally bad. However, the water demand indicator aims to assess water use efficiency and not pollution, which is better controlled by other instruments, as discussed in section 4.4.2.

Therefore, the proposed indicator differs from the water consumption concept of the ISO 14046 standard for water footprint (INTERNATIONAL ORGANIZATION FOR

STANDARDIZATION, 2014) and the water footprint assessment manual (HOEKSTRA *et al.*, 2011). Both define water consumption as the volume of water removed from and not returned to the same drainage basin. This definition requires regionalizing water flows according to the drainage basin in which they occur. However, knowing the drainage basin of water flows might be challenging. For example, the city of São Paulo is located in the Paraná River watershed. Still, some of the reservoirs that supply water to the city are located in other watersheds. The origin of the supply varies according to the management of the system (SABESP, 2021). There are also different levels of granularity to define a watershed (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2021), which can lead to inconsistency. Furthermore, the drainage basin is not essential to benchmark water use efficiency, as the indicator does not aim to assess water scarcity.

Another difference is that "green water" is not considered. Green water refers to the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation (HOEKSTRA *et al.*, 2011). The indicator also does not consider "grey water", which is the volume of freshwater required to dilute pollutants so that water quality standards of the receiving water body are met (HOEKSTRA *et al.*, 2011). These differences are highlighted here because although both indicators – the water demand and the water footprint – are expressed in terms of volume of water, they are not comparable.

The water demand indicator can be disaggregated into each water source (Equation 16). Note that harvested rainwater is hardly metered. By disaggregating the water demand indicator, it is possible to ensure the consistency of at least the other water sources throughout the life cycle.

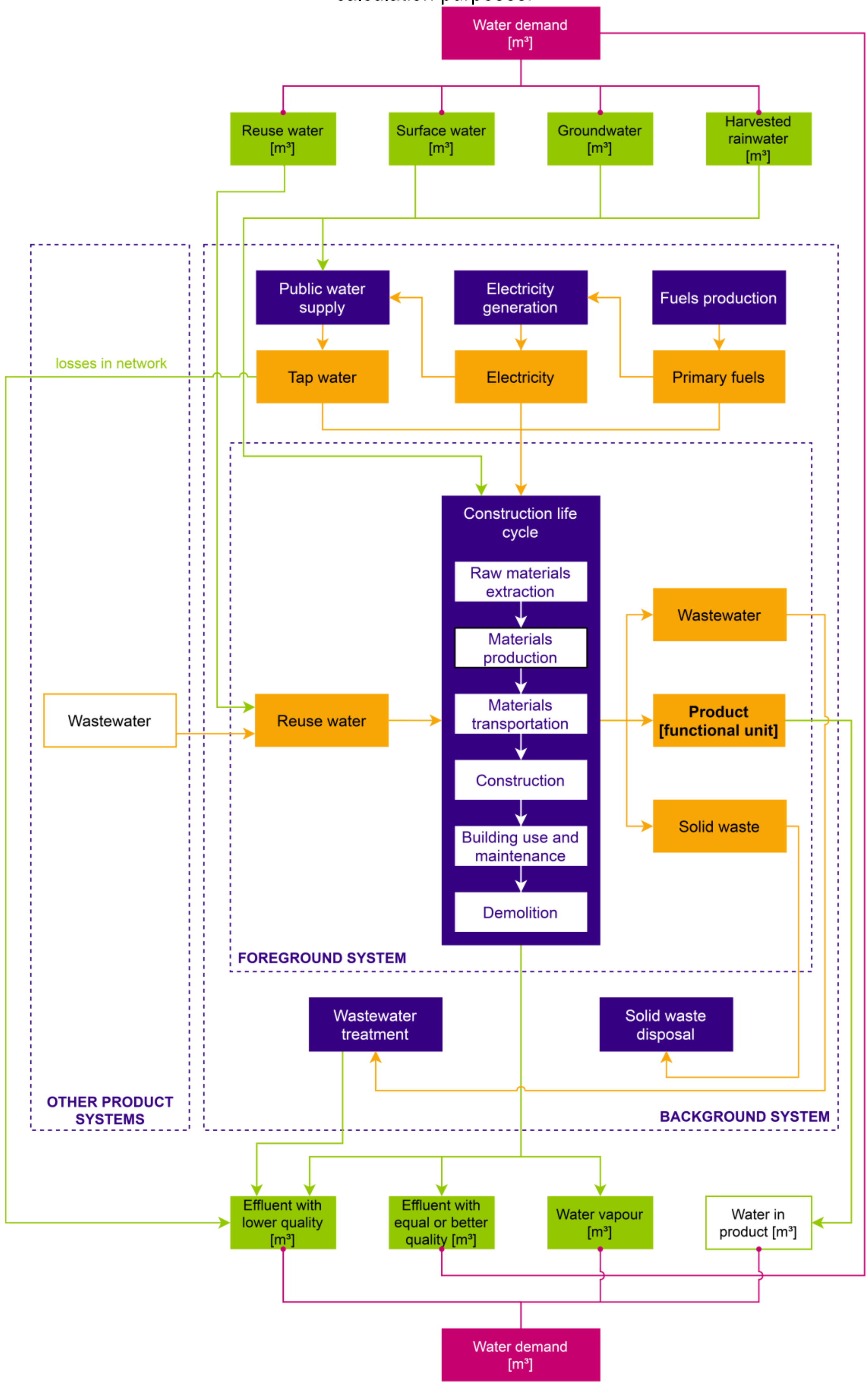
$$W_{total} = W_{surface} + W_{ground} + W_{reuse} + W_{rain} \quad \text{Equation 16}$$

- W_{total}: total water demand (m³/functional unit)
- $W_{surface}$: surface water demand (m³/functional unit)
- W_{ground}: groundwater demand (m³/functional unit)
- W_{rain}: rainwater demand (m³/functional unit)
- W_{reuse}: reuse water demand (m³/functional unit)

Many processes contribute to the water demand throughout the construction life cycle. Water is used for excavation and dust suppression during materials extraction from nature. Manufacturing processes use water for cooling (when the water evaporates), cleaning or as part of the process, such as water added to clay for producing ceramic products and to cement-based products. Transportation processes usually do not consume water. During construction, water is consumed to prepare construction materials and for cleaning. During the use stage, water is consumed for cleaning, drinking, hygiene, sanitation, and recreation (e.g., swimming pools). The production and application of materials for repair and replacement over the service life may also consume water, such as paints and mortars. Building demolition may also consume water, especially for dust suppression, but this volume tends to be low compared to other life cycle stages.

All building-integrated water-consuming processes should be considered during the use stage, including water for drinking, hygiene, heating, cooling, ventilation, humidification, sanitation, irrigation of landscape areas, and recreation (such as swimming pools and saunas). Appliances that are not building-related, such as dishwashers and washing machines, should not be considered (DEUTSCHES INSTITUT FÜR NORMUNG, 2012). However, if it is impossible to disaggregate them, they should be included in the calculation for consistency reasons. Like the energy demand, estimating the water demand associated with operational water use requires assumptions about user behaviour over decades, which implies an associated uncertainty.

Figure 64 – Schematic representation of the water demand indicator, with the two alternatives for calculating it. “Water in product” is not formally an elementary flow, but it can be modelled that way for calculation purposes.



Source: the author.

4.3.4 Land occupation

The land occupation indicator considers the direct occupation of terrestrial land for anthropogenic activities. It consists of the sum of the areas occupied (in m²) multiplied by the corresponding time of occupation (in years), divided by the functional unit (or declared unit), as presented in Equation 17 and Figure 65. It is a measure of land-use efficiency, similar to the indicators measuring the efficiency of using other resources – materials, energy, and water.

$$L_{total} = \frac{\sum_i (A_i . t_i)}{FU} \qquad \text{Equation 17}$$

- L_{total}: total land occupation (m².a/functional unit)
- A_i: area "i" occupied (m²)
- t_i: time of occupation of area "i" (a)
- FU: functional unit (or declared unit)

The land cover classes considered here follow the land cover classification for LCA proposed by (KOELLNER *et al.*, 2013), considering only the classes corresponding to the anthropogenic occupation of land:

a) Forest: applies to native forests with extractive use; planted forests are considered in agriculture.
b) Agriculture:
   - agriculture, arable: cultivated areas regularly ploughed (annual crops);
   - agriculture, permanent crops: perennial crops, including wood plantation;
   - agriculture, mosaic: agroforestry.
c) Artificial areas:
   - urban land: areas with infrastructure for living and business;
   - industrial land;
   - mineral extraction site;
   - dumpsite;
   - construction site;
   - traffic area.

Natural land cover classes (wetlands, shrublands, grasslands) are excluded because the indicator only considers land occupied for human activities associated with the construction life cycle. Aquatic land cover classes are also excluded, as the indicator only considers terrestrial land use. Equation 18 shows the disaggregation of the land occupation indicator according to the principal land cover classes.

$$L_{total} = L_{forest} + L_{agri} + L_{artificial}$$ Equation 18

- L_{total}: total land occupation (m².a/functional unit)
- L_{forest}: forest land occupation (m².a/functional unit)
- L_{agri}: agricultural land occupation (m².a/functional unit)
- L_{urban}: artificial land occupation (m².a/functional unit)

The land cover class corresponds to that at the time of the occupation. For instance, if grassland is converted into an urban area for real estate development, the land cover should be classified as “urban”. The proposed indicator does not account for land transformation.

Over the life cycle of buildings, the land is occupied to extract or produce raw materials, such as quarries and forests. The area occupied by quarries must be multiplied by the operation time and divided by the total production expected for that area. Such information is usually declared in environmental licensing documentation. For cultivated biobased materials (e.g., planted wood), the area must be multiplied by the total cultivation time, from seeding to felling, and divided by the amount of material produced.

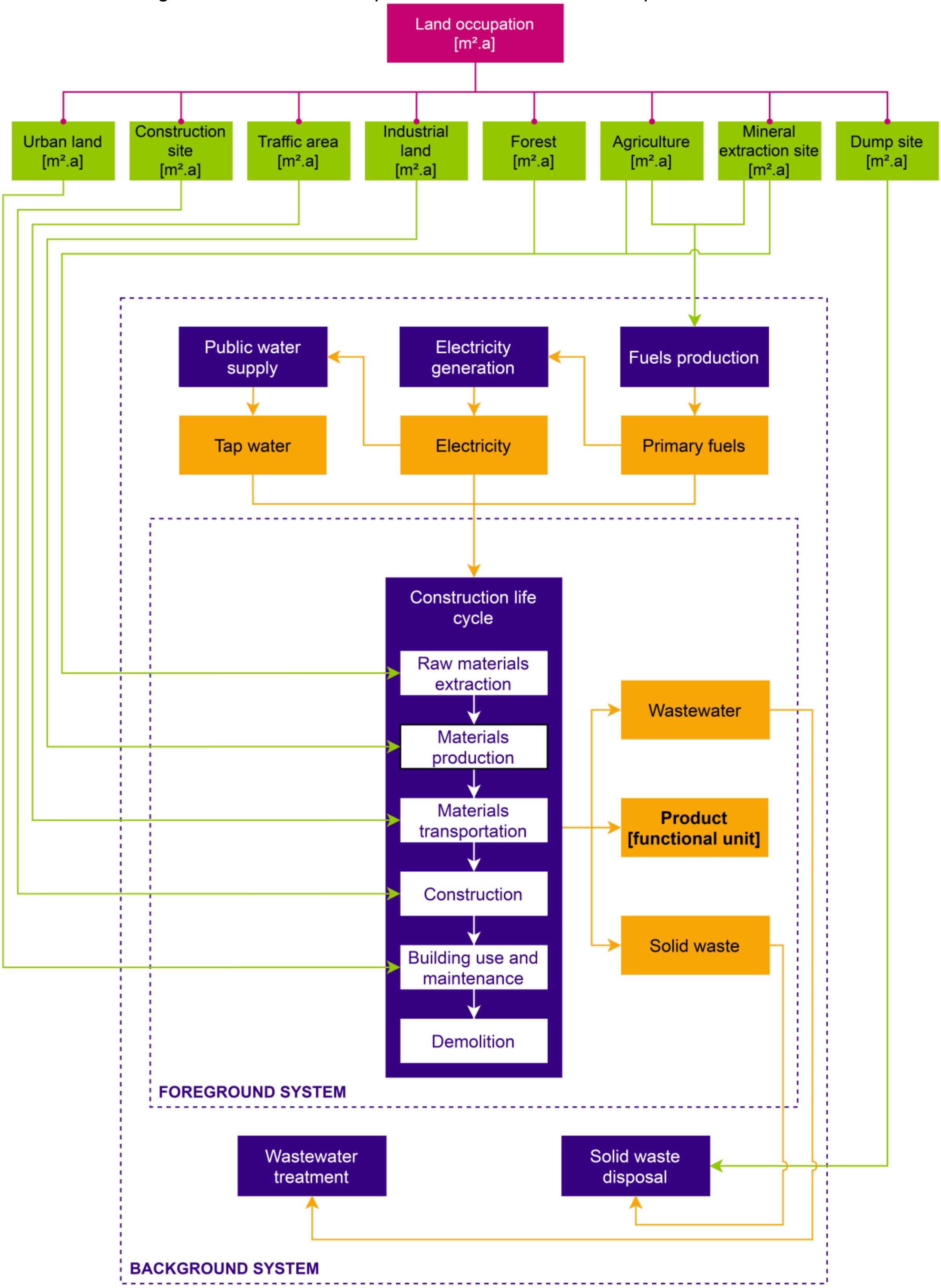
In the case of wood sourced from native-managed forests, the occupation time corresponds to the rotation cycle between the authorized forest areas. However, the definition of the area to be considered requires further analysis. In principle, only the area directly affected by forestry activities should be considered, including the area left fallow after tree felling, log extraction paths, and storage areas in the forest. However, the undisturbed natural area contributes to forest recovery and, hence, future tree extraction, which is part of the production system (NUMAZAWA *et al.*, 2017). Furthermore, native forests are multifunctional systems that provide multiple ecosystem services and preserve biodiversity (CHAUDHARY *et al.*, 2016), which requires proper allocation. These questions are beyond the scope of this study and should be the object of future research.

Land occupation during materials production in industrial facilities is calculated by dividing the area occupied by the industry by the corresponding yearly production. Land occupation for transportation tends to be negligible compared to other life cycle stages. However, to consider it, the area occupied by roads (or rails) would have to be divided by their yearly capacity to transport goods. Land occupation during the construction stage considers the area occupied by the construction site (including surrounding areas that can be eventually used for material storage) multiplied by the construction period.

During the use stage, the area occupied by the building must be multiplied by its service life. The entire land area belonging to the building should be considered, including common areas but excluding natural areas left undisturbed for preservation. Areas outside the development, such as roads necessary to access it, should not be considered. Although developments in remote areas may require additional land occupation to provide basic infrastructure, it is difficult to define an allocation factor since other activities might benefit from it.

Demolition tends to be a rapid activity and contributes little to land occupation. However, the occupation of land for landfilling waste must be considered. Since the occupation time of landfills is difficult to estimate, it is recommended to adopt a standard value of 100 years, following the guidance of ISO 21930 for considering emissions from landfills (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017). Note that landfilling demolition waste is an activity that happens in the future, after decades, which requires considering a scenario for future waste disposal with the corresponding uncertainty.

Figure 65 – Schematic representation of the land occupation indicator.



Fonte: the author.

4.3.5 CO_2 emission

The CO_2 emission indicator considers emissions from fossil fuel combustion, direct emissions from production processes, and the oxidation of non-renewable biomass through combustion or decomposition (Equation 19 and Figure 69).

$$CO_{2,total} = CO_{2,fossil} + CO_{2,proc} + CO_{2,nrenbio} = \frac{\sum CO_{2,i}}{FU} \quad \text{Equation 19}$$

- $CO_{2,total}$: total CO_2 emission (kg/functional unit)
- $CO_{2,fossil}$: CO_2 emission from fossil fuel combustion (kg/functional unit)
- $CO_{2,proc}$: CO_2 emission from production processes[4] (kg/functional unit)
- $CO_{2,nrenbio}$: CO_2 emission from non-renewable biomass oxidation (kg/functional unit)
- $CO_{2,i}$: CO_2 emission from source “i” (kg)
- FU: functional unit (or declared unit)

The emission of CO_2 from combustion can be calculated by multiplying the fuel consumed by the corresponding emission factor (Equation 20). The IPCC discloses CO_2 emission factors for stationary (GÓMEZ *et al.*, 2006) and mobile combustion (WALDRON *et al.*, 2006), which are widely recognized and employed for CO_2 calculations. In addition to these documents, the IPCC maintains an online emission factor database (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021a). Emissions from the combustion of non-renewable waste materials such as used tyres and plastics should also be considered since these wastes would not necessarily be incinerated.

$$CO_{2,fuel} = x_{fuel}.LHV_{fuel}.ef_{fuel} \quad \text{Equation 20}$$

- x_{fuel}: the amount of fuel consumed (unit of fuel)
- LHV_{fuel}: the lower heating value of fuel (in MJ/unit of fuel)
- ef_{fuel}: CO_2 emission factor of fuel (in kg/MJ)

[4] Chemical reactions other than combustion or decomposition of non-renewable biomass

Process CO_2 emissions from chemical reactions can be estimated using stoichiometry (WORLD RESOURCES INSTITUTE; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2011). The main chemical reaction emitting CO_2 is calcination, at the core of cement and lime production. Equation 21 shows the calcination reaction of calcium carbonate ($CaCO_3$) into calcium oxide (CaO, contained in cement and lime) and CO_2. CO_2 emission from calcination can be calculated using the molar masses of chemicals. However, the IPCC discloses emission factors for carbonates that already take the stoichiometry into account ((HANLE *et al.*, 2006), table 2.1) (Equation 22). Carbonates are also used as fluxes and slagging agents in metals smelting and refining and as raw materials in glass production (HANLE *et al.*, 2006). Other processes that emit CO_2 include metallic ore reduction and carbon anode consumption during aluminium production (MARKS *et al.*, 2006).

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{Equation 21}$$

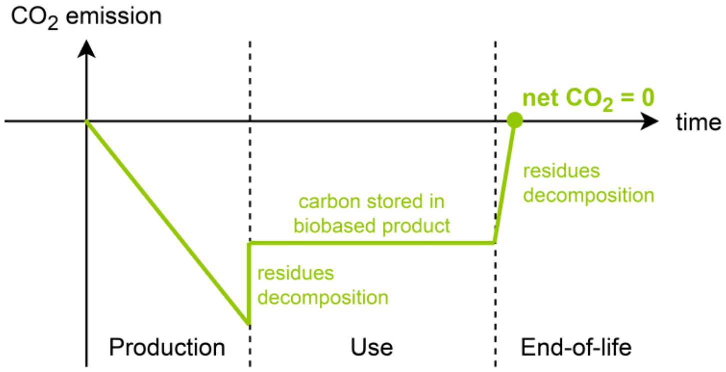
$$CO_{2,proc} = x_{proc}.ef_{proc} \qquad \text{Equation 22}$$

- x_{proc}: the amount of a process with a chemical reaction that emits CO_2
- ef_{proc}: CO_2 emission factor of chemical reaction

Chemical reactions may also remove CO_2 from the atmosphere. Carbonation occurs when CO_2 diffuses into the pores of calcium oxide products and reacts with them forming carbonates. It is a slow process that occurs throughout the life cycle of cement-based materials, including when these materials are transformed into waste. Carbonation depends on materials' porosity, exposed surface area, atmospheric CO_2 concentration, among other factors (XI *et al.*, 2016). Since CO_2 uptake by carbonation is difficult to estimate, it is not considered in the proposed indicator. If desired, the amount of CO_2 potentially absorbed by carbonation can be reported separately.

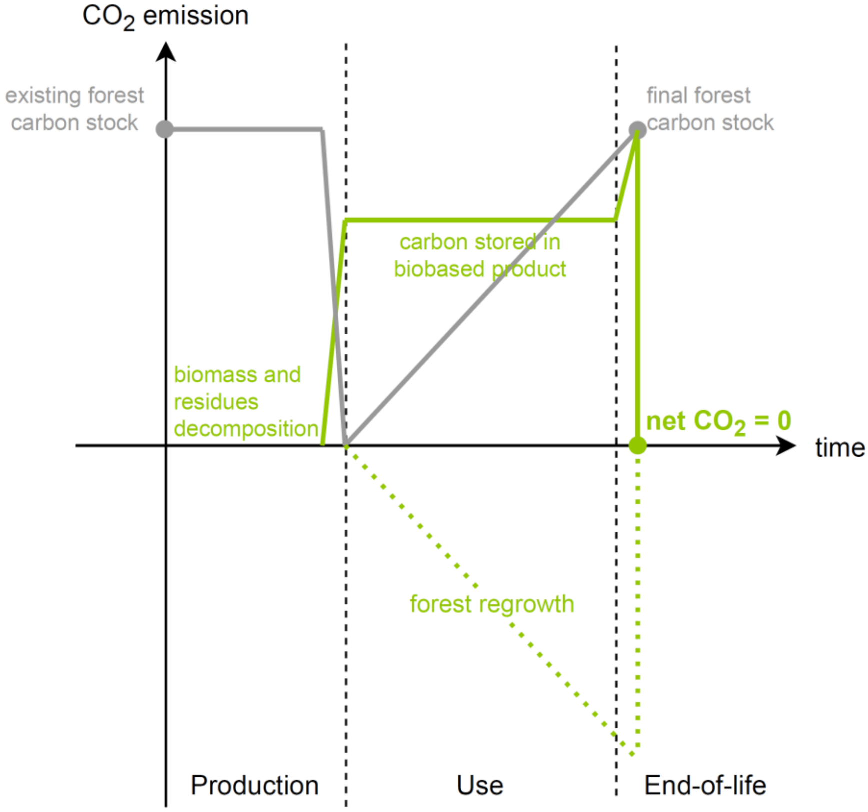
The oxidation of the carbon contained in biomass can only be considered neutral if the biomass comes from renewable sources (BRITISH STANDARDS INSTITUTION, 2014). For biological products originating from plantations, the biomass absorbs CO_2 from the atmosphere through photosynthesis and emits it afterwards through combustion or degradation so that the net CO_2 emission over the life cycle equals zero (Figure 66) (BRITISH STANDARDS INSTITUTION, 2014). In sustainably managed native forests (where forest biomass is allowed to recompose), the carbon stock contained in the biomass can be considered stable over the rotation cycle, and CO_2 neutrality can be assumed (Figure 67) (NUMAZAWA *et al.*, 2017). On the other hand, native forests that are not managed sustainably lose biomass permanently. Therefore, CO_2 emission from the combustion or degradation of the lost biomass should not be considered neutral (Figure 68) (CAMPOS; PUNHAGUI; JOHN, 2021).

Figure 66 – CO_2 emissions and removals over the life cycle of planted biobased products. All biomass is considered renewable.



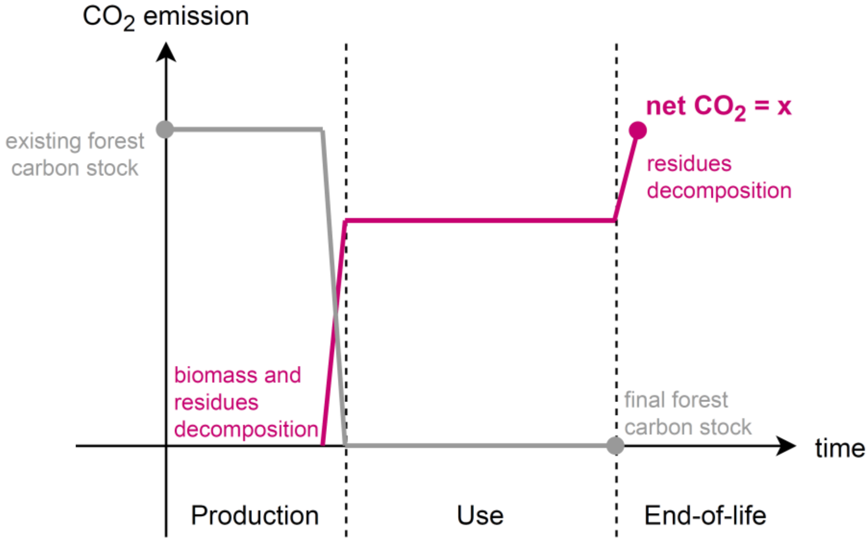
Source: the author.

Figure 67 – CO_2 emissions and removals over the life cycle of native biobased products, with total forest biomass recovery. All biomass is considered renewable.



Source: the author.

Figure 68 – CO_2 emissions and removals over the life cycle of native biobased products, with no recovery of the forest biomass (deforestation). All biomass is considered non-renewable.



Source: the author.

CO_2 emission from the oxidation of non-renewable biomass can be calculated according to Equation 23. The amount of carbon in the biomass corresponds to 50% of its dry mass (RÜTER *et al.*, 2019).

$$CO_{2,nrenbio} = C_{nrenbio}.\frac{44}{12} = m_{nrenbio,dry}.0{,}5.\frac{44}{12} \qquad \text{Equation 23}$$

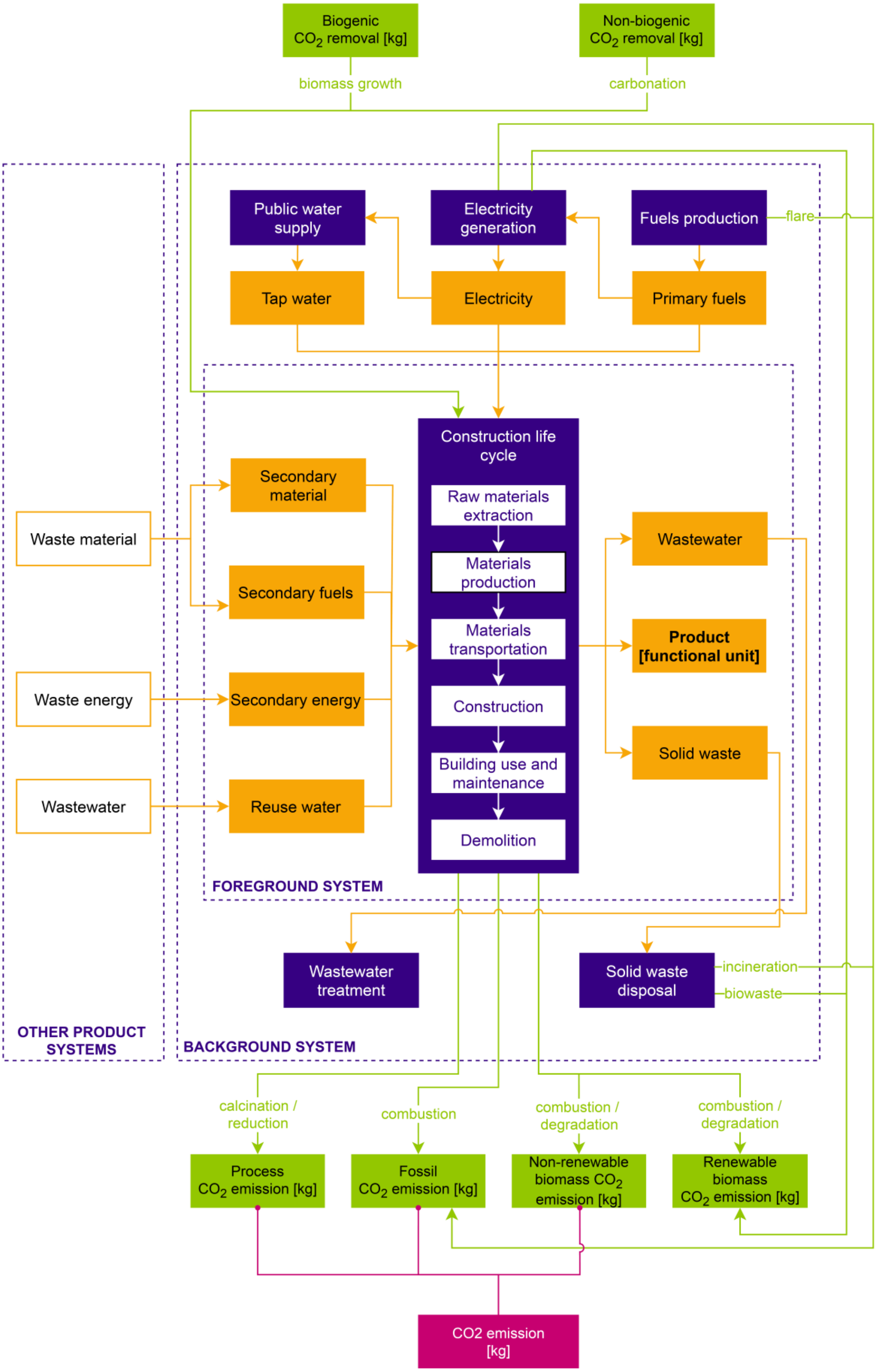
- $CO_{2,nrenbio}$: CO_2 emission from non-renewable biomass oxidation (kg/functional unit)
- $C_{nrenbio}$: quantity of carbon contained in non-renewable biomass (kg/functional unit)
- $m_{nrenbio,dry}$: dry mass of non-renewable biomass (kg/functional unit)

The indicator does not consider CO_2 removals and emissions from renewable biomass because this calculation can result in negative CO_2 emissions at intermediate life cycle stages (Figure 66). Although biobased products store the carbon initially absorbed by the living biomass, that storage is temporary, as sooner or later, that carbon is released back into the atmosphere (RÜTER *et al.*, 2019). Therefore, the CO_2 emission indicator accounts only for the emissions of non-renewable biomass since the goal is to reduce CO_2 emissions that contribute to global warming. Biogenic CO_2 emission and temporary carbon storage by renewable biobased products may be reported separately (DEUTSCHES INSTITUT FÜR NORMUNG, 2020).

CO_2 emissions from non-renewable biomass should account for the total biomass lost above ground, including the biomass extracted from the forest and residues left in the forest to rot. Native vegetation removed to open space for developments or construction work must also be considered. According to the IPCC guidelines, these emissions are part of the land-use change emissions. However, below-ground biomass and carbon in the soil are hard to quantify and are therefore excluded from the indicator. Although biomass decomposition happens over time, CO_2 emissions are assumed to happen at the time of the event that generated the dead biomass (OGLE *et al.*, 2019).

Emission offsetting measures, such as planting forests elsewhere or buying carbon credits, should not be included in the CO_2 emission indicator because they occur outside the product system (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; WORLD RESOURCES INSTITUTE; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2011). Also, weighing factors to account for emissions delayed over time, such as emissions happening at the end-of-life of buildings (typically after decades), should not be considered (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017; WORLD RESOURCES INSTITUTE; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2011).

Figure 69 – Schematic representation of the CO_2 emission indicator.



Source: the author.

4.4 Discussion

4.4.1 Use of the proposed indicators

The proposed indicators allow assessing the most important environmental aspects of construction, among those that can be described quantitatively. They also allow assessing the most important synergies and trade-offs of sustainable construction strategies, as shown in Table 11, which considers a non-exhaustive list of strategies.

Table 11 – Synergies and trade-offs between sustainability strategies for construction, considering the proposed construction environmental performance indicators. The arrows indicate a potential increase or decrease in the indicators over the life cycle of buildings if strategies are applied. Green indicates improvements, orange indicates worsening, and yellow indicates an unknown trend.

	Material demand					**Energy demand**					**Water demand**				**Land occupation**	**CO_2 emission**
Strategy	**Total**	**Renewable**	**Non-renewable**	**Primary**	**Secondary**	**Total**	**Renewable**	**Non-renewable**	**Primary**	**Secondary**	**Total**	**Surface and groundwater**	**Rainwater**	**Reuse water**	**Total**	**Total**
Increase energy efficiency	-	-	-	-	-	↓[1]	↓	↓	↓	↓	-	-	-	-	-	↘
Use renewable energy sources	-	-	-	-	-	-	↑	↓	-	-	↗[2]	↗[2]	-	-	↗[3]	↓
Dematerialization	↓	↓	↓	↓	↓	↕[4]	-	-	-	-	-	-	-	-	-	↕[4]
Use renewable materials	↗[5]	↑	↓	-	-	↘[6]	-	-	-	-	↗[7]	↗[7]	-	-	↗[8]	↘
Use recycled materials	↗[9]	-	-	↓	↑	↕[10]	-	-	-	-	-	-	-	-	-	↕[10]
Increase water efficiency [11]	-	-	-	-	-	-	-	-	-	-	↓	↓	↓	↓	-	-
Harvest rainwater [12]	-	-	-	-	-	-	-	-	-	-	↘[13]	↓	↑	-	-	-
Reuse water [14]	-	-	-	-	-	-	-	-	-	-	↘[13]	↓	-	↑	-	-
Verticalize buildings	↗[15]	-	-	-	-	↗[15]	-	-	-	-	-	-	-	-	↘	↗[15]
Densify urban areas	↕[16]	-	-	-	-	↕[16]	-	-	-	-	↘	-	-	-	↓	↕[16]

1) Considering that no rebound effect occurs; 2) Irrigation of cultivated biomass used as energy source; 3) Land occupation for producing cultivated biomass used as energy source; 4) Dematerialization can reduce or increase the energy demand and CO_2 emissions (for example, steel and aluminium are lightweight materials that can be energy-intensive and emit more CO_2 than bulk materials); 5) Renewable materials are usually less resistant and therefore require more material to fulfil the same function (e.g., wood versus steel); 6) Renewable materials are usually less energy-intensive to produce than non-renewable materials; 7) Cultivated bio-based materials might require irrigation; 8) Land occupation for cultivated bio-based materials; 9) Recycled materials are usually less resistant and therefore require more material to fulfil the same function (e.g., recycled aggregated versus virgin aggregates); 10) Recycled materials can consume less energy (e.g., recycled steel, recycled aluminium) or more energy (e.g., concrete with recycled aggregates that requires more cement for the same strength) than virgin materials. That applies to CO_2 emission; 11) Increasing water efficiency can reduce energy consumption for water treatment and distribution, but since these indicators are determined mainly by other processes, these reductions were not considered; 12) Building a separate hydraulic system for rainwater harvesting and supply may consume more materials and, consequently, more energy and emit more CO_2, but since these indicators are determined mainly by other processes, these increases were not considered; 13) If the harvested rainwater or reuse water is used to replace water from the public supply, water losses in the distribution system are avoided; 14) Treating wastewater for reuse is more energy-intensive than treating water withdrawn from nature, but since the energy demand is determined mainly by other processes, this increase was not considered; 15) High-rise buildings usually require more materials, consume more energy (e.g., in lifts) and consequently emit more CO_2 than low-rise buildings; 16) It depends on the strategy for increasing the density of urban areas (POMPONI *et al.*, 2021).

Other studies have also recommended life cycle inventory indicators as proposed here. STEINMANN *et al.* (2017) carried out a Principal Component Analysis to investigate the correlation between footprint indicators and impact indicators, based on a set of 976 products from the ecoinvent database (including construction products). Four resource footprints – (non-renewable) energy, (abiotic) material, water, and land – explain more than 90% of the variance of two endpoint impact indicators – human health and biodiversity. These resource footprints also cover 84% of the total variance of 135 different midpoint indicators, as investigated in a previous study (STEINMANN *et al.*, 2016). Similarly, GILJUM *et al.* (2011) propose the following indicators: material input (including materials used to produce energy, i.e., fuels), water footprint, land use, and carbon footprint (considering all greenhouse gases).

These proposed indicators cover different environmental aspects, are relevant for policymaking, are easy to communicate, and are based on a life cycle perspective. Moreover, they can be consistently aggregated from products via sectors to countries, an important feature for policy-making and fostering environmental performance improvement (GILJUM *et al.*, 2011). To illustrate this, Table 12 presents the relationships between the proposed indicators and the indicators used by the United Nations to monitor the achievement of the Sustainable Development Goals. Except for land occupation, which does not figure among the SDG indicators, all other indicators have an UN-SDG counterpart, with some similarities.

Table 12 – Relationship between the proposed construction environmental performance indicators and the indicators used to monitor the United Nations Sustainable Development Goals.

Sustainable Development Goal (SDG)	SDG Indicator	Proposed indicator
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Indicator 12.2.1: Material footprint (tonnes)	Material demand (kg/functional unit)
7 AFFORDABLE AND CLEAN ENERGY	Indicator 7.3.1: Energy intensity level of primary energy (MJ/USD GDP)	Energy demand (MJ/functional unit)
6 CLEAN WATER AND SANITATION	Indicator 6.4.1: Water use efficiency (USD/m³)	Water demand (m³/functional unit)
13 CLIMATE ACTION	Indicator 13.2.2: Total greenhouse gas emissions per year (tonnes)	CO_2 emission (kg/functional unit)

Source: the author and (UNITED NATIONS, 2022).

4.4.2 *Comparison with LCA*

LCA is currently the most recommended method for quantitatively assessing the environmental performance of construction, so it makes sense to compare the proposed environmental performance indicators to LCA. Compared to the scope specified by construction LCA standards (DEUTSCHES INSTITUT FÜR NORMUNG, 2020; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017), the indicators proposed are less comprehensive. In addition, the analysis is performed at the inventory level. The proposed simplification can be argued to increase the risk of unintended burden shifting (BEEMSTERBOER; BAUMANN; WALLBAUM, 2020).

However, existing correlations between the proposed inventory and life cycle impact indicators suggest a low risk of unintended burden shifting.

Furthermore, the fact that the proposed indicators do not assess some environmental impacts does not mean that these impacts are not controlled. For example, local air pollution regulations limit the concentration of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter, and other pollutants in exhaust gases and the air (BRASIL, 2007, 2018; LI; JIN; KAN, 2019; WORLD HEALTH ORGANIZATION, 2015). These pollutants are considered in the life cycle impact categories of photochemical ozone creation, acidification, fine particulate matter formation, and terrestrial eutrophication. Local environmental regulations also limit emissions of pollutants to water (BRASIL, 2005, 2011), including phosphates and nitrates considered by the freshwater and marine eutrophication impact categories. The emission of potentially toxic substances is also regulated for relevant processes, i.e., processes likely to generate these substances (BRASIL, 2000, 2005, 2007, 2011).

The negative consequences these pollutants may have on human health and ecosystems depend on their concentration in the emissions and the characteristics of the receiving environment. In general, LCA does not model these impacts accurately since doing so requires regionalizing inventory flows and characterization factors at a very detailed level. Moreover, LCA aggregates emissions over products' entire life cycle and divides them by the corresponding functional unit. This procedure can hide eventual acute emissions at a specific life cycle stage (SCHALTEGGER, 1996). On the other hand, local environmental regulations require monitoring the concentration of pollutants at specific sites and are, therefore, more appropriate to control local environmental impacts. As a result of these regulations, pollution levels are decreasing in many parts of the world, although improvements are still necessary (MAAS; GREENFELT, 2016; SCHMALE *et al.*, 2014), particularly regarding water pollution (FLÖRKE *et al.*, 2013; UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION; UN-WATER, 2020).

Impacts controlled by instruments other than LCA also include stratospheric ozone depletion, human and eco-toxicity, and ionizing radiation. Stratospheric ozone depletion is tackled by the Montreal Protocol (UNITED NATIONS ENVIRONMENT PROGRAMME, 2019a), which reached universal ratification in 2009 and has been so successful in phasing out the production (and consequently the emission) of ozone-depleting substances that the ozone layer is recently recovering (SOLOMON *et al.*, 2016). International protocols limit or ban the production of some toxic compounds, such as the substance aldrin (identified as the primary driver of toxicity-related impacts), which is part of the Stockholm Convention on Persistent Organic Pollutants (UNITED NATIONS ENVIRONMENT PROGRAMME, [*s. d.*]). Different local regulations and initiatives also limit the use of products containing hazardous substances, such as the REACH regulation in the European Union (EUROPEAN CHEMICALS AGENCY, 2022). The handling of radioactive substances considered in the ionizing radiation impact category happens under strict regulations at the national and international levels (UNITED NATIONS ENVIRONMENT PROGRAMME, 2016b). Moreover, the exposure of humans to radioactivity emitted from nuclear power plants and related activities is negligible compared to other sources, including natural radiation (UNITED NATIONS ENVIRONMENT PROGRAMME, 2016b).

Therefore, little is lost in terms of environmental performance management by applying a simplified approach compared to conventional LCA. On the contrary, there are relevant gains as the proposed indicators broadly meet the expectations of construction sector stakeholders. Meeting stakeholders' expectations increases the likelihood of their adoption to support decisions (SILVA; NUZUM; SCHALTEGGER, 2019), compared to the limited adoption of LCA (INTERNATIONAL ENERGY AGENCY; UNITED NATIONS ENVIRONMENT PROGRAMME, 2018). The environmental aspects covered by the proposed indicators (energy, materials, water, land, and CO_2) and the number of indicators (5) agree with the opinions of most stakeholders from the Brazilian construction sector who took part in the survey.

Furthermore, the proposed indicators can be implemented more quickly than LCA because their calculation depends on a reduced set of elementary flows that are relatively simple to inventory:

a) The material demand indicator requires information about the mass of materials consumed that can be retrieved from material composition data, design documents, bills of materials, ERP systems, among other sources;
b) The energy demand indicator requires data about fuel and electricity consumption, which can be retrieved from management systems (for the production stage), design documents, and estimates (for the use stage);
c) The water demand indicator requires inventorying water flows, which are metered or estimated with reasonable precision;

d) The land occupation indicator requires data about the area occupied by activities over the construction life cycle, which can be based on design documents, environmental licenses, and other sources. The occupation time can be estimated or retrieved from environmental licenses for mining and forestry;
e) The CO_2 emission indicator requires calculating CO_2 emission from fossil fuels or non-renewable biomass combustion, which can be done using energy consumption data and publicly available emission factors. CO_2 emissions from chemical reactions can be calculated using emission factors or stoichiometry.

Except for CO_2 emissions, all other elementary flows accounted for by the proposed indicators correspond to costs for companies and are therefore routinely monitored, including by small and medium enterprises. Thus, the proposed environmental performance indicators use existing information, which makes it easier and faster to implement than LCA. The cost and speed of implementing construction environmental performance indicators are crucial aspects to consider, especially when these indicators are intended for public policy development (SCHALTEGGER, 1996; SEIDEL, 2016). As is the case of LCA nowadays, complex and expensive environmental performance assessment methods exclude a relevant share of the construction value chain.

Furthermore, the reliability of indicators is increased because fewer elementary flows need to be inventoried, reducing the number of data gaps to be filled with secondary data that are hardly representative. Nevertheless, secondary data remain necessary for background processes. The proposed indicators facilitate the development of local life cycle inventory databases by reducing the scope of elementary flows to be covered. This is important, considering that many countries, including Brazil, still lack representative life cycle databases.

Moreover, by making it easier to collect primary inventory data, the proposed indicators contribute to increasing the availability of life cycle data to support decisions. Instead of spending resources on collecting many inventory data for a few products or buildings (to cover all elementary flows required by LCA), it is possible to collect a few inventory data for many products and buildings. Making primary inventory data collection easier also facilitates considering specific aspects of each product system, including regional aspects. It is also essential for developing environmental performance benchmarks, which are required to interpret the indicators, support decisions, and identify opportunities for environmental performance improvement.

Apart from these comparisons, it is important to mention that the proposed construction environmental performance indicators and LCA are not conflicting but complementary methodologies. One can start by inventorying the elementary flows required to calculate the proposed indicators and then complement the inventory with the missing elementary flows required by LCA (eventually using secondary LCA databases). On the other hand, one can start from a life cycle inventory compiled for a conventional LCA study and filter the elementary flows required for calculating the proposed construction environmental performance indicators.

Nevertheless, this study proposes environmental performance indicators to address the most critical and urgent environmental issues associated with the construction life cycle. It is not about assessing every possible interaction between construction and the environment. Furthermore, these indicators must be consistently applied throughout the construction value chain, including small and medium enterprises; otherwise, the life cycle approach is unfeasible. Simplified indicators used by many stakeholders are likely to yield more significant impact reductions than detailed indicators used only by a few companies (FULLANA I PALMER *et al.*, 2011). This decision-oriented approach justifies the reduced scope compared to conventional LCA (FREIDBERG, 2015; FULLANA I PALMER *et al.*, 2011; GRAEDEL, 1998; SCHALTEGGER, 1996).

It can still be argued that the criteria used to select the proposed environmental performance indicators are not purely scientific, and that is true, but neither are they merely subjective, nor is LCA strictly scientific (BRAS-KLAPWIJK, 1998; FREIDBERG, 2018). The applied criteria consider the best practices for environmental indicators to be used for decision-making, including the opinion of the stakeholders expected to use these indicators and a deep analysis of the LCA results. Therefore, the proposed indicators result from a combination of scientific and practical choices, which are explicitly recognized here, as recommended by best practices on environmental performance management (FREIDBERG, 2018; GLOBAL REPORTING INITIATIVE; UNITED NATIONS GLOBAL COMPACT; WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT, 2019; RAMETSTEINER *et al.*, 2011).

4.4.3 Limitations of the proposal

The indicators proposed here cover the most important environmental aspects of construction. Still, they do not cover all relevant environmental impacts that buildings can cause. Specific construction materials, building typologies, and use patterns, among other factors, may require specific analyses that extend over the environmental aspects covered by the proposal. However, it does not mean that the conventional LCA approach would properly address them. For example, paints and adhesives may inform the emission of volatile organic compounds (VOCs). Non-residential buildings such as hospitals and industries may emit harmful substances into the air, water, and soil. There are undoubtedly many other examples of environmental concerns that other instruments must control. Therefore, the proposal presented in this thesis should not be regarded as the only instrument for analyzing all relevant environmental aspects of construction, but only those that can be adequately measured based on the life cycle approach using primary data.

The proposed indicators focus on the environmental priorities of construction. Therefore, environmental aspects that might be important for other sectors are not considered; for example, eutrophication, which is important for agriculture. Some companies may act in different sectors and would benefit from a standardized list of indicators. LCA and EPDs require essentially the same indicators regardless of the sector. However, this approach increases the number of impact categories, making it very difficult to use primary data and leading to an overuse of secondary data, which is inappropriate for decision-making. Furthermore, the proposed indicators cover environmental aspects widely recognized as a priority.

Due to time constraints, the practical application of this proposal in companies belonging to the construction sector was impossible. Such an application would allow assessing the feasibility of collecting the life cycle inventory data, calculating the proposed indicators, and evaluating the performance of this simplified approach compared to the conventional LCA process (for instance, in terms of adoption speed). Nevertheless, based on the author's experience collecting primary life cycle inventory data of cement-based products in Brazil (SILVA et al., 2018), it can be affirmed that the proposed streamlined approach significantly reduces the effort of collecting and compiling life cycle data.

The proposed indicators have partially been applied to develop the Information System for Environmental Performance in Construction (Sidac) (MINISTÉRIO DE MINAS E ENERGIA; CONSELHO BRASILEIRO DE CONSTRUÇÃO SUSTENTÁVEL, 2022), which was used in the sensitivity analysis presented in item 3.4.6. The system allows users to calculate the cradle-to-gate energy demand and CO_2 emission indicators of construction products. It contains a generic database of 86 construction products and 40 basic supplies, based on Brazilian data gathered from the literature. A scientific committee validated the methodology of the system. Without such a simplified approach, it would be impossible to develop the system with the generic datasets in such a short time (from January 2021 to April 2022). Therefore, Sidac can be regarded as a practical validation of this proposal.

Finally, this proposal can be revised in the future, considering the evolution in data collection methods, digitalization, the internet of things etc.

4.5 Conclusion

This chapter presented the logic for selecting a set of indicators for assessing the environmental performance of construction based on a life cycle approach. The LCA results are taken as a starting point, including the recommendation of simplifying the scope of the assessment to cope with the requirements for effective environmental performance indicators. LCA simplification strategies were reviewed, and the strategy considered most promising was the exclusion of impact categories, since some impacts assessed in LCA proved redundant or not relevant to the construction sector. Redundant indicators were eliminated from the 16 impact categories required by construction LCA standards. Impact categories mainly determined by background processes were excluded from the scope to focus on construction stakeholders' priorities. Inventory indicators were chosen instead of impact indicators to simplify the calculation and make indicators more easily comprehended. Five indicators are proposed: material demand, energy demand, water demand, land occupation, and CO_2 emission. The rules for calculating each indicator were presented. The connection between the basic concepts and the mathematical formulation of LCA was also discussed, even though the proposed indicators cannot be formally considered LCA.

The proposed indicators allow assessing the most important quantitative environmental issues associated with the construction life cycle based on elementary flows that are easy to monitor. They also allow us to see the synergies and trade-offs of sustainable construction strategies as they measure uncorrelated environmental aspects. Furthermore, the proposal is aligned with the stakeholders' expectations regarding the construction sector's environmental priorities and the number of appropriate indicators for decision-making.

A comparison between the proposed construction environmental performance indicators and LCA is presented. The environmental impacts not considered by the proposed indicators are addressed by environmental regulation and other instruments so that the losses in terms of environmental performance management are minimal. On the other hand, the proposed indicators are more likely to be adopted for decision-making and public policy development than conventional LCA due to stakeholder acceptance and accessibility. Broad adoption of a simplified environmental performance assessment is more likely to generate economy-wide impact reductions than limited adoption of complex methodologies. Finally, the proposed indicators can be implemented at a lower cost and higher speed than LCA, allowing resources to be directed towards improvement actions rather than to the assessment, with the urgency required by current environmental challenges.

5 CONCLUSION

This study proposes five inventory indicators to measure the environmental performance of construction: material demand (kg), energy demand (MJ), water demand (m^3), land occupation (m^2.a), and CO_2 emission (kg), all expressed relative to the product's functional unit. These five indicators focus on priority environmental aspects of the construction life cycle that can be assessed using life cycle-based indicators. They can be calculated using easy-to-measure inventory data and transparent methods, producing reliable information for decision-making. The life cycle approach is maintained, allowing for comparable indicators. Stakeholder surveys demonstrate that the proposed indicators are easy to comprehend and coherent with the number of indicators considered ideal for supporting everyday decisions.

The proposed indicators allow for a life cycle-based quantitative assessment of the environmental performance of construction while observing the characteristics that potentially increase the chances of using these indicators for decision-making. The effective adoption of these indicators by the construction sector is required to reduce the environmental impacts over the construction life cycle. Reducing the complexity of indicators also reduces the cost and workload for measuring them, making the life cycle approach accessible for small and medium-sized enterprises that are an essential part of the construction value chain. The proposed set of indicators also facilitates the adoption of life cycle metrics for construction by developing countries. Considering that future population growth and urbanization will be concentrated in these countries, they must be equipped with tools to assess the environmental performance of the necessary construction works.

Furthermore, the proposed indicators can be consistently required from the whole construction sector, allowing for developing environmental performance benchmarks. Benchmarks offer a range of values that can be expected for a particular indicator, which helps interpret the results and evaluate whether a specific product has a good or bad environmental performance compared to its competitors. Benchmarking can also drive environmental performance-based competition. With the increasing availability of environmental performance indicators, these benchmarks can form the basis for proposing environmental performance targets and limit values, thus driving the necessary reduction in the environmental impacts caused by the construction sector.

The proposed indicators cover a smaller scope than LCA. However, the practical implications in terms of decision-making are small. The omitted indicators are either well correlated with the proposed inventory indicators, determined mainly by background processes that construction stakeholders cannot change, or controlled by other instruments. On the contrary, the environmental benefits are likely greater than those obtained by LCA since decision-makers in the construction sector are more likely to adopt the proposed indicators. Nevertheless, the indicators proposed here and LCA are not contradictory but complementary. Companies can start with a simplified approach and eventually evolve to a conventional LCA, or vice versa.

While the construction sector causes significant impacts on the environment, it also bears great opportunities for mitigating these impacts. The proposed indicators aim to help companies and professionals to identify these opportunities and define the best alternatives for improving the environmental performance of construction. Only with the broad, unrestricted, and rapid engagement of the entire construction value chain will it be possible to limit the environmental impacts caused by construction and keep the planet habitable for future generations.

5.1 Recommended future work

Future research can use the proposed indicators to answer the following questions:

a) How much faster can the proposed indicators be implemented than the conventional LCA approach?
b) How does adopting the proposed indicators contribute to improving the environmental performance of construction (compared to the business-as-usual situation)?
c) What is the best way to present environmental performance indicators to different decision-makers (architects, engineers, investors, and public authorities) to guide environmental performance improvement?
d) What is the environmental performance of the most used construction products and systems (in Brazil), and how much can it be improved? (development of environmental performance benchmarks of products)

e) What is the environmental performance of buildings of different typologies (in Brazil), and how much can it be improved? (development of environmental performance benchmarks of buildings)
f) How much does each decision (architectural design, structural design, supplier selection etc.) contribute to improving the environmental performance of buildings?
g) How do environmental performance indicators relate to construction costs for different products and buildings?
h) How do different parts of buildings contribute to their environmental performance indicators (private areas, shared areas, parking, amenities etc.), and how can public policies (such as city masterplans) influence building design towards improving their environmental performance?

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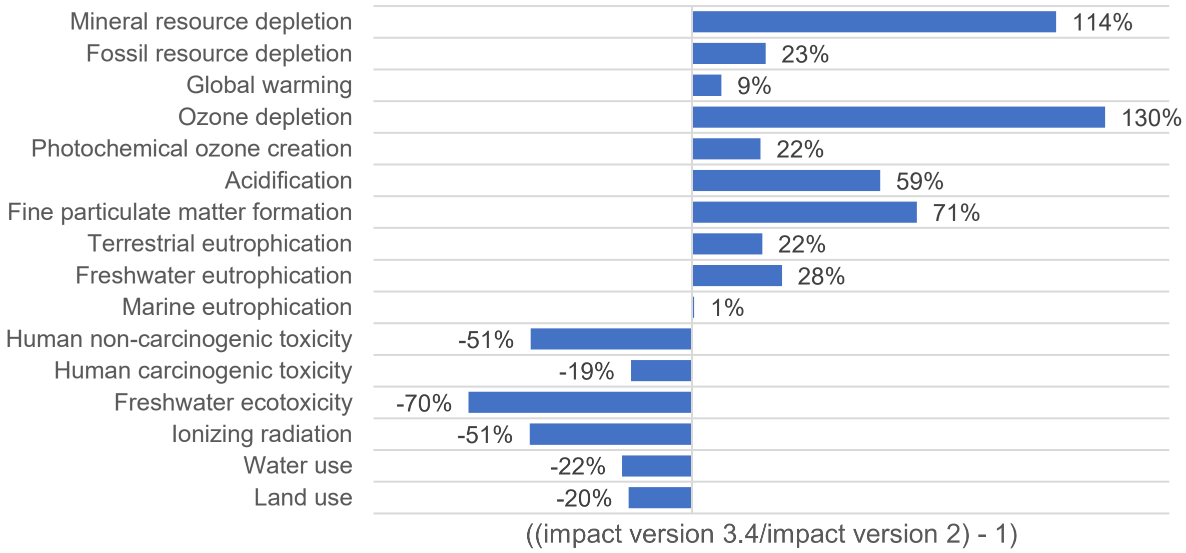
APPENDIX A

Sensitivity analysis of using ecoinvent version 3 for the Life Cycle Assessment of the analyzed building

To assess the effect of using more recent ecoinvent data on the LCA results of the analyzed building, the cradle-to-grave LCI of the house was remodelled, replacing version 2 datasets with their version 3.4 counterparts whenever available. LCA results were recalculated using the updated LCI. The updated LCI and the results are available in the Electronic Supplementary Material (https://dx.doi.org/10.17632/k4mnt33tyc.2). From the 46 datasets used in the LCI, 14 (30%) had no counterparts in version 3.4, including elementary processes of waste disposal and wastewater treatment. The remaining 32 datasets were updated, of which 24 have identical elementary processes compared to ecoinvent version 2, i.e., they have not been individually updated and are only affected by systemic database changes (such as the division of activities between market and transformation activities). The 8 datasets individually updated in version 3 include electricity (at the grid), heat generation from natural gas, tap water supply, road transportation, and concrete, aluminium, clay brick, and sawn wood production.
Figure 70 shows the relative difference between LCA results calculated using version 3.4 and version 2 datasets.

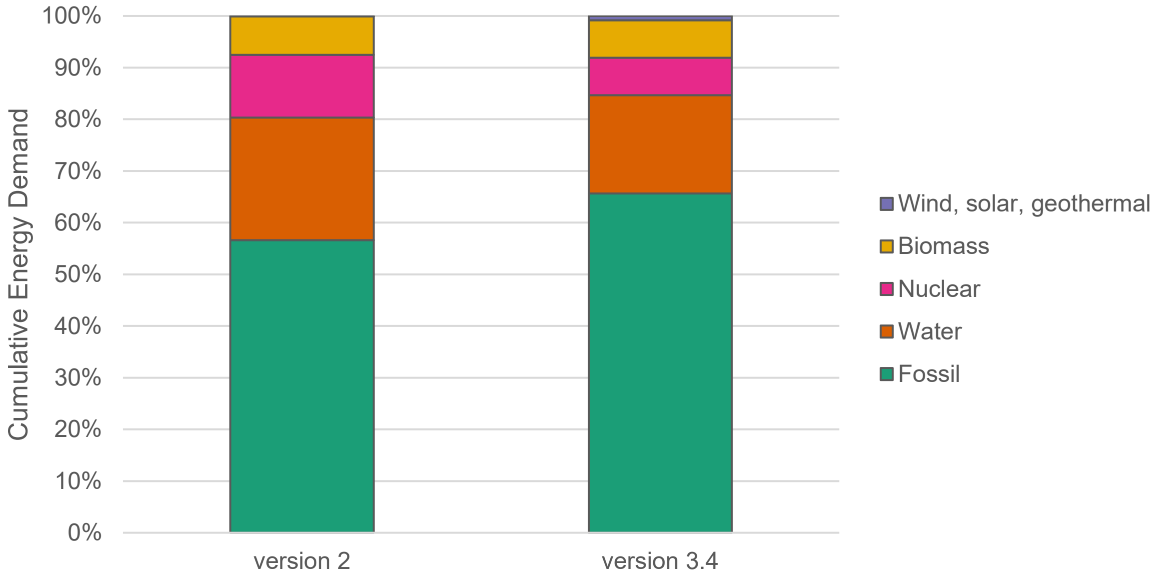
Figure 70 – Relative difference between cradle-to-grave LCA results of the analyzed building, calculated using ecoinvent version 3.4 and version 2 datasets.



Source: the author.

Ten impact categories show an increase in the LCA results using version 3.4 data. Some of these impacts are predominantly caused by fossil fuel use and combustion. Therefore, the cumulative energy demand was calculated using ecoinvent version 3.4. The comparison with the results of version 2 is presented in Figure 71. The updated data have a higher share of fossil energy than version 2, explaining the increase of fossil energy-related impacts. It also explains the decrease in the ionizing radiation result as the share of nuclear power decreases.

Figure 71 – Cradle-to-grave cumulative energy demand of the analyzed building, calculated using ecoinvent version 2 and version 3.4 LCI data.



Source: the author.

The increase in ozone depletion is explained by the update of the electricity transmission datasets, with a 10 times higher emission of N_2O through the ionization of the air surrounding high-voltage transmission lines ($5{,}0.10^{-5}$ kg/kWh) compared to version 2. The increase in mineral resource depletion is explained by an update in the allocation of the zinc-lead mine operation dataset. Updates explain the increases in the fine particulate matter formation and acidification results in electricity generation datasets (lignite and oil) and corresponding airborne emissions.

The decrease in toxicity-related impacts is explained by the update in the electricity generation datasets. While the results obtained with ecoinvent version 2 indicated the emission of pesticides from sugarcane production (the bagasse used for generating electricity), this process does not exist in version 3.4. The emission of acrolein to air declared in transportation datasets causes human non-carcinogenic toxicity. The emission of formaldehyde during the production of clay-based products causes human carcinogenic toxicity. Freshwater ecotoxicity is caused by the emission of pollutants into the water from petroleum platforms and chemical plants producing phenol (used as an adhesive in wood-based products).

Updates in tap water supply datasets explain the decrease in water use. The decrease in land use is caused by updates in the wood production datasets (yield). Table 13 shows the main elementary flows and processes causing the impacts, considering the LCI using ecoinvent version 3.4 data.

Table 13 – Summary of the analysis of the impact categories assessed in the LCA of the house considering ecoinvent version 3.4 data. Text in bold refers to differences compared to the results obtained using ecoinvent version 2.

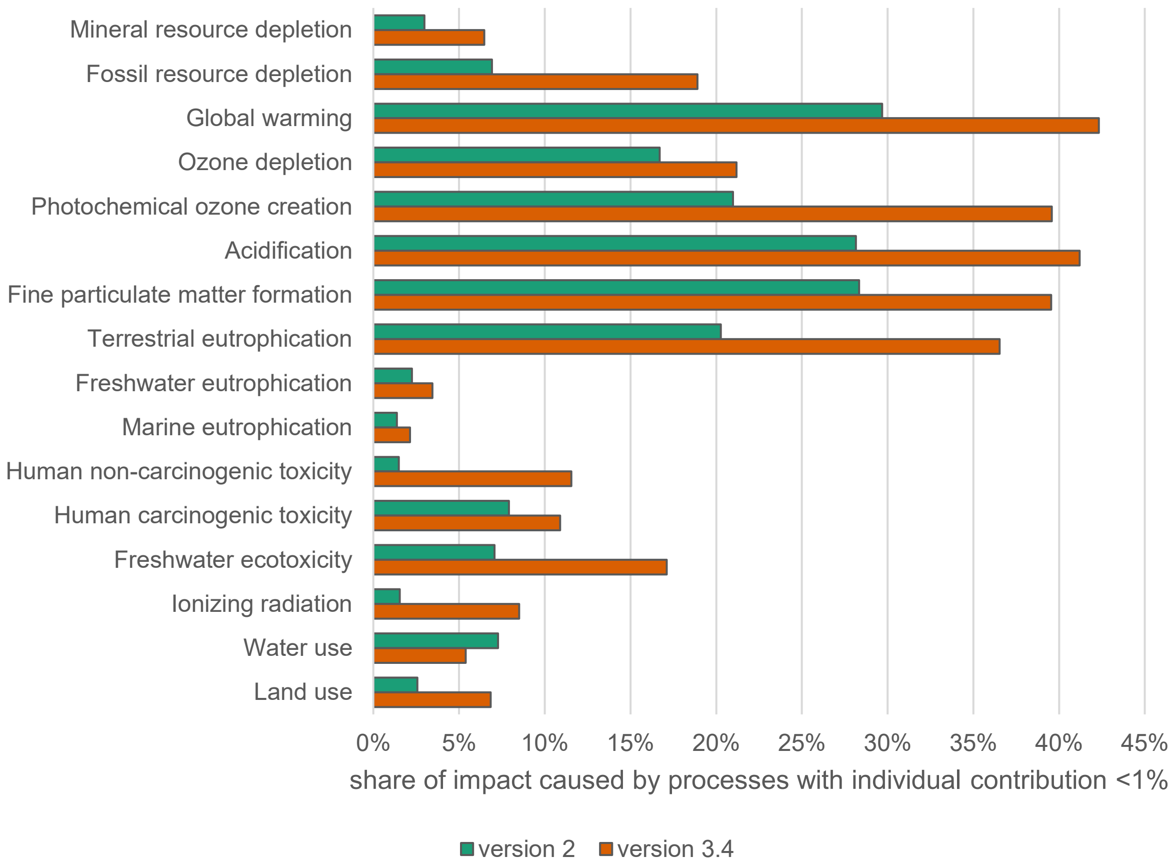
Impact category	Main elementary flows causing the impacts	Main processes causing the impacts
Depletion of mineral elements	Consumption of cadmium, copper, and lead	Consumption of metallic minerals
Depletion of fossil fuels	Consumption of natural gas, crude oil, and coal	Consumption and combustion of fossil fuels
Global warming	Emission of CO_2 into the air	
Photochemical ozone creation	Emission of NO_x into the air	
Acidification	Emission of SO_2 and NO_x into the air	
Fine particulate matter formation	Emission of PM 2.5 µm, SO_2, and NO_x into the air	
Terrestrial eutrophication	Emission of NO_x into the air	
Freshwater eutrophication	Emission of phosphate into the water	
Marine eutrophication	Emission of nitrate and ammonium ion into the water	Sewage treatment
Ozone depletion	Emission of N_2O into the air	Electricity transmission
Human non-carcinogenic toxicity	**Emission of acrolein into the air**	**Transportation**
Freshwater ecotoxicity	**Emission of phenol, cumene, and acetic acid into the water, and emission of formaldehyde into the air**	**Discharge of water from petroleum platforms, production of products containing phenol, combustion of fossil fuels**
Human carcinogenic toxicity	**Emission of formaldehyde and dioxin into the air**	**Combustion of fossil fuels**
Ionizing radiation	Emission of Radon-222 and carbon-14 into the air	Nuclear electricity production
Water use	Water consumption	Water consumption during the use phase
Land use	Urban area occupation and forest area occupation	Land occupation by the house and forestry

Source: the author.

Despite the differences observed between ecoinvent version 2 and version 3.4, the main conclusions of this work remain valid regarding indicators' correlations, level of influence of the construction value chain on the different environmental impact categories, and measurability of elementary flows.

Figure 72 illustrates the drawback of using version 3.4 data, as the share of elementary processes whose contribution falls below the cut-off level of 1% of total impact increases significantly. Impacts are diluted because the new data structure adopted in ecoinvent version 3 artificially increases the number of datasets, dividing them into market and transformation datasets and mixing different geographies in “Rest-of-the-World” datasets.

Figure 72 – Share of the impact caused by elementary processes with an individual contribution to LCA results of less than 1% (cut-off level), considering LCI data of ecoinvent version 2 and version 3.4.



Source: the author.