CIRCULAR BUILDINGS

Guideline for improving efficiency indicators of buildings

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PREAMBLE

Energy, carbon and water are important and common indicators of the environmental performance of buildings. They can be divided into two parts: embodied and operational impacts. The former refer to energy, carbon and water needed during the extraction of raw material and manufacturing of building products and the construction of the building. The latter refer to impacts that arise during the use stage of a building. Both are important but embodied impacts are particularly relevant for the concept of circular material flows for buildings. This guideline focuses on the analysis of embodied impacts.

After a brief introduction, building efficiency indicators are described. Subsequently, critical aspects in building efficiency frameworks are highlighted. These sections are divided into material quantities and environmental impacts, since these aspects are most commonly used as an expression of the circularity of buildings. Afterwards, three examples, one each for energy, carbon and water, is provided to highlight critical aspects and recommendations to overcome them through practical application. The last chapter of this guideline is a summary of recommendations for an increased robustness of efficiency indicators for circular buildings.

This guideline is an output of the Circular Buildings project, which is funded by EEA grants under the Environment, Climate Change and Low Carbon Economy Programme. The project seeks to increase the application of circular economy principles in the construction sector through the development of decision support tools directed at stakeholders in the value chain, which promote an increase in the reuse of materials and a reduction in the production of waste. Two additional guidelines were developed within the project, namely the “Guideline for promoting circularity in Environmental Product Declarations” and the “Guideline for creating Circular Materials Passports”.

PREÂMBULO

A energia, o carbono e a água são indicadores importantes e comuns do desempenho ambiental dos edifícios. Podem ser divididos em duas partes: impactes incorporados e operacionais. Os primeiros referem-se à energia, carbono e água necessários durante a extração da matéria-prima e fabrico dos produtos de construção e a construção do edifício. Os segundos referem-se aos impactes que surgem durante a fase de utilização de um edifício. Ambos são importantes, mas os impactes incorporados são particularmente relevantes para o conceito de fluxos de materiais circulares para edifícios. Este guia centra-se assim na análise dos impactes incorporados.

Após uma breve introdução, são descritos os indicadores de eficiência dos edifícios. Subsequentemente, são destacados aspetos críticos nos sistemas de eficiência dos edifícios. Estas secções dividem-se em quantidades de materiais e impactes ambientais, uma vez que estes aspetos são normalmente utilizados como expressão da circularidade dos edifícios. Posteriormente, são fornecidos três exemplos para a energia, carbono e água de forma a destacar aspetos críticos e recomendações para os ultrapassar através da sua aplicação prática. O último capítulo deste guia apresenta um resumo das recomendações para uma maior robustez dos indicadores de eficiência para edifícios circulares.

Este guia é um resultado do projeto Edifícios Circulares que é financiado pelo EEA Grants ao abrigo do Programa Ambiente, Alterações Climáticas e Economia de Baixo Carbono. O projeto procura aumentar a aplicação dos princípios da economia circular no sector da construção através do desenvolvimento de ferramentas de apoio à decisão dirigidas aos intervenientes na cadeia de valor, que promovem um aumento na reutilização de materiais e uma redução na produção de resíduos. Foram desenvolvidos dois guias adicionais no âmbito do projeto, nomeadamente o "Guia para a promoção da circularidade nas Declarações Ambientais de Produto" e o " Guia para a criação de Passaportes de Materiais Circulares ".

1 INTRODUCTION

1.1 CONTEXT

Among the Sustainable Development Goals (SDG) from the United Nations, the number 12 "Ensure Sustainable Consumption and Production Patterns" targets to significantly reduce waste generation through prevention, reduction, recycling and reuse. Construction materials are, after water, the second biggest material flow in cities. Figure 1 shows the projected development of global material use until 2060 by the OECD (2018). It is predicted that the use of non-metallic minerals, including the essential building raw materials sand, gravel and limestone, will almost double from 44 Gt in 2017 to 86 Gt in 2060. Moreover, concrete is expected to be the highest contributor across materials to climate change in 2060.

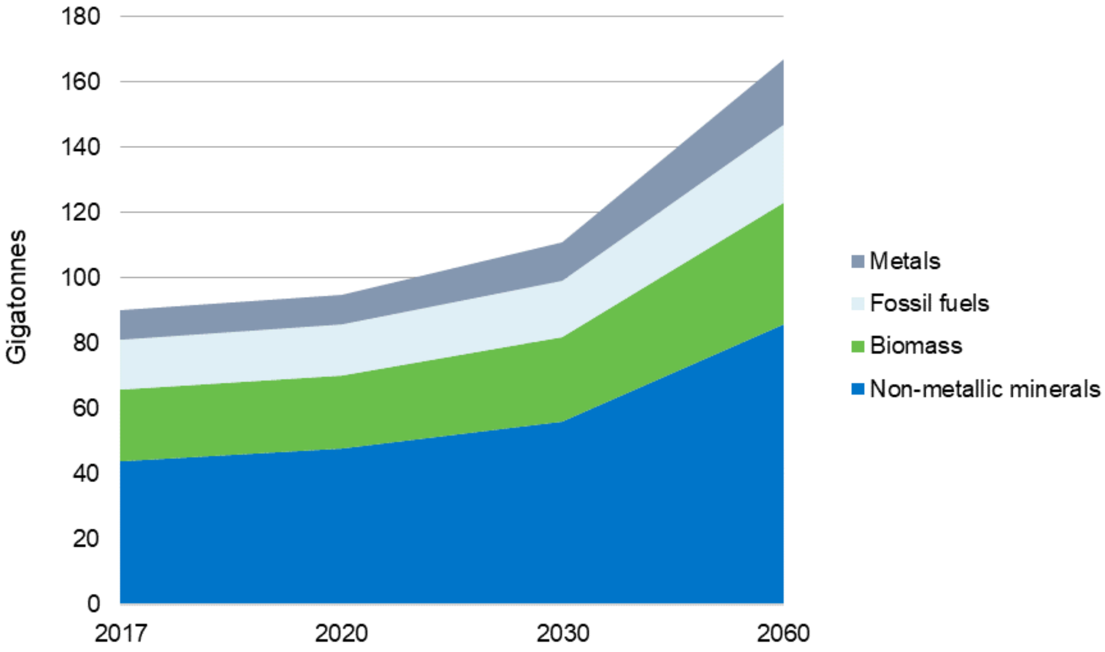

Figure 1: Projected growth of global material extraction (baseline scenario)
Source: Data taken from OECD (2018, 124)

The building sector has been repeatedly identified as a key sector to mitigate climate change. In regions of the world that are undergoing rapid economic growth, an expansion of cities is most dominant. In the developed world, including Europe, the building stock mostly exists already. Here, the challenge is to improve the existing stock. In Portugal, 70 % of the building stock was built before 1990, the year in which the first Portuguese regulation on thermal comfort was published (Statistics Portugal 2019). Circa one third of the Portuguese building stock needs major retrofit (Rodrigues and Freire 2017; Statistics Portugal 2019). Improving buildings' energy efficiency leads to, on the one hand, self-sufficient buildings in regard to energy. On the other hand, it requires significant amounts of material for the construction of new buildings and the thermal retrofit of existing buildings to live up to these new standards (Ioannidou *et al.* 2017). The Circular Economy Action Plan of the European Commission wants to reduce waste and to minimize environmental impacts and energy consumption related to the extraction of primary materials (EC 2020a).

1.2 OBJECTIVE AND STRUCTURE OF THE GUIDELINE

This guideline intends to provide a general framework to improve the robustness of efficiency indicators for buildings, thus contributing to the assessment of the resulting environmental impacts and their impact on circularity.

In order to achieve this objective, the present document is organized as follows:

- In section 2, the importance of efficiency indicators for buildings is outlined and detailed information on the quantification of materials and environmental impacts is given. A focus on energy, carbon and water as efficiency indicators is established.
- In section 3, critical aspects in building efficiency frameworks, namely in the analysis of a bill of quantities and lifetime estimates, as well as for a life cycle assessment of environmental impacts, are described.
- In section 4, specific examples are provided on how stakeholders that want to promote circular buildings can conduct or interpret a robust analysis of the efficiency indicators energy, carbon and water.

Therefore, this guideline aims to promote circularity in buildings through promoting a robust metric analysis of efficiency indicators. The guideline’s scope is Portugal and Europe.

2 BUILDING EFFICIENCY INDICATORS

Different indicators and criteria to define the circularity level of a building can be found in the literature. The best known circularity indicator is probably the one defined by the Ellen MacArthur Foundation (2015a), which is called Material Circularity Indicator (MCI). It can be applied across sectors to all types of products. The MCI is based on three parameters:

- Virgin Material;
- Product Utility;
- Unrecoverable Waste.

Different authors have then further developed the MCI to better suit their needs. Verberne (2016) and later Cottafava and Ritzen (2021) proposed a Building Circularity Indicator that respects the different elements and layers of a building. For more information on circularity indicators please refer to the “Best practice guide for promoting circularity in EPD”.

Attia and Al-Obaidy (2021) conducted a literature review and concluded that there are four main design criteria for circular buildings:

- Reused and recycled material;
- Disassembly potential;
- Adaptive building design;
- Environmental impacts.

These criteria were found to be effective and strategic for design decisions of circular buildings. The first three criteria are usually measured in amount of material: either from secondary resources, or for secondary use, or to be saved. These are described in section 2.1. The last criteria, environmental impacts, can have an array of units since different impact categories can be analysed. Environmental impacts are described in section 2.2.

2.1 MATERIALS

The concept of circular economy is intrinsically linked to designing out waste by decoupling economic growth from material consumption (Ellen MacArthur Foundation 2015b). This means that materials are at the centre of circular economy, and therefore, at the centre of circular buildings. However, construction materials and buildings need to be analysed from various dimensions to achieve circular material loops: materials, components and processes (Nan *et al.* 2021). The following sections describe different approaches to reduce the amount of virgin material used, considering the different dimensions.

Reused and recycled material

It is important to maintain and renovate buildings to ensure their long lifespan and adequate service provision. By simply prolonging the lifespan of buildings, waste generation can be avoided, or at least postponed. Therefore, the time a material is retained in the building system is an important parameter. However, once a building, or a building element, does reach its end of life, the material it is composed of should be reused or recycled to minimize the use of primary resources (Kovacic *et al.* 2020). By recovering, recycling or reusing material from another building, the material enters a new life cycle and can be considered a secondary resource. There are two sides of the same coin: existing buildings can provide secondary resources, or new buildings can be built from secondary resources. The use of secondary resources is focused on the material perspective that assumes that the reuse, or recycling, of material brings environmental benefits. The extraction of secondary resource, however, is a more complex issue that is related to the building components and technological processes. The issue of analysing the environmental burdens of recovering and recycling building materials is further explained in section 2.2.

Disassembly potential

The building stock is an "urban mine" that contains vast secondary resources that can potentially enter another life cycle (Hashimoto *et al.* 2007). Yet, it is often challenging to recover these materials. In order to assess the potential recoverability of material in an existing building, one should analyse the criteria for disassembly. Cottafava and Ritzen (2021) proposed a set of criteria for disassembly, which can be seen in Table 1. For more information on the quantification of these criteria please refer to the "Best practice guide for promoting circularity in EPD" and to the "Guideline for creating Circular Materials Passports".

Table 1: Criteria for disassembly of an existing building

Source: Taken from Cottafava and Ritzen (2021)

	Options
TYPE OF CONNECTION	Dry connection, connection with added element, direct integral connection, soft chemical compound, hard chemical connection
TYPE OF CONNECTION ACCESSIBILITY	Free accessibility, accessibility with additional actions that do not cause damage, accessibility with additional actions with reparable damage, not accessible irreparable damage to objects
TYPE OF CROSSINGS	Modular zoning of objects, crossings between one or more objects, full integration of objects
TYPE OF FORM CONTAINMENT	Open and no inclusions, overlaps on one side, closed on one side, closed on several sides

When designing a new building, the potential design for disassembly (DfD) should be integrated. Based on Akinade *et al*. (2017) there are three types of factors for an improved DfD. These can be seen in Table 2.

Table 2: Design factors for DfD for new construction

Source: Taken from Akinade *et al*. (2017)

	Critical factors for improved DfD
MATERIAL	Durability, simple finishing (avoid secondary finishing), toxicity of materials, simple materials (avoid composites), minimal number of building elements, efficient manufacturing and installation of materials
DESIGN	Prefabrication, modularity, open building plans, layering approach, standard structural grid, retractable building foundation
SITE	High skilled workers, functioning tools and equipment

Adaptive building design

It is impossible to foresee the future, but it is important to ensure an adaptive building design to avoid a premature demolition of a building. Buildings are service providers with a long lifespan during which the user requirements can change. By anticipating potential functional adaptation of the building use, and therefore, potential changes in the building layout, a prolonged building lifespan can be promoted.

2.2 ENVIRONMENTAL IMPACTS

Environmental consequences of human actions can be quantified manifold (Hellweg and Canals 2014). However, during the last decades one approach in particular has emerged: Life Cycle Assessment (LCA). It has been developed since the 1970s as a tool and method to quantify the environmental impacts of goods and processes (Guinée *et al.* 2011). Today, LCA is standardized at the international and European level. It is widely used across sectors and stakeholders. Therefore, this guide focuses on quantifying environmental impacts through LCA.

2.2.1 Definition of LCA

The main phases of a LCA are: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation, as shown in Figure 2.

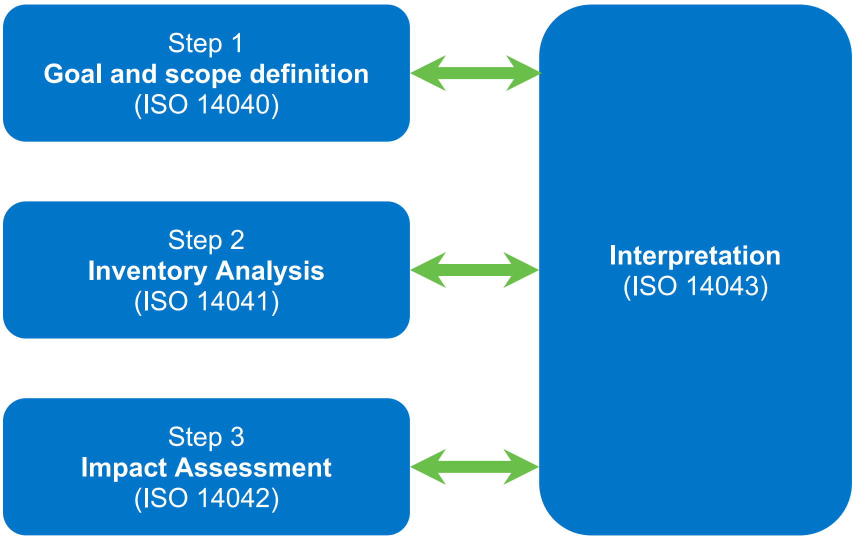

Figure 2: Main phases of LCA
Source: ISO/TC 207/SC5 (1998, 2000a, 2000b, 2006a)

Before starting to collect any data for the LCA, the *goal and scope* needs to be defined. This is a crucial step that is often neglected (Curran 2017). However, it defines the purpose of the LCA study and the system boundaries.

The *LCI* comprises the data collection and accounting of everything that forms part of the system. Flows in and out of the product system are tracked in detail and include raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance. A LCI can be complex and usually involves many individual unit processes in a supply chain, such as the extraction of raw resources, various primary and secondary production processes, and transportation. Moreover, it can involve hundreds of tracked substances (Curran 2016).

Three different LCI methods are the Process, Input-Output (IO) and Hybrid Analysis. Each one has its advantages and disadvantages:

- *Process Analysis* is a bottom-up approach that only includes those processes inside the studied product system boundaries. This method does not consider impacts associated with inputs and outputs located outside of the system boundaries.
- *IO Analysis* is used for studies at the country level and relies on national data. If a specific product is assessed, then an IO method might not be representative.
- *Hybrid Analysis* is a combination of Process and IO Analysis. It is based on Process Analysis and includes IO data for completing the system.

During the *LCIA*, elementary flows resulting from the emissions and resources are grouped according to the impact categories chosen and converted to the corresponding impact unit using characterization factors. There are various methods globally for categorizing and characterizing the life cycle impact of the flows to and from the environment, which can somewhat complicate the comparability of different LCA studies. Other variables in LCIA include the system boundary that defines how far upstream, downstream and side stream the analysis goes, also the functional unit, and specific choices such as allocation.

2.2.2 Modelling approaches in LCA

There are different modelling approaches in LCA. The following subsections describe their advantages and disadvantages.

Attributional LCA

Attributional LCA (ALCA) looks at products or services at a particular point in time for a given amount of the functional unit. This “classic” LCA modelling approach can fail to describe the directly and indirectly related impacts when the LCA is supposed to inform on the consequences of a change in demand for the functional unit underlying a decision process.

Consequential LCA

To overcome the limitation of attributional LCA, consequential LCA (CLCA) includes the impacts generated by all the systems affected by the change in demand of the functional unit, also including processes affected through market relationships and not through physical ones. CLCA implies the integration of marginal impacts of technological changes in the LCI instead of relying on average data (Baustert and Benetto 2017).

A study that compares the results of an ALCA and CLCA of an apartment located in Belgium revealed a discrepancy of more than 13% of the total impact, and of over 20% when only considering construction materials, mainly due to differences in the end-of-life stage, recycling and electricity consumption (Buyle *et al.* 2014). As stated by Guinée *et al.* (2011) CLCA is strong in mapping impacts of indirectly affected processes of a decision. However, modelling macroscopic land use changes on the basis of microscopic consequential product LCAs (bottom-up) is not likely to result in long-run sustainability. The authors suggest starting to think how more realistic, macroscopic scenarios for land use, water, resources and materials, and energy (top-down) can be transposed to microscopic LCA scenarios.

The conclusion of a study on the environmental impacts of milk production to compare ALCA and CLCA (Thomassen *et al.* 2008) state that the main reason of the differences between the two tools is the simple fact that different systems are modelled. The research question itself and the intended outcome define the system under study. Generally, the CLCA wants to assess environmental consequences due to a change in demand, whereas ALCA wants to assess the environmental burden of a product, assuming a status-quo situation. However, it seems that these days most LCA practitioners choose one methodology independent of their research question (Thomassen *et al.* 2008). A comparative LCA by Bernstad Saraiva *et al.* (2017) also investigated the differences between ALCA and CLCA, but in their case for alternatives in waste management. The authors' findings confirm that the chosen approach affects both, absolute and relative, results. However, results were dependent on the processes that were identified as being affected by the investigated changes, and not just the chosen modelling approach. Furthermore, they state that potential future choices between waste management alternatives are, in fact, intrinsically uncertain. Therefore, the comparison is helpful as a decision support tool but, after all, both outcomes are uncertain. Brander (2017) argued that, in the case of bioenergy, CLCA needs to adopt policy method structures to really become a useful tool for sufficient planning. Despite these limitations other scholars argue that CLCA is a robust tool for assessing indirect effects of products (Brandão *et al.* 2017).

Dynamic LCA

Buildings have a long life span and high potential for changes in usage patterns over time (Collinge *et al.* 2013), and retrofit scenarios of are often unknown. Therefore, buildings should be understood as service providers with different future scenarios that ask for a dynamic LCA (Vilches *et al.* 2017). Erlandsson and Borg (2003) advocated using services provided as the functional units, treating buildings as dynamic service providers that might change with modifications and rebuilding over time, using a sequential approach in LCA and developing a flexible LCA modelling structure that enables the user to have choices. Scheuer *et al.* (2003) recognized the challenges in developing a life cycle model of a complex dynamic system with a long service life, realizing that many model parameters are going to change over the projected building lifespan. Collinge *et al.* (2013) defined dynamic LCA as "*an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems*". Collinge *et al.* (2013) applied the method in two different studies: One included different scenarios for the decarbonization of the energy mix in an institutional building (2013). The other one dealt with the post-occupancy phase of a LEED gold university building case study (2014).

In a dynamic LCA, the temporal profiles of emissions are considered so that the LCI result for each emission is a function of time rather than a single number. There are two different types of dynamics: on the one hand, the dynamics of emissions, and on the other hand, the dynamics of raw materials and their supply chain, affecting, for example, land use and sequestered carbon for a bio-based material. Once a dynamic inventory is calculated, the LCIA characterization model is solved dynamically, i.e. without using steady-state assumptions, to obtain time-dependent characterization factors that depend on the moment when the pollutant is emitted (Levasseur *et al.* 2010). The dynamic approach can be applied for any desired time horizon. In contrast to "classic" impact calculation methodologies, like the IPCC-Methodology (Palut and Canziani 2007), in a dynamic LCA according to Levasseur's method (2010) the results are calculated for each year until the end of the chosen time horizon.

Levasseur *et al.* (2013) used a fictitious case study to assess the life cycle of a wooden chair for different end-of-life (EoL) scenarios in order to compare different approaches. The dynamic inventory they used details each emission through time, meaning it details the amount of pollutant released at every given time-step. The results, for a 500 year time horizon and for landfill as the end of life (EoL) scenario, vary between -16.3 kg CO_2 eq. for dynamic LCA, and 2.9 kg CO_2 eq. for attributional LCA without considering biogenic carbon (Levasseur *et al.* 2013).

It is important to note that dynamic temporal modelling is not standard in LCA, and temporal issues are handled on an ad hoc basis. In energy research, temporal issues are often considered as part of scenarios, or to accommodate changes in future electricity grid mixes (Hertwich *et al.* 2015). Currently, time issues are generally included by comparison between results at different time points or using linear averaging over the project timeline (McManus and Taylor 2015). The topic of dynamic LCA is further discussed and illustrated with an example in section 4.2 of this guideline.

2.2.3 Impact categories and LCIA methods

There are many different impact categories. ILCD, which is the LCIA method from the European Commission, includes the following mid-point impact categories (EC-JRC 2011):

- Climate change;
- Ozone depletion;
- Cancer, and non-cancer, human toxicity;
- Particulate matter;
- Ionising radiation potentials on human health, and ecosystem;
- Photochemical ozone formation;
- Acidification;
- Freshwater, marine, and terrestrial, eutrophication;
- Freshwater eco-toxicity;
- Land use;
- Water resource depletion;
- Mineral, fossil fuel, and renewable, resource depletion.

Besides ILCD, other common LCIA methods like ReCiPe, IPCC, CML, Eco-indicator99, IMPACT 2002+, or Ecological Scarcity include different arrays of impact categories. However, across LCIA methods not only the type of impact categories vary but also the characterization factors for each indicator. A study by Owsianiak *et al*. (2014) compared the characterization of the methods IMPACT 2002+, ReCiPe 2008 and ILCD 2011 and found that the impact scores can vary with more than three orders of magnitude for human health impacts from ionizing radiation and ecosystem impacts from land use. For metal depletion and for toxicity-related impact categories, the variation was found to be between one and three orders of magnitude.

Despite the vast array of impact categories, a review of LCA studies of the built environment found that the two most commonly used impact categories are energy use, particularly, primary energy use, and Global Warming Potential, measured in CO_2 equivalents (Mastrucci *et al.* 2017). This is because these impact categories relate to key drivers of current national and international policy making in the built environment. Moreover, a study of correlations in LCIA methods suggested that many impact categories are, in fact, correlated (Lasvaux *et al.* 2016). Lasvaux *et al*. (2016) identified the following environmental themes as the only ones that show no significant correlations between them:

- Ionising radiation and ozone layer depletion;
- Eco-toxicity, and human toxicity driven by water emissions;
- Land use;
- Fossil fuel energy consumption;
- Mineral resources depletion.

2.3 IMPORTANCE OF ENERGY, CARBON AND WATER

Level(s) is a recent framework that was developed by the Joint Research Centre of the European Commission (JRC-EC), and improved through a dialogue with construction practitioners and researchers. In this way, it is most relevant for the sustainability analysis of buildings in terms of temporal, political and geographical scope. The Level(s) framework, includes a set of six holistically sustainable core indicators:

1. Greenhouse gas and air pollutant emissions along a building life cycle
2. Resource efficient and circular material life cycles
3. Efficient use of water resources
4. Healthy and comfortable spaces
5. Adaptation and resilience to climate change
6. Optimized life cycle cost and value

This guide wants to promote circular buildings, meaning to optimize the use of resources. Resource use is mirrored in indicators 1, 2 and 3.

Global warming is driven by the burning of fossil fuels. In regard to buildings, the energy supply plays an important role throughout the whole life cycle: directly during the operational phase and indirectly during the manufacturing of building products. Even though there is a shift towards renewable energy sources, fossil fuels are still the main source for energy supply. There are three main types of emissions that are caused by burning of fossil fuels: heat, carbon, and water. This fact, in combination, with the consideration of the most common used impact categories, as well as the correlation of environmental themes, and the Level(s) indicators, as described above, puts the spotlight on three measures of environmental burdens: energy, carbon and water. Therefore, the present guide focuses on these three types of burdens. A global study by Pomponi and Stephan (2021) using environmentally-extended input-output analysis showed that, for the construction sector, energy and carbon (dioxide) footprints are correlated while there is no correlation between these two and water footprint. However, the three footprints cannot be estimated through any one of the individual flows.

The following sections provide background information and benchmarks for buildings for energy, carbon and water. The provided benchmarks are taken from different sources and, therefore, provided at different resolutions, e.g. some values are for residential buildings while others are per archetype or specific type of structure. All benchmarking values should be used carefully and analysed critically regarding their suitability in terms of temporal and spatial suitability.

2.3.1 Energy

Energy is the most common focus in LCA studies of buildings (Cabeza *et al.* 2014). There is even a specific “life cycle energy analysis” (LCEA) that analyses all energy inputs during a building’s life cycle, including the direct energy use of the building's operation and the indirect energy use that arises during the manufacture and demolition (Cabeza *et al.* 2014). Energy is commonly measured in kWh or MJ. A key indicator is the cumulative energy demand (CED), which is also called primary energy consumption (Frischknecht *et al.* 2015). There is a difference between final energy and primary energy.

> "*Primary energy consumption measures total domestic energy demand, while final energy consumption refers to what end users actually consume. The difference relates mainly to what the energy sector needs itself and to transformation and distribution losses.*"
>
> - European Commission (2020b)

The direct energy use is related to heating, ventilation and air conditioning (HVAC), domestic hot water, lighting and powering appliances in a building. Electricity represents a major share of operational energy. However, other types of energy can also play an important role. This type of energy consumption is referred to as the **operational energy**. In contrast, **embodied energy** refers to the energy that is required to source all materials, manufacture the building components and technical installations, construction processes and renovation activities. Often embodied energy refers to the LC stages A1-A3 in accordance with EN 15978 (CEN/TC 350 2011). However, the energy that is required to deconstruct or demolish a building, to transport the remaining materials to a waste treatment facility or recycling plant, as well as for its end-of-life treatment, is at times also included in the embodied energy.

As an example, Figure 3 shows the energy consumption of the residential sector in Portugal. In other words, it shows the operational energy demand of residential buildings. A slight trend for less space heating and more space cooling can be observed, while the energy demand for residential appliances is increasing. There is no clear trend regarding the total energy consumption (in 2000 it was 48.6 PJ, it peaked in 2005 at 56.6 PJ, and was at 49.7 PJ in 2018).

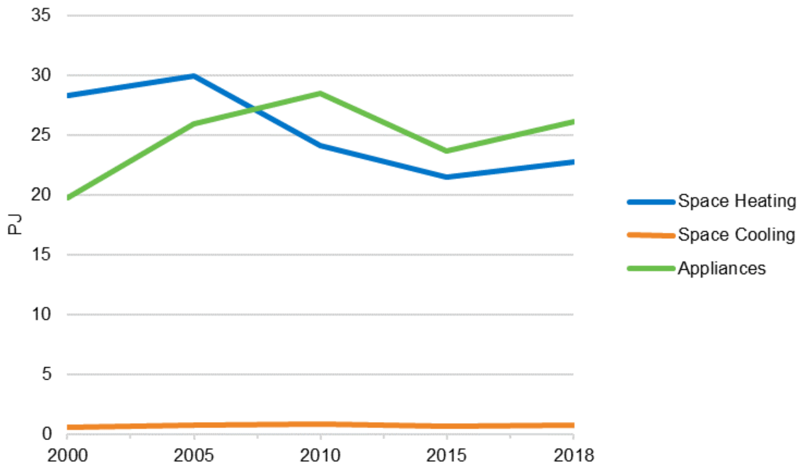

Figure 3: Energy consumption for the residential sector, Portugal 2000-2018⁽¹⁾
Source: Data taken from the International Energy Agency (IEA 2019)

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(1) Note to Figure 3: 1 PJ (Petajoule) is equal to 10^9 MJ

A review by Gervasio *et al.* (2018) of available energy benchmarks for three types of residential buildings (single-family house "SF", multi-family house "MF", high-rise building "HR") in three climatic zones of Europe (south, central, north) found that there is a huge diversity due to a lack of reliable models for the benchmark quantification. The authors subsequently defined a consistent LCA-based framework and formulated a set of benchmarks for residential buildings. The values for primary energy use for single family houses can be seen in Figure 4. This work was part of the *EFIResources* research project and results were also published by the Joint Research Centre of the European Commission (EC-JRC 2018). This, in turn was based on the EU-funded research *IMPRO-Building* project that defined building typologies (EC-JRC 2008).

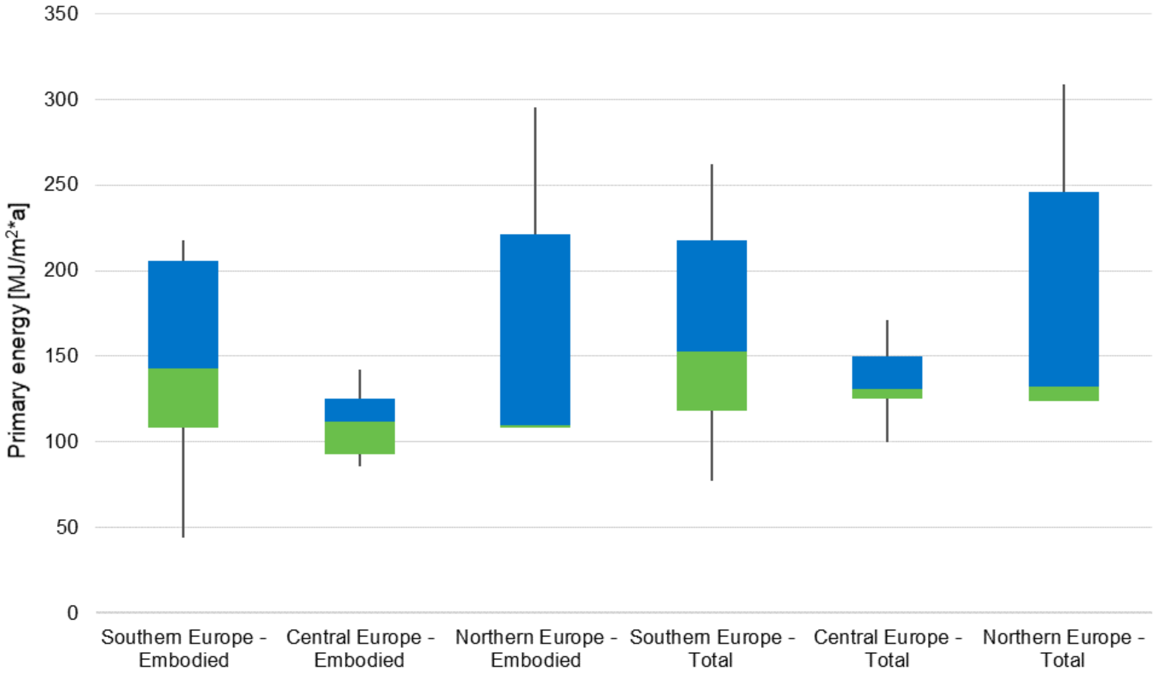

Figure 4: Primary energy ranges for single-family houses for three different climate regions in Europe(2)
Source: Data taken from EC-JRC (2018)

Monteiro *et al.* (2017) did a detailed study of the urban energy consumption for the *SusCity* area in Lisbon based on archetypes and their average primary energy consumption (Monteiro 2018). The values for average annual electricity consumption for heating, cooling and domestic hot water (DHW) systems can be seen in Table 3.

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(2) Note to Figure 4 – "Embodied" refers to LC stages A1-A3

Table 3: Average annual electricity consumption for heating, cooling, and domestic hot water systems

Source: Data taken from Monteiro (2018, Table 9). Abbreviations: “SF” – Single family, “MF” – Multi family.

Type	Construction period	Building height [m]	Number of floors	Window-to-wall ratio	U-value exterior walls [W/(m²K)]	Annual electricity consumption [kWh/m²]
SF	before 1919	5	1	10%	2.38	57.2
SF	1946-1960	6.6	2	8%	2.38	46.9
SF	1961-1990	6.5	2	8%	1.89	44.5
SF	1991-2005	7.1	2	8%	1.02	43.8
MF	1946-1960	11.6	4	19%	1.01	36.4
MF	1961-1990	17.5	6	27%	0.96	36.2
MF	1991-2005	23.3	8	31%	0.63	34.3
MF	2006-2011	19.9	7	29%	0.56	34.5

For more specific benchmarking values of energy consumption of typical residential construction in Portugal please refer to the study by Bastos *et al*. (2014). The authors analysed three typical residential buildings in the Alvalade neighbourhood of Lisbon to define benchmarks for primary energy use and GHG emissions.

2.3.2 Carbon

Carbon is important because it is a part of carbon dioxide (CO_2), which is an important **Greenhouse Gas** (GHG) that absorbs and re-emits heat in the atmosphere, thereby causing **global warming**. The main GHGs in the Earth’s atmosphere are water vapour, CO_2, methane (CH_4), nitrous oxide (N_2O) and ozone. CO_2 is often used as a comparative measure for global warming potential. For this purpose, different types of GHGs are converted into CO_2 equivalents for a 100-year time horizon. For example, the GWP_{100} of 1 kg of CH_4 corresponds to 28 kg of CO_2 eq., the GWP_{100} of 1 kg of N_2O corresponds to 265 kg of CO_2 eq. according to the fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC 2013, 731 ff.). The time horizon, i.e. 100 years, is important since GHGs decay at different speeds. This can be accounted for through dynamic LCA (refer to section 2.2.2).

Operational and embodied energy are often translated into CO_2 emissions by using conversion factors, e.g. from final energy to CO_2 emissions in kg CO_2 per kWh. The terms “embodied carbon” and “operational carbon” are common. A recent review by Röck *et al*. (2020) of more than 650 buildings around the world showed that building LC emissions are reducing thanks to energy efficiency improvements, while embodied emissions are increasing and now dominate the overall LC impacts. The authors showed that the effect of higher energy performance standards on embodied emissions does not only increase in relative terms but also in absolute terms.

Figure 5 is taken from Röck *et al*. (2020) and shows the global trends for embodied carbon of residential and office buildings, in absolute terms (on the left vertical axis) and in relative terms (on the right vertical axis), for different energy performance classes. The graphic highlights that the trend towards higher energy efficiency, e.g. passive house standard for advanced thermal performance, requires more material, resulting in higher embodied impacts. This underlines the need for increased circularity measures to enable a higher rate of secondary material use. At the same time, Figure 5 provides an indicator for kg CO_2 eq. per m^2 floor area and year. The values per type of building, residential and office, can be found in Appendix A. For the complete description please refer to the original review by Röck *et al*. (2020).

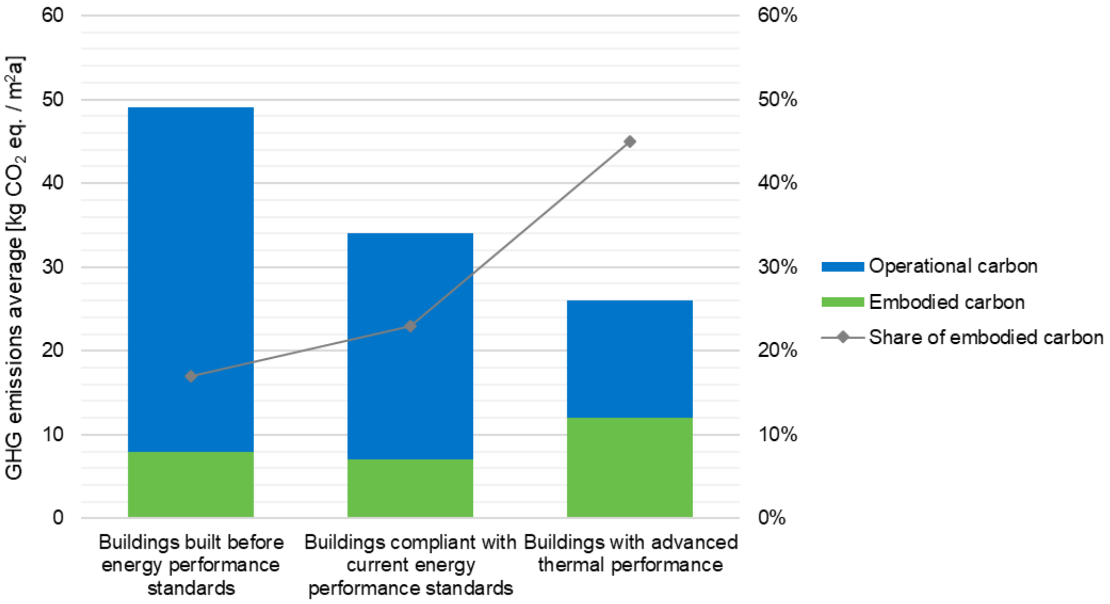

Figure 5: Absolute and relative contribution of operational and embodied carbon for different energy performance classes for all buildings (office and residential)
Source: Data taken from Röck *et al.* (2020)

The energy source has a great impact on the CO_2 intensity: coal and oil have higher intensities than gas, for example (Zabalza Bribián *et al.* 2009). The exact factors depend on the geographical and temporal scope, as well as on the data source. The energy supply and CO_2 emissions by energy source for Portugal (for all sectors) can be seen in Figure 6. Oil accounts for the biggest share of energy supply and CO_2 emissions.

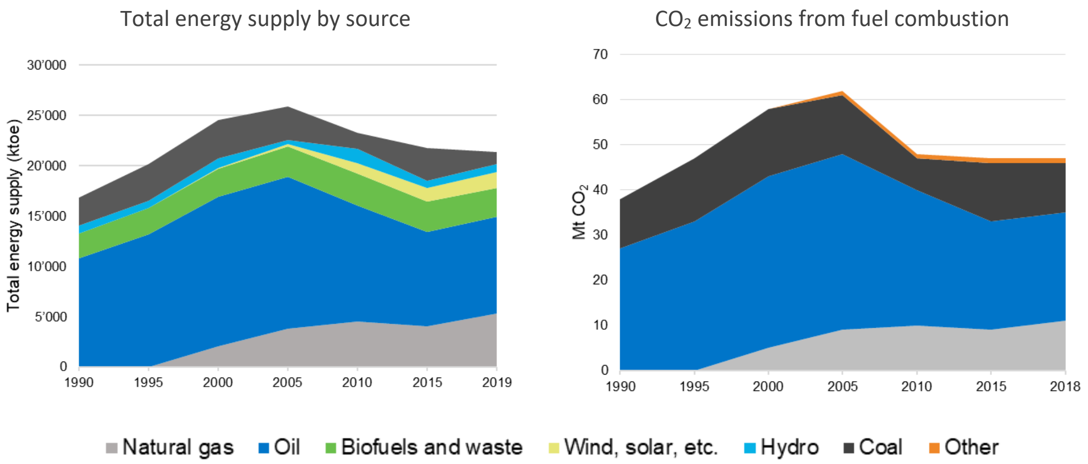

Figure 6: Evolution of the energy supply (left) and corresponding CO_2 emissions (right) in Portugal since 1990
Source: Data taken from the International Energy Agency (3)

2.3.3 **Water**

The World Resource Institute analysed various water risk indicators until 2040, considering the impacts of climate change and socio-economic developments. For the indicator "baseline water stress", which includes residential water use, eight European countries, including Portugal(4), are classified with an extremely high or high risk factor (WRI 2013). In Mediterranean countries, usually agriculture is responsible for the highest share of water consumption. In Portugal, the agricultural sector is responsible for 75%, industry for 5% and buildings for 20% of the total water consumption. In northern European countries, this picture is different. In Germany, for example, agriculture is only responsible for a 12% share of the national water consumption. On the one hand, this difference is related to the relative size of the primary sector in relation to other sectors, and, on the other hand, to the difference in climate and annual rainfall. For buildings, it needs to be noted that Portugal has a high income elasticity for water consumption, meaning that with increased income, a household increases over-proportionally its water consumption (EC-JRC 2015). This suggests that with a growing gross domestic product (GDP), Portuguese households will continue to use more water, despite the existing water scarcity. Currently, the average price of water in Portugal (circa 1.80 Euro per m^3) is among the cheapest in the European Union (EurEau 2017).

> *The number one victim of Climate Change is water.*
> *Either there is too much or too little, and at the wrong time.*
> - Johan Rockström from the Potsdam Institute for Climate Impact Research,
> "Water Matters", Nobel Week Dialogue, 2018

As for energy and carbon, buildings' water consumption is usually divided between the product and construction stage (i.e. embodied impacts), and the use stage (i.e. operational impacts). "Water footprint" (Hoekstra *et al.* 2011) or "virtual water" (Allan 1998) is often used to refer to embodied water impacts that are related to the material extraction, production, transportation, and construction of a building. The

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[3] IEA data browser: https://www.iea.org/countries/portugal (Accessed 12.04.2021)

[4] Per district in Portugal for baseline water stress: Setúbal, Faro, Évora, and Portalegre are classified as extremely high risk. Beja and Madeira are classified as high risk. The remaining districts are classified as medium to high risk. For the full list please refer to https://www.wri.org/resources/data-sets/aqueduct-country-and-river-basin-rankings (Accessed 14.04.2021)

embodied water impacts of buildings have received comparably little attention from stakeholders from science and policy (Gerbens-Leenes *et al.* 2018). However, a recent study by Hosseinian and Ghahari (2021) analysed the effects of the building area and height, construction materials, slab, and the lateral load resisting system, as well as of building site characteristics, on the water footprint of steel and concrete structures. The authors found that water consumption of residential buildings varies between 4.1-5.6 m^3/m^2 for steel structures, and between 3.3-4.7 m^3/m^2 for concrete structures. Moreover, they found that on-site construction is only responsible for 2.2% of the total water footprint of structures, while the remaining 97.8% are related to indirect water use. Overall, the authors concluded that:

- Steel structures reduce the water footprint by 22% compared to concrete structures;
- Short buildings have a smaller water footprint than tall buildings per square meter;
- Composite slabs are better than steel deck and cobute-precast slabs(5);
- A building site with dense soil reduces the building's water footprint compared to soft soil ground.

The water consumption during the operational phase is referred to in different terms in the literature: residential water use, use stage water consumption, freshwater use, or domestic water consumption. The residential drinking water consumption for all EU countries can be seen in Figure 7. Portugal's average resident consumes circa 170 litres per day, while the European average is 128 litres per day (EurEau 2017). Besides water being a critical resource, domestic hot water consumption (DHW) is also responsible for a significant share of energy use in buildings (Fuentes *et al.* 2018). Therefore, reducing the operational water use of buildings should be a key objective.

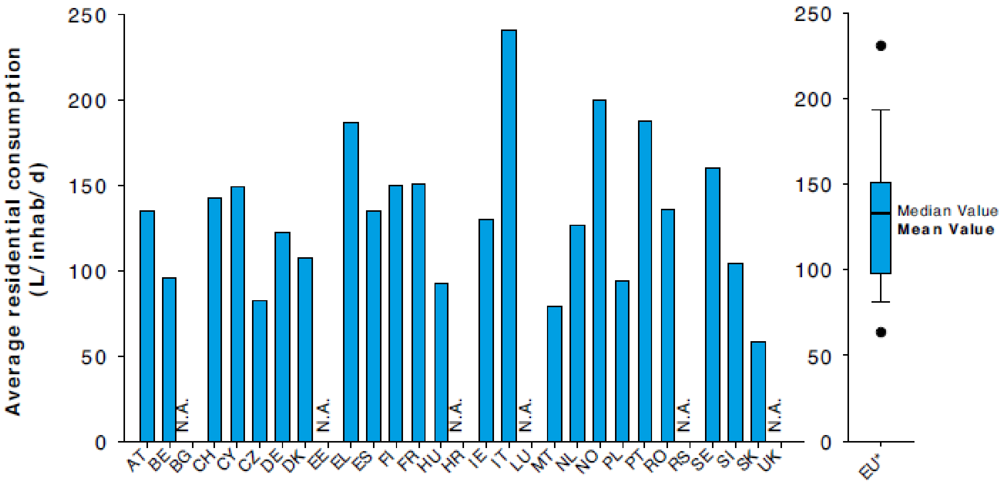

Figure 7: Average daily residential drinking water consumption across the EU
Source: Diagram taken from EurEau (2017)

There are two groups of water management strategies: alternative water sources and improved water use efficiency (Silva *et al.* 2015). Against the background of circular buildings, the potential of rainwater harvesting to save freshwater use in buildings should be highlighted. Especially for non-potable purposes, rainwater harvesting has a great potential since it can be easily collected and does not require further

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[5] "Cobute-precast" refers to a three-element concrete slab with in place reinforced concrete, precast longitudinal stiffening lattice joists and precast concrete blocks. For more information please refer to Hosseinian and Ghahari (2021)

processing. A study by Amado and Barroso (2013) found that rainwater harvesting and grey water treatment in combination with increased awareness, efficient hydraulic devices and leak reduction can potentially lead to a reduction of up to 76% for a single family house in Portugal. However, economic concerns are often standing in the way of such measures. Referring back to the issue of current low water prices, it was shown for Portugal that water fees would have a great influence on the economic viability of rainwater harvesting (Silva *et al.* 2015). In other regions of the world that are facing an even higher risk of water scarcity, buildings can be used to regulate the urban water cycle and reduce water demand, thereby increasing water circularity (Schuetze and Santiago-Fandiño 2013).

3 CRITICAL ASPECTS IN BUILDING EFFICIENCY FRAMEWORKS

This guideline highlights the need for a robust analysis of efficiency indicators to promote circularity of buildings, meaning increased recovery, reuse and recycling of building material, considering impacts in terms of energy, carbon and water. To analyse energy, carbon, and water impacts of buildings throughout their life cycle, it is necessary to know first the materials quantities and their expected lifespans. The so-called “material footprint” is an inventory of all elements and materials in a building and the basis for a subsequent LCA to analyse carbon, energy and water. However, the analysis of both aspects, the material footprint and environmental performance (i.e. LCA) includes critical aspects. This section is dedicated to highlight important critical aspects and to propose ways to overcome them. Buildings have long life spans with often complex and changing service provision. Therefore, there is no one-size-fits-all solution. Consequently, the information that is presented hereafter should be understood only as recommendations to reflect on circular buildings that depend on the situation and characteristics of the building project. Critical aspects related to the material footprint are described in section 3.1. and critical aspects related to environmental impact assessment follow in section 3.2.

3.1 MATERIAL FOOTPRINT

Being able to accurately estimate the material footprint and lifespan is crucial for an increased building sustainability and circularity. A bill of quantities (BoQ) is widely used to quantify the materials used in a building. If it includes all relevant building elements and materials, it represents the material footprint of a building project. It can be defined as a list that provides categorization, description and quantities of materials, labours, resources and associated costs that are necessary for the construction and maintenance of buildings. Describing the lifespan of a building or building element can only always be an estimate of the period during which it can fulfil its purpose (United-BIM 2021; Birgisdottir and Haugbølle 2019; Nadeem *et al.* 2015; Herrero-Garcia 2020).

Moreover, tracking the BoQ through time and space is an essential part of the planning process in a building project since it reduces the chances of error and inventory shortage that might cause delays. Specifically, it helps project planners and contractors understanding the inventory requirements associated with a building project. A BoQ increases the understanding of a project, defines the basic scope of work in line with the project design and ascertains the substantial quantities required to be communicated to suppliers (United-BIM 2021).

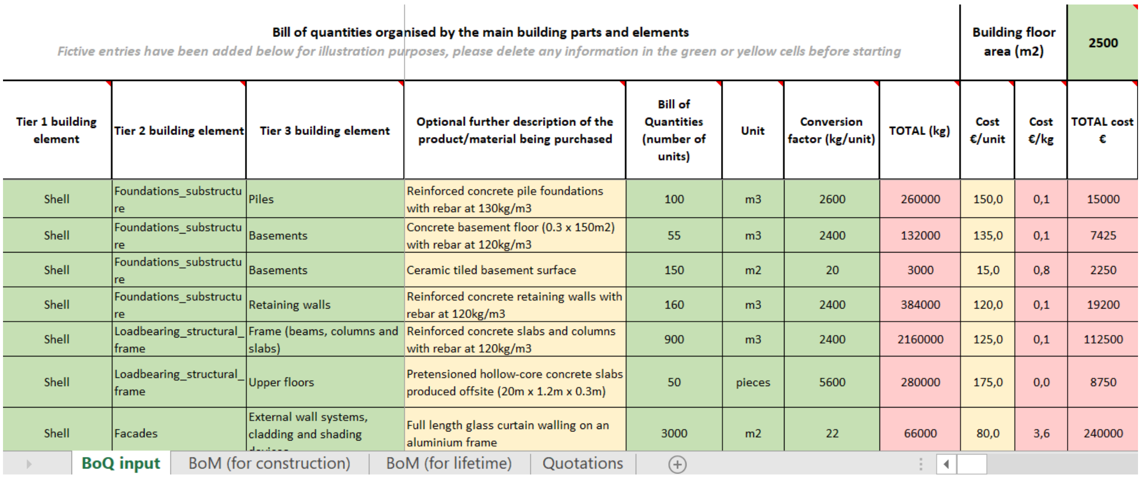
It is important to notice that while the International Organization for Standardization (ISO) and the International Alliance for Interoperability (IAI) are currently still developing standards for BoQ generation, the lack of knowledge of some construction stakeholders and general users led to the creation of several tools and documentation to determine a BoQ (Martínez-Rojas *et al.* 2016). Examples are the cost management software tools by Presto (2015) or Premeti (2015) to assist with a BoQ and its documentation. For lifetime estimates, Marsh (2017) found that over 100 peer-reviewed scientific articles indicate the lack of methodological documentation regarding the chosen selection of building lifespan. In addition, Goulouti *et al*. (2020) mentioned the difficulty to calculate this parameter due to its high uncertainty and complexity.

Due to the diversity, lack of knowledge and standards, and the fact that most articles are outdated, the present guide focuses on the recommendations provided in the European Level(s) framework (Dodd *et al.* 2020b) to estimate a BoQ and lifespan.

European Level(s) framework

Level(s) indicator 2.1 is called "Bill of quantities, materials and lifespan". It measures the performance and contribution of a building regarding resource-efficient and circular material life cycles by clustering the BoQ, the bill of materials (BoM), and lifespan information of buildings and components. It was designed to encourage users to handle and process specific data about their building as an aid to life cycle thinking (Dodd *et al.* 2020b), namely information of products and materials that are used in new construction and renovated buildings.

A guidance document and an MS Excel® spreadsheet to estimate indicator 2.1. "Bill of quantities, materials and lifespan" are available for free on the Level(s) website[6]. It highlights the importance of data reporting through a hierarchy of construction elements in order to improve consistency and comparability in different buildings. Figure 8 shows an example of the MS Excel® spreadsheet, namely for the BoQ data input, where the green cells are mandatory data input, the yellow cells are optional and the red cells are automatically calculated or reported outputs.



Bill of quantities organised by the main building parts and elements

Fictive entries have been added below for illustration purposes, please delete any information in the green or yellow cells before starting

Building floor area (m2) **2500**

Tier 1 building element	Tier 2 building element	Tier 3 building element	Optional further description of the product/material being purchased	Bill of Quantities (number of units)	Unit	Conversion factor (kg/unit)	TOTAL (kg)	Cost €/unit	Cost €/kg	TOTAL cost €
Shell	Foundations_substructure	Piles	Reinforced concrete pile foundations with rebar at 130kg/m3	100	m3	2600	260000	150,0	0,1	15000
Shell	Foundations_substructure	Basements	Concrete basement floor (0.3 x 150m2) with rebar at 120kg/m3	55	m3	2400	132000	135,0	0,1	7425
Shell	Foundations_substructure	Basements	Ceramic tiled basement surface	150	m2	20	3000	15,0	0,8	2250
Shell	Foundations_substructure	Retaining walls	Reinforced concrete retaining walls with rebar at 120kg/m3	160	m3	2400	384000	120,0	0,1	19200
Shell	Loadbearing_structural_frame	Frame (beams, columns and slabs)	Reinforced concrete slabs and columns with rebar at 120kg/m3	900	m3	2400	2160000	125,0	0,1	112500
Shell	Loadbearing_structural_frame	Upper floors	Pretensioned hollow-core concrete slabs produced offsite (20m x 1.2m x 0.3m)	50	pieces	5600	280000	175,0	0,0	8750
Shell	Facades	External wall systems, cladding and shading	Full length glass curtain walling on an aluminium frame	3000	m2	22	66000	80,0	3,6	240000

Figure 8: Screenshot of Level(s) indicator 2.1 excel spreadsheet
Source: Donatello *et al.* (2021)

For this guideline, current critical aspects of the Level(s) indicator 2.1 were identified through a critical analysis and complemented by the key findings from the literature, namely from Dodd *et al.* (2020a) that reports the official Level(s) test phase, from the evaluation of Level(s) by Birgisdottir and Haugbølle (2019), and other relevant studies (Ogbu *et al.* 2012; Martínez-Rojas *et al.* 2016; Marsh 2017; Lendo-Siwicka *et al.* 2019; Goulouti *et al.* 2020). An overview of the identified critical aspects can be seen in Table 4.

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[6] https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/412/documents

Table 4: Overview of general obstacles in the development and application of Bill of Quantities and Lifespan indicators for material accounting

NO.	CRITICAL ASPECTS
1	Unclarity of the use of BoQ and lifespan in life cycle modules
2	Lack of reference standards for BoQ determination
3	Unavailability and uncertainty of information for building lifespan estimation
4	Lack of guidance to general users (without LCA or sustainability knowledge)
5	Access costs to technical standards, databases and/or calculation tools

The following subchapters propose robust measures to overcome the identified barriers.

3.1.1 Unclarity of the use of Bill of Quantities and Lifespan in life cycle modules

There is a growing awareness of the boundaries and scope of estimating a BoQ and building lifespan. The Level(s) instructions of indicator 2.1. “Bill of quantities, materials and lifespan” highlight the use of this indicator in life cycle stages set out in EN 15978 “Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method” (CEN/TC 350 2011). Nevertheless, there is the potential to further clarify the indicator’s application throughout all life cycle stages and in module D, in order to link the indicator with existing standards and, subsequently, to minimize the stakeholders’ efforts for a consistent analysis. Figure 9 highlights in which life cycle modules a BoQ and lifespan estimate can be applied.

Figure 9: Bill of quantities and lifespan application in the context of the Life cycle stages
Source: Adapted from EN 15804 (CEN/TC 350 2019)

The life cycle stages are divided as follows: A1-A3 - Product stage, A4-A5 - Construction process, B1-B7 - Use, and C1-C4 - End of Life (EoL). Additionally there is D - Benefits and loads beyond the system boundary. In this context, the BoQ and building lifespan have a strong influence on Product stage, Construction process, Use and End of Life.

The Product stage (Modules A1-A3) provides the quantities of all building materials used in the foundation and structure of the building, from raw material extraction until they leave the factory gate. However, it is crucial to notice that during the building construction stage, the actual quantities may change, and the materials may even be replaced by alternatives ones.

For the Transportation stage (Module A4), the quantified material mass and volume, through maximum loading capacity of the transport vehicle, directly influence the transport-related impacts from the factory to the construction site, e.g., the results of the Global Warming Potential indicator.

A BoQ can be beneficial for the Construction process stage (Module A5) because it allows to easily identify variations of materials and design, additional labour and associated cost. Therefore, the risk of a client being confronted with additional works can be minimized and the cost savings of a project can be clearly identified and calculated. Moreover, the recorded material quantities determine the amount of construction waste and ensure the comparison between the actual registered purchases.

When the lifespan for different building elements and materials is considered in the BoQ, it influences the environmental and economic impacts in the Use (Module B) and the End-of-Life (Module C) stages. This indicator is applied for asset management purposes and optimized life cycle costs. It is equally used to determine the material replacement or disposal, i.e., with the material inventory and their lifespan, it is possible to assess the necessity of material change (Bauer *et al.* 2016; Gervasio *et al.* 2018; Oladazimi *et al.* 2020; Donatello *et al.* 2021).

3.1.2 Lack of reference standards

A BoQ is considered as an important tool for building management and materials assessment. Nowadays, the construction stakeholders, i.e. architects, engineers, contractors, and others, tend to use different wording and internal structures for determining and assessing a BoQ. However, heterogeneity in the documentation of BoQ has been reported as an obstacle for data management. Moreover, the lack of reference standards leads to an increased complexity and diversity of a BoQ, thereby reducing the potential of reusing and comparing data. Martínez-Rojas *et al.* (2016) compared two projects to highlight the diversity of current BoQ documentation and show that similar construction processes are referred to in completely different terms (see Table 5).

Table 5: Example of the diversity of Bill of Quantities documentation

Source: Adapted from Martínez-Rojas *et al.* (2016)

LEVELS	PROJECT 1	PROJECT 2
Level 1	Land preparation	Earthworks
Level 2	To clear scrub and clearance made by manual resources	Preliminary actions
Level 3	-	To clean the scrub by manual means

However, the new European Level(s) framework (Dodd *et al.* 2020b) helps to overcome this barrier since it is the most pertinent and recommended by the European Commission in terms of temporal, political and geographical scope. By establishing Level(s) hierarchical structure and the respective descriptions, there is the potential to store and manage BoQ data and to compare the material data between different buildings projects.

3.1.3 Unavailability and uncertainty of information for building lifespan estimation

Over the years, the demand for accurate service life data to predict the building lifespan has grown as it is needed to assess building and material performance from a life cycle perspective. The recognition of this situation has led to the development of standards for the prediction of service lives of building components and assemblies by the International Organization for Standardization (ISO):

- ISO 15686-1:2011: Building and Constructed Assets – Service Life Planning – Part 1: General Principles and Framework;
- ISO 15686-2:2012: Buildings and Constructed Assets – Service Life Planning – Part 2: Service Life Prediction Procedures;
- ISO 15686-3:2002: Buildings and Constructed Assets – Service Life Planning – Part 3: Performance Audits and Reviews;

- ISO 15686-5:2017: Buildings and Constructed Assets – Service Life Planning – Part 5: Life Cycle Costing;
- ISO 15686-6:2004: Buildings and Constructed Assets – Service Life Planning – Part 6: Procedures for considering Environmental Impacts;
- ISO 15686-7:2017: Buildings and Constructed Assets – Service Life Planning – Part 7: Performance Evaluation for Feedback of Service Life Data from Practice;
- ISO 15686-8:2008: Buildings and Constructed Assets – Service Life Planning – Part 8: Performance Evaluation for Feedback of Service Life Data from Practice;
- ISO/TS 15686-9:2008: Buildings and Constructed Assets – Service Life Planning – Part 9: Guidance on Assessment of Service Life Data;
- ISO 15686-10:2010: Buildings and Constructed Assets – Service Life Planning – Part 10: When to Assess Functional Performance.

Besides standards relating to service life prediction, many countries have published several studies on the determination of service life which results in different lifespan estimates for the same building element. The reference lifespan of a building or building component can be predicted through an empirical or probabilistic approach. Table 6 shows an example of different lifespans proposed as deterministic values by different standards and studies (Grant *et al.* 2014; Silvestre *et al.* 2015). However, these values need to be carefully reviewed considering their accuracy in terms of time, place, and usage.

Table 6: Example of different service life of two types of external claddings proposed by different studies and standards

Source: Adapted from Silvestre *et al.* (2015)

STUDIES AND REFERENCES	EXTERNAL CLADDING – RENDERING (YEARS)	EXTERNAL STONE CLADDING (YEARS)
BS-7543:1992 recommended design life	>60 (most external claddings for buildings with normal life – new housing)	
The Architectural Institute of Japan (1993) recommended planned service life	>10	
Shohet *et al.* (1999) - Standard life expectancy	20	40
So 15686:2000 (2000) - Suggested service life for components	25 (buildings with a design life of 60 years)	
Shohet and Paciuk (2004) - For situations in which components are required to perform at high levels – Standard life expectancy	15	44
Shohet and Paciuk (2004) - For situations in which components are required to perform at high levels – Predicted service life interval	12-19	39-50
Shohet and Paciuk (2004) - For situations in which owners want to minimize maintenance costs - Standard life expectancy	23	64
Shohet and Paciuk (2004) - For situations in which owners want to minimize maintenance costs - Predicted service life interval	19-27	59-70

Considering the existence of various methods for building and building components lifespan prediction, Marsh (2017) and Grant (2014) have conducted extensive literature reviews and noted that building and building components service life estimation have a significant uncertainty due to the inexistence of methodological documentation for choosing the lifespan.

Table 7 provides examples from the literature for the empirical and probabilistic approaches. Marteinsson (2005) proposed to use empirical data from buildings under similar conditions to estimate the end of life, or service life duration, of building components. Müller's approach (2006) to model the expected lifetime through a probability density function (normal distribution) is well suited for estimating high quantities of future materials flows, especially in building stocks. This knowledge is helpful for estimating the urban mining potential of cities, therefore, for planning future circular construction. Göswein *et al.* (2019) reviewed other building stock studies and found that the most common probability density functions used in the literature are Normal, Log normal and Weibull distributions.

Table 7: Comparison of empirical and probabilistic approaches for lifespan estimates

APPROACH	DEFINITION	RECOMMENDATIONS	REFERENCES
EMPIRICAL	Building lifespans are estimated based on reference lifetimes of other buildings with similar geographical and temporal conditions. Empirical data is collected during field work under real conditions. For the maintenance phase of a building, data of replaced components from other buildings can be used but should consider the dominant performance under technical, economic, social and functional aspects.	The *Factor Method* is a robust method to modify empirical data due to the variety of temporal and geographical conditions and to match it with the buildings project characteristics under study. However, acquiring empirical data in real service life conditions is challenging	Marteinsson (2005)
		There are three types of statistical methods, namely graphical, multiple linear regression, and artificial neural networks. Multiple linear regression is considered as an efficient method since it considers more than one factor to estimate the service life of buildings or building components. This method is easy to communicate to construction stakeholders to support decision-making process.	Silvestre *et al.* (2015)
PROBABILISTIC	A probability density function is used to predict the EoL of a building. It is not accurate for singular buildings, cannot be easily applied in practice, but is a valuable approach for building stocks models. Probabilistic models do not include all parameters that can influence the service life of a building or building components. It is helpful for estimating the urban mining potential of cities, and for planning future circular construction.	A Normal distribution is used for large scale material flow analysis. It assumes that a consistent number of short-lived buildings are demolished within their first year after construction and since it does not have upper or lower limits, extreme values for lifespan may be presented.	Müller (2006)
		There are different probability density functions to approximate the lifespan of a group of buildings, namely Weibull, Normal and Log-normal distributions. The Log normal and Weibull distribution match with the theoretical assumption that buildings have an initial demolition free period.	Göswein *et al.* (2019)

Moreover, in the absence of a deterministic method for lifespan calculation, this guide recommends the use of the lifespan referred in another output of Circular Buildings projects, namely the “Guideline for creating Circular Materials Passports”, which includes typical service lifespan for tier 2 of a building (Table 8).

Table 8: Typical service lives for the minimum scope of building parts and elements

Source: Adapted from Donatello *et al*. (2021)

TIER 1 BUILDING ASPECT	TIER 2 BUILDING ASPECT	TIER 3 BUILDING ASPECT	EXPECTED LIFESPAN
SHELL	Loadbearing structural frame	- Frame (beams, columns and slabs) - Upper floors - External walls - Balconies	60 years
	Non-load bearing elements	- Ground floor slab - Internal walls - Partitions and doors - Stairs and ramps	30 years
	Facades	- External wall systems	30 years (35 years glazed)
		- Cladding and shading devices	30 years (35 years glazed)
		- Façade openings (including windows and external doors)	30 years
		- External paints, coatings and renders	10 years (paint), 30 years (render)
	Roof	- Structure - Weatherproofing	30 years
	Parking facilities	Above ground and underground (within the curtilage of the building and servicing the building occupiers)	60 years
CORE	Fittings and furnishings	- Sanitary fittings	20 years
		- Cupboards, wardrobes and worktops (where provided in residential property)	10 years
		- Ceilings[1]	30 years
		- Wall and ceiling finishes	20 years (finishes); 10 years (coating)
		- Floor coverings and finishes	30 years (finishes); 10 years (coatings)
		- Skirting and trimming	30 years
		- Sockets and switches	30 years
	In-built lighting system	- Light fittings - Control systems and sensors	15 years
	Energy system	- Heating plant and distribution	20 years
		- Radiators	30 years

TIER 1 BUILDING ASPECT	TIER 2 BUILDING ASPECT	TIER 3 BUILDING ASPECT	EXPECTED LIFESPAN
		- Cooling plant and distribution	15 years
		- Electricity generation	15 years
		- Electricity distribution	30 years
	Ventilation system	- Air handling units	20 years
		- Ductwork and distribution	30 years
	Sanitary systems	- Cold water distribution - Hot water distribution - Water treatment systems - Drainage system	25 years
	Other systems	- Lifts and escalators	20 years
		- Firefighting installations	30 years
		- Communication and security installations	15 years
		- Telecoms and data installations	15 years
EXTERNAL WORKS	Utilities	- Connections and diversions - Substations and equipment	30 years
	Landscaping	- Paving and other hard surfacing	25 years
		- Fencing, railings and walls	20 years
		- Drainage system	30 years

3.1.4 Lack of guidance to general users

Construction stakeholders, such as architects and engineers, are familiar with reading and interpreting BoQ documentations and lifespan estimates. In contrast, general users have a lack of knowledge in detailed building sustainability and LCA issues. Therefore, if a general user attempts to estimate a building footprint they are likely to use “self-made” methods, inconsistent data and references and, subsequently, omit important aspects, obtain incorrect measurements, or misinterpret the results. Yet, to raise awareness and improve the understanding of circular building amongst the wider population, it is important to include the general user as a target audience in the current methods and documentation. This can be achieved by simplifying the instructions and results assessment. Additionally, a graphical representation of the results is always helpful to support the understanding, improve readability and allow for identifying patterns, especially for a general user (Lortie *et al.* 2013). Figure 10 shows an example for general user evaluate the BoQ outputs from Level(s) excel spreadsheet.

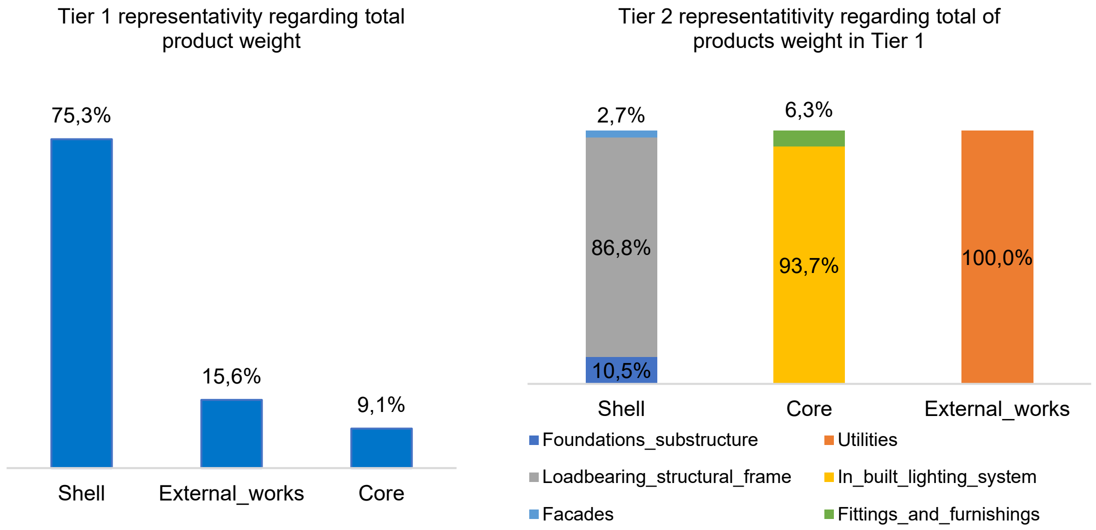

Figure 10: Example of Bill of Quantities results through graphical demonstration

To improve the documentation and method of material footprinting for the general user, the present guide suggests developing the following aspects:

1. Brief introduction of BoQ and lifespan, as well as life cycle thinking, providing definitions, objectives and scope;
2. Simple instructions on BoQ and lifespan estimated;
3. List of open data sources for data input and management.

Regarding the first point, this guide attempts to provide interesting information for all stakeholders, including the general user. It includes definitions and explanations of important concepts related to indicators of circular buildings. Regarding the second point, the new Level(s) framework is a leap forward as it contains a helpful text description and easy-to-use MS Excel spreadsheet for the indicator 2.1 “Bill of quantities, materials and lifespan”. Regarding the third point, sections 3.1.5 and 3.2.3 include lists of useful data sources.

3.1.5 Access costs to technical standards, databases and calculation tools

The Level(s) framework identifies several reference standards, data sources and calculation tools to use for data input of BoQ, materials and lifespan indicator. For example, in case of considering the service life data in the BoQ, it is advisable to follow the rules of EN 15978, ISO 15686-8, BCIS, DGNB, ETool, specific standards for specific elements know-how, e.g., EN 15459 for heating systems, or Level(s) typical service lifespan. In terms of the assessment of the BoQ, estimated building lifetime and associated costs, it is recommended to use special software or calculators, such as the EU-funded CILECCTA software to analyse future scenarios for different building designs, and for calculating carbon footprints and any other life cycle environments impacts it is recommended to use Environmental Product Declarations or Life Cycle Inventories.

In general, these tools increase credibility and provide a comparison between construction project processes and results, but it is important to notice that due to their costs not every construction stakeholder has access to these basic tools. Moreover, some of these tools require an understanding of sustainability and life cycle thinking, which does not ease the application of Level(s) indicator 2.1. Therefore, the present guideline suggests the following list of free sources to overcome the cost barrier and cover the use for all types of construction stakeholders:

- Gerador de Preços, Portugal[7], is a free webpage that provides a set of data to measure and control the budget and financial work of construction projects. The prices vary depending on the location of the building project in the respective country;
- STACK Takeoff & Estimating Software[8] is free construction software cloud-based for constructions stakeholders or general users to streamline the bid process and accurately estimate materials, equipment and labour. This tool also provides access to an extensive database of prebuilt and industry-specific materials. An upgraded paid version exists as well;
- ESTIMATE[9] is a free and open-source construction software that has the ability to manage a Bill of Materials, multiple costing standards, suppliers and client's database and can generate BoQ and an extensive cost sheets;
- CatalystiK[10] is a free construction software and open source to estimate quotations for all types of construction projects and aid to determine work estimation such as material and labour cost, tasks scheduling, budget planning and others.

3.2 ENVIRONMENTAL IMPACT ASSESSMENTS

As explained above, the most common methodology for environmental impact assessment is Life Cycle Assessment. This section highlights critical aspects related to LCA in terms of uncertainty and variability, data quality, and data sources.

3.2.1 Uncertainty and variability in LCA

Life cycle assessments are inherently heterogeneous, even for the same type of product (AzariJafari *et al.* 2021). That is due mostly to uncertainty and variability that hinder the credibility and comparability of LCA results (AzariJafari *et al.* 2021). No standardized method exists to minimize the impacts of uncertainty and variability in LCA. However, there are some recommendations to be found in the ISO standards: ISO 14044 (ISO/TC 207/SC5 2006b) recommends that for comparative studies that are disclosed publicly, local sensitivity analyses (e.g. one at a time) and uncertainty analyses should be performed.

The following paragraphs provide more information on the types of uncertainty and variability to draw attention to these issues, therefore, contributing to a higher robustness of results.

Uncertainty

Uncertainty in LCA stems from the conversion of real-world data into models, which implies simplifying the reality, making subjective choices, or lacking precision parameters (Huijbregts *et al.* 2001). Uncertainty can

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[7] http://www.geradordeprecos.info/
[8] https://www.stackct.com/
[9] https://estimate.wanhive.com/support.php
[10] https://www.catalystk.com/

be divided into three groups: (1) parameter uncertainty, (2) model uncertainty, and (3) uncertainty due to choices (Huijbregts 1998):

1. The uncertainty of parameters includes empirical inaccuracy (imprecise data), unrepresentativeness (incomplete or old data), or a sheer lack of data. In order to perform an uncertainty analysis of parameters one needs to analysis the uncertainty distributions and parameter correlations (Huijbregts 1998). Stochastic modelling, e.g. with Monte Carlo simulations, can be a promising technique (AzariJafari *et al.* 2018). Important uncertainty parameters for the LCA of buildings are the service life and maintenance periods (Goulouti *et al.* 2020).
2. The uncertainty of the model includes the choice of LCIA method, thereby the characterization factors, and the response of ecological processes to environmental burdens. A comparison between methods can help the interpretation of results. A study by Pittau *et al.* (2018) of bio-based construction compared the IPCC method for Global Warming Potential at 100 years with the novel dynamic LCA method by Levasseur *et al.* (2010) and found differences in the range of more than 500%.
3. The uncertainty due to choices includes the choice of a functional unit or allocation rules (AzariJafari *et al.* 2021). If the weighting step is included in the LCA, then this represents a central source of uncertainty. Inappropriate system boundaries are another source of uncertainty, especially for the comparability of different LCA studies (Häfliger *et al.* 2017). Common boundaries are: Cradle-to-Gate and Cradle-to-Grave (Silvestre *et al.* 2014). Especially for the latter, the system boundaries have great effect on the benefits and burdens of a product (defined in module D).

Variability

Variability stems from inherent changes in the real world, such as real differences in production technologies, materials, or regions (AzariJafari et al. 2018). Variability can be divided in three groups, namely into variability in (i) space, (ii) time, and (iii) between objects and sources (Huijbregts 1998). All types can lead to false representativeness of LCI data (Henriksen *et al.* 2021).

i. Spatial variability between regional contexts due to, for example, different physical-chemical and ecological characteristics, background concentrations of chemicals and usage patterns of buildings.
ii. Temporal variability between the target year and the year of data generation can be due to a change in technology that directly (through manufacturing processes) or indirectly (e.g. through a changing electricity supply) affects the product's manufacturing, or through changing user behaviour, or external factors such as a changing climate.
iii. Variability between objects and sources can be due to differences in inputs and emissions of comparable processes in a product system. Different data sources can lead to different results, which should be counter-acted through a data quality assessment of flows, processes and the LCI model (EPA 2016).

3.2.2 Data quality analysis

Large amounts of data are required for a LCA and data collection is a time-intensive part of any LCA study. Therefore, efforts should be prioritized to collect most accurate data for those aspects with the greatest impact on the final results (Henriksen *et al.* 2021). The importance of aspects can be dependent on the LC stages or modules, processes, building components and elementary flows. For this purpose, a data quality analysis on the importance and accuracy of the individual data should be performed. Common parameters for a data quality analysis, according to the European Commission's Product Environmental Footprint method (EC-JRC 2012) and Level(s) framework (Dodd *et al.* 2021), are the following:

- Technological representativeness of data;
- Temporal representativeness of data;
- Geographical representativeness of data;
- Uncertainty of data.

The technological representativeness refers to how the dataset reflects the true population of interest regarding technology (Dodd *et al.* 2021). Since LCA databases can always only include historic data, the technological representativeness of data is particularly critical for LCA studies of new products (Wender *et al.* 2014). Especially for emerging technologies, including new ways of manufacturing buildings through digital fabrication in what is called "construction 4.0" (García de Soto *et al.* 2018), critical data are unknown and highly uncertain (Göswein *et al.* 2020b). Moreover, the long lifespan of buildings requires an analysis of the potential long-term behaviour and corresponding emissions. Therefore, to improve the technological representativeness, a structured scenario analysis can be recommended (Wender *et al.* 2014).

The temporal representativeness refers to how the dataset reflects the specific conditions of the system under study regarding the age of the data. In other words, it refers to the difference between the year under study and the given year of the data. In this sense, it is intertwined with the technological representativeness. There is no hard line between "old" and "new", or "outdated" and "valid", data. Yet, it can be strongly recommended to do a background check on significant technological and societal (i.e. behavioural) changes that might have happened during the time step. If such changes have occurred, then the data should be updated accordingly.

The geographical representativeness refers to how the dataset reflects the true population of interest regarding geography (Dodd *et al.* 2021). Attention should be paid to the location of raw materials in the LCI since the location of manufacturing the final product is often different from the source of raw materials. For example: a pre-fabricated building element made in Portugal can contain steel from China. This influences foremost the electricity mix. However, the geographical representation of data is also important in regard to local pollutants, such as nitrogen oxides (NOx) that cause respiratory problems and acid rain close to the original source of emittance (11), and for water consumption, especially in areas that are confronted with water scarcity.

Uncertainty of data can refer to parameter uncertainty, model uncertainty, and uncertainty due to choices, as described in section 3.2.1.

3.2.3 Data sources for energy, carbon and water assessments

This section gives recommendations for choosing data for energy, carbon and water of construction products and processes.

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[11] Please note that CO_2 is a global pollutant.

A list of data sources, ordered by country, can be seen in Table 9. The provided references are a mix of LCI data and LCA data. The list is based on the previous overviews of data sources from Kounina *et al.* (2013), De Wolf *et al.* (2017), Pagnon *et al.* (2020), and an additional manual online search. The list is non-exhaustive. The search terms used were “LCA OR Life Cycle Assessment OR Life Cycle Analysis OR LCI OR Life Cycle Inventory” AND “Carbon OR CO_2 OR Energy OR Water” AND “data OR database OR repository OR inventory”.

Table 9: Overview of available data sources for energy, carbon and water

NAME	COUNTRY	SOURCE	ENERGY	CARBON	WATER
AusLCI	Australia	ALCAS (2011)	x	x	x
EPiC	Australia	Crawford *et al.* (2021)	x	x	x
Bau EPD	Austria	The Bau EPD GmbH	x	x	x
BBRI EPD database	Belgium	FPS	x	x	x
CENIA	Czech Republic	Czech Environmental Information Agency	x	x	
EPD Danmark	Denmark	Danish Technological Institute	x	x	x
EcoPlatform EPD	Europe	Eco Platform	x	x	x
ELCD	Europe	EC-JRC (2021)	x	x	x
EUCoMDat	Europe	The EPD registry	x	x	
GreenBookLive	Europe	BRE Global	x	x	
RTS EPD	Finland	Building Information Foundation	x	x	x
Base Carbone	France	ADEME agency		x	
INIES EPD database	France	INIES (2020)	x	x	x
IBU	Germany	German Institute for Construction and Environment	x	x	
Ökobaudat	Germany	BMI (2021)	x	x	x
The International EPD System	International	EPD International	x	x	x
EPD Ireland	Ireland	Irish Green Building Council	x	x	x
EPD Italy	Italy	EPD Italy	x	x	x
IVAM	Netherlands	IVAM (2016)		x	
Milieudatabase	Netherlands	NMD (2020)	x	x	
Alcorn	New Zealand	Alcorn (2003)	x		
EPD Norge	Norway	The Norwegian EPD Foundation	x	x	x
ITB EPD	Poland	Polish Building Research Institute	x	x	x
DAP Habitat	Portugal	DAP Habitat	x	x	x
DAP construcción	Spain	CAATEEB, Agenda de la construcción sostenible	x	x	x

NAME	COUNTRY	SOURCE	ENERGY	CARBON	WATER
IVL	Sweden	IVL (2021)	x	x	
Klimatkalkyl	Sweden	Swedish Transport Administration 2019	x	x	
KBOB	Switzerland	KBOB 2021	x	x	x
TurCoMDat	Turkey	Metsims Sustainability Consulting, SÜRATAM	x	x	
Hutchins UK Building Blackbook	UK	Hutchins, Franklin and Andrews (2011)		x	
Inventory of Carbon and Energy	UK	Hammond and Jones (2008)	x	x	
UK CoMDat	UK	Metsims Sustainability Consulting, UK Ecolabel Center	x	x	
Carbon Working Group	US	Webster *et al.* (2012)		x	
CORRIM on timber	US	CORRIM (2017)		x	x
NRMCA on concrete	US	NRMCA (2016)		x	
Quartz	US	Healthy Building Network (2015)	x	x	
US LCI	US	NREL (2012)	x	x	
Ecoinvent	World	Ecoinvent (2021)	x	x	x
GaBi	World	Sphera (2021)	x	x	x
Metals	World	Chapman and Roberts (1983)		x	
Pfister *et al.*	World	Pfister *et al.* (2011)			x
Quantis	World	Quantis (2018)			x
WBCSD on cement	World	WBCSD (2015)		x	
WFN	World	WFN (2005)			x
World Steel	World	World Steel (2020)		x	

According to Martínez-Rocamora *et al.* (2016) it is important to check that the following features of a LCA database are in line with the objectives of the LCA study: scope in terms of territory and categories, completeness, transparency, comprehensiveness including sufficient documentation, validity based on the last update, and the accessibility (open source vs. licensed).

Civil engineers and architects consult and compare the environmental performance of construction products by using EPD. However, EPD often have a lack of transparency and data quality, which hinders a robust application of EPD in the environmental performance analysis and product comparison for procurement decisions. Waldman *et al.* (2020) recommends that input data should be specific to the:

- Manufacturer;
- Facility;
- Product;

- Time;
- Supply chain.

Yet, often EPD are based on generic data sets since specific data is not available and average data sets do not exist (Modahl *et al.* 2013). In addition, data and method uncertainty, as well as a lack of confidence intervals lead to non-robust results (Bhat and Mukherjee 2019).

4 CASE STUDIES OF WATER, ENERGY AND CARBON INDICATORS

This section presents three practical examples in order to demonstrate the most common issues of using existing methods and data. A critical reflection on data and methods ultimately leads to increased robustness of efficiency indicators. One example is presented per indicator: energy, carbon and water. The first example, in section 4.1, uses cement production to demonstrate the importance of accurate data for the energy process. The second example, in section 4.2, uses bio-based renovation to demonstrate the importance of the life cycle impact assessment (LCIA) for carbon results as a measure of Global Warming Potential (GWP). The third example, in section 4.3, analysis the replacement cycles and material alternatives for water pipes to highlight the uncertainty of those parameters.

4.1 CEMENT PRODUCTION AS AN EXAMPLE FOR ENERGY ANALYSIS

When resorting to construction products or LCA databases as a data source in the assessment of the environmental impacts of a product or building, one needs to carry out a critical analysis of the data as opposed to merely accepting the data as accurate. There is a certain level of uncertainty, even in life cycle inventories from renowned LCA databases such as Ecoinvent (2021), which require a validation process. This case study dives into the example of cement production.

In Ecoinvent, there are several different processes of cement production. To determine which, if any, is representative of the cement process under analysis, one needs to analyse the inventory data. Assuming the cement production process under analysis is the cement produced in Portugal, a preliminary assessment of the associated impacts regarding energy and water consumption can be developed by resorting to publicly available data in the national cement plants' Environmental Declarations. This data analysis allowed to define an average national cement production process (*PT*), which can serve as a reference process with which to compare the Ecoinvent processes.

Therefore, in this practical example, to assess the applicability of the cement production processes available in the LCA databases, a critical analysis was made of three parameters, namely thermal energy consumption, electric energy consumption and water consumption. Seven processes of Portland cement production were analysed, identified in Table 10.

Table 10: List of processes for cement production under analysis

PROCESS NUMBER	CEMENT PRODUCTION PROCESSES FROM LCA DATABASES	DATABASE
1	Portland cement, strength class Z 52.5, at plant/CH U	Ecoinvent
2	Portland cement (CEM I), CEMBUREAU technology mix, CEMBUREAU production mix, at plant, EN 197-1 RER S	ELCD
3	Cement, Portland {US}| production | Alloc Def, U	Ecoinvent
4	Cement, Portland {RoW}| production | Alloc Def, U	Ecoinvent
5	Cement, Portland {Europe without Switzerland}| production | Alloc Def, U	Ecoinvent
6	Cement, Portland {CH}| production | Alloc Def, U	Ecoinvent
7	Cement, Portland {CA-QC}| production | Alloc Def, U	Ecoinvent

The input flows of these processes related to the consumption of thermal energy, electric energy consumption and water consumption were consolidated and compared to the reference values of the national cement production processes. The obtained results are presented in Figure 11, Figure 12 and Figure 13.

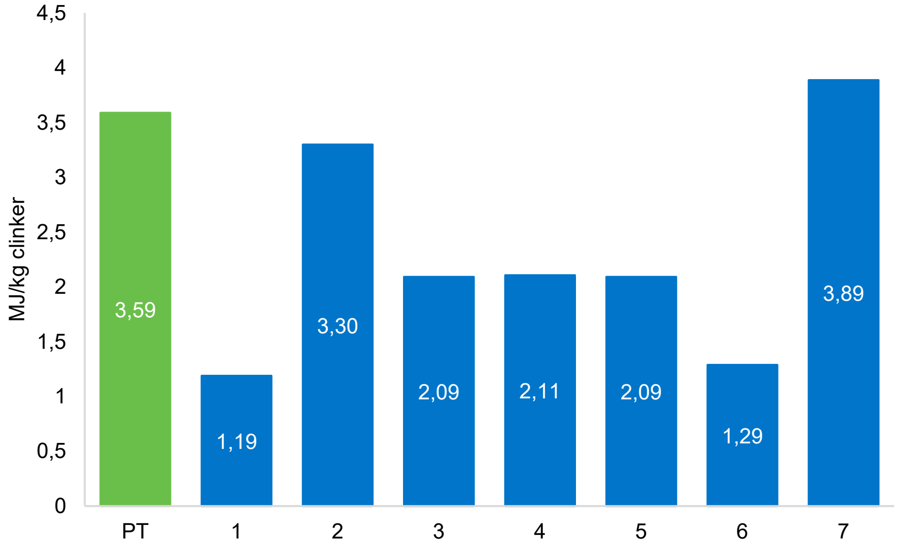

Figure 11: Thermal consumption of cement production processes
Source: Data taken from Portuguese cement plants' Environmental Declarations (PT in green) and from Ecoinvent processes (in blue)

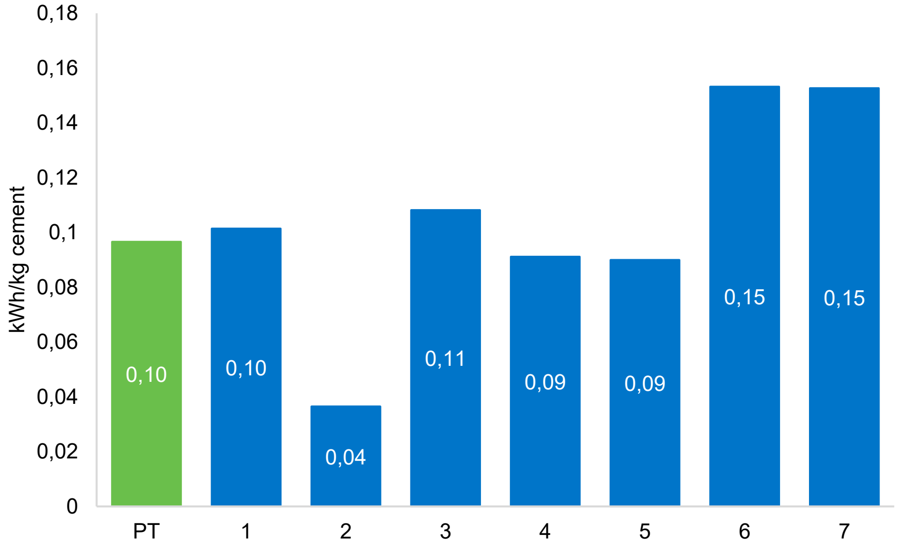

Figure 12: Electricity consumption of cement production processes
Source: Data taken from Portuguese cement plants' Environmental Declarations (PT in green) and from Ecoinvent processes (in blue)

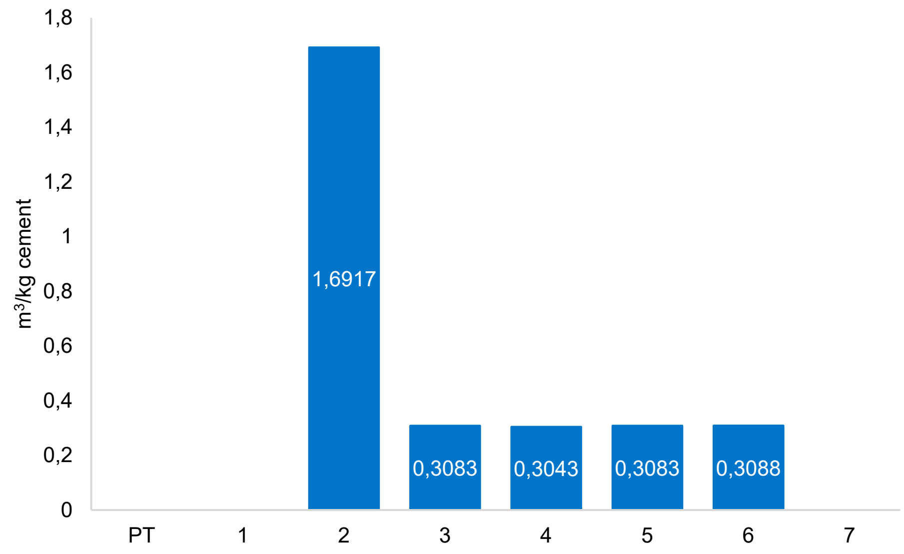

Figure 13: Water consumption of cement production processes
Source: Data taken from Portuguese cement plants' Environmental Declarations (PT in green) and from Ecoinvent processes (in blue)

An environmental impact assessment of these processes can also be carried out, when an LCA software is available. Any process which neglects relevant impacts due to the definition of the system boundaries are shall be excluded. The results of this example are given in Table 11.

Table 11: Environmental Impact Assessment of cement production processes

Source: Results obtained from SimaPro software

IMPACT CATEGORY	UNIT	PT	1	2	3	4	5	6	7
Climate change	kg CO_2 eq	696.40	831.98	900.39	893.04	914.71	870.19	740.46	819.06
Ozone depletion	kg CFC-11 eq	0.00001	0.00002	0.00004	0.00003	0.00002	0.00003	0.0000	0.0000
Terrestrial acidification	kg SO2 eq	1.16242	1.19085	2.14509	1.60679	1.84832	1.53008	1.0584	4.2819
Freshwater eutrophication	kg P eq	0.00346	0.00497	0.00023	0.01797	0.01164	0.01068	0.0084	0.0176
Marine eutrophication	kg N eq	0.05084	0.05060	0.07529	0.05678	0.06049	0.05517	0.0431	0.0901
Human toxicity	kg 1,4-DB eq	9.49208	23.5317	18.3599	30.3172	29.4377	28.5778	12.734	15.801
Photochemical oxidant formation	kg NMVOC	1.40165	1.42568	2.20950	1.5326	1.6498	1.49164	1.1409	2.5655
Particulate matter formation	kg PM10 eq	0.49712	0.47951	0.74165	0.8683	0.8744	0.63542	0.44758	1.26656
Terrestrial ecotoxicity	kg 1,4-DB eq	0.00978	0.00891	0.00626	0.01459	0.0159	0.01423	0.01015	0.00851
Freshwater ecotoxicity	kg 1,4-DB eq	0.05384	0.05483	0.02548	0.19382	0.1274	0.09548	0.02999	0.04667
Marine ecotoxicity	kg 1,4-DB eq	0.09757	0.11482	0.05489	0.18891	0.17754	0.16318	0.08007	0.11541
Ionising radiation	kBq U235 eq	3.98210	30.6377	13.8800	16.2110	9.69269	14.1649	27.7185	3.41917
Agricultural land occupation	m^2a	2.82255	4.16459	0.00000	5.32029	8.29779	11.1940	5.29396	7.35854
Urban land occupation	m^2a	1.02652	1.34543	0.00000	2.61499	2.72061	2.17403	1.20963	3.45274
Natural land transformation	m^2	0.02541	0.03323	0.00000	0.05367	0.06058	0.05271	0.01393	0.10765
Water depletion	m^3	2.20704	3.41474	0.39038	1.70900	1.91271	2.08347	1.64660	3.89736
Metal depletion	kg Fe eq.	2.37036	6.01352	7.27045	8.10692	8.19234	8.37225	4.81999	10.5381
Fossil depletion	kg oil eq.	32.8106	66.9943	78.3642	81.7704	80.7834	75.1562	39.2811	69.0594

Analysing the graphs, and comparing the Ecoinvent processes with the reference process ‘PT’, there is an underestimation of the thermal consumption of the clinker by processes 1, 3, 4, 5 and 6, which means they should not be used in the assessment, while processes 2 and 7 can be considered to be adequate. In fact, there is a theoretical thermodynamic limit of energy consumption for cement clinker manufacturing of 3,000 MJ/tonne (CSI 2016), which allows to conclude that it is not possible to have a cement production process with energy consumption below that value. This analysis demonstrates the need to employ critical analysis using thermodynamics and engineering principles to confirm the robustness of existing life cycle inventories.

Additionally, while analysing the results of the previous table of environmental impacts, one can conclude that there is a very relevant underestimation of the impacts in the category of water depletion, which indicates that the process is not considering water consumption upstream of cement production, in the production of electricity. Therefore, one can decide to consider the data from process 7 (Cement, Portland {CA-QC} | Alloc Def, U) as the best approximation to the process under analysis since it appears to be more in line with the system being studied.

4.2 BIO-BASED RENOVATION AS AN EXAMPLE FOR CARBON ANALYSIS

Depending on which LCIA method is used, the results of a LCA can vary. Different scholars, such as Monteiro and Freire (2012) and AzariJafari *et al.* (2021) have analysed this variation and found that, in comparison to other uncertainty and variability issues, the choice of LCIA method does not greatly influence the results of an LCA. Owsianiak *et al.* (2014) compared the LCIA methods ILCD 2009, IMPACT 2002+ and ReCiPe 2008 at midpoint level for different window designs in a residential building. The authors found that despite the different impact scores of impact categories, all analysed LCIA methods allow identifying the design option with the lowest environmental burden. This would lead to the conclusion that the choice of LCIA method does not hamper obtaining robust results, neither comparing results between studies.

These findings from comparative analyses are based on LCIA methods that neglect the temporal profiles of emissions, such as the standard ILCD or ReCiPe methods. However, during the last decade, new research, led by Levasseur *et al.* (2010), has pointed out that the timing of carbon emissions and the choice of a time horizon for the LCA, in fact, greatly influences the results of a global warming impact assessment. So far, in LCA, carbon accounting and carbon footprinting methods, it is standard to define the time horizon before conducting the actual calculation and to neglect the timing of emissions (Levasseur 2010). To explain this better: In the LCI phase (refer to Figure 2), all emissions of a specified GHG pollutant, e.g. CH_4, are aggregated into a single value. This value is then multiplied with its GWP for a specific time horizon (most often for 100 years) to obtain the global warming impact of this aggregated emission (remember the example: the GWP at 100 years of 1 kg of CH_4 is 28 kg of CO_2 eq.). This is done for all pollutants under study and subsequently the impact of each GHG is summed to obtain the life cycle impact for the global warming category in kg CO_2 eq.

A fixed time horizon is particularly problematic for the LCA of buildings since buildings usually have long lifespans, around 70 years in Europe (Aksözen *et al.* 2017). When the GWP is assessed for a 100-year time horizon, as it is common, the atmospheric radiative forcing during the first 100 years after the occurrence of the emission is considered. This means that for the LCA of an average building that stands 70 years, the GHG emissions arising from the construction phase in year 1 are analysed over the first 100 years, but the GHG emissions arising from the building’s EoL phase in year 70 are analysed over a time period from year 70 to 170 after the construction. This is illustrated in Figure 14. For a comparative LCA of buildings with different temporal profiles, in other words with varying year of construction, renovation or demolition, the time frame during which the global warming impact is calculated would not be the same for both systems, thereby impairing robust results.

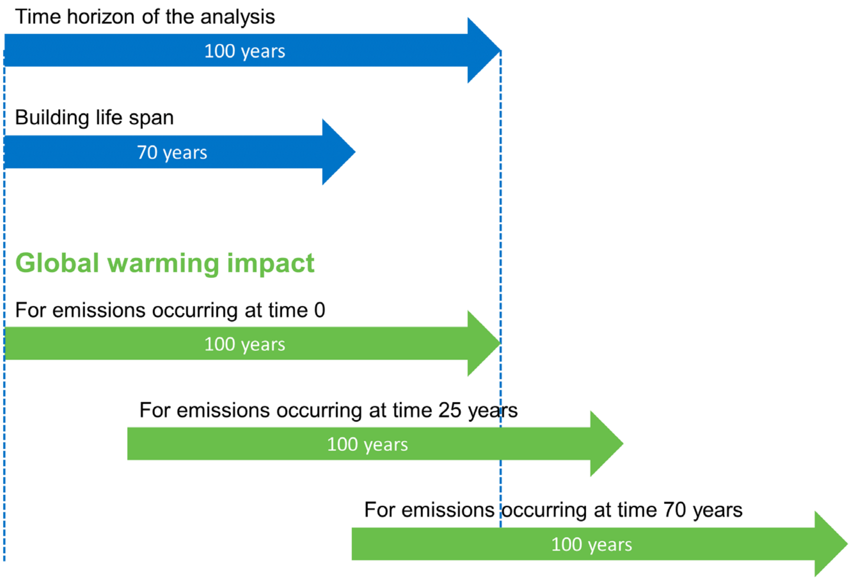

Figure 14: Illustration of inconsistent temporal boundaries for the assessment of global warming impacts according to standard LCA methods
Source: Based on Levasseur *et al.* (2010)

The dynamic LCA method that was proposed by Levasseur *et al*. (2010) and since then tested by many scholars (Cherubini *et al.* 2011; Demertzi *et al.* 2018; Pittau *et al.* 2018; Göswein *et al.* 2020a) allows comparing buildings and other products consistently, since it employs a flexible time horizon to assess the impact of each GHG emission, beginning with the occurrence of the emission and ending with the selected time horizon for the analysis. This is especially important when analysing the global warming impact of building scenarios where time is dominant, such as for questions as turning buildings into carbon sinks, gradual carbon sequestration in biomass, and delaying GHG emissions.

Following is an example of a bio-based refurbishment system that can be applied on the exterior wall of an existing building[12]. It consists of a wood frame infilled with straw. The data is taken from Göswein *et al.* (2020a, 2021) and more information on the model and assumptions can be found there. It is assumed that the system is installed in year 1, the external cladding is maintained in year 30, and the system reaches its end of life in year 60 when a new system would be installed in the building. On average, wheat straw is regenerated every year, while a tree needs 75 years to regrow. These values are just exemplary but give a good sense of the complex temporal profiles of building emissions. The GWP, expressed in CO_2 eq., is calculated with the standard IPCC 2013 method at 100 years and compared to dynamic LCA for the same time frame (100 years). The whole life cycle (LC stages A, B, C) and module D are accounted for. Three different EoL scenarios are compared: landfill vs. energy recovery vs. material recovery. The results can be

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[12] For more information on the bio-based system please refer to the report "*TES EnergyFaçade – prefabricated timber based building system for improving the energy efficiency of the building envelope*" (Lattke *et al.* 2011) that was developed during a research project within the transnational WoodWisdom-Net Research Programme, funded by Germany, Finland, and Norway.

seen in Figure 15. In the IPCC method, carbon storage is not included. The impacts that are obtained with the dynamic LCA method are significantly lower than the ones obtained with the IPCC method. IPCC method, as a conventional LCIA method, shifts all the emissions along the life cycle to time zero, and neglects the effects of delayed emissions and carbon uptake in the different EoL scenarios. The difference between methods is the biggest for the LC with material recovery as the EoL scenario. For this scenario, employing the conventional IPCC method results in positive emissions for the total LC impacts while the dynamic LCA method results in total negative results. This means that, with the IPCC method, the system under study is a carbon source while with the dynamic LCA method, it is a carbon sink. This emphasizes the need for the choice of a robust methodology to analyse, compare and highlight the benefits of circular construction in regard to carbon emissions. Even though the method is not yet included in any national or international building standard, the LCA community is converging (Lueddeckens *et al.* 2020) to support the higher accuracy of the dynamic LCA method as proposed by Levasseur et al. (2010). As mentioned, the timing of emissions gains importance for products with long lifespans, such as buildings, and for products made from organic content such as timber buildings. Therefore, it can be concluded that it is necessary to use dynamic LCA for the environmental impact assessment of buildings.

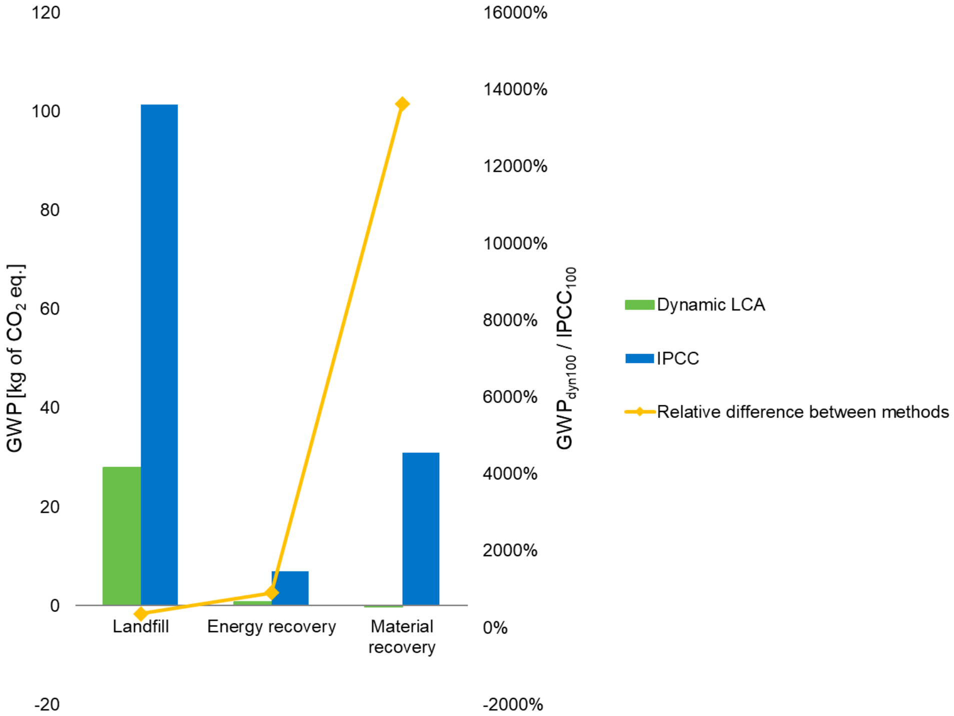

Figure 15: Comparison of IPCC and dynamic LCA method at 100 years for 1 m^2 of bio-based façade
Data taken from Göswein *et al.* (2020a, 2021)

4.3 REPLACEMENT OF PIPES AS AN EXAMPLE FOR WATER ANALYSIS

The service life of building elements plays an important role when deciding between refurbishing a building (element) or demolishing (decommissioning) and reconstructing (replacing) it since the service life defines for how long the building element is serviceable and when, from a technical point of view, it is necessary to maintain or replace it. In general, maintenance can lead to a small increase of efficiency and prolonged lifespan, while the installation of a new product leads to a big increase in efficiency but relatively higher embodied impacts.

Ferreira *et al*. (2015) calculated a groundwater replenishment indicator (mm/m^2) for a case study building in Lisbon and found that for refurbishment it accounts for 0.0043 mm/m^2 while for demolition and reconstruction it accounts to, almost double, 0.0082 mm/m^2. In addition, the material and product choice is crucial for the environmental impacts associated to a construction activity.

The following example illustrates the importance of service life, product and material choice, for a theoretical example of a leaking water pipe: Assuming there is a leaking water pipe that wastes one litre per day. The exact leak cannot be located in the building, meaning that in order to fix the situation the whole 20 m of the pipe need to be exchanged. Four scenarios are defined: 0) Do nothing; 1) Exchange the leaking pipe with a new plastic pipe; 2) Exchange the leaking pipe with a new steel pipe; 3) Exchange the leaking pipe with a new copper pipe. The parameters of these scenarios, which differ in terms of embodied water and service life, can be seen in Table 12. The “embodied water” refers to water needed for the extraction of raw material and manufacturing of the new pipe.

Table 12: Overview of the scenarios for the leaking water pipe

	UNIT	DO NOTHING	SCENARIO 1	SCENARIO 2	SCENARIO 3
New pipe material	--	--	Plastic	Copper	Steel
Leakage	litres per day	1	0	0	0
Embodied water	total litres	0	47.5	149	199
Service life	years	0	15	50	35

These values are used to analyse the total water used (meaning embodied water from raw material extraction, manufacturing, and water loss from the leakage) during different time spans. The results can be seen in Figure 16. After one year, the lost water through the leakage is negligible compared to the embodied water for the three scenarios. However, when considering a prolonged timespan, the lost water grows linearly into thousands of litres. The plastic pipe is the first one to reach its environmental return on investment: within three years. However, after 45 years, or three replacement cycles of the plastic pipe (assuming it has a 15 year service life), the copper pipe with a higher embodied water but longer service life is beneficial from a total water perspective.

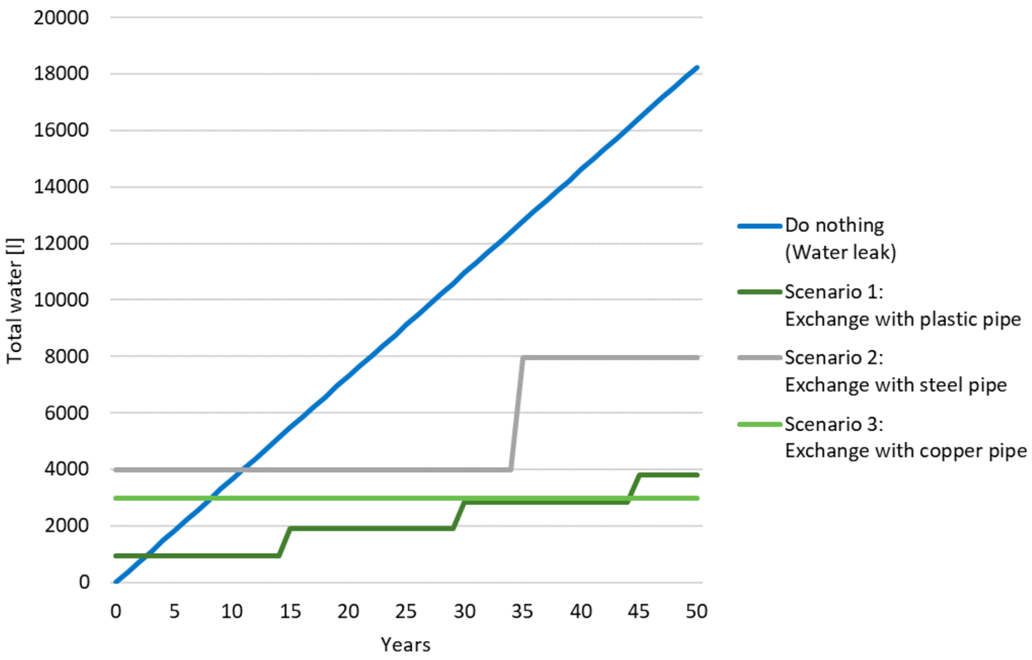

Figure 16: Theoretical example of exchange vs. do nothing scenarios for water pipes over time in terms of embodied water, calculated with the median from Figure 17

The values for embodied water and lifespan used for the analysis in Figure 17 were assumed fixed. However, in reality these values, in particular the embodied water for different construction materials, have a significant variance. Figure 17 visualizes the embodied water for three different types of materials for water pipes. The data was taken from Crawford *et al.*'s (2021) database for different pipes (in terms of product specifications). The box plots show that plastic pipes can have the lowest embodied water. However, depending on the exact product properties and data sources, the embodied water can have a high uncertainty and in some cases overtake the impacts of sturdier materials such as copper and steel.

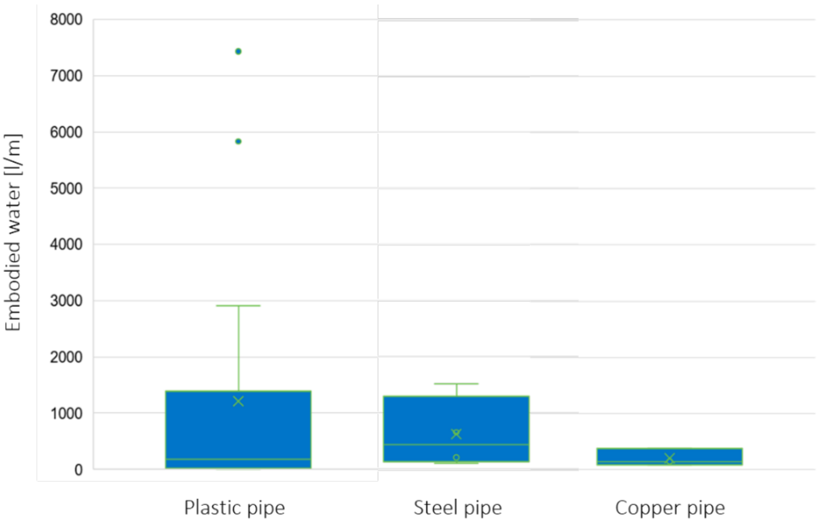

Figure 17: Value ranges for embodied water for different types of types
Data taken from Crawford et al. (2021)

5 SUMMARY OF RECOMMENDATIONS

This section summarizes the different recommendations that were previously discussed. Please note that in most cases the recommendations are sensitive to the specifics of a building project and need to be evaluated by experts of the field.

Recommendations for a robust quantification of a building’s material footprint

- Label material quantities in the bill of quantities in accordance with the standardized life cycle stages (EN 15978);
- Assemble the bill of quantities considering all life cycle stages of a building, i.e. from cradle to grave;
- Use the Level(s) framework indicator 2.1 spreadsheet, which is recommended by the European Commission;
- Refrain from using unstandardized and confusing terminology;
- Use an empirical lifespan approach for a singular building and a probabilistic approach for groups of buildings, otherwise resort to literature for reference lifespan values but review their context;
- If possible, include a cost estimate and refer to free resources.

Recommendations for a robust environmental performance analysis

- Conduct a LCA following the ISO and EN standards;
- If possible, conduct a data quality analysis in regard to the technological representativeness, temporal representativeness, geographical representativeness, and uncertainty of data;
- Otherwise, review the uncertainty of parameters, models and choices for the LCA, and check representativeness of LCI data in terms of spatial and temporal variability, as well as variability between objects and sources;
- Collect specific data whenever possible, if not, use average or generic data from sensible data sources.

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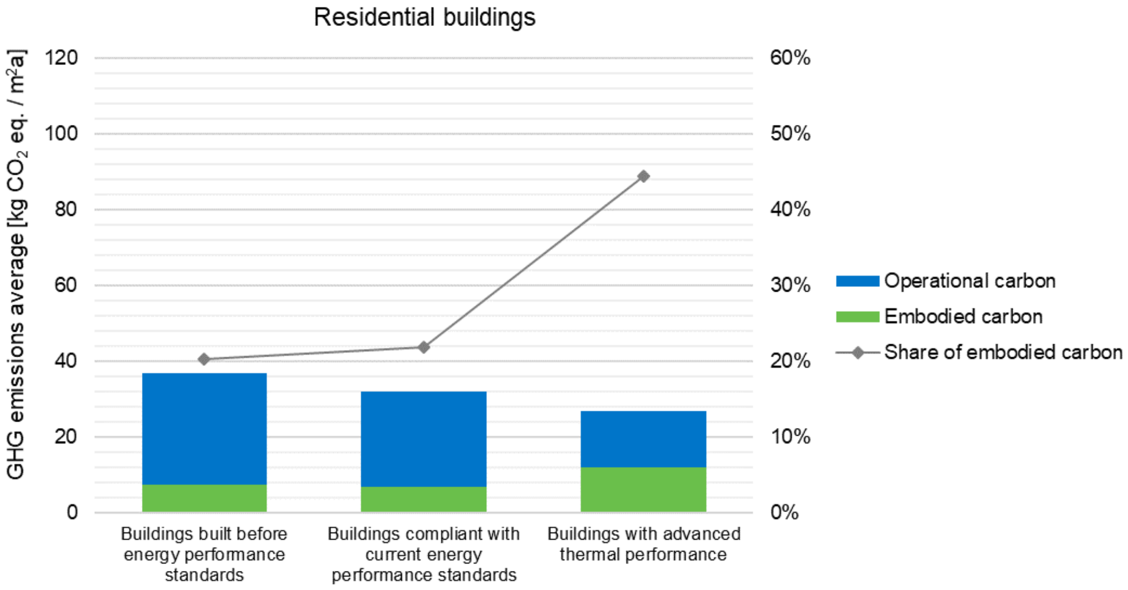
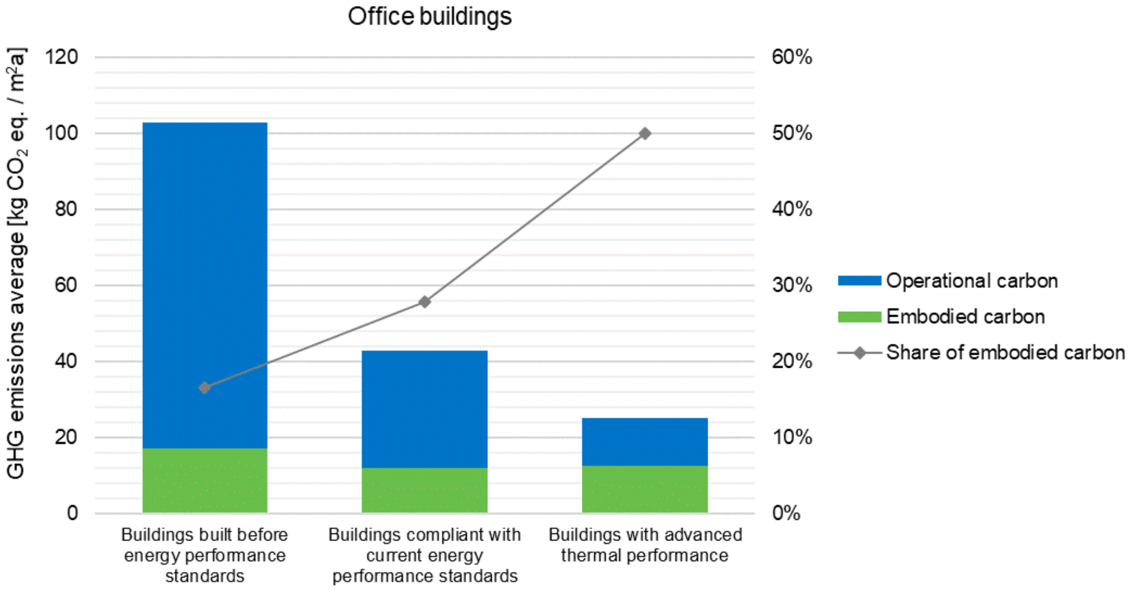
APPENDIX A – INDICATORS FOR EMBODIED AND OPERATIONAL CARBON

The data for the following figures is taken from Röck et al. (2020) and provides indicators for embodied and operational carbon. The first figure is for residential buildings, the second figure is for office buildings.





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