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Life cycle assessment of mortars: a review on technical potential and drawbacks

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Abstract

The in-depth research on efficient processes and alternative constituents for mortars production has a lack on the quantification of their environmental impacts. This work presents a critical review of life cycle assessment (LCA) studies performed in the construction sector, namely related to mortars. The gaps and barriers of these methods and final results are discussed through an overview of the main achievements on mortars' environmental life cycle studies in Europe. Despite the future trends, LCA studies are more focused on cement-mortars and few researches on air lime, gypsum or earth mortar binders are reported in the literature.

Keywords: Environmental impacts, life cycle assessment, masonry mortar, plaster, render.

Abbreviations

ADP-E – Abiotic resource depletion potential for elements

ADP-F – Abiotic resource depletion potential of fossil fuels

AP – Acidification potential of land and water

$Ca(OH)_2$ – Calcium hydroxide

CC – Climate change

CEN – European committee for standardization

CO_2 – Carbon dioxide

EIAM – Environmental impact assessment method

EC – European Commission

EP – Eutrophication potential

EPD – Environmental product declaration

FD – Fossil fuels depletion

GWP – Global warming potential

ILCD – International life cycle data system

ISO – International organization for standardization

LCA – Life cycle assessment

LCI – Life cycle inventory

LCIA – Life cycle impact assessment

PEF – Product environmental footprint

POCP – Formation potential of tropospheric ozone photochemical oxidants

ODP – Ozone depletion potential

OEF – Organizational environmental footprint guidelines

1. Introduction

During the past decades, concerns on environmental deterioration, energy consumption and materials scarcity have pushed the development of life cycle approaches aiming the environmental profiling of products [1] and the shift towards circular economy principles [2].

In the European context, around 50% of processed raw materials are applied in construction and approximately 30% of waste is generated during construction and demolition activities [3]. Also, the construction industry is on the top of the list of greenhouse gas contributors and is responsible for up to 40% of the global primary energy demand [4].

The focus on sustainable construction is now relevant in terms of buildings operational phase, energy demand, resources, emissions, waste generation, maintenance and the end-of-life stages. Thus, research on the assessment of the environmental impacts of building products over their entire life cycle have been intensified [3]. To evaluate and compare the advantages and drawbacks of emerging construction materials and products in an economic, social and environmental perspective, coupled with the chemical, mechanical and physical performance of the final products, with or without eco-friendly substitutes, methods should be optimized in order to provide reliable tools for the users.

Moreover, it is increasingly necessary for professionals, as architects, engineers, builders, decision-makers and investors, to analyze the impacts related to the entire life cycle of a building by means of empirical and comparable data, based on well-stablished indicators of building performance [5].

Life cycle assessment (LCA), an approach that evaluates the environmental impacts of products/services from raw material acquisition to waste disposal [6], has been providing new insights and led to changes in policy [1]. There is therefore a growing need to understand, critically appraise and apply the information that LCA studies provide, particularly in the construction sector regarding mortars' sustainability. Other tools may also be used for the sustainability assessment of buildings, regarding environmental, social and economic pillars. Nevertheless, the environmental dimension is the most used and standardized method worldwide [5].

The present work aims at reviewing the existing literature on mortar studies performed using LCA. Herein, the methodologies applied for different mortar types and goals are discussed, presenting their advantages and drawbacks, as well as mortars sustainability evolution overtime.

2. Mortars characteristics

Common mortars are porous materials produced with at least one mineral binder (agglomerate) and one aggregate (natural or artificial sand), which are knead with water. There are records of the use of earth as a building material since the prehistoric period [7] and of lime mortars before Christ [8]. From the middle of the 19th century, there was a gradual replacement of earth and lime by cement-based mortars [8].

Generally, sand is the mortar component incorporated in a higher ratio (in volume and/or weight). The binder and filler paste should be present in a suitable proportion to fill the voids promoted by the sand grains [9]. Nowadays secondary materials are being reused as artificial sand to increase mortars' circularity [10].

Numerous binders can be applied in mortars formulation as clayish earth, gypsum, lime (air, hydraulic, natural or formulated) or cement, generating composites with diverse technical properties and embodied energy [11]. The energy involved on mortar binder production depends on raw material extraction, milling processes, thermal treatment and the transportation involved. The production of cement and limes with hydraulic properties requires calcination temperatures of around 1,500ºC and 1,100ºC, respectively. Air lime requires lower temperatures for its production (about 900ºC), but still higher than the temperature required to produce current gypsum (about 120-180ºC) [12]. The clayish earth, as a mortar binder, does not require calcination, avoiding thermal energy consumption. Currently, cement is the second most used material worldwide (after water) and, to produce 1 ton of cement, approximately 900 kg of CO_2 are released into the atmosphere [13].

The replacement of traditional (with high environmental impacts) by alternative binders, which require less energy for production and transportation, would be advantageous in a technical and social way. Simultaneously, the use of recycled aggregates in mortars instead of natural sand can also bring benefits [14]. This would lead to a reduction in the extraction of raw material, in the energy consumption for thermal treatment and in a lower volume of waste for landfilling.

Additions and admixtures can enhance mortars' fresh or hardened properties, even at extremely low contents. The additions can be fibers, fillers – fine non-reactive aggregates, such as stone dust – or pozzolans – fine compounds rich in silica and/or alumina in a non-crystallized state that, in the presence of moisture, react with $Ca(OH)_2$, promoting its hardening even without contact with CO_2 [15]. The addition of natural/artificial fibers may contribute to reduce shrinkage and cracking. The natural fibers may have a broad origin [16]. Some examples are: (1) agricultural wastes, such as wheat, barley, oat straw [17] or rice husk; (2) textile industry waste, as cotton [18] or linen; (3) wood processing residues (e.g. wood chips, sawdust); (4) plant stems, as typha [19], hemp [20], flax or jute; (5) stem and ears of aquatic plants (e.g. reeds, planks or algae) [21] and (6) leaves and fruits of plants (e.g. olive [22], sisal, palms or coconut).

Mortars are frequently used as bedding mortars, to layer masonry units, to re-point masonry joints [23], to coat outdoor and indoor walls and ceilings (renders and plasters, respectively) [24] or as screeds in floor. The selection of appropriate components, and of their proportion, to achieve adequate workability, strength and durability requirements, are key challenges for mortars production in a cost-effective way [25].

After decades where cement was the most common binder used for mortars, the study of raw earth and other clayish resources as construction materials is moving mortars development towards a cleaner production. There is a growing interest in earth as a building material, a resource composed by clay (binder), silt (filler), sand (aggregate) and coarser aggregates, including on earth mortars. For mortars that growing interest have been stimulated by their advantages: (1) based on a natural raw material; (2) available and with no shipping needs (local earth can be used); (3) low cost material; (4) reusable (considering no chemical stabilization); (5) non-toxic; (6) low CO_2 emissions associated to its manufacturing and application [26]. Although earth mortars have generally low mechanical resistances when compared to gypsum or cement mortars, they report high capacities to adsorb/desorb water vapor. Therefore, earth plasters can be key factor on relative humidity control, improving indoor air quality and energy performance in buildings [17].

Advances in solid waste management resulted in alternative materials to replace or add to conventional raw materials on construction materials production. These materials can be applied directly (e.g. as pozzolans, fillers and coarser aggregates with mortar sand size) or used after particle size and/or thermal treatments [27]. Thus, a wide range of secondary resources are being tested on mortars as feasible substitutes, namely to overcome cement carbon footprint, such as mining residues [28], construction and demolition wastes [29], sewage sludge [30], recycled plastic waste fibers [31] and ceramic wastes [32].

In the past, ceramic waste was used to partially replace aggregates and binders in air lime mortars due to pozzolanic characteristics of ceramic dust and for fragments reuse as aggregates in lime mortars [33]. This may potentiate the pozzolanic reaction between $Ca(OH)_2$ and the amorphous silica and alumina of the dust, resulting in an improved performance of the mortars [33], as well as a filler effect [34].

Mining residues have been applied in mortars with aggregate or binder functions. For instance, the introduction of mining residues were studied for bedding and coating mortars, where iron ore tailings replaced natural aggregates or lime [35], and where gold-mine tailings replaced Portland cement contents [36]. Base-metal tailings where also applied on rendering and masonry mortars, as aggregates, with minor risks of metals release [37]. These approaches provided mortars with improved mechanical properties when compared to the conventional production [35] and CO_2 emissions minimization due to cement manufacture [36].

3. Life cycle assessment requirements

3.1 Standards and guidelines

In the European context, standards were published regarding the evaluation of construction performance under sustainability pillars, as shown in Table 1. The adoption and development of LCA resulted from the release of ISO 14040 series standards. In 2006, and complemented later in 2008, the ISO 14044 [6] combined all the previous standards detailing LCA requirements and guidelines. Other standards aiming technical guidance for LCA studies were addressed in ISO 14000 series.

Table 1. Life cycle assessment standards.

Standard	Goal	Reference
ISO 14040:2006	Principles and framework	[38]
ISO 14044:2006+A1:2017	Requirements and guidelines	[6]
ISO 14006:2020; ISO 14062:2002	Technical guidance reports on LCA applications	[39,40]
ISO 14020:2000; ISO 14063:2020	Communication of environmental performance	[41,42]
ISO 14025:2006; ISO 21930:2017; EN 15804:2012+A2:2019	Requirements of the Environmental Product Declaration (EPD)	[43–45]
ISO 14064-1:2018; ISO 14064-2:2019; ISO 14064-3:2019	Greenhouse gas reporting and reduction	[46–48]
EN 15643-1:2010; EN 15643-2:2011; EN 15643-3:2012; EN 15643-4:2012	Guidelines on environmental, social and economic performance assessment on buildings	[49–52]
EN 15978:2011	Calculation method	[53]

Furthermore, the European Commission developed an international life cycle data system (ILCD) including a life cycle inventory database and methodological guidelines [54]. Afterwards, the European Commission launched the Product Environmental Footprint (PEF) and Organizational Environmental Footprint (OEF) Guidelines as abbreviated versions of the ILCD. Herein, different categories of products/services are presented particularly for companies/organizations reporting on their environmental performance [55].

The impact categories considered for LCA studies of construction products are defined in EN 15804+A2 [45]. The EN 15643-2 [50] shows the principles and requirements for the environmental performance assessment of buildings considering technical and functional characteristics. Based on LCA and quantified environmental data related to buildings' environmental performance, EN 15978 [53] describes the calculation method and its interpretation for reporting and communicating the outcomes of an assessment.

3.2 LCA methodology

The LCA enables the estimation of cumulative potential environmental impacts under categories as global warming, ozone layer depletion, soil and water acidification, eutrophication, abiotic depletion for non-fossil resources and for fossil resources [45]. These cumulative environmental impacts, that result from all stages of a product life cycle, can also be used to determine the embodied energy. This method includes impacts not considered in traditional analyses, where mainly raw material extraction, material transportation and product disposal are considered.

Typically, the LCA process is systematic and divided into four phases, according to ISO 14040 [38] and ISO 14044+A1 [6] as seen in Figure 1: (1) Goal and scope definition; (2) Inventory analysis; (3) Impact assessment; (4) Interpretation.

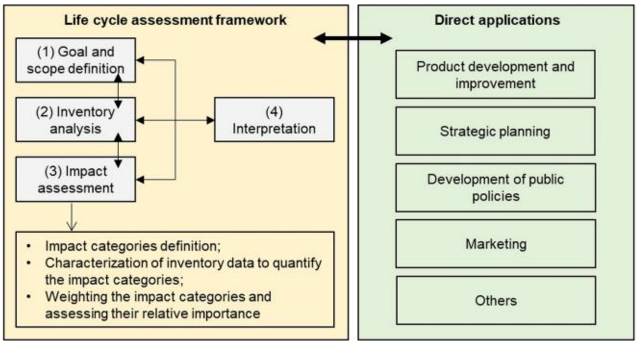


Figure 1. LCA phases (adapted from ISO 14040 [38]).

First, the product/process/activity system boundaries and the declared unit are defined and described. Then, the life cycle inventory (LCI) is developed aiming a detailed description of the product production process and the quantification of inputs and outputs from all unit processes included in the product life cycle (energy, water and materials use and environmental releases). The life cycle impact assessment (LCIA) phase provides the LCA results and additional information to complete and support the environmental importance of LCI results. Finally, the interpretation of the results is carried out, based on LCI and LCIA.

The LCIA stage evaluate the magnitude and significance of the potential environmental impacts of a product and should include [5]:

(1) Selection of the impact categories, category indicators and characterization models.

(2) Classification: each elementary flow of the inventory is assigned to the impact categories selected according to the material’s contribution to the different environmental problems.

(3) Characterization: calculation of the results for each category indicator, where in each impact category several materials contribute with specific magnitudes.

After the conclusion of the LCIA, it is necessary to carry out an analysis of the quality of the data presented, and this may require additional techniques and information to better understand the significance, uncertainty and sensitivity of the LCIA results. The latter can be necessary because LCA practice often justifies modelling choices and omissions.

The occurrence of uncertainties of different types and sources in LCA results is a fact. However, if managed, they can allow the quantification and the improvement of the precision and robustness of studies. LCA practice often justifies modelling choices and omissions. The terms variability and uncertainty are often not distinguished or overarching one another, where variability is often included as one aspect of uncertainty [1].

This analysis helps to distinguish whether or not significant differences are present, to identify insignificant LCI results or to guide the iterative process of LCIA [6]. The specific techniques to analyze the quality of LCIA data are [6]:

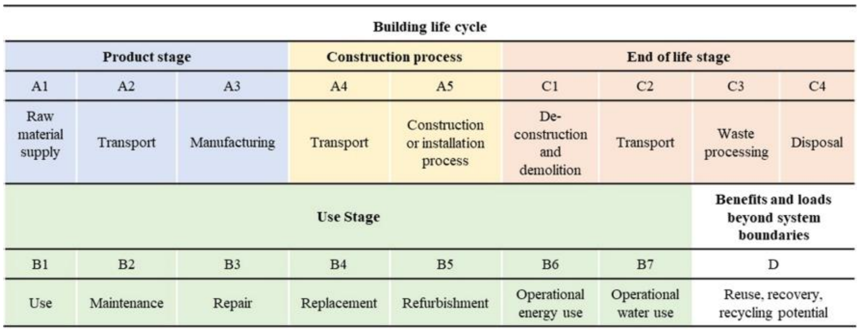
(1) Gravity analysis: statistical procedure that identifies those data having the greatest contribution to indicator result (e.g. Pareto analysis). So, this data can be investigated with a higher priority to ensure that the right decisions are made.

(2) Uncertainty analysis: procedure to determine how the uncertainties from the data and assumptions calculated may affect the reliability of the LCIA. The uncertainty of the results can be characterized by ranges and/or probability distributions.

(3) Sensitivity analysis: procedure to determine how changes in data and methodological choices affect the results.

These techniques can be applied alone or combined, depending on the accuracy and level of detail necessary to fulfil the goal and scope defined for the LCA. Since LCA is an iterative process, the result of the analysis of the quality of LCIA data can lead to a revision of the LCI [6].

Site-specific data shall be used, as much as possible, instead of generic data, since the latter may not be sufficiently (geographically, temporally and/or technologically) representative of the product under analysis. For this reason, the gravity, uncertainty and sensitivity analysis are very important to determine the way forward and what data should be used or excluded from the LCA analysis. Additionally, to convert the impacts of all categories in a common equivalent unit (normalization), equivalence or weighting factors can be applied during this step. The EN 15978 [53] defines the unit process for products and processes. In the construction sector, LCA generally includes production, use, construction and end of life stages. The benefits and loads beyond the system boundaries may be considered, as demonstrated in Figure 2.



Building life cycle								
Product stage			**Construction process**		**End of life stage**			
A1	A2	A3	A4	A5	C1	C2	C3	C4
Raw material supply	Transport	Manufacturing	Transport	Construction or installation process	De-construction and demolition	Transport	Waste processing	Disposal
Use Stage							**Benefits and loads beyond system boundaries**	
B1	B2	B3	B4	B5	B6	B7	D	
Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Reuse, recovery, recycling potential	

Figure 2. Different stages of the LCA of construction materials (adapted from EN 15978 [53]).

LCA requires system boundaries definition to limit the unitary processes. These boundaries can be defined as [45]:

(1) Cradle to gate: includes the supply of raw materials, transport, production and associated processes.

(2) Cradle to grave: includes the steps mentioned above, plus transport and installation in the building, use and maintenance, replacements, demolition and final disposal.

(3) Cradle to cradle: in addition to the previous stages, includes reuse, recovery and/or recycling.

Commonly, the analysis of the phases subsequent to the manufacture and application of product (B-C phases, Figure 2) is based on scenarios, constructed and evaluated mainly based on generic data, which should be realistic and representative. This generic data can bring uncertainty to the results. So, these scenarios lack an uncertainly and sensitivity analysis.

The environmental product declaration (EPD) is a voluntary basis with quantified environmental data about individual products' life cycle, such as a dry pre-mixed mortar. EPD allows the comparisons between products that fulfil the same function [43] and is based on data related to a material/product LCA. The results for each impact categories are engaged in EPD that are verified by an independent scientific body or other related organizations. In the European context, there are several EPD programs for the construction sector, being INIES (France) and IBU (Germany) the most widely known. In Portugal, EPD are managed by DAPHabitat [56].

Both LCA and EPD must define the product declared or functional unit to guarantee the comparability of the LCA results between different studies. These units describe what is being analyzed since it provides a reference to which the inputs and outputs are related [38]. Regarding mortar studies, declared or functional units are commonly defined as 1 ton of dry mortar [57], 1 m^3 of pre-mixed mortar [58] and 1 kg of mortar or 1 m^2 of wall [59].

Allocation is also an important topic and, according to EN 14040 [38], consists of "*partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems*". The allocation should be used when the system involves several products – due to the need to split the environmental impacts of multiple industrial processes – and in industrial processes with recycling systems – when recycled or rejected intermediate products are used as raw materials (e.g. sub-products). Allocation procedures should be considered for comparisons between studies and systems. The differences on these aspects, between studies, must be clearly identified and reported, as it may influence the results.

The sum of allocated inputs and outputs of a unit process should be equal before and after the allocation. When several allocation procedures are possible to be used, a sensitivity analysis shall be carried out to illustrate the consequences of not using the selected practice [6].

EN 14044 [6] defines that, wherever possible, allocation should be avoided by: diving unit process to be allocated into two or more sub-processes, and collecting the input and output data related to these sub-processes; or expanding the product system to include the additional functions related to the co-products, taking into account the requirements of system boundaries. Also defines that when reuse and recycling activities are considered, it is crucial to consider that inputs and outputs associated to unit processes for extraction and processing of raw materials, and final disposal of products, are to be shared by more than one product system; reuse and recycling may change the inherent properties of materials in subsequent use; and specific care should be taken when defining system boundary with regard to recovery processes. If feasible, allocation should be applied preferentially in sequence: physical properties (e.g. mass); economic value (e.g. market value of recycled material in relation to primary material); and the number of subsequent uses of the recycled materials.

ReCiPe is an environmental impact assessment method (EIAM) commonly applied for the LCIA [60]. The group of authors include the developers of the CML 2001 method, where results are grouped in midpoint categories according to common mechanisms/accepted groupings, and of Ecoindicator 99, a top-down model that identifies environmental damage endpoints and shows the final result in a single score [61]. The CML 2001 and Ecoindicator 99 methods are LCIA methods that can play an important role in the results of LCA, depending on the type of analysis intended, due to their different approaches.

Studies have been conducted to assess and overcome mortars impacts. LCA allows to identify opportunities to improve the production of materials/products while reducing their environmental impacts. This approach provides a baseline to compare the performance of conventional or alternative raw materials, final products, processes, applications and end-of-life scenarios.

4. Environmental sustainability evaluation of mortars

4.1 Methodology

The scientific research status on LCA studies of mortars was performed using Scopus database (October 2020). With the search words “life cycle assessment”, “mortar”, “plaster” and “render”, a total of 124 scientific papers were obtained from 1994 to 2020 across Europe, with a more pronounced increasing trend in the scientific community during the last few years (Figure 3). The dominant research areas are engineering (30.7%), environmental science (21.2%) and energy (11.3%), being

Germany, Spain and Italy the top 3 countries. The documents published are mainly in article format (57.3%). This work is based on the referred sample of scientific literature.

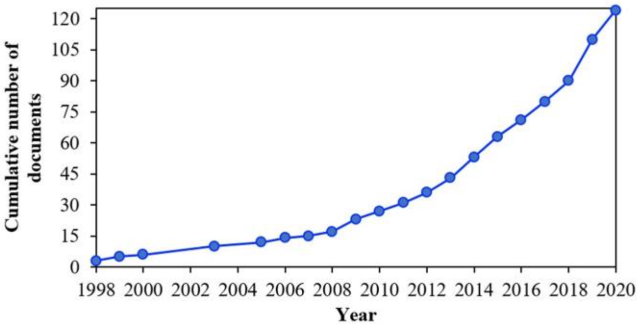


Figure 3. Documents on LCA of mortars – evolution between 1994 and 2020 in the SCOPUS database, accessed in 01.10.2020.

4.2 LCA studies

The most common software applied on LCA studies are SimaPro, Gabi, Umberto and OpenLCA [62]. Umberto software is useful to evaluate the carbon footprint of a product, building or service according to ISO 14040 [38] and ISO 14044+A1 [6], although with minor applications on construction materials analysis [63]. The OpenLCA platform, which is a free open source, can provide fast and reliable determinations on sustainability assessment and/or LCA [62]. Additionally, companies have developed their own software, making the standardization of these approaches difficult for comparison with other works [1].

Table 2 presents some examples of scope and purposes for mortar studies reported in literature, emphasizing the wide range of LCA studies.

Table 2. Scope and purposes of reported LCA studies of mortars.

Scope	Purpose	Reference
Supplementary/ Symbiotic cementitious materials	• Comparison of mortars with different replacement ratios of secondary resources - recycled concrete • Alternative secondary resources vs conventional production - ash recycling in Portland cement production as clinker substitution, earth vs industrial plasters • Alternative resources incorporation - woody biomass types, sewage sludge, recycled fine aggregates from construction and demolition waste, sanitary ware, glass fiber reinforced polymer, forest biomass, textile fibers, LCD scrap	[10,26,57,58,64–74]
Energy performance	• Comparison of alternative fuels with fossil fuels used on binder’s production • Thermal insulating – alternative lightweight materials (e.g. cork waste) vs reference mortars	[69,75–77]

Scope	Purpose	Reference
	• Comparison of alternative mortars and paints - aerogel-based thermal renders for external walls of buildings	
Type of construction	• Mitigation potential of specific mortar materials/resources when employed at real scale (e.g. urban houses) in specific regions of the world - limestone, lime, fired brick, solid cement blocks and earth blocks	[59,78,79]
Material applications	• Compare the same material for different purposes - biomass fly ash for cement replacement vs alkaline material • Compare the same material for different structural options - local replacement of damaged masonry, mortar injection, steel chain installation, grid-reinforced • Alternative concrete mixtures comparison with ordinary reference mixtures - steel slags on industrial pavement and pervious paving blocks, heavyweight concrete, shotcrete and ready-mixed repair mortar	[80–83]
Leaching	• Comparison between mortars with different binders to predict the longevity of the rendering (e.g. cement vs lime)	[84]

Additionally, the boundaries defined in the literature for mortar systems are presented in Figure 4. Considering that only 21 of the 124 scientific documents analyzed in this work reported the boundaries of the system processes, the most common approach was cradle-to-gate (71%). Although the need to deep reuse/recycling strategies for materials being on the top of the list, few studies consider a cradle-to-cradle approach, probably due to unavailable data and other difficulties on determining the benefits involved in the scenarios from gate to grave.

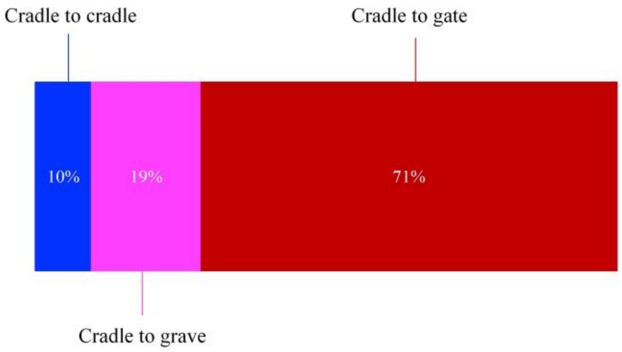


Figure 4. System boundaries distribution of 21 mortars' LCA studies, from 1994 to 2020, found in literature.

4.3 Life cycle inventory

LCA requires an inventory analysis to ensure a representative assessment of all inputs and outputs of mass and energy across the whole phases of the product life cycle, notated by LCI [57].

The LCI should include site-specific data for the product analyzed by measurements, calculations or estimations, which can be complemented by LCI database and EPD [1].

The Ecoinvent database contains datasets as an average for a region [85]. The data selection for modelling each process is a major issue since it varies greatly between regions and production plants. The compilation of a credible LCI is essential since LCA relies heavily on the availability and completeness of LCI data. The development of the inventory should be detailed to be reproductible by an independent practitioner [57].

Considering each unit process that is included within the system boundary, quantified data about the raw materials, energy and fuels needed for the processes involved, and of transportation and emissions across the production chain shall be collected from available and reliable sources [86].

System inputs may include resources (e.g. stone, water), services (e.g. transportation) or energy supply, and the use of maintenance materials (e.g. lubricants for equipment). The outputs can include products, co-products/waste and releases to air, water and soil [6].

The requirements on data quality must be specified through references and details about the data collection process (e.g. time when data was collected/analyzed). Data from specific sites or representative averages should be used for the unit processes that contribute to the major mass and energy flows of the system processes. If possible, data from sites should be used for unit processes that are considered to have environmentally relevant inputs/outputs [6]. In LCIA, the operational steps outlined in Figure 5 should be performed.

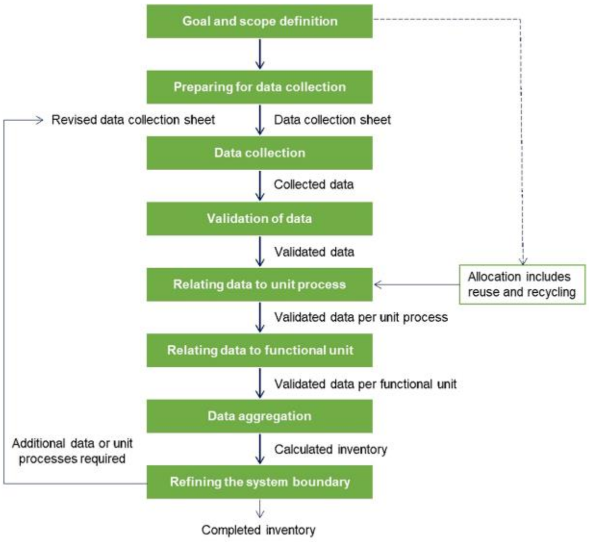


Figure 5. LCA steps (based on EN ISO 14044 [6]).

4.4 Impact assessment and results interpretation

Cement-based mortars are the most common construction products reported by LCA studies. After analyzing several studies, those with comparable declared units and impact categories and with quantitative results were selected. Examples of studies found in literature aiming the introduction of alternative materials to replace cement in mortars and their impacts in the considered categories are presented in Table 3. Figure 6 and Figure 7 show a comparison of the results from the mortars studies presented in Table 3, according to the declared unit used. Only GWP and ADP-F were considered since both categories have often been included in the works developed in this field, demonstrating to be the most relevant environmental categories.

Table 3. Examples of LCA applied to cement-based pre-mixed mortars production with secondary resources.

Mortar composition	**Impact category**							**Declared units**
	GWP ($kg.CO_{2\text{-}eq}$)	ODP ($kg.CFC^{11}{}_{\text{-}eq}$)	AP ($kg.SO_{2\text{-}eq}$)	EP ($kg.(PO_4)^{3-}{}_{\text{-}eq}$)	POCP ($kg.Ethene_{\text{-}eq}\ \times 10^{-2}$)	ADP-E ($kg.Sb_{\text{-}eq}$)	ADP-F (MJ)	
Mortars with addition of ultrafine recycled siliceous or limestone concrete (obtained by diesel or biomass fuel*) to replace 5% of cement [69]	7.72×10^{2} (REF, diesel and biomass)	2.25×10^{-5} (REF) 2.14×10^{-5} (diesel and biomass)	1.44×10^{0} (REF) 1.37×10^{0} (diesel and biomass)	4.0×10^{-1} (REF) 3.8×10^{-1} (diesel and biomass)	5.45 (REF) 5.22 (diesel) 5.19 (biomass)	3.02×10^{-4} (REF) 2.88×10^{-4} (diesel) 2.87×10^{-4} (biomass)	2.88×10^{3} (REF) 2.80×10^{3} (diesel) 2.74×10^{3} (biomass)	1 ton of mortar
Mortars with different types of binders and with or without metakaolin (mix 1: hydrated air lime and sand; mix 2: hydrated air lime, metakaolin and sand; mix 3: cement and sand) [58]	Mix 1 ≈ 1.7×10^{-1} Mix 2 ≈ 1.6×10^{-1} Mix 3 ≈ 2.3×10^{-1}	-	Mix 1 ≈ 2.3×10^{-4} Mix 2 ≈ 1.6×10^{-4} Mix 3 ≈ 6.6×10^{-4}	Mix 1 ≈ 2.4×10^{-5} Mix 2 ≈ 2.0×10^{-5} Mix 3 ≈ 1.22×10^{-4}	-	-	-	1 ton of mortar
Mortars with industrial wastes (sanitary ware, glass fiber reinforced polymer, forest biomass ashes, and textile fibers) replacing sand and/or cement [10]	1.66×10^{2} (REF) 1.31×10^{2} – 1.66×10^{2} (modified mortars)	8.45×10^{-7} (REF) 2.51×10^{-7} – 8.41×10^{-7} (modified mortars)	3.40×10^{-1} (REF) 2.53×10^{-1} – 3.35×10^{-1} (modified mortars)	5.40×10^{-2} (REF) 4.06×10^{-2} – 5.40×10^{-2} (modified mortars)	2.99 (REF) 2.30–2.96 (modified mortars)	2.82×10^{-4} (REF) 2.39×10^{-4} – 2.82×10^{-4} (modified mortars)	3.19×10^{2} (REF) 2.22×10^{2}– 3.25×10^{2} (modified mortars)	1 m^3 of mortar
Mortars with addition of superplasticizer, replacement of cement or hydrated air lime by coal fly ash and biomass fly ash [82]	5.66×10^{2} (REF) 3.31×10^{2} – 3.66×10^{2} (modified mortars)	2.70×10^{-5} (REF) 1.87×10^{-5} – 2.11×10^{-5} (modified mortars)	1.29 (REF) 8.1×10^{-1} – 9.6×10^{-1} (modified mortars)	3.26×10^{-1} (REF) 2.19×10^{-1} – 2.39×10^{-1} (modified mortars)	5.20 (REF) 3.34–4.23 (modified mortars)	-	3.06×10^{3} (REF) 2.02×10^{3} – 4.23×10^{3} (modified mortars)	1 m^3 of mortar

Notation: GWP - Global warming potential; ODP – Ozone depletion potential; AP – Acidification potential of land and water; EP – Eutrophication potential; POCP – Formation potential of tropospheric ozone photochemical oxidants; ADP-E – Abiotic resource depletion potential for elements; ADP-F – Abiotic resource depletion potential of fossil fuels; REF – reference mortar; *ultrafine recycled siliceous or limestone concrete were produced using different energy sources (diesel and biomass fuel) in order to assess their impacts on the final product.

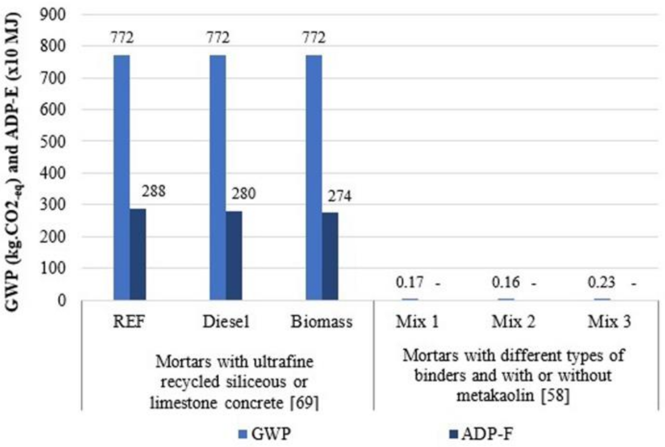


Figure 6. Comparison of the results from studies with declared unit of 1 ton of mortar (adapted from [58,69]).

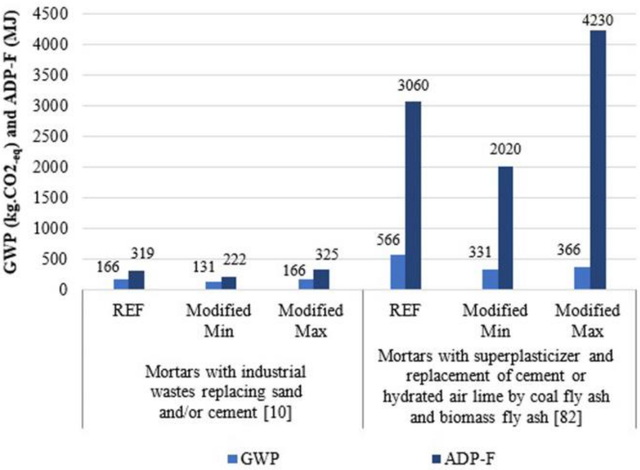


Figure 7. Comparison of the results from studies with declared unit of 1 m^3 of mortar (adapted from [10,82]).

The normalization of the results provides a way to compare different LCA studies, with similar purposes. However, it is crucial to have in mind the methodology applied (e.g. database selected, software used), since the estimations of each method have uncertainties. The variability and uncertainty from a group of LCA studies could be considered to improve the accuracy of the data used and present a more realistic approach of the analysis. In this sense, the uncertainty related to parameters, models and choices and the spatial, temporal and objects/sources variability should be taken into account during the LCA interpretation phase. The most evident uncertainties/variabilities in the works analyzed are related to functional units, data from databases, allocation methods, impact categories, normalized data and regional differences.

Moreno-Juez *et al.* [69] performed an analysis from a cradle to gate perspective using the OpenLCA software and considering the CML impact assessment method to calculate the environmental impacts of several mortar mixing solutions with ultrafine recycled concrete. For the same LCA purpose, Moropoulou *et al.* [58] used the Eco-indicator 95 method. In the case of Farinha *et al.* [10] and Teixeira *et al.* [82], the impacts' assessment was carried out through an cradle to gate analysis using SimaPro software. Therefore, different methods and software can be used to analyze environmental impacts for the same purpose.

Field Code Changed

Farinha *et al.* [10] and Teixeira *et al.* [82] analyzed a vast number of mortars. Table 3 shows the impacts of each category for the reference mortar (REF) and the minimum and maximum value obtained for the remaining ones (modified mortars). Herein is observed that REF mortars presented the highest environmental impact in all categories. The exception occurred in GWP, EP and ADP-E impacts, where mortars with sanitary ware presented impacts equal (1.66×10^{2} kg. $CO_{2\text{-eq}}$ for GWP, 5.40×10^{-2} kg. $(PO_4)^3{}_{\text{-eq}}$ for EP and 2.82×10^{-4} kg.$Sb_{\text{-eq}}$ for ADP-E) to the reference mortar in Farinha *et al.* [10]. In ADP-F category, the impact of modified mortars was higher than the reference mortar: mortar with forest biomass ash from Farinha *et al.* [10] and with 50% of biomass fly ash from Teixeira *et al.* [82]. In Moreno-Juez *et al.* [69] it is also observed a decrease in the environmental impacts of modified mortars with ultrafine recycled siliceous or limestone concrete (2.14×10^{-5} kg.$CFC^{11}{}_{\text{-eq}}$ for ODP, 1.37×10^{0} kg.$SO_{2\text{-eq}}$ for AP, 3.8×10^{-1} kg.$(PO_4)^3{}_{\text{-eq}}$ for EP, 5.22×10^{-2}–5.19×10^{-2} kg.$Ethene_{\text{-eq}}$ for POPC, 2.88×10^{-4}–2.87×10^{-4} kg.$Sb_{\text{-eq}}$ for APD-E, 2.80×10^{3}–2.74×10^{3} MJ for ADP-F) compared to REF (2.25×10^{-5} kg.$CFC^{11}{}_{\text{-eq}}$ for ODP, 1.44×10^{0} kg.$SO_{2\text{-eq}}$ for AP, 4.0×10^{-1} kg.$(PO_4)^3{}_{\text{-eq}}$ for EP, 5.45 $\times10^{-2}$ kg.$Ethene_{\text{-eq}}$ for POPC, 3.02×10^{-4} kg.$Sb_{\text{-eq}}$ for APD-E, 2.88×10^{3} MJ for ADP-F).

The studies reported have different declared units (1 ton and 1 m^3 of mortar). Since mortars have different densities, generally not defined by the authors, the results should be analyzed individually. From Table 3, ultrafine recycled siliceous or limestone concrete obtained by diesel or biomass fuel additions to replace 5% of cement promoted the highest GWP (772 kg.$CO_{2\text{-eq}}$) observed. On the other hand, mortars with alternative binders and with or without metakaolin achieved approximately 0.2 kg.$CO_{2\text{-eq}}$ on the GWP category. Both studies were conducted considering the same declared unit (1 ton of mortar). The use of ultrafine recycled siliceous or limestone concrete obtained by diesel or biomass fuel did not promote any change in the GWP. The use of distinct energy sources (diesel or biomass fuel) only impacted negatively POCP, ADP-E and ADP-F categories. Mortars with hydrated lime and cement as binder, and with or without metakaolin, presented low acidification (≈ 2–7×10^{-4} kg.$SO_{4\text{-eq}}$) and eutrophication potential ($\approx 0.2\times10^{-4}$–1.2×10^{-4} kg.$PO_{4\text{-eq}}$). The incorporation of industrial wastes, such as sanitary ware, glass fiber reinforced polymer, forest biomass ashes and textile fibers, to replace sand and/or cement promoted lower impacts in the categories analyzed [10], in comparison to mortars with superplasticizer additions and cement or hydrated lime replacement by coal fly ash and biomass fly ash for 1 m^3 of mortar [82]. The categories that show the major differences on the results presented were: GWP (131–166 and 331–556 kg.$CO_{2\text{-eq}}$, respectively), ODP (0.0251–0.0845 and 1.87–2.70×10^{-5}kg.$CFC^{11}_{\text{-eq}}$, respectively), EP (4.06–5.40 and 21.6–32.6×10^{-2} kg.$(PO_4)^{3-}_{\text{-eq}}$, respectively), and ADP-F (222–325 MJ and 2020–4230 MJ, respectively).

Moropoulou *et al*. [58] analyzed a traditional hydrated air lime mortar with and without metakaolin. Traditional mortars were reported as more sustainable options compared to cement-based mortar, since the latter had higher impacts on GWP, AP and EP categories. For all impact categories, the hydrated lime mortar with metakaolin (mix 2) had the lowest impacts, while the cement mortar (mix 3) had the highest ones. This is explained by the fact that cement production is a more energy intensive process, with temperatures of approximately 1,300ºC and, consequently, with larger CO_2 emissions, in comparison to air lime, that is obtained at a lower firing temperature and with CO_2 capture when drying. The use of about 5% of metakaolin, obtained by firing kaolin at ≈700–800ºC [58], to replace hydrated air lime promoted a lower environmental impact when compared to the same mortar without metakaolin. This impact decrease can also be justified by the energy required to produce hydrated lime, since air lime is obtained at 900ºC.

The ultrafine recycled siliceous/limestone concrete replacing cement [69] promoted mortars with higher impacts on GWP, AD and EP, when comparing with mortars with different binders and with or without metakaolin [58], with the same declared unit of 1 ton of mortar. This can be justified by the way LCA results are presented, since Moreno-Juez *et al.* [69] and Moropoulou *et al.* [58] applied different impact assessment methods (CML and Eco-indicator 95 method, respectively).

The industrial wastes replacing sand and/or cement [10], the replacement of cement or hydrated lime by coal fly ash and biomass fly ash and the addition of superplasticizer [82] showed similar impacts (declared unit of 1 m^3 of mortar). The replacement of cement or hydrated lime by coal and biomass fly ash and the addition of superplasticizer presented the highest impact in all categories considered, namely regarding ADP-F. The need of thermal processes to convert the raw material into ash involves the highest energy impacts of the process.

Other LCA studies aiming to compare mortars produced with different binders are reported. Environmental impacts of earthen and conventional industrial mortars (cement and hydraulic lime) were compared in terms of energy demand, CO_2 emissions and ReCiPe impact categories [26]. Table 4 shows an overview of the major impacts from these three approaches. Herein it is possible to confirm that cement and hydraulic lime mortar production implies a higher energy demand and, consequently, higher CO_2 emissions are associated. Both binders are considered more harmful to climate change issues. Contrarily, an earth mortar showed lower energy demand and CO_2 emissions, with major impacts on fossil fuels depletion.

Table 4. Comparison of energy demand, CO_2 emissions and impact categories more affected by the use of cement, hydraulic lime and earth as mortar binders (adapted from [26]).

Mortar binder	Energy demand	CO_2 emissions	Categories more impacted
Cement	++	++/+++	CC>FD
Hydraulic lime	+++	+++	CC>FD
Earth (ochre/yellow)	+	+	FD> CC

Notation: +++: high proportion; ++: medium proportion; +: low proportion; CC: Climate change; FD: Fossil fuels depletion.

5. Discussion and research perspectives

During the past decades, the minimization of environmental impacts in the construction sector is receiving increased attention by researchers, policymakers and companies. The main focus is on energy consumption and alternative materials use, while the application of the concept of life cycle thinking is growing [87].

The LCA application in the construction sector, as a strategy to reduce its environmental impacts, is often identified as complicated and time-consuming [5]. Most of the EIAM commonly result in a set of categories that are not easily understood or interpretable. LCA requires an intensive use of data to estimate the potential impacts of the entire life cycle of a product, from resource extraction, through production, use and recycling. Despite these limitations, LCA is a tool that allows the identification of “critical points” and opportunities to improve the product environmental performance in the various stages of its life cycle.

LCA also provides a platform to support professionals from the construction industry and decision markers, in the search for sustainable strategies of consumption and production, by designing or redefining products. Thus, relevant environmental performance indicators should be selected for marketing activities and EPD development [5,38].

As a decision supporting tool, LCA results should be presented in a clear and simple way. In the present study, the presentation of the results is very broad, due to the wide-ranging methods available, limiting the comparison of mortars from different studies found in the literature. The main drawback identified in current practices of LCA is the generation of significantly different results by the application of different methods to identical cases, such as carbon footprint study vs studies with a set of more differentiated impact indicators [87]. In fact, different methods can allocate dissimilar relevance to properties/impacts, resulting in diverse results, namely regarding the actions to reduce the environmental burdens.

The definition of the declared unit of the study is not always reported in the publications, as well as the system boundaries, also limiting the comparisons between LCA approaches. The selection of different declared units in the studies reviewed also turned difficult to compare results between them. In addition, several authors presented drawbacks in boundary scoping, methodology framework, data inventory and practices, which compromise LCA as a decision making support tool for sustainable building design [88].

Another constraint is the presentation of LCA results in non-absolute values by some publications. These studies do not express the impacts of a product/service but might be useful to compare them.

The comparison of LCA studies is only feasible when mortars fulfil exactly the same function in accordance with their goal and scope definitions (e.g. mortars applied as plasters). Additionally, the quantification of local impacts should be improved through risk assessment-based tools, as generally environmental damage is calculated on global scale. However, common trends and specification of some aspects, namely regarding impact categories and declared units, could be clearly identified, turning the comparisons between studies feasible in a general way.

The combination of data from production and unit processes allows the development of production inventories in terms of materials and, in greater detail, the inventories of mortars, namely regarding the equipment used for the production processes. This should result in a clear LCI that match the reality of the process, promoting the reproducibility and the identification and quantification of the inputs/outputs related to the mortars' life cycle.

Summing-up, LCA can be evaluated under three premises: (1) comprehensiveness; (2) "best estimate" principle; (3) better scenario [1]. All these evidences can present strengths and limitations on mortars' LCA studies, as presented in Table 5.

Table 5. Strengths and limitations of LCA mortars studies.

Premise	Strengths	Limitations
Comprehensiveness	Life cycle perspective and coverage of environmental issues (through impact categories definition) allows the comparison of environmental impacts of mortars systems that are made up of several processes, resource uses and emissions.	Simplifications in the activities/processes, and generalizations from standards or available data in world's leading databases, are needed for modelling the mortar system and to quantify the environmental impacts. Uncertainties in mapping of resource uses/emissions and on modelling their corresponding impacts (calculated by impacts aggregation over time and space).
"Best estimate" principle	In the context of comparative assessments, unbiased comparisons since the same level of precaution is applied throughout the impact assessment modelling.	LCA mortars' production models are based on the average performance of the processes and do not support the consideration of rare risks.
Better scenario	LCA is suitable for answering which mortar is better for the environment.	LCA cannot corroborate if a mortar product/process is environmentally sustainable, in absolute terms, only because of having lower environmental impacts than another mortar.

The bibliometric analysis of LCA research applied to mortars showed that cement-based mortars studies predominated, with or without additions and/or substitutions. Only few studies were related to other types of binders, such as clayish earth. Currently, and in IBU [89] and DAPHabitat [56] programs, only approximately 13 EPD on mortars/plasters were identified. The lack of EDP constrains the availability of data for inventories and the comparison of results.

In addition to the environmental impacts of products and/or construction solutions, the cost of these strategies is also important. Monetization expresses the relative importance of an environmental impact category in a monetary value and can be determined based on the associated costs (e.g. damage costs using market prices) or the cost that people are willing to pay to avoid a particular environmental impact [5]. Although a solution has positive effects on environmental impacts, it may introduce extremely high costs to the system, making the application unfeasible. Thus, a balance between the assessment of the environmental and economic impact of a product should be obtained.

Durão *et al*. [5] presented a summary of the monetization approaches and methods/weighting sets that were developed to weight the environmental impacts resulting from LCA studies (e.g. Eco-costs, Ecotax 2002, Ecovalue 08).

Considering standard buildings, the use phase (when heating and/or cooling are needed) contributes to above 90% of the total environmental burdens. New buildings built considering present requirements for comfort are more energy efficient, turning other phases of the life cycle more relevant, such as the selection of materials, construction, end-of-life and water use [87]. Thus, an in-depth research on these topics should be conducted, coupled with economic issues, the improvement of data quality and statistical analysis.

The impacts from off-site generation of electricity or processing of raw materials must be considered when selecting the Best Available Techniques (BAT) for plant facilities [90]. The measures recommended by BAT are related to the improvement of the output and energy efficiency of raw materials production process through replacement of the old equipment with new one, less energy-consuming, in order to minimize CO_2 and other greenhouse gases emissions [91]. Thus, BAT can contribute to decrease energy consumption and CO_2 emissions in the European Union's construction industry, where the environmental benefits of BAT implementation can also be quantified using LCA.

The use of different impact categories, depending on the methodology applied in a study, often difficult the comparison between studies and products. Defining the impact categories/subcategories that must be analyzed for a single or group of mortars could be advantageous. The standardization on outcomes presentation leads to a better understanding and comparison of the results.

In addition to the mortar life cycle analysis data, Moreno-Juez *et al*. [69] also presented a normalization of the results based on European data. The normalization factor used was the European emission considering a citizen emission unit in the year 2000, which was proposed by CML. These results showed that GWP is the most affected category from the production of cement-based mortars in all induvial systems. Despite presenting less expression when compared to GWP, AP and ADP-F categories are also affected by the production of cement mortars. Additionally, the ODP was the category with lower impacts associated. On the other hand, the reference mortar presented high impacts in all categories. Similar results were obtained by Moropoulou *et al*. [58], considering the contribution analysis of each impact category (GWP, AP and EP) on the total environmental score. Herein, GWP was the most affected category followed by AP. The inverse trend was observed in the cement mortar (mix 3), where AP showed the highest impacts.

Currently, it is imperative to rethink the use of cement as major binder and the possibility of integrating by-products into mortars, at least for some types of applications. Farinha *et al*. [10] performed the LCA of cement mortars with incorporation of industrial wastes. The binder was the component that showed the highest impacts on GWP: cement contributed more than 85% and natural sand only 8%. When natural sand and/or cement were replaced by industrial wastes, there was generally a decrease in the GWP compared to the reference mortar. On the other hand, sand and admixtures from these mortars contribute significantly to increase ADP-F impacts: sand was responsible for 40–60% and admixtures for about 30% of the total emissions. The waste also pursued the impacts increase on ADP-F due to the transport involved, since transport is the main factor related to the fossil fuels component [10]. In general, 16 of the 19 mortars analyzed by these researchers showed, in all impact categories, a performance equal to or better than the reference cement mortar. Also, the transportation of industrial waste influenced the LCA results of some mortars. Thus, local waste should be considered as a first option to alleviate shipping impacts. The availability of resources and the pressure on their exploitation is also an important indicator that should be deeply addressed in future LCA practices.

Construction materials may be able to reabsorb CO_2 during their lifetime, decreasing the impacts of the overall life cycle. This is also the case of mortars, but none of the studies analyzed focused this aspect. This should be addressed by further LCA studies by quantifying the benefits that may came and the potential to achieve a carbon neutral construction product, for instance.

6. Conclusions

LCA is an approach with few decades of development and application, although over the years this methodology and applications have matured in a scientific perspective. LCA is crucial for mortars optimization since these are buildings products with many applications in modern construction and throughout the service life of buildings. Hence, mortars with less environmental impacts can significantly reduce the embodied energy in buildings.

In the present work, the LCA general methodology was synthetized and LCA studies of mortars were discussed in terms of goals, specific methodologies, results, limitations and strengths, as well as their contribution to support decision making.

SimaPro, Gabi, Umberto and OpenLCA are common software used for LCA studies. They offer many options in terms of methodologies and quantification of impacts. The main focus of mortars' LCA has been cement-based composites, although, currently, there are still few studies regarding mortars. Typically, GWP is an impact category considered in most of the studies reviewed. Nonetheless, impact categories such as ODP, EP and ADP are also often analyzed in LCA studies.

The use of alternative materials, as a replacement or addition to conventional raw materials in the mortars manufacture may represent an environmental benefit that can be quantified by LCA. This may empower materials' circular economy and provide mortars with increased performance properties, namely due to eventual pozzolanic characteristics and filler effect. The reduced need of treatments and transport of materials, that are the most energy consuming steps of materials processing, turns the use of clayish earth advantageous in a social, economic and environmental way, compared to other types of mortars. Nonetheless, earth mortars may not be as efficient as other mortars to all kind of applications.

LCA presents drawbacks, namely the use of subjective criteria, limitations on scientific knowledge about impacts, lack of a consolidated method, data access and analysis difficulties. This could be overcome by a clear and uniform LCA report with the data needed to reproduce the study. The development of specific databases for mortars with real data could be key factor to improve LCA studies. A complementary economic analysis could show if the best solution in environmental terms is also cost-efficient.

CRediT author statement

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