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Menzies, Gillian Frances; Khasreen, Mohamad Monkiz; Banfill, Phillip Frank Gower

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Review

Life-Cycle Assessment and the Environmental Impact of Buildings: A Review

Mohamad Monkiz Khasreen [1], Phillip F.G. Banfill [2,*] and Gillian F. Menzies [3]

[1] Heriot Watt University, School of the Built Environment, WA 4.02. EH14 4AS, Edinburgh, UK;
E-Mail: m.khasreen@hw.ac.uk
[2] Heriot Watt University, School of the Built Environment, EC 1.31. EH14 4AS, Edinburgh, UK
[3] Heriot Watt University, School of the Built Environment, EC 2.29. EH14 4AS, Edinburgh, UK;
E-Mail: G.F.Menzies@hw.ac.uk

* Author to whom correspondence should be addressed; E-Mail: P.F.G.Banfill@hw.ac.uk;
Tel.: +44 131 451 4648; Fax: +44 131 451 3161.

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Abstract: Life-Cycle Assessment (LCA) is one of various management tools for evaluating environmental concerns. This paper reviews LCA from a buildings perspective. It highlights the need for its use within the building sector, and the importance of LCA as a decision making support tool. It discusses LCA methodologies and applications within the building sector, reviewing some of the life-cycle studies applied to buildings or building materials and component combinations within the last fifteen years in Europe and the United States. It highlights the problems of a lack of an internationally comparable and agreed data inventory and assessment methodology which hinder the application of LCA within the building industry. It identifies key areas for future research as (i) the whole process of construction, (ii) the relative weighting of different environmental impacts and (iii) applications in developing countries.

Keywords: life-cycle assessment; buildings; environment; sustainability

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1. Introduction

The World Commission on Environment and Development [1] at their final meeting stated that: “We remain convinced that it is possible to build a future that is prosperous, just, and secure. The possibility depends on all countries adopting the objective of sustainable development as the overriding goal and test of national policy and international co-operation".

Of the many environmental impacts of development, the one with the highest profile currently is global warming, which demands changes from government, industry and public. Concerns about the local and global environment situation are rising all over the world. Global warming is the consequence of long term build up of greenhouse gases (CO_2, CH_4, N_2O, etc.) in the higher layer of atmosphere. The emission of these gases is the result of intensive environmentally harmful human activities such as the burning of fossil fuels, deforestation and land use changes [2]. This is generally accepted to be the reason that average global temperatures have increased by 0.74 ℃ in the last 100 years. Global temperatures are set to rise by a further 1.1 ℃ in a low emissions scenario, and by 2.4 ℃ in a high emissions scenario, by the end of the century [3]. It is necessary to reduce Green House Gases (GHG) emissions by 50% or more in order to stabilise global concentrations by 2100 [3]. The Tyndall Centre has suggested that a 70% reduction in CO_2 emissions will be required by 2030 to prevent temperature rising by more than 1 ℃ [4]. UK emissions of greenhouse gases fell by nearly 14.6% between the 1990 base year and 2004, but have risen by about 1 % since 2002, most recently because of increased oil and gas consumption. The UK has a legally binding target under the Kyoto [1] protocol to reduce its emissions of the basket [2] of six major greenhouse gases [5], and has announced its intention to put itself on a path towards a reduction in CO_2 emissions of 80% by about 2050 [6].

Perhaps because GHG emissions can be more readily quantified than other impacts, they have attracted most attention from researchers and policy makers but GHG emissions are just one of a range of parameters that should be considered in assessing environmental impacts. Others are ozone depletion, water consumption, toxicity, eutrophication of lakes and rivers, and resource depletion, and the aim of this paper is to review Life Cycle Assessment (LCA) as a means of evaluating the environmental impact of buildings.

2. Role of the Built Environment

Environmentally harmful activities differ from one industry to another, but it is well known that the biggest contributor to GHG emissions is the built environment, accounting for up to 50% of global carbon dioxide emissions [7]. In addition, the embodied environmental impacts generated by the building during its whole life-cycle, can be of the same order of magnitude as those generated during the utilisation stage [8]. The building construction industry consumes 40% of the materials entering the global economy and generates 40–50% of the global output of GHG emissions and the agents of acid rain [9].

The construction sector is responsible for a high percentage of the environmental impacts produced by the developed countries [10]. In the European Union, the construction and building sector is responsible for roughly 40% of the overall environmental burden [10]. Homes in the UK (their construction and occupation) are responsible for the consumption of 40% of primary energy in the country [11]. If the other 30% of the building stock (non-residential) is considered, the impact of buildings is greater [12]. The construction industry is a highly active sector all over the world [10], and

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[1] The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change.

[2] The basket comprises the six main gases with a direct greenhouse effect: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

it is the largest industrial employer, accounting for 7% of total employment, and 28% of industrial employment. It is responsible for a high rate of energy consumption, environmental impact and resource depletion [13]. Most European governments have introduced new policy instruments such as the European Community's energy performance directive for buildings (EPBD) in order to reduce the negative impacts from the building sector [14].

3. Life-Cycle Assessment

There are many methods available for assessing the environmental impacts of materials and components within the building sector. While adequate to an extent for a particular purpose, they have disadvantages. LCA is a methodology for evaluating the environmental loads of processes and products during their whole life-cycle [15]. The assessment includes the entire life-cycle of a product, process, or system encompassing the extraction and processing of raw materials; manufacturing, transportation and distribution; use, reuse, maintenance, recycling and final disposal [16]. LCA has become a widely used methodology, because of its integrated way of treating the framework, impact assessment and data quality [17]. LCA methodology is based on ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the life-cycle inventory, assessing the impact and finally interpreting the results [18]. Employed to its full, LCA examines environmental inputs and outputs related to a product or service life-cycle from cradle to grave, i.e., from raw material extraction, through manufacture, usage phase, reprocessing where needed, to final disposal.

ISO 14040 defines LCA as: "A technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases. LCA is often employed as an analytical decision support tool." [19]. Historically it has found popular use comparing established ways of making and processing materials, for example comparing recycling with incineration as a waste management option [20]. LCA is increasingly being seen as a tool for the delivery of more eco-efficient life-cycles.

4. Brief History of Life-cycle Assessment

The usage of life-cycle assessment as an environmental management tool started in the 1960s in different ways and under a variety of names. [20]. There is a confusing similarity between some of the terms that reflect different depths and types of study, especially in the literature of the early 1990s. The term life-cycle assessment has since been adopted to reflect environmental life-cycle studies. The origin of life-cycle thinking has been attributed to the US defense industry [21]. It has been used to consider the operational and maintenance costs of systems. This has become a costing technique known as "Life-Cycle Accounting" or "Life-Cycle Costing". The first appearance of LCA in its current modern environmental understanding was in a study held by Coca-Cola to quantify the environmental effects of packaging from cradle to grave [22]. The emphasis at that time was primarily on solid waste reduction, rather than on environmental emissions or energy use. The UK's first experience of the life-cycle perspective was published as a handbook of industrial energy analysis authorized by Boustead and Hancock [23]. During that era many life-cycle studies had appeared followed by significant increase of public interest in the subject [22].

The Society of Environmental Toxicology and Chemistry (SETAC) held two LCA workshops during 1992. The first was on life-cycle impact assessment [19] and the second concentrated on data quality. The North American and European SETAC LCA advisory groups met in Portugal 1993. And produced Guidelines for Life-cycle Assessment: A "Code of Practice" [16], sometimes referred to as the "LCA Bible" [24]. Apart from SETAC work, some LCA guidelines which appeared during the 1990s include the publication of the Dutch guidelines on LCA [25]. Authors from Nordic countries namely; Swedish, Finnish, Danish and Norwegian authors, published Nordic Guidelines on Life-cycle Assessment [26]. The UN Environment Program published the Life-cycle Assessment: What Is and How to Do it, and The European Environment Agency's Life-cycle Assessment: A Guide to Approaches, Experiences and Information Sources [20].

There were many initiatives to standardize the methodology of life-cycle assessment; the Canadian Standards Association released the world's first national LCA guideline Z-760 Environmental Life-cycle Assessment in 1994, to provide in-depth information on LCA methodology [27]. But the most recognized standards were the ones published by the International Standards Organization ISO [28]:

- ISO 14040 Environmental management, LCA, Principles and framework (1997).
- ISO 14041 Environmental management, LCA, Goal definition and inventory analysis (1998).
- ISO 14042 Environmental management, LCA, Life-cycle impact assessment (2000).
- ISO 14043 Environmental management, LCA, Life-cycle interpretation (2000).

5. The Need for Life-Cycle Assessment in Buildings

Although LCA has been widely used in the building sector since 1990, and is an important tool for assessing buildings [29], it is less developed than in other industries, including perhaps the engineering and infrastructure sector. The building industry, governments, designers and researchers of buildings are all affected by the trend of sustainable production and eco-green strategies. The importance of obtaining environment-related product information by LCA is broadly recognized, and LCA is one of the tools to help achieve sustainable building practices.

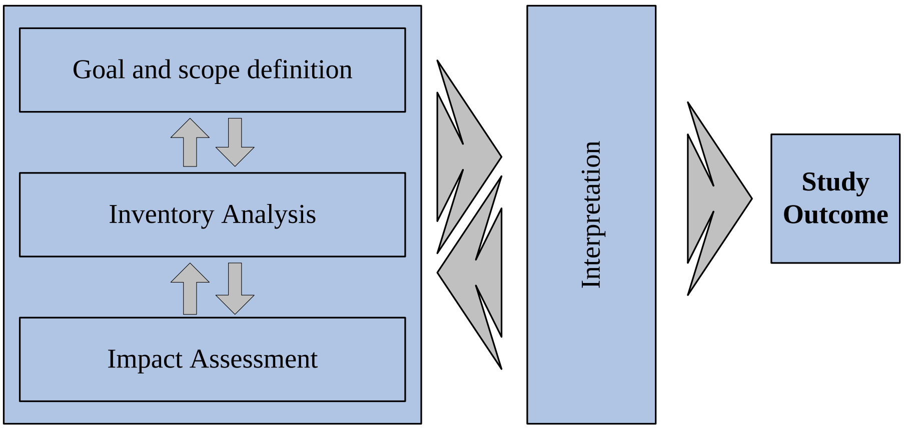
Applying LCA in the building sector has become a distinct working area within LCA practice. This is not only due to the complexity of buildings but also because of the following factors, which combine to make this sector unique in comparison to other complex products. First, buildings have long lifetimes, often more than 50 years, and it is difficult to predict the whole life-cycle from cradle-to-grave. Second, during its life span, the building may undergo many changes in its form and function, which can be as significant, or even more significant, than the original product. The ease with which changes can be made and the opportunity to minimize the environmental effects of changes are partly functions of the original design. Third, many of the environmental impacts of a building occur during its use. Proper design and material selection are critical to minimize those in-use environmental loads. Fourth, there are many stakeholders in the building industry. The designer, who makes the decisions about the final building or its required performance, does not produce the components, nor does he or she build the building. Traditionally, each building is unique and is designed as such. There is very little standardization in whole building design, so new choices have to be made for each specific situation.

The comparability of LCAs of distinct products and the way these LCAs are applied to design and construct environmentally sound buildings is a main point of attention in LCA practice. Several initiatives for harmonization and standardization of methodological developments and LCA practice in the building industry have taken place at a national level, but in general much scope remains for wider involvement and co-operation.

6. Life-Cycle Assessment Methods in Building

ISO 14040 defined four main phases of life-cycle assessment study, each affecting the other phases in some way (Figure 1).

Figure 1. Life-cycle assessment framework [18].



When LCA is applied to the building, the product studied is the building itself, and the assessment will be defined according to a certain level and contain all the materials processes. This level could be called "whole process of building" and there are many tools available to work at this level, e.g., BREEAM, (UK). If the LCA is concerned with a part of the building, building component or material, the level could be called "building material and component combination" (BMCC), and in this case it is very important to recognize the component impact equivalent according to the functional unit of the building.

LCA should be part of the design process as a decision making support tool, to be used by the designers of the building in parallel with other aspects like cost, and functional requirements. The balance between these three criteria is the task of the architect/designer to achieve the optimum performance of the building. Brainstorming during LCA in the early stages of the design will help find alternatives to the current proposals which better achieve this balance. It is very necessary to consider the functions of the studied construction itself, as the environmental impacts of civil constructions are different from those of buildings, which are dominated by energy consumption. It has been estimated that the use phase in conventional buildings represents approximately 80% to 90% of the life-cycle energy use, while 10% to 20% is consumed by the material extraction and production and less than 1% through end-of-life treatments [30]. By the development of energy-efficient buildings and the use of less-polluting energy sources, the contribution of the material production and end-of-life phases is expected to increase in the future. Lastly it is important to note that the building's location and orientation will have considerable impacts on its energy consumption, and therefore on the overall environmental impacts, even if the same BMCCs and construction techniques were used. For example, the benefits from the use of passive solar energy or natural ventilation will need to be incorporated in the assessment.

6.1. Goal and Scope Definition

The first step of life-cycle assessment, this is a critical step to identify the purpose of the study, and determine the questions to be answered. It can affect the results of the LCA [20]. Within this step the study holder forms the objectives, limitations and constraints of the study, and sets many important assumptions: mainly identifications of system boundaries, such as the full life time of a product or one phase of production; functional unit e.g., m^2 floor area; data quality; and other limits. These should all be specified at this stage. The goal definition and scoping exercise ultimately defines the direction of the study and the benchmarks, with which the study will later be appraised in the interpretation stage. Within the life-cycle of any product there might be some areas of limited interest, these could be omitted within this phase, however, even describing the elements of whole life-cycle in general fashion will prevent missed opportunities for improvement [20]. The goal and scope of a study may change according to many considerations within the study e.g., data unavailability, impact insignificance, etc. According to ISO 14040, the goal of any LCA states the intended application, the reasons for carrying out the study and the intended audience. This includes the product system to be studied, its functions, the functional unit, the system boundaries, allocation procedures, impact categories selected, methodologies of impact assessment, data requirements, assumptions, limitations, initial data quality requirements, and the type of critical review and report required for the study [18]. The functional unit determination in this phase is critical as it is a reference to which all the inputs and outputs are related, and in the case of buildings there are many functional units which could be considered (m^2, m^3, each, number of occupants, etc.).

The general goal of holding an LCA on the level of buildings is to minimize the environmental burdens over the whole life-cycle [19]. Whether designer or researcher, the life-cycle practitioner will have direct effect on the type of audience. In the case of designers the audience may be clients, but in the case of researchers the audience may be policy-makers, developers and investors. Buildings are always described as complex products, complexity which lays in the process of production. Due to the complexity of construction industry and the long life span of buildings, and because the scenarios within a building life span are not very clear, all subsequent phases of LCA will affect and modify the goal and scope definition phase in some way or another, so it will need review and modification within and after each phase.

LCA studies in the literature differ in terms of their goal and scope definition, and it is sometimes clear that their goals have changed according to unexpected problems raised during the LCA studies. Scheuer *et al*. employed an LCA to find the environmental burdens of a university building in Michigan [31]. They set the study boundaries to include only the building itself (structure, envelope, interior and backfill), and set the life span to 75 years, which is very long compared to most other studies, which typically assume 50 years. The study neglected the insignificant contributions, e.g., impacts from facilities used for production, and omitted the factors which are not related to building design, e.g., furniture, movable partitions, street and side walk modifications, etc. Lack of data had its influence on the scope of the study due to data unavailability; the study holder was forced to omit materials used during the construction process, and small replacement materials. For this case the materials omitted did not affect the results significantly, but in other cases, unavailability of national and realistic data might drive the study in the wrong direction, or change its goal and scope [31]. Junnila *et al.* [32] assumed the study boundaries to be from raw materials acquisition through production and use to disposal. The main purpose of the study was to find the environmental impacts of a specific well described high-end office building in Finland, and used a national up-to-date manufacturer's data, verified by independent third party. Lack of data affected the study, forcing omission of heavy metal emissions from transportation and use of construction equipment. The life span was assumed to be 50 years as in many other LCA studies applied to buildings. The study was limited to calculating the impact categories identified as most important in Finland, but again lack of data had its influence on the study forcing omission of ozone depletion and biodiversity, although they were mentioned as most important within the Finnish impact categories list [32]. Within the goal and scope definition phase, Asif *et al.* addressed eight different materials (timber, glass, concrete, aluminum, ceramic tiles, plaster board, slate and damp course), which he considered as significant in the studied Scottish house [33]. The study identified five main materials, which are most important in terms of their embodied energy. The studied house had a specified description and layout, and the study allocated the embodied energy distribution according to the studied materials, and calculated one impact category - global warming potential [33].

In many other examples of LCA studies presented later, it is clear that one of the main reasons hindering comparison is the difference in goal and scope definition. Within the goal and scope definition, a well established description of the case study building is necessary. The description should include as much detail as possible starting with: the function and the geographical location of the building, and passing through other technical features. The system boundaries should be clearly set, whether the study will consider the whole building life-cycle, or one phase of it; the whole building, or one system; and the environmental impact categories to be studied should be determined. Within this step, the LCA practitioner should also consider the functional unit, methodologies of impact assessment, data requirements, assumptions, limitations, initial data quality requirements, type of critical review and type of the report required for the study [18].

In the case of whole building LCAs, the functional unit could be one of many (m^2, m^2 internal space, m^3, each, number of occupants, etc.). The ease of comparing the outcome of the study to other studies is a very important factor in determining the functional unit [34]. There have been many attempts to standardize the functional unit for buildings e.g., [16], but there are no results available yet. Within the literature the most commonly used functional unit in life-cycle assessment of buildings is square meter floor area, however in specific cases this unit had been changed, for instance some studies considered the square meter of living floor area in the case of dwellings, some others used the ton of material as the unit when the study is related to a material environmental burden. It is important to note that all the environmental impacts calculated within one LCA study must refer to the chosen functional unit.

6.2. Inventory Analysis

The second step of the LCA is inventory analysis. It contains the "data collection and calculation procedures" [18], and is of key importance since this data will be the basis for the study. Inventory is also tied to the scoping exercise since data collection and other issues may lead to refinement or redefinition of the system boundaries. Lack of data may result in changing the scope and/or objectives of the study, so data completeness is very important. ISO defines several levels in the inventory phase starting by data collection from available high quality resources; passing through data calculation, which involves validation of data collected, relating data to unit processes and relating calculated data to functional unit, down to allocation procedures when dealing with systems involving multiple products and recycling systems. The wider the system boundaries, the less the need for allocation, and in some cases there is no need for allocation, especially when there are no multiple products, and when the system boundaries are very wide (e.g., from cradle to grave) [20]. Choosing the most appropriate data is critical as the quality of data sources is very important to assure the correctness of the results, and in some cases the data will drive the study and determine its quality level. Data quality is very important to determine the success of the study or its failure. Data nationality is an important factor to be considered when choosing the data sources (Table 1).

This step is the more time intensive in the case of buildings as complex products (production process is complicated), the data collection includes all data related to input-output of energy, and mass flow in terms of quantities and emissions to air, water and land [35]. The life-cycle of a building consists of many phases. The number of phases differs according to the goal of the study, and it could be three or more, but the sum of the proposed phases must result in the whole life-cycle of the building in all cases. For example, some studies use three phases starting by the pre-construction phase, which includes all the processes from materials extraction up to the start of building occupation, followed by usage phase, and ending with demolition phase, but each of these phases could be divided into many sub-phases according to the goal and scope of the study.

The life-cycle inventory phase (LCI) generally uses databases of building materials and component combinations. The availability and accuracy of data should always be clearly described within the goal and scope definition phase. This concerns the materials, components, and scenarios already finished, but building construction includes past, current and future activities and scenarios. All of them, and any assumptions related to them should be clearly mentioned [19]. What is generally included within an LCA of buildings is the embodied energy of materials and building component combinations, the transport of materials and building components to site, the use of the building (as energy use), the waste of materials (sometimes), water consumption (sometimes), maintenance and replacement, demolition of the building, and transport of waste to the treatment site. What is generally not included is the transport of equipment to site, the construction phase at the site of the building, and construction waste [36]. The goal of the study is the main driver to determine what is and what is not included, and data availability has direct effect on this as well, and it consequently can change the goal of the study. Whether included or not any process or item within the life-cycle assessment must be set clearly in the scope of the study, because any process included in the life-cycle of a building requires data to be included in the data inventory, whether collected, measured or estimated. The data should quantify the input and output of the building, and should be described well and thoroughly referenced.

Life-cycle inventories, until recently, lacked completeness and many problems hindered the production of an internationally accepted protocol to be used in LCA analyses. Currently available databases fit four categories: Public database developments, academic, commercial, and industrial [37]. The most important is the fact that these data differ from one source to another in many ways: mainly boundary definitions, energy supply assumptions, energy source assumptions, product specifications, manufacturing differences, and complications in economic activities [37]. For example, Sinclair [38], found a variation in the embodied energy of a brick of between 5 and 50 MJ. Geographical factor has the greatest effect, as it underlies most of the variations mentioned early in this paragraph; accordingly it is important for each country to have its own data according to its construction industry resources and traditions. LCI involves collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water and land. It includes calculating both the material and the energy input and output of a building system. The limitations associated with LCI have a subsequent impact on the reliability of the overall LCA findings. A higher level of completeness and reliability in LCI is needed to permit a more accurate and precise assessment of life-cycle environmental loadings from the manufacture of a particular product. There are many methods to calculate the LCI across a range of disciplines, but many obstacles are still unresolved. A lack of transparency between data centers (data or data origins and references are not accessible) makes it difficult to compare the results. There are some national and international databases that might be accepted in some cases, but in detailed local studies these databases should not be used as the international ones differ, and the national ones generally discuss the simple basic construction materials [37]. However, these could be identified as a background source of data.

Researchers suggest that three approaches could be used to overcome data problems, namely process analysis, input/output analysis and hybrid analysis. The traditional method is process analysis, involving analysis of direct and indirect energy inputs to each product process. It usually begins with the final product and works backwards to the point of raw material extraction. In many cases the process of production might be difficult to understand, and problems will arise in the calculation phase, because of this lack of understanding. So this method is impracticable on its own [39]. Process analysis results are found to be considerably lower than the findings of other methodologies [40]. Input/output analysis can overcome the problems of process analysis. It is based on input/output tables, where the inputs may include energy and natural resources, and the outputs may include CO_2 and other gases emissions. Both methods are widely used, but each of them has its own benefits and disadvantages. Process analysis can be significantly incomplete, due to complexity of the requirements for goods and services [41]. While the accuracy of process analysis method can be higher, it is only relevant to the particular system considered, and can be subject to considerable variability [42]. Input/output analysis uses national average data of each sector of the economy, and is considered to be more comprehensive than process analysis [41]. It has a complete system boundary, but is generally used as a black box, with little understanding of the values being assumed in the model for each process. This method could give valuable estimates of the embodied energy but it is not as accurate as process analysis. Hybrid analysis is a combination of both methods and results in better quality data inventories. It minimizes the limitations of the other methods, and there are several types of hybrid analysis: input/output based hybrid analysis, process based hybrid analysis, tiered hybrid method and integrated hybrid analysis.

Each works in a different way to deal with the deficiencies of traditional methods (the incompleteness of process analysis, and the low level of accuracy in the case of input/output analysis).

The quality of life-cycle assessment is directly related to the quality of inventory data, its correctness and its concordance with the goal of the study. The source of data might be one or more of direct measurements, laboratory measurements, governmental and industrial documents, trade reports and databases, national databases, environmental inventories, consultancies, academic sources, and engineering judgments [43]. The source of data plays a role in its reliability, accompanied by acquisition methods and verification procedures used. Another important factor to be considered is the completeness of data, which relates to its statistical properties, and shows how representative the sample is, and whether the sample includes a sufficient amount of data. Three other indicators relate to the correlation between the data and the data quality goals, namely temporal correlation, geographical correlation, and technological correlation [44]. Data quality indicators should be used to improve the data collection strategy, allowing the study holder to highlight the main data problems in the study, and help overcome data problems. Table 1 gives criteria for assessing the quality of data for LCA.

Table 1. Data quality assessment matrix [44].

Indicator score	**1** Excellent	**2**	**3**	**4**	**5** Unreliable
Reliability	Verified data based on measurement	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years different from year of study	Less than six years different	Less than 10 years different	Less than 15 years different	Age of data unknown or more than 15 years different from year of study
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 2. Some databases and tools of life-cycle assessment of WCP and BMCC.

Database	Country	Function	Type	Level	Software	Website
Athena	Canada	Database + Tool	Academic	whole building design decision	Eco Calculator	www.athenaSMI.ca
Bath data	UK	Database	Academic	product comparison	No	people.bath.ac.uk/cj219/
BEE	Finland	Tool	Academic	whole building design decision	BEE 1.0	-------------------------
BEES	USA	Tool	Commercial	whole building design decision	BEES	www.bfrl.nist.gov/oae/software/bees.html
BRE [3]	UK	Database + Tool	Public	whole building assessment	No	www.bre.co.uk
Boustead	UK	Database + Tool	Academic	product comparison	Yes	www.boustead-consulting.co.uk
DBRI [4] **Database**	Denmark	Database	Public		No	www.en.sbi.dk
Ecoinvent	SL	Database	Commercial	product comparison	No	www.pre.nl/ecoinvent
ECO-it	NL	Tool	Commercial	whole building design decision	ECO-it	www.pre.nl
ECO methods	France	Tool	Commercial	whole building design decision	Under development	www.ecomethods.com
Eco-Quantum	NL	Tool	Academic	whole building design decision	Eco-Quantum	www.ecoquantum.nl
Envest	UK	Tool	Commercial	whole building design decision	Envest	envestv2.bre.co.uk
Gabi	Germany	Database + Tool	Commercial	product comparison	Gabi 4	www.gabi-software.com
IO-database	Denmark	Database	Academic	product comparison	No	---------------------
IVAM	NL	Database	Commercial	product comparison	No	www.ivam.uva.nl
KCL-ECO	Finland	Tool	Commercial	product comparison	KCL-ECO 4.1	www.kcl.fi/eco
LCAiT	Sweden	Tool	Commercial	product comparison	LCAiT	www.ekologik.cit.chalmers.se
LISA	Australia	Tool	Public	whole building design decision	LISA	www.lisa.au.com
Optimize	Canada	Database + tool	---------	whole building design decision	Yes	----------------------
PEMS	UK	Tool	Public	product comparison	Web	----------------------
SEDA	Australia	Tool	Public	whole building assessment	SEDA	----------------------
Simapro	NL	Database + Tool	Commercial	product comparison	Simapro 7	www.pre.nl
Spin	Sweden	Database	Public	product Comparison	No	http://195.215.251.229/Dotnetnuke/

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[3] Building Research Establishment

[4] Danish Building Research Institute

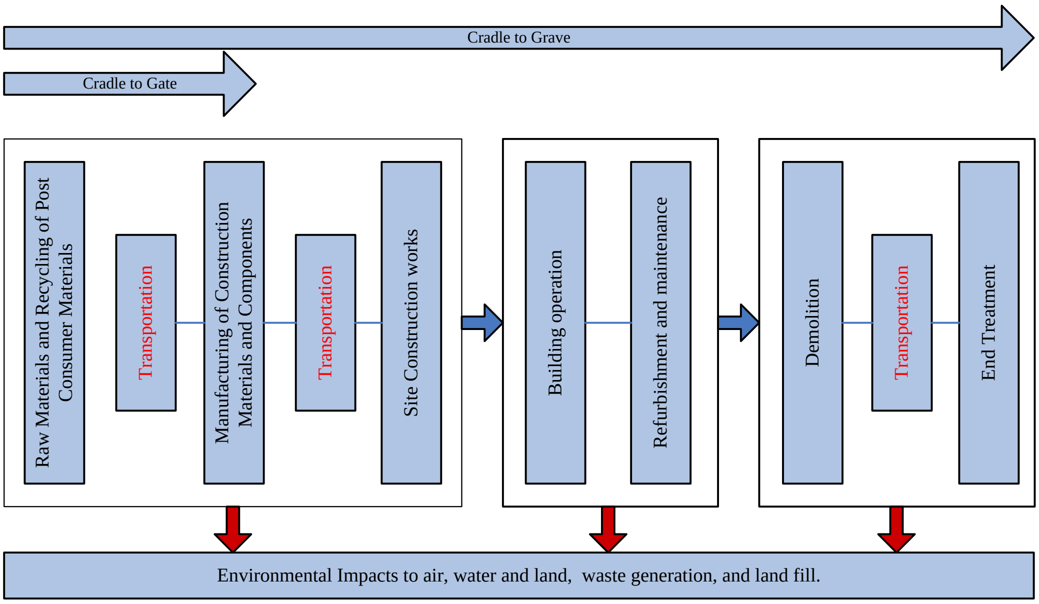
Table 2. *Cont.*

TEAM	France	Database + Tool	Commercial	product comparison	TEAM 3.0	www.ecobilan.com
Umberto	Germany	Database + Tool	Commercial	product comparison	Umberto	www.umberto.de
US LCI data	USA	Database	Public	product comparison	No	www.nrel.gov/lci

Some of the datasets listed in Table 2 are complete, or there are extensive efforts of people working on completing them, but due to the wide range of materials in the construction industry, and the variety of construction techniques, none of these tools and data sets are able to model or compute the environmental impacts of a whole building or construction, including all the life-cycle phases and production processes in detail [31]. The databases and tools listed vary according to study goal, users, application, data, and geographical location [35]. Databases differ from one country or region to another according to many factors, including energy sources, supply assumptions, product specifications, manufacturing differences and complications in the economic activities [37]. Each of these factors can produce significant variations in the environmental impact assessment, for instance, (whether delivered or end use) energy supply assumptions can cause significant differences in the embodied energy calculations, as different countries have different energy sources. For example, France depends strongly on nuclear power, while the UK depends more on gas and electricity, and this fundamental difference in the energy sources affects the environmental impacts of production.

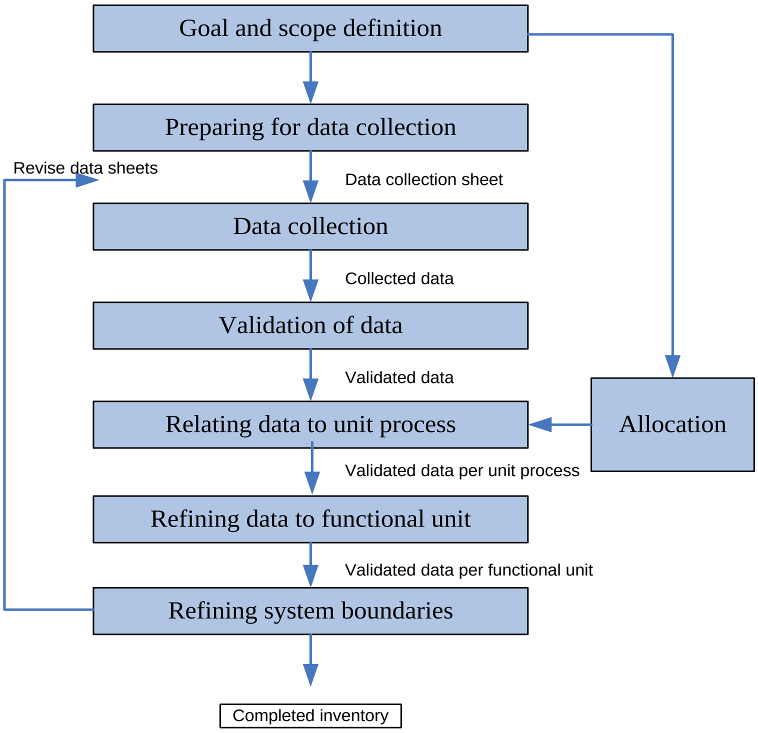
The key steps to produce a life-cycle inventory are to: develop a flow diagram of the process being evaluated, develop a data collection plan, collect the data, and evaluate and report the results. The diagram of the process should be as detailed as possible to get a high level of accuracy, which means spending more time to get this level of detail in this step, which is already time and effort intensive. Of course the more detailed the diagram is, the more accurate the results are. Figure 2 is an example of a process flow diagram.

Figure 2. Medium detailed flow diagram of a building/construction.



After drawing the detailed production diagram, the next step will be setting a data collection policy, and it will be useful to start by dividing the flow into sub flows, to be able to understand the inputs and outputs of each sub phase of the process. Defining data quality goals and setting benchmarks will take place before data collection, to test whether the data meets the goal requirements. Data sources and types should be explained well within this step, and then at the end of this step data spread sheets should be produced [43]. After that, the data collection step will start followed by evaluation and validation of data, according to the benchmarks already set [45]. The next step will be relating data to the functional unit of the building, which is different from the functional unit of BMCCs. For example, the functional unit of the concrete might be a ton of material, while the functional unit of the building might be m^2 of floor area, so to relate the quantity of concrete used within the building to the functional unit used the sum of concrete used is divided by the area of the building (Figure 3).

Figure 3. Simplified procedures for inventory analysis [45].



In the case of studying the whole life-cycle of a building using process analysis, there is no need for allocation procedures, which means distributing the impacts and relating them to the unit process. The allocation procedures are dependent on and directly related to the goal of the study. For example, if the goal of the study is to compare building systems in terms of their environmental impacts, the allocation procedures will be different from comparing the impacts of construction phases. The last step in the data inventory analysis is refining the system boundaries. This step includes verification of data collected using benchmarks, so the initial system boundaries may be revised, and then the results of the refining process and the sensitivity analysis shall be documented. Sensitivity analysis may result in exclusion of life-cycle stages or unit processes shown to have no significance, exclusion of inputs and outputs which are not significant to the results of the study, or inclusion of new unit processes inputs and outputs that are shown to be significant in the sensitivity analysis [45].

6.3. Impact Assessment

ISO 14042 is the international standard for life-cycle impact assessment (LCIA); it defines the impact assessment as aiming to: “Examine the product system from an environmental point of view using impact categories and category indicators connected with the LCI results. The LCIA also provides information for the life-cycle interpretation phase [46].”

The impact assessment framework is a multi-step process, starting by selecting and defining impact categories, which are relevant to the buildings (such as, global warming, acidification, toxicity, etc., as listed in Table 3 which is an extended version of the table of published LCAs applied within the building sector in Europe and the USA within the last 15 years, produced by [35] in 2007). This is followed by a classification step, which assigns LCI results to the impact categories, e.g., classifying carbon dioxide emissions as causing global warming, and modeling the impacts within impact categories using conversion factors, e.g., modeling the potential impact of carbon dioxide and methane on global warming using their respective GHG potentials [45]. These steps could be followed by optional steps to express potential impacts in ways that can be compared. For instance, comparing the global warming impact of carbon dioxide and methane for two options, weight them and identify the most significant ones. At the end of the study all the results should be evaluated and reported [43]. Impact categories could be grouped according to their region of effect, e.g., global warming has a global effect, whereas eutrophication has a local effect [45].

The impact categories included within the LCA studies carried out by researchers of building environmental impacts differ according to the goal of the study, data availability, and significance of the impacts. For instance, among the researchers who produced whole construction process LCAs, Adalberth studied four dwellings located in Sweden and calculated five different impacts (GW, A, E, OD, HT, EL—Table 3) [47], however Peuportier studied three types of houses with different specifications located in France, and calculated twelve different impact categories [48]. Again among other researchers who produced LCAs of BMCCs, Asif *et al.* studied eight different building materials in a Scottish dwelling, and calculated one impact (GW) [33], but Saiz *et al.* studied green roofs in Spain and calculated eight different impacts [35]. Within the literature of LCAs applied to whole buildings, the most commonly studied impacts were global warming, acidification, eutrophication, and ozone depletion, which were present in most studies (Table 4).

Table 3. Published LCAs applied within the building sector in Europe and the USA within the last 15 years, after [35], with additional information.

Reference	BMCC	WPC	Content, country and year	Environmental impacts studied (see footnote)													
				En	**GW**	**A**	**E**	**OD**	**HT**	**EL**	**WC**	**DA**	**W**	**EC**	**RS**	**AR**	**O**
Adalberth *et al.*		x	Life-cycle of four dwellings located in Sweden (2001)	x	x	x	x	x	x	x							
Ardente *et al.*	x		LCA of a solar thermal collector, Italy (2005)	x							x		x		x	x	
Asif *et al.*	x		LCA for eight different materials for a dwelling in Scotland (2005)	x	x												

Table 3. *Cont.*

Citherlet *et al.*	x		LCA of a window and advanced glazing systems in Europe (2000)	x	x	x		x								x
Cole and Kernan		x	LCA of a three-storey, office building for alternative structure materials in Canada.	x												
Gustavsson and Sathre	x		LCA Sweden case study: wood and concrete in building materials (2006)	x												x
Junnila		x	LCA for a construction of an office: a Finland case study (2004)	x	x	x	x						x			
Junnila and Horvath		x	LCA of a high end office building in Finland (2003).	x	x	x	x						x			
Junnila *et al.*		x	Comparative LCA of office buildings in Europe and the United States (2006)	x	x	x	x									
Koroneos and Dompros	x		LCA of brick production in Greece (2006)	x	x	x	x			x						x
Koroneos and Kottas		x	LCA for energy consumption in the use phase for a house in Greece (2007)	x	x	x	x						x			x
Morel *et al.*	X		Comparison of energy embodied in local construction materials with imported ones, France (2000)	x												
Nebel *et al.*	x		LCA for floor covering, Germany (2006)	x	x	x	x	x								x
Nicoletti *et al.*	x		LCA of flooring materials (ceramic versus marble tiles), Italy (2002)	x	x	x		x	x			x				x
Nyman and Simonson	x		LCA of residential ventilation units over a 50 year life-cycle in Finland (2005)	x	x	x		x				x			x	
Peuportier		x	Comparison of three types of houses with different specifications in France (2001)	x	x	x	x	x	x	x	x	x	x	x	x	
Petersen and Solberg	x		LCA by comparing wood and alternative materials in Norway and Sweden (2005)	x		x	x	x	x							
Prek	x		LCA of heating and air conditioning systems. Dwelling in Slovenia (2004)	x	x			x								
Saiz *et al.*	x		LCA for green roofs located in downtown Madrid, Spain (2006)	x	x	x	x	x	x		x		x			x
Scheuer *et al.*		x	LCA to a new University building in the USA (2003)	x	x	x		x		x			x			x
Seppala *et al.*	x		LCA for Finnish metal products (2002)	x			x		x	x	x		x			x
Thormark		x	LCA of residential houses in Sweden (2001)	x												
Van der Lugt *et al.*	x		LCA for using bamboo as building material in Western Europe (2006)	x												x
Wilson and Young	x		Embodied energy payback period of photovoltaic installations in the UK (1995)	x												
Yohanis and Norton		x	LCA of open-plan office building in the UK (1999)	x												

Abbreviations: WPC, whole process construction; BMCC, building and materials components combinations. Impact categories: En, energy consumption; GW, global warming potential; OD, photochemical ozone creation; WC, water consumption; DA, depletion of a biotic resource; A, acidification; HT, human toxicity; W, waste creation; EC, eco-toxicity; E, eutrophication; EL, energy consumption; RS, resources consumption; O, others; AR, air emissions.

Table 4. Commonly used WPC impact categories.

Impact category	Abbreviation	Scale	LCI data i.e., classification	Characterization factor
Global warming	GW	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFC_S) ‘Hydro chlorofluorocarbons’ ($HCFC_S$) Methyl Bromide (CH_3B_r)	Global warming potential
Acidification	A	Regional Local	Sulphur Oxides (SO_X) Nitrogen Oxides (NO_X) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)	Acidification potential
Eutrophication	E	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates, and Ammonia (NH_4)	Eutrophication potential
Ozone depletion	OD	Global	Chlorofluorocarbons (CFC_S) Hydro chlorofluorocarbons ($HCFC_S$) Halons, and Methyl Bromide (CH_3B_r)	Ozone depletion potential

6.4. Interpretation

The final phase of LCA is “Interpretation”. The purpose of this is to: “Analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results of the life-cycle interpretation in a transparent manner. Life-cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or an LCI study, in accordance with the goal and scope definition of the study [18].”

7. LCA Studies for Buildings

7.1. Building Materials and Component Combinations (BMCC)

Nearly two thirds of the studies listed in Table 3 relate to materials and components. Materials are naturally found in impure form, e.g., in ores, and extraction or purification not only consumes energy but also produces waste [33]. Many industrialized countries have made steps towards environmental improvement of the construction process, building occupation and demolition, and these steps differ to the extent that building construction is strongly determined by local traditions, local climate and locally available natural resources. As a result, many LCA studies calculating the environmental impacts of BMCC have been done during the last fifteen years.

In 2001 a study in India focused on embodied energy in load bearing masonry buildings. A brickwork building and a soil–cement block building were compared, and the study showed that the total embodied energy can be reduced by 50% when energy efficient building materials are used [49]. Another study of flooring materials in Italy showed that marble tiles are more environmentally friendly than ceramic tiles [50]. In Finland, Seppala *et al.* produced a Life-cycle Inventory (LCI) of steel plate and coil, steel bar, steel wire, stainless steel, copper, nickel, zinc and aluminum, as part of the Finnish Environmental Cluster Research Programme 1998–2000 [51].

Researchers have compared timber to other framing materials in buildings. Borjesson *et al.* compared CO_2 emissions from the construction of a multi-storey building with a timber or concrete frame, from life-cycle and forest land-use perspective. The primary energy input (mainly fossil fuels) in the production of materials was found to be about 60-80% higher when concrete frames were considered instead of timber frames [52]. Lenzen *et al.* analyzed the timber and concrete designs of the same building in terms of its embodied energy using an input-output based hybrid framework instead of the process analysis Borjesson used. Their estimations of energy requirements and greenhouse gas emissions were double [40]. Gustavsson *et al.* studied the changes in energy and CO_2 balances caused by variation of key parameters in the manufacture and use of the materials in a timber- and a concrete-framed building. Considered production scenarios, the materials of the timber-framed building had lower energy and CO_2 balances than those of the concrete-framed building in all cases but one [53]. Xing *et al.* compared a steel-framed office building in China with a concrete-framed one. The life-cycle energy consumption of the building materials ‘per area’ in the steel-framed building is 24.9% that of the concrete-framed building, whereas, in the usage phase, the energy consumption and emissions of steel-framed building are both larger than those of concrete-framed building. As a result, the energy consumption and environmental emissions achieved by the concrete-framed building over its whole life-cycle is lower than the steel-framed one [54].

Asif *et al.* calculated the CO_2 emissions of eight construction materials for a dwelling in Scotland timber, concrete, glass, aluminum, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that 61% of the embodied energy used in the house was related to concrete. Timber and ceramic tiles comes next with 14% and 15%, respectively, of the total embodied energy. Concrete was responsible for 99% of the total of CO_2 emissions of the home construction, mainly due to its production process [33]. Nebel *et al.* studied the environmental impacts of wood floor coverings manufactured in Germany, and held analyses to help the industry partners to improve their environmental performance and use the results for marketing purposes. The study did not aim to compare products, but to produce an LCI and find the environmental impacts of this industry [55]. Wilson *et al.* calculated the embodied energy payback periods of photovoltaic installations applied to UK buildings in 1995, and found that “energy used in their manufacture is more than they can save in their life-time.” In the case of the UK buildings studied, the embodied energy payback period for photovoltaic modules was 8–12 years and this set an agenda for research to enhance the reliability of this technology in the UK [56].

This selection of LCA studies confirms the difficulty of making comparisons, because there are differences in the final products studied and their impacts. The methods of calculating the embodied energy in BMCCs used were different—process analysis, input-output data calculation, and hybrid analysis. Nevertheless these studies are very important for advancing sustainable development, because of the embodied energy and environmental impacts they calculated, and the suggestions they proposed to reduce the environmental burdens of buildings, through manufacture, and transport of various materials. Another important point is that these studies could be considered as data inventories, or benchmarks when undertaking a whole building LCA. Conservation of energy becomes important in the context of limiting GHG emission into the atmosphere, and reducing costs of materials [49], and the embodied energy payback period should always be one of the criteria used for comparing the viability renewable technologies [56].

To promote environmental impact reduction the European Commission released the integrated product policy (IPP) in 2003, which aimed to enhance the life-cycle of products. The life-cycle of most construction products is long and involves many complicated procedures and stake holders (e.g., designer, manufacturer, assembly, construction, marketing, sellers, and final users). IPP is trying to improve the environmental performance of each phase of production [57] by identifying products with high environmental impact reducing them through three stages: environmental impact products (EIPRO), environmental improvement products (IMPRO) and Policy Implications.

The first phase EIPRO of the IPP project identifies the products that have the greatest life-cycle environmental impact, and then assigns them to environmental impact categories. The second phase IMPRO identifies different methods or production scenarios to reduce the environmental impacts, considering technically feasible steps first followed by other socio-economic impacts. The third step is the implementation of the policy, and within this step there are two strategies used-environmental product declarations (EPD) and Eco-design. EPD is a strategy adopted for external communication, defined as "quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information", committed to reducing the environmental impact of a product [58]. One example of the EPDs is that of concrete roof tiles studied by Gambale, which is a company based in Italy certified to ISO 9001. The study calculated the environmental impacts of four types of concrete roof tiles per the functional unit, which in this case is ton of sold (production capacity–scrap capacity) [58]. These EPDs are a source of data, but there are many risks in depending completely on them, especially when calculating environmental impacts of products from different countries. However, these EPDs could be used as background supportive data. Eco-design means considering the environmental burdens of the product at the earliest stage of product design. It is very important to enhance the environmental performance of the product because it can share in deciding the process and materials [13]. Eco-design proposals include the environmental impact of the whole production-consumption chain [59].

Eco-design principles underpin the Green Guide to Specification [60] which aims to guide designers and specifiers to make the best environmental choices when selecting materials and components. It gives environmental profiles of over 1200 common specifications for a range of building types. These profiles have been produced using data obtained with an LCA methodology [61] that has not yet been published but is reported to have "involved the widest possible consultation with … [a range of bodies] … [and] … the subject of more rigorous peer review procedures than its predecessors …" [60]. The LCA data sources were 28 product trade associations and manufacturers, supported by some of the databases listed in Table 2. However, in the interests of ease of use for practitioners the ratings are given as overall grades A+ to E and the build-up through the process is not shown. An overall grade gives insufficient information to allow producers to improve their manufacturing process, and the range of materials or components given could limit design innovation, since it is difficult to apply generic information to a specific situation with confidence.

Many researchers have been interested in studying the environmental benefits of using recycled, reused or recyclable, reusable materials in the building industry. A study by Erlandsson *et al.* set a new method for reused materials, and confirmed that using reused materials is better for the environment than building with new, their case study data showing a reduction in environmental impact by up to 70% [62]. Selecting durable and renewable materials could also be an alternative for grouping materials, as well as recycling, reusing and recovering materials for optimum waste disposal [63].

The LCA calculations should assess all materials, as some materials used in very small quantities have large environmental impacts, e.g., lead [32]. A study comparing plastics to wood and concrete in Swedish dwellings found that although plastics were only 1%–2% by weight, their manufacturing energy was 18%–23% of the entire amount required for the three dwellings [47].

Researchers classified building materials in different ways. For example, Asif *et al.* categorized them into main families, i.e., stone, concrete, metals, wood, plastics and ceramics [33]. Junnila *et al.* classified them according to the Finnish national building classification system, and over 50 different materials were identified [32], while in another study [64], there were 42 materials under the same Finnish building materials classification system. Sun *et al.* classified materials as glass and ceramics, ferrous metal, no-ferrous metal, paper, polymers or wood [63]. All this confirms that building materials classification considerations differ according to national construction industry categorization or structure.

7.2. Whole Process of Construction (WPC)

LCA for Dwellings

Four of the studies listed in Table 3 deal with dwellings. Adalberth studied the energy use during the life-cycle of three single-unit dwellings, built in Sweden in 1991 and 1992 [47]. The houses were prefabricated and timber framed. The study emphasized the importance of LCA, to gain an insight into the energy use for a dwelling in Sweden. The functional unit was m^2 of usable floor area (i.e., gross area minus walls area), and the study assumed a 50 years life-span. The life-spans of different building components and materials were collected from the maintenance norm of the Organization for Municipal Housing Companies in Sweden to estimate how many times each would be replaced during the life of the dwelling. The study showed that the difference between percentage energy and percentage by weight for materials (e.g., the concrete used was 75% by weight of the whole, while the energy used to produce it is only 28% of the production energy of the whole dwelling). Adalberth performed a sensitivity analysis on the building material data, energy use and electricity mix, which had been discovered to be of a greatest environmental burden [47]. This study concluded that the greatest environmental impact (70%–90%) occurs during the use phase. Approximately 85% and 15% of energy consumption occurs during the occupation and manufacturing phases, respectively [47].

A study carried out in France as part of the EQUER project (evaluation of environmental quality of buildings) considered different phases of dwelling’s life-cycle, using the functional unit of m^2 living area, with the sensitivity analyses based on alternative building materials, types of heating energy, and the transport distance of the timber. This study showed that the dwellings with greatest environmental impact were not those whose area is larger, and emphasized the importance of choosing materials with low environmental impact during the pre-construction phase (i.e., employing LCA as a decision making supporting tool during the design stage) [48].

Involving the recycling potential scenarios within the life-cycle of low energy dwellings had been studied by Thormark, for energy efficient apartment housing in Sweden. Over a 50 year life-span, embodied energy accounted for 45% of the total energy requirement, and about 37%–42% of this embodied energy could be recovered through recycling [65]. In a Japanese urban development case study, Jian *et al*. suggested that to reduce life-cycle CO_2 emissions timber dwellings were preferred to other materials, and that open spaces such as parks and green areas should be maximized to work as a breathing lung inside the development [66].

LCA for Offices

Six of the studies listed in Table 3 refer to offices. Some descriptive work on office buildings has been done, but there is limited research published on complete LCA of office buildings [35], although they are significant sources of energy use and emissions. There are no quantitative comprehensive studies including all the phases of an office life-cycle [64]. Cole and Kernan suggest that a detailed focus on the embodied energy of every material or building component alone, without looking on their relative significance is insufficient [67]. They examined the total life-cycle energy use of a three-storey generic office building, for alternative timber, steel, and concrete structural systems. The study considered the initial estimated embodied energy, maintenance embodied energy, operational energy and demolition, and again found predominance of energy consumption during the occupation phase, emphasizing the need to consider design alternatives to significantly reduce it. When that has been done, the significance of the embodied energy will increase and work should then emphasize alternative materials and processes to reduce the embodied energy. The embodied energy could reach 67% of the operational energy over a 25-year period even when additional maintenance, refurbishment, or modification within the life-cycle of a building is also included [67].

Yohanis and Norton calculated the life-cycle energy (operational and embodied) of a UK generic single-storey office building, using Early Design Model EDM [68], which is an integrated simplified energy model based on a proven well-established algorithm, and studied the energy effects on the capital costs. They found that, there is a critical ratio of glazing which affects the balance between embodied and operational energy: embodied energy is higher below about 55%, but operational energy is higher above 55% glazing. Heating costs decrease sharply with glazing ratio reaching a minimum when glazing ratio is 15% [69].

Scheuer *et al*. studied a new university building (75 years life-span, six storeys, and 7,300 m^2 area, in USA). They identified 60 building materials and showed that the operational energy amounted to 97.7% of the whole energy consumption, which can be explained by the long life-span. The energy of the demolition phase was only 0.2%. The study translated the energy consumed in the life-cycle into environmental impacts-global warming 93.4%, nitrification potential 89.5%, acidification 89.5%, ozone depletion potential 82.9%, and soil categories waste generation 61.9%. Data were taken from Simapro, Franklin associates, DEAMTM, and the Swiss Agency for the Environment, Forests and

Landscape. The study emphasized the need for data on unusual performance characteristics, or detailed evaluations of building features in the design stage, which they say is "impossible with current building data" [31].

To find out the significant environmental impacts of a new office building over a 50-year life span in Finland, Junnila *et al*. carried out a comprehensive environmental LCA, including data quality assessment, establishing causal connections between the different life-cycle elements and potential environmental impacts. The operational energy of the building was responsible for most of the environmental burdens. The impact categories included acidification, climate change, eutrophication and dispersion of harmful substances (summer smog, heavy metals), but not ozone depletion and biodiversity loss due to lack of data. The results showed that the impacts of two life-cycle phases (operational and components manufacturing energy) seem to be significant. The study prioritized the life-cycle elements according to their environmental impacts as following; electricity use in lighting, HVAC, and power outlets; heat conduction through the structure; manufacture and maintenance of steel, concrete, and paint; water use and waste water generation; and office waste management [32]. Within another study Junnila calculated the environmental impacts of another office building of approximately 24,000 m^2 gross floor area and a volume of 110,000 m^3. The study calculated the impacts of forty life-cycle elements and defined two hundred environmental aspects, and found that the most significant elements were again electricity used in power outlets, HVAC, lighting, but in this case also the internal surfaces in the maintenance phase. The impact categories studied were climate change, acidification, summer smog, eutrophication, and heavy metals. The study emphasized on the notion that a life-cycle assessment has to include all the building phases from cradle to grave, and insisted that studying some phases and neglecting others is not valid [70].

A further step by Junnila *et al*. compared a European office building with one from the United States. This comparison study assessed the two buildings throughout their full life-cycle, defining 42 different building materials in total. The comparison found that the ratios of emissions associated with different life-cycle phases to the whole emissions of each building in the two buildings cases are similar, while the Finnish building uses a third less energy and emits half the CO_2 emissions for the same functional unit [64]. In another comparative study of concrete and steel structured office buildings, Xing *et al*. found that the life-cycle energy consumption of building materials per unit area in the steel-framed building is only 24.9% that of the concrete-framed building, but during the usage phase the energy consumption and emissions of the concrete framed building are lower than the steel building. The life-cycle energy of the steel-framed office building was found to be 75.1% that of concrete-framed one [54].

This work from the last 15 years is considered to be the most comprehensive as other researchers typically restricted their studies to the occupation phase, to improve the thermal comfort and reduce the energy use which accounts for a high percentage of the whole building life-cycle energy, especially if the building is not environmentally friendly, or if the life-span supposed is more than 50 years. However, there are indications that the average life-span of an office building is decreasing, with a trend in Europe to reconstruct or reconfigure office buildings constructed in the 1960s to meet the functional and aesthetic criteria of the new tenant [64]. Other researchers concentrated on one or two environmental indicators without calculating the others because of lack of data, time limitations, and significance of aspect [33,65]. The Carbon Trust's Energy Consumption Guide (ECG19) categorizes offices into four main groups namely, naturally ventilated cellular, naturally ventilated open plan, air-conditioned standard and air-conditioned prestige, and is a reference or guide for office occupiers to know if their energy bills are reasonable. The study concentrates on the occupation phase of the office buildings, and explains “how and where” the energy goes. The study uses m^2 treated floor area as functional unit and ranges between the good practice and typical cases [71].

The usage of glass cladding systems has become a trend for architects designing office buildings, to create buildings which are airy, light and transparent with more access to daylight, but their energy efficiency is questionable. To optimize glass area, Poirazis *et al*. studied the impact of high percentage glazing in office buildings by calculating the building operational energy at 30%, 60% and 100% glazed area. The lower the glass ratio, the more the energy efficient the building is, but the most energy efficient 100% glazed alternative results in only 15% higher total energy use [72]. The balance between environmental sustainability and occupant comfort concerning the design of windows for office buildings had been studied by Menzies and Wherrett. The study examined four office buildings in the UK with double glazed windows of different specifications and U values, and calculated the energy needed to maintain each building at the same temperature during working hours. Occupant comfort was studied by holding a post-occupancy survey, showing that sustainable efficient windows can be more comfortable by joining the building and window designs together, but the final result showed no relationship between the window factor and the level of the environmental sustainability in the windows of the office buildings [73].

8. Discussion and Conclusions

Life-cycle assessment of buildings is less advanced than in other industries, but researchers are working to enhance the possibilities of adopting LCA as a decision making support tool within the design stage. It is clear that LCA is well explained, and its methodologies are well established and accessible to users, but there are still many impediments to its use for buildings, and these set the research agenda for the future.

The main problem is the building, whose production process is complicated, and whose life span is long with future phases based on assumptions. There is little standardization within the building sector, so there is a clear lack of data inventory. Researchers are working hard to overcome this problem, but the nature of the building industry makes it difficult to have an international dataset available for all users, which can make the life-cycle assessment studies comparable. There should be an internationally accepted framework, protocol, and conversion tools based on different factors, to enable the comparison between one LCA study and another. The currently available datasets are typically not transparent, and most of them are based on local and simple materials but not components or composites. There is a need to produce accurate local datasets with the possibility to convert their results to an internationally comparable form. Among the literature cited within this paper, there are no two studies which could be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used.

More studies have calculated the embodied impacts of building materials and component combinations than have been concerned with the whole process of building construction. There is a need to hold whole life-cycle assessment studies to establish the effect of alternative materials on the energy performance of the buildings, and to find the optimum relationships between them. At the building scale, more has been done to evaluate the environmental impacts of dwellings, possibly because of their prominence in the building stock and their lesser complexity than non-residential buildings, especially offices, which are considered to be of high significance in terms of their greenhouse gas emissions. It is clear in the literature that not all impact categories were present, because researchers highlighted the significant ones, but what is not significant in a single building can be highly significant at the community or regional level.

Considering the overall environmental impact of buildings is difficult because the 13 or more impact categories (Table 3) are measured in different units. Simply adding the impacts is insufficient and it is necessary to first reduce them to a common scale, and then apply weighting factors to account for their relative importance. In the BRE methodology [60] the emissions in each impact category are normalized by comparing them to those emitted by the average European citizen in one year, thus producing a single dimensionless number for each category. This number is multiplied by a weighting factor (referred to as a valuation factor in ISO 14040) obtained by consulting a panel of 10 experts [74,75] and the numbers so produced are totaled and scaled to 100. Thus the environmental impacts are scored according to their perceived importance, with the highest proportion (21.6%) allocated to CO_2-equivalent emissions, water extraction next at 11.7%, then others down to 3.0% for eutrophication, 0.20% for photochemical ozone creation and the lowest proportion (0.05%) to acidification. A similar scoring approach (but with different categories and values) is used by the UK's Code for Sustainable Homes to force reductions in the environmental impact of new housing [76]. This approach is subjective and the normalization and weighting process is variable both in time and across geographical boundaries. Furthermore, it is susceptible to manipulation to suit the political or other agenda of the specifying authorities, who may wish to concentrate on particular impacts of local significance without regard to the global situation. Simplifying the information relating to product lifecycles to make it more accessible and easily understood has to be balanced against the need to align the objectives and boundaries of LCA studies to avoid information being used erroneously or out of context. A full LCA of a product provides useful and accurate information, but is costly and time consuming, while using generic data and information in a specialized application could lead to a wrong choice.

Finally, all of the studies reviewed were carried out in developed countries and no published papers analyzing the environmental impact of buildings in developing countries have been found. In view of the vast potential for building construction in the less developed world, this should be addressed as a matter of urgency.

Despite the limitations and criticisms presented in this paper LCA is a powerful tool for the evaluation of environmental impacts of buildings. It has the potential to make a strong contribution to the goal of sustainable development.

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