# Methodology for Assessing Environmental Quality of Materials and Construction

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ABSTRACT **As architects and engineers work at different scales, the ecological impact generated within the scope of their professional activities can be differentiated between material, component, building, and city levels. By focusing on the material and component levels, this chapter introduces and gives a detailed analysis of the structure of the life cycle assessment (LCA) method used for quantifying environmental impact. The review encompasses the following issues: LCA goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and results interpretation. Subsequently, the scope of LCA data is discussed and the criteria to be sought when working with LCA data are proposed and described. Finally, the chapter considers the application of the LCA data, especially in formats such as Environmental Product Declaration (EPDs) and LCA databases, provides relevant examples, and thus concludes the presentation of the facts necessary for the application of life cycle assessment methodology in different design and engineering contexts.**

KEYWORDS ecological assessment, environmental impact, evaluation criteria, LCA, material

# 1 Introduction

The development of reliable methods to quantify ecological impact was initiated in the 1970s. Since then, the tendency to reduce impact on nature resulting from the anthropogenic behaviour has been gaining relevance in political discussion and marketing. Simultaneously, companies started to advertise characteristics of products and processes in order to highlight the ecologically-friendly approach, but the content and quality of the given information represented mixed facts, often referred to as greenwashing. In the 1990s, the methods for quantifying ecological impacts were introduced to the building sector. At that time, only a small number of professionals who understood the methods of calculating environmental impact were able to draw guidance from results.

Although the methods for ecological impact qualification evolved over time (Table 1.1), their primary concept, based on a list of resources and emissions used for a life cycle phases analyses (input and output analyses), has been preserved.

| ACRONYM | TITLE | INSTITUTE | WEBPAGE |
|---|---|---|---|
| C2C | Cradle to Cradle | Braungart and McDonough | www.c2ccertified.org |
| - | Ecological Footprint | Global Footprint Network 2009 | www.eea.europa.eu |
| - | Faktor X | Aachener Stiftung Kathy Beys, UBA | www.umweltbundesamt.de |
| MFA | Material Flow Analysis | Wassily Leontief | - |
| MIPS | Material Input per Service | Wuppertal Institute | www.wupperinst.org/en/a/wi/a/s/ad/141/ |
| LCA | Life Cycle Assessment | Various | Various |
| PEF | Product Environmental Footprint | Environment and Sustainability of the European Commission | www.ec.europa.eu/environment/eussd/smgp/policy_footprint.htm |

TABLE 1.1 Methods to calculate environmental impact

In the last decade, the number and intensity of impact quantification methods used in the building sector have increased (Hollberg, 2016). Today, different approaches can be found, but the most common and documented method is the *Life Cycle Assessment (LCA)*. LCA calculates resources and emissions assigned to a particular defined service or product.

## 1.1 Development of LCA

Although the LCA emerged as a narrow concept, its meaning has been made significantly more complex over time. A method for systematic screening of energy and material flows, developed by biologist and economist Geddes in 1884, accounts for one of the first documented approaches leading to what is today defined as 'life cycle assessment' (Frischknecht, 2006; Geddes, 1884). Having determined that every production inevitably implies energy utilisation, the starting point of any product assessment was, and still is, energy.

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Over the last 50 years, LCA methodology has evolved internationally. Following the oil crises in the 1970s, different institutes started researching the possibilities of enhance efficiency in energy generation, and additionally to reduce waste, e.g. by comparing the life cycle of glass bottles versus cans. One of the first mentioned pieces of research in the field of LCA was a study carried out for the Coca Cola Company by the Midwest Research Institute (MRI) in 1969, where resource consumption for beverage containers was compared to environmental releases (Guinée et al., 2011; Jensen, Hoffman, Møller, & Schmidt, 1997). Boustead explained the application of the method for quantifying the amount of energy used in beverage cans production, and the publication *Handbook of Industrial Energy Analysis* (Boustead & Hancock, 1979) enabled the spread of the method for quantifying energy on a physical basis into other disciplines in the UK. The term *Life Cycle Assessmen*t was coined by the Institute Eidgenössische Materialprüfanstalt in St. Gallen in 1978 (Kümmel, 2000), followed by the introduction of the term *Grey Energy* referring to the quantified expression of primary energy used for a service or product as an indicator for environmental impact (Spreng & Doka, 1995). The period from 1970-1990 is the *Decades of Conception* of basic LCA concepts, and the period from 1990-2000 the *Decade of Standardisation* (Guinée et al., 2011). During the last decade of the 20th century, several institutes dealing with the LCA standardisation were founded. Following the initiative of the Nordic Council of Ministers, the Nordic Guidelines for LCA were formulated in 1991. The results of two LCA coordinating workshops organised by the Society of Environmental Toxicology and Chemistry (SETAC) in 1992, which formed the *Guidelines for life-cycle assessment*, i.e. the *Code of Practice* published in 1993 (Consoli et al., 1993), marked a notable progress in the harmonisation of LCA methods. In 1992, the *Environmental Life Cycle Assessment of Products*, often referred to as *The Guide*, was published (Heijungs at al., 1992). To meet the need for standardisation, the first *ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework* was published in 1997. In 2002, the United Nations Development Programme and SETAC together founded the *Life Cycle Initiative,* thus offering a networking platform for engaging in life cycle thinking (Hildebrand, 2014). In the *Decade of Elaboration* (Guinée et al., 2011), LCA as a method of quantifying the ecological impact is applied in different fields and disciplines, from energy generating industry to process technology.

## 2 LCA Structure

Life cycle assessment began with listing and quantifying the ecological impact of energy sources, where the data related to raw material extraction and transportation were based on information provided by the industry. The information on one process is called flow. Several flows form one module or product. Several products constitute a system. Hierarchy enables the provision of sufficient data for the building sector. In this logic, products add up a building.

As a method for ecological impact quantification, LCA can be applied to materials, buildings, and neighbourhoods. This section describes fundamental facts and specificities of the LCA method used for material and component evaluation.

Matthews, Hendrickson, and Matthews (2015) provide an easy-to-understand introduction to the LCA and a comprehensive overview of different approaches. The procedure itself is regulated by standards ISO 14040:2006 and ISO 14044:2006. While ISO 14040 describes the framework, more detailed information regarding the LCA implementation can be found in ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines (Hildebrand, 2014). As defined in ISO 14040 (2006), LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". Inputs can be resources, energy, pre-products or auxiliary material. Outputs are usually emissions into the air, water or earth, waste and side-products.

Standards ISO 14040 and ISO 14044 regulate four phases in the procedure of environmental impact measurement (Fig. 2.1): a) Goal and scope definition; b) Life cycle inventory analysis (LCI); c) Life cycle impact assessment (LCIA); and d) Interpretation. LCA consists of mandatory (a, b, c) parts and optional (d) part, which can be adjusted to specific requirements (Hildebrand, 2014).

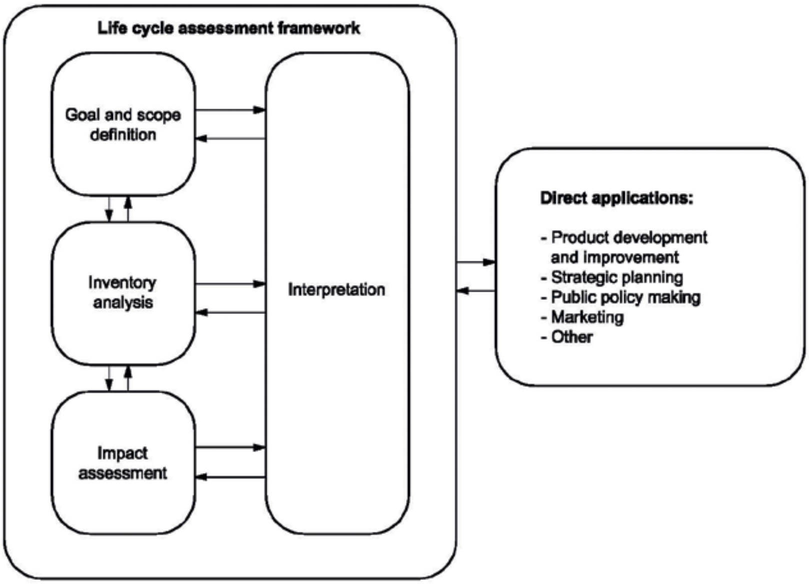

FIG. 2.1 The structure of LCA according to ISO 14040

## 2.1 Goal and Scope

Precise definition and description of the goal and scope account for the first stage in LCA. Intended application should be specified concerning motivation, audience, and context of the study (Hildebrand, 2014). The goal and scope are defined within the following dimensions: Functional units; Life cycle phases; and System borders.

### 2.1.1 Functional Unit

The description of an object of evaluation (product, service, or company), called functional unit, needs to be precisely specified. Here, a functional description explaining in detail the performance of an object of ecological evaluation by using a range of physical numbers is required (for example, ten square meter exterior wall with a certain thermal resistance).

### 2.1.2 Life Cycle Phases

From one aspect, the scope of evaluation is described by life cycle phases. The life cycle phases of a product can be subdivided into production, usage, and end of life phase (Hildebrand, 2014). When comparing different products, all framework parameters should be aligned, especially the life cycle phases.

If the objective is to evaluate only production of a material or a component, then the included scope is called *from cradle to gate*: the cradle refers to excavation of resources and the gate to factory. When the complete cycle until the end of the usage phase is included, the scope is *from cradle to grave*. A LCA can consider the phases from cradle-to-gate (upstream processes), from gate-to-gate (manufacturing processes), from gate-to-grave (downstream processes), or include all phases in a cradle-to-grave consideration (Hildebrand, 2014) (Fig. 2.2; Table 2.1). BS EN 15804:2012 defines the phases in more detail (DIN, 2012).

The cycle is applied to both materials and buildings. The cycle of a building material and the cycle of a building differ specifically in the phase of utilisation. For comparison, while building utilisation relates to the significant energy consumption, the usage phase for materials only includes energy needed for material maintenance, replacement, or reparation.

The most prevailing segments in the LCA of a material are (mandatory) production and the end-of-life. The following text reviews the most significant steps of a LCA developed on the basis of the BS EN 15804:2012 (DIN, 2012).

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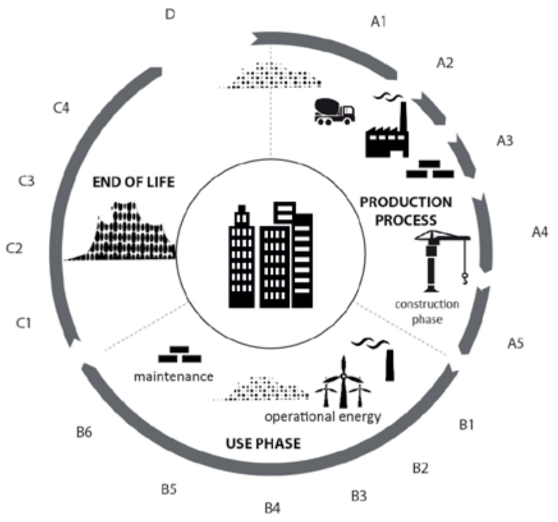

| A1 | RAW MATERIAL SUPPLY |
|---|---|
| A2 | Transport |
| A3 | Manufacturing |
| A4 | Transport |
| A5 | Construction/ installation process |
| B1 | Use |
| B2 | Maintenance including transport |
| B3 | Repair and transport |
| B4 | Replacement including transport |
| B5 | Refurbishment including transport |
| B6 | Operational energy use |
| B7 | Operational water use |
| C1 | De-construction demolition |
| C2 | Transport |
| C3 | Waste processing |
| C4 | Disposal |
| D | Re-use recovery and recycling potential |

FIG. 2.2 Life cycle of building materials in phases *(Hildebrand, 2014)*;
TABLE 2.1 List of phases according to EN 15804

### Production stage (A1-A3)

The life of any product starts with resources depletion. It is then followed by the transportation of raw material to processing facilities and production. The distance from source to factory and the mode of transportation together influence the strength of environmental impact caused by transport. During the production process, utilisation of energy accounts for the main environmental burden, and the amounts of accompanying generated emissions depend on the primary energy resource. For example, 1 MJ from a brown coal power station releases significantly more emission than 1 MJ from wind energy (Hildebrand, 2014).

### Transport and construction stage (A4-A5)

The energy and emissions related to transportation depend on the distance between the construction site and the manufacturer's plant. In the studies published by Kellenberger & Althaus (2009), transportation accounted for 5-8% of the total primary energy demand. However, the data for building material are not available, which most commonly leads to an exclusion of this stage. In the phase of construction, all efforts on the site and between manufacturing facilities are calculated. Therefore, gathering the data on this life cycle phase requires sufficient detailing.

### Usage stage (B1-B7)

The utilisation of building materials starts when a building is completed and its operating system begins to provide useful forms of energy. In terms of materials and components, building operation is not relevant, but the flows related to their repair, replacement, and maintenance are. Rarely, building elements require energy supply for their performance, e.g. permanently inflated foil cushions. The extent of ecological impact in usage stage highly depends on the building context, its exposure to weather and other forces, as well as on material content.

**End-of-life stage (C1-C4, D)**
End-of-life starts when an item has lost its function. The actual processes cannot be foreseen, and so the end-of-life scenarios are simplified and their accuracy accordingly questioned. Generic scenarios cover the flows for most building material. The generic end-of-life scenarios are: Building rubble procession; Recycling; Energetic recycling; and Landfill (Hildebrand, 2014).

### 2.1.3 System Border

The border of a system undergoing life cycle assessment identifies included and excluded parameters. In addition to the life cycle phases, the flows included and excluded from the calculation are mentioned.

Only significant processes should be included in assessment in order to balance complexity in gathering the data. The significance is defined by a certain percentage of contribution of individual product to the whole system, based on mass, energy, or ecological significance (DIN EN ISO 14044, 2006). The percentage and the units should be documented under this category.

LCA method can be classified as comparative or descriptive. The assessment of variants and the delivery of decision-basing data represent the scope of comparative LCA. On the other hand, descriptive LCA analyses the distribution of different components of an assessed product or service (Hildebrand, 2014).

## 2.2 Life Cycle Inventory Analysis (LCI)

All relevant processes are defined within the life cycle inventory analysis (LCI). Usually, this is the most resource-intensive evaluation stage and an iterative process (Klöpffer & Grahl, 2014). In the inventory, all flows are quantified and categorised as input or output flows. Elementary flows are resource consumption and emission. Inputs and outputs are categorised as follows: Energy inputs, raw material inputs, ancillary inputs, other physical inputs; Products, co-products and waste; Releases to air, water and soil; and Other environmental aspects (Hildebrand, 2014).

A special relevance in the process of data collection is given to the following factors: time, geographic origin, and data consistency. Validation in terms of comprehensiveness and plausibility and proper data documentation are mandatory. Accompanying sensitivity analysis, as a part of the LCI, enables confirmation and an adjustment where necessary.

Most industrial processes have more than one product as output. When co-products occur in the process of an investigated product, input and output flows have to be partitioned. The ISO 14044 (2006) standard defines this action as "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". Due to variability found in functional units, the so-called allocation becomes intricate and should, as such, be avoided. Division of inputs and outputs should be done according to the weight, volume, or monetary value.

## 2.3 Life Cycle Impact Assessment (LCIA)

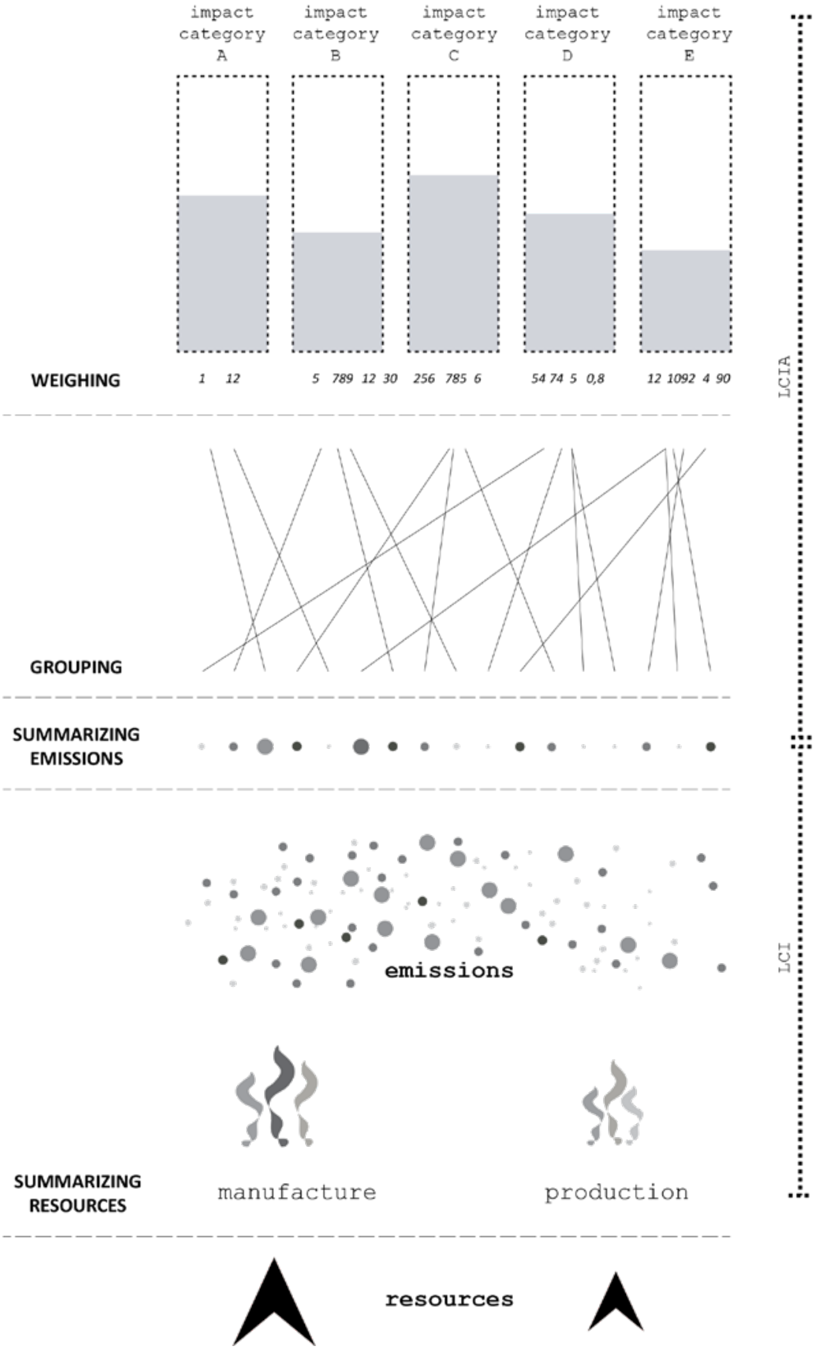

FIG. 2.3 LCI and LCIA built up on one another *(Hildebrand, 2014)*

LCIA is the quantification of all input and output flows related to a functional unit. Emissions (impact indicators) with different levels of harmfulness are taken into account in one category group by weighting (Fig. 2.3) (Hildebrand, 2014). The results are sorted into impact categories on the basis of ecological effects. LCIA stage is, according to the ISO 14040, divided into three mandatory steps: 1) Selection of impact categories, category indicators and characterisation models; 2) Classification: Assigning the LCI results to impact categories; and 3) Characterisation: Calculation of the category indicator results.

## 2.3.1 Characterisation Models

In comparison with the emissions that can be monitored and calculated, the measurement of environmental impact related to a process is more complex. Different methods for translating emissions into ecological impairment were developed to estimate the harm on nature. Ecological protection targets are defined and all emissions affecting them are listed in a target or impact category. Within a group, the weight of emissions is defined on the basis of their environmental harm. For example, both carbon dioxide and methane contribute to global warming potential. However, since methane has a higher environmental impact than carbon dioxide, a factor is applied to compensate for this difference. When a common denominator is found, the two emissions can be expressed using the same unit (category indicator, in LCA terms) (Hildebrand, 2014).

| IMPACT ASSESSMENT METHODS | PUBLISHER /DEVELOPER | COUNTRY CODE |
|---|---|---|
| BEES | National Institute of Standards and Technology (U.S. Department of Commerce) | USA |
| CML-IA | University of Leiden CML | NL |
| Eco-indicator 99 | PRé Consultants bv | NL |
| EDIP 2000/ EDIP 2003 | Institute for Product Development (IPU) | DK |
| EPS 2000 | Swedish Environmental Research Institute (IVL) | SE |
| Impact 2002+ | Risk Science Center | USA |
| Ecological Scarcity (UBP Method) | Öbu/ FOEN | |
| ReCiPe | RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. | NL |
| Traci 2 | U.S. Environmental Protection Agency | USA |
| TWIN2010 | NIBE/ Stichting Bouwkwaliteit | NL |
| USEtox | UNEP-SETAC | USA |

TABLE 2.2 International characterisation models *(Hildebrand, 2014)*

An overview of different developed characterisation models is provided in Table 2.2. Every model contains protection targets expressed by impact categories, category indicator, and a list of emissions that belong to the impact category, and the factor by which these emissions need to be quantified. Impact indicators address target on midpoint or endpoint level. For example, while midpoint level addresses ozone depletion potential, the endpoint would express contribution to cancer.

(For further information: Bare, 2002; Finnveden et al., 2009; Guinée et al., 2011; Heijungs et al., 1992; Matthews et al., 2015; Ministry of Housing, Spatial Planning and the Environment, 2000)

Most characterisation models offer a weighting for normalisation, thus describing the method by which to calculate one of the several indicators. ISO 14040 names three optional steps: 1) Normalisation: Calculation of the magnitude of category indicator results relative to a reference; 2) Grouping: Sorting and ranking of impact categories; and 3) Weighting: Multiplication of indicator results.

For the normalisation, indicator results are divided by a selected reference value, for example, the results for global warming potential (GWP) are divided by whole annual GWP of Europe. The aim is to reveal which indicator contributes more to the overall problem area (Lützkendorf, 2009).

Grouping defines a hierarchy of categories based on value-choices (Klöpffer & Grahl, 2014).

Weighting accumulates different indicators into a holistic one to provide a clearer suggestion and avoid contradictions (Crawford, 2011). This complex process is comprehensively discussed in the research sphere. Wegener Sleeswijka, van Oersc, Guinée, Struijsd and Huijbregtsb (2007) describe the constraints in merging different factors into a single value, and present an overview of applied normalisation methods. In the building sector, this action seldom finds its application due to constrained traceability. Green building certificates try to meet the demand by displaying a variety of indicators and calculating them into one grade.

## 2.3.2 Indicators

The characterisation is, as explained, organised in impact categories. These count as indicators for quantifying the environmental impact. The most common indicators are introduced below.

*Embodied* or *grey energy* describes the amount of energy used to produce, maintain, and demolish or deconstruct a building. In contrast to operational energy, this type is not visible on one bill, but has to be calculated from different process steps. Primary energy (PE) consists of primary energy from renewable and from non-renewable resources. Since primary energy from non-renewable resources has a more harmful impact on nature, this indicator finds a broader application. Non-renewable primary energy PE(nr) originates from fossil and nuclear energy sources. Renewable primary energy PE(r) contains energy generated by wind, water, solar radiation, and biomass. PE is typically measured in megajoules (MJ), or less often in kilowatt hours (kWh) (Hildebrand, 2014).

Embodied energy (EE) is not defined by standards. In literature, the examples in which EE expresses other emission indicators can be found. In Eco-Devis, for example, 2g of a solvent account for 1 MJ of primary energy (Pestalozzi, 2014). This mixture of parameters leads to incomparable indicators. In order to counteract such complications, the *cumulated energy demand* (CED) was developed by Kasser (2003), and elaborated upon by Frischknecht (2006). CED defines energy categories and excludes any other factors. It is regulated by the VDI standard 4600 (2012): Cumulative energy demand (CED) - Terms, definitions, methods of calculation (VDI, 2012). CED includes the expenditure of primary energy for production (CEDH), use (CEDN) and the end of life phase (CEDE) of a product or service similar to the EN 15804. VDI 4600 (2012) distinguishes between primary energy from non-renewable energy sources (KNAR) and from renewable resources (KAR). Both are included in the CED indicator (Hildebrand, 2014).

Besides embodied energy, the *embodied emissions* represent the common set of indicators used to quantify the environmental impact of a product or a service. In this group, the following indicators are found:

- Global Warming Potential (GWP 100);
- Ozone Depletion Potential (ODP);
- Acidification Potential (AP);
- Eutrophication Potential (EP);
- Photochemical Ozone Creation Potential (POCP); and
- Abiotic resource depletion potential (material) (ADP element) / Abiotic resource depletion potential (ADP energy) (fossil).

### Global Warming Potential (GWP 100)

The increase of greenhouse gases in the atmosphere causes temperature increases, which further affect poles and advances the depletion of their ice volume, resulting in the rising sea level. Global warming provokes climate change and intensifies the occurrence of extreme weather events. Due to the awareness of these interdependencies, the *Global Warming Potential (GWP 100)* indicator is the most commonly used. Being the most common greenhouse gas, carbon dioxide ($CO_2$) is used as a reference for this impact category ($CO_2$-equivalent). Other emissions contributing to greenhouse effect are factored in as explained earlier.

### Ozone Depletion Potential (ODP)

With the depletion of the protective ozone layer, ultraviolet (UV) radiation penetrates the filter, enhances air warming and potentially causes harm to human health and living organisms. In the past, the main contributor to ozone depletion was Chlorofluorocarbon (CFC), which is often used as freezing agent. With the CFC/Halon prohibition ordinances (OzonAction Programme, 2000), depletion decreased significantly but the effects that had already been generated will remain. Trichlorofluoromethane (R11) is used as an equivalent within this emission category.

### Acidification Potential (AP)

The conversion of emissions of some harmful substances that reduce the pH value (such as sulphur dioxide and nitric oxides) can provoke the occurrence of acid rains which further affect water and soil, and cause forest die-back. *Acidification Potential (AP)* is indicated in sulphur dioxide equivalents ($SO_2$ equivalent).

### Eutrophication Potential (EP)

As a response of the water ecosystem to increased presence of fertilisers, eutrophication describes the growth of algae in surface water. Newly-formed algae cover blocks the penetration of sunlight into deeper water layers, decreases photosynthesis, and reduces oxygen levels. Consequently, fish and plants lose the fundamental requirements of existence and die. The *Eutrophication Potential (EP)* is expressed in phosphate equivalent ($PO_4$- equivalent).

### Photochemical Ozone Creation Potential

High ozone concentration is toxic for humans as it can lead to breathing difficulties. In addition, it is suspected to be responsible for damage to vegetation and material. A high concentration of ozone in the troposphere occurs under high summer temperatures accompanied by low humidity and the absence of air movement. A typical example of a photochemical ozone occurrence in late summer is in an enclosed area of a highway with a high traffic load. Photochemical ozone develops in a complicated chemical process, when $CO_2$ and $SO_4$ are emitted with high intensity. The *Photochemical Ozone Creation Potential (POCP)* is measured in ethene equivalent ($C_2H_4$-equivalent).

### Abiotic Resource Depletion Potential (material) (ADPe), and Abiotic Resource Depletion Potential (fossil energy) (ADPf)

Abiotic depletion relates to the extraction of minerals and fossil fuels. It considers the amount of global reserves that can be exploited economically. Annual extraction is divided by the reserves squared. Hence, the amount of abiotic resources for a process, in relation to the global amount of this resource, defines the abiotic resource depletion potential (Hildebrand, 2014). According to Oers, Koning, Guinée, and Huppes (2002, p. 29), the "abiotic resource depletion is the decrease of availability of functions of resources, both in the environment and the economy". ADPe result is related to the reference element antimony (Sb). By including the annual extraction rate, the current importance of a given resource is captured (JRC, n.d.). ADPf is calculated analogously, with the difference being that the lower heating value of the fossil fuel is used instead of material mass. Therefore, the unit is Mega Joule (MJ).

## 2.4 Interpretation

The interpretation after LCI or LCIA is aimed at identifying the achievement of significant results in line with defined items in goals and scope. According to ISO 14044 (2006), significant results can be "inventory data, such as energy, emissions, discharges, waste, impact categories, such as resource use, climate change, and significant contributions from life cycle stages to LCI or LCIA results, such as individual unit processes or groups of processes like transportation and energy production". By controlling compatibility with aims and scope, interpretation verifies requirements fulfilment.

# 3 The Scope of LCA Data: Evaluation Criteria

Scale defines the potential to influence the ecological quality of a planned object. For materials and components, the scale can be differentiated from small to large. Buildings and urban or neighbourhood scales, on the other hand, build up on smaller units.

On the urban scale, energy supply and mobility associated with the location of the site predefine the ecological impact. For new developments, the increased share of renewable energy and the integration into a network (e.g. smart grid, or smart city) reduce (non-renewable) energy demand and thereby emissions, as compared to conventional supply. The decision about the location of a new development will impact the energy needed for transportation. While in rural areas individual transport is required, re-densification can include options for public transportation. On the building level, the decisions are similar. Site limitations and potentials shape the options for energy supply and mobility types, and passive properties such as orientation and heat insulation, as well as the active energy systems, influence the ecological dimension.

Building material is the smallest module of a building. To that end, ecological analysis on the material scale provides a generic comprehension of the impact that building fabric makes on environment. The motivation to calculate or measure the ecological impact of a service or product is informed by the need to make a responsible decision. Not just on material scale, it is therefore necessary to have different options evaluated against each other. As explained within the section *Goal and Scope* of this work, these options are called 'functional units' in LCA-terms. On the material scale, functional unit is one unit of weight or volume or sometimes area. The most common scenario in which to use LCA data on a material level is to compare two or more different products with equal functional characteristics.

The increasing amount of standardised LCA information has improved communication between stakeholders (companies, planner, and client). LCA information that is available for building materials ranges from various database sheets to environmental product declarations (EPDs), and from concise to very detailed presentations. Categories to express LCA results need be comprehensible and practical at the same time. To support readability, Hildebrand (2014) recommended the following criteria to be sought when working with the LCA data:

- Evaluation goal;
- Data source;
- Generic and specific LCA data and its validity;
- System borders;
- Reference unit;
- Life cycle phases;
- Considered time span; and
- Indicator.

**Evaluation goal: What is the purpose of evaluation?**
If only one item is assessed, the purpose of evaluation could be to present ecological impact of a function, product or service. More likely, the goal of evaluation is the comparison of different products or services. Both the evaluation (with at least two items included) and the LCA goal (one item) relate to quantification, i.e. to the definition of ecological dimension by using numbers. On the basis of comparison, the evaluation most frequently aims at finding the solution with the lowest ecological impact. With the identification of detailed (research) questions, evaluation is deepened. Other possible evaluation goals could be the comparison of generic and specific data or the variation with regard to changeable durability (Hildebrand, 2014).

**Data source: Where does the data come from and is it complete?**
Firstly, the source of all data needs to be traceable, meaning that the documents of data's origin should be accessible. All included impact categories must be explained and the life cycle phases shown. When relevant, it might also be useful to include the information on pre-chains.

Consistency represents the key to data selection. Selected data should correspond to the evaluation scope and goal and should as such be documented. When applying more than one database, their belonging to the same framework needs to be secured. Third party document review is preferred over the manufacture information on products.

**Generic and specific LCA data: Does the information base on an average value or a specific product?**
Generic data is obtained by averaging the values from different published sources. For certain products, generic information is the only provided as manufacture did not include the LCA. Specific or product-related data are suggested rather than general data. The specification additionally affects data validity. According to the EN 15978 (CEN, 2011), generic data should not be older than ten years, as this is the assumed period of time during which the general processing line will not undergo significant changes, and any small change will not affect the average values considerably. On the other hand, specific data should

be derived within the last five years, as any change introduced to the production process could potentially reflect on ecological impact.

**System borders: Which boundary conditions are included?**
Like stated earlier, system borders define the information that is significant for assessment. Here, the recycling approach presented by displaying life cycle phases is relevant.

**Reference unit: What unit is the basis for comparison?**
The reference unit for a building material relates to a mass (1 kg), volume (1 m$^2$) or an area (1 m$^2$). These units are applicable to general comparison and simplified approach. A typical illustrative question could be: What material embodies more GHGs – steel or aluminium?

While material comparison only represents the starting point, the inclusion of functionality increases information value. The inclusion of load-bearing capacity, cost or heat transmission characteristics therefore indicate a more complex evaluation goal.

**Life cycle phases: Which phases are included?**
Life cycle phases included in a LCA are based on the EN 15804 description. On material level, production and partly end-of-life phases are the most common. Depending on the life span, replacement cycles can be added. The energy used for building operation is included on building level.

**Considered time span: For how long is function provided?**
In ecological evaluation, time dimension is used in three different ways. For describing scenarios and expressing the expected number of year of a function, the *life span*, also called the *duration*, is often used. Life span may refer to a certain aspect of performance such as technical where the time during which an object functions as initially expected is defined. L*ife time* describes the period of existence of an object. To express emissions contributing to a certain effect, the term *time span* used. It is defined per indicator group in which the effect of one emission is accounted. For example, the effect of $CO_2$ in the atmosphere is assessed for the period of hundred years as it is believed that the impact is traceable within this time span (Hildebrand, 2014). The life span of materials differs, and combinations and connections impact the exchange cycles.

**Indicator**
Indicator is chosen within the LCA scope and goal. Most commonly, global warming potential and primary energy (non-renewable) will be displayed.

## 4 Application of LCA Data

In building industry, LCA data are available as generic or product based information. In order to provide fact-based alternatives to the so-called greenwashing information, data were gathered and made publicly available. Another attempt was the introduction of a third-party review certificate, i.e. the Environmental Product Declaration (EPDs).

Online portals today enable the acquirement of information about building materials through *databases.* Every database is referring to different assessment terms. Some well-known databases include Ecoinvent (http://www.ecoinvent.org), Inventory of Carbon and Energy (http://opus.bath.ac.uk/12382/), Ökobau.dat (http://www.oekobaudat.de/en.html), and Wecobis (https://www.wecobis.de, available in German language).

The aim of an *Environmental Product Declaration* is to "present quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function" (Belavicqua, Ciarapica & Giacchetta, 2012, p. 349). All products subjected to comparison need to be assessed under equal circumstances. Product Category Rules (PCR) were developed to regulate parameters such as life cycle phases, in- and excluded process or allocated products for each product category group. While ISO 14025 (2006) defines the PCR structure, the content is filled by institutes issuing certificates in collaboration with industry partners. The introduction of the PCR essentially helps to build objective comparison, and therefore enhances LCA data acceptance.

Among others, Swedish Environdec and German Institute for Construction and Environment have to-date issued EPDs in more than 20 categories within the construction sector (IBU, n.d). Usually, it is the company that approaches an institute with the request for EPD. If a PCR is available, a LCA consultancy can conduct the calculations. In the opposite case, PCR will be developed. According to the ISO 14025, an external professional will be asked to verify accordance with the ISO 14040 standard and the PCR.

EPD based on standard ISO 14025 contributes to the integration of life cycling into practice and the trustworthy and clear presentation of ecological information. The introduction of EPDs and the availability of databases prepared the foundations for LCA data utilisation in building industry. Today, green building certification systems like LEED and DGNB require LCA in order to reach the highest standard.

## 4.1 Material Evaluation and Comparison

The application of ecological information is no longer reserved for LCA professionals as the data are freely accessible. Still, a fundamental understanding of the LCA is needed among architects and engineers working with sustainability. To that end, it seems helpful to have an overview of the LCA material data.

Hildebrand (2014) carried out the evaluation of all five basic types of materials: minerals, wood, metal, synthetics and insulation materials, grouped according to the ecological impact.

In total, eighty materials from the open access data base *Ökobau.dat* were analysed regarding the primary not renewable energy (embodied energy, EE) and GWP for the production of one kilogram of material. To compare the ecological qualities on material level, one kilogram is isolated from its functional context and the primary energy embed in different materials could be compared. The results of research are presented below.

Embodied energy (EE) ranges from 0 to 200 MJ for 1 kg and from 0 to 900,000 MJ for 1 $m^3$, for all material groups. Mineral materials show value from 0.5-9 MJ per kilogram except the glass with approximately 18 MJ/kg. Aggregates have the lowest values with 0.5 MJ (gypsum stone). The maximum values of embodied energy are found in natural stone. For cementous products, EE raises with the percentage value of steel reinforcement. This is also true for growing amounts of cement sinter, while blast furnace slag, aggregates cement or other recycled content help to reduce the impact.

Wood based products embody a range from 5- 21 MJ/kg of energy. Primary renewable energy is even higher, from 8-53 MJ/kg, having regarded that this material captures $CO_2$ in the growing phase and releases it when rots or burnt. The longer the carbon is stored in the building context, the later it can function as GHG. Installing a wood product in a building, as compared to letting it rot in the forest, helps extend the storage period and postpones the moment of release (Walz, Taverna & Stöckli, 2010), and additionally prevents the use of fossil resources for building materials.

EE for metals varies from 14 MJ/kg for copper (bronze) to 149 MJ/kg for aluminium casting. Steel products vary from 20-30 MJ; only the stainless steel is higher with 61 MJ/kg. Aluminium marks the highest values with 130-150 MJ/kg. Compared to other material groups, metal has the highest potential for material recycling. Up to 90% of EE can be saved when using recycled aluminium instead of a virgin material.

EE value for synthetic materials is from 30-150 MJ/kg. The least value of embodied energy is found in linoleum. On the other hand, materials that are more transparent embed the highest amounts of energy. Obtained values can be compared with those valid for primary aluminium. The main reason for the high value of EE is the nature of production chain (from raw material to final product) which is consisted of many steps. Regarding recycling, material purity determines to a large extent the achievement of level of quality as compared to the first-time produced material.

## 4.2 Functional Unit in the Building Context

Ecologic values introduced in the previous section aim at gaining a profound understanding of the evaluation comparing LCA results on the basis of mass. Nonetheless, this type of material consideration is isolated from building context because it doesn't include functionality.

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A material can perform different tasks; only when placed in functional context, a fair comparison between different materials can be made.

When functional unit is defined, LCA uses it as a base for comparing multiple solutions. The function of a unit is ideally described numerically. As isolated functions are described more easily, LCA evaluation on material and component levels is recommended. For insulation material, for example, the function can be determined according to one property that is heat conductivity (Fig 4.1).

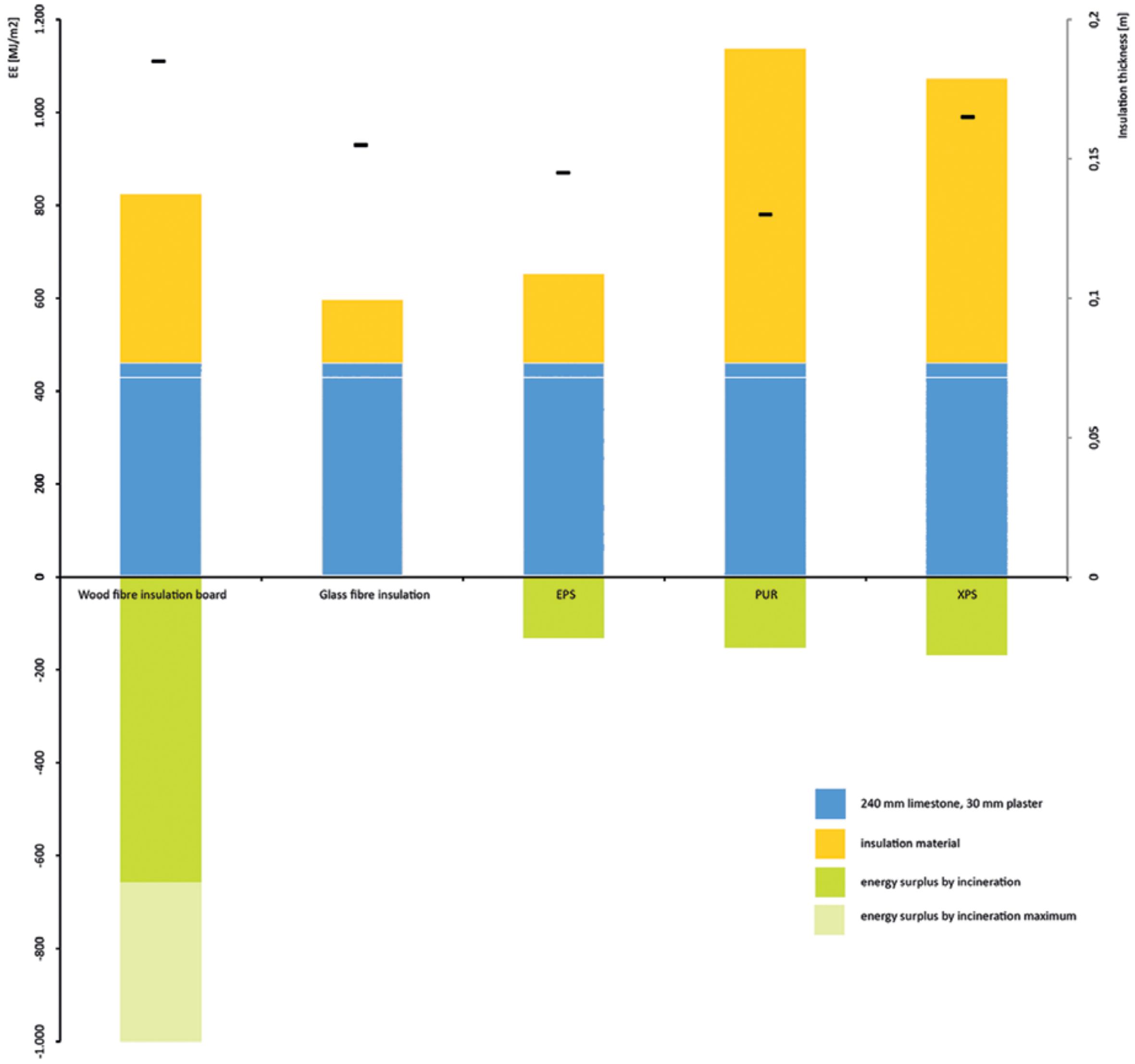

FIG. 4.1 Comparison of different insulation material (0,2 W/sqmK, 240 mm limestone, 30 mm plaster) *(Hildebrand, 2014)*

Here, LCA application can be demonstrated by example where the task is to identify insulation material with the least environmental burden. The function to be performed is heat resistance of 0,2 W/m$^2$K. For that objective, a limestone wall with five different insulation material types is compared based on EE and GWP. To fulfil functional requirement and keep the same thermal resistance of compared materials, insulation thickness varies from 155mm for glass fibre insulation to 145mm for expanded polystyrene (EPS). The EE varies from 134- 190 MJ/m$^2$. Even it is thinner, synthetic insulation material requires more energy in production. When end-of-life scenario is included, the intensity is more accentuated (Hildebrand, 2014).

Although calorific value of synthetic materials leads to improved performance regarding embodied energy, an extensive separable demolition represents the precondition of this end-of-life scenario. The same interdependency applies to wood fibre insulation. To draw end-of-life scenario, the connectivity of materials and hence the potential for reuse and recycling are defined on construction level. When the type of construction and the simplified end-of-life scenario are aliened, LCA becomes a method to compare different planning solutions against each other and to quantify the ecological dimension of each of them.

# 5 Discussion and Conclusions

## 5.1 Potential and Constraints of the LCA

The purpose of the paper is to stimulate awareness about ecological impact of building materials and to provide an overview of the method which supports design decision-making process.

Progressive application of the LCA data in building sector is supported by the availability of different types of third party review certificates (EPDs) used by companies to promote products. Especially in Western Europe, the increasing product evaluation leads to data availability, where results are gathered and updated in databases. In Germany, UK and Netherlands, LCA is often accessible free of charge.

While positive marketing aspect in some countries improved the data situation, the application as a decision-making basis cannot be documented due to its voluntary nature. According to the environmental relevance of materials, which will grow with the reduced (not renewable) energy needed for building operation, LCA data should be included in building permits. For this to happen, the conditions need to be developed on political level and to include not only the display but also the benchmarks for embodied energy and emissions. In existing green certificates, different benchmarking approaches can be found. For example, Swiss model assigns to every inhabitant 1 ton of carbon dioxide per year based on the planetary boundaries. Such models are needed to bring climate goals into practice, like agreed by the Paris Agreement.

The iterative process of developing solution, assessing operational and embodied energy and emissions, and comparing results against

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an alternative can be simplified and accelerated by using the tools. To that end, the number of tools integrating LCA data as a decision basis in the planning phase is growing, just like the open access tools for comparing alternatives on component or building levels.

Especially in early design phase, working with LCA data as decision basis requires the definition of assumptions regarding cubature and choice of products. Nonetheless, the studies have shown that the uncertainty related to these assumptions does not impact result essentially. The relevance of information for the LCA grows with the level of detail.

The choice regarding end-of-life scenario accounts for a highly uncertain subject due to the time span from planning to demolition, as economic background, technical developments, legislation and user requirements can change significantly in a period from 50-100 years. In all cases, decision about the end-of-life scenario must be such as to secure the protection of material value.

- The challenges in reducing the ecological impact of building materials can be summed up as:
- Gathering of sufficient national data, as a prerequisite;
- Development of legal background including benchmarks;
- Access to the tools that support integration on material and building level;
- Addressing the uncertainty in order to define the scope;
- Inclusion of the end-of-life scenario in construction.

## 5.2 Outlook

The general trend of growing complexity of data in the building context points at the need to improve data management systems that support decision-making in all planning stages: in design phase, the selection of the best material and construction type; in operational phase – provision of information on exchange cycles; and in the end-of-life – informing about the designated reuse and recycling scenario.

One of the greatest challenges in the field is transition between life cycles. The potential for re-integration of materials and products for further use on component (reuse) or substantial (recycling) level needs to be enhanced in many aspects. On practical level, the legal issues must be solved, the provision of secondary resources needs to be decentralized and, most of all, planners and clients need to demonstrate the willingness to use products with recognisable traces from the former usage phase or/and the products that do not communicate sustainable attitude only by visible marks.

In the context of the LCA, methods are needed to reflect the value of material after its first usage phase. Ecological benefits of reusing and recycling, or the preparation for reuse and recycling need to be quantified. Only then the sensible solution can be implemented and the purpose of the LCA, which is to support the design option with the best environmental performance, can be fulfilled.

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