MASTERARBEIT

A Review of International LCA Standards in the Building Sector

ausgeführt zum Zwecke der Erlangung des

akademischen Grades einer Diplom-Ingenieurin

unter der Leitung von

Univ.-Prof. Dipl. -Ing. Dr. techn. Ardeshir Mahdavi

&

Senior Scientist Dipl. -Ing. Dr.techn. Ulrich Pont

E 259-3 Forschungsbereich für Bauphysik und Bauökologie

Institut für Architekturwissenschaften

eingereicht an der

Technischen Universität Wien

Fakultät für Architektur und Raumplanung

von

Mira Grahovac, BSc.

Matrikelnr. 1227081

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KURZFASSUNG

Das primäre Ziel dieser Masterthese ist es, einen fundierten Überblick über den Stand der Vorgaben und normativen Dokumente, sowie Empfehlungen über Ökobilanzierung (im englischen als „LCA“ oder auch Life Cycle Assessment / Lebenszyklusbilanzierung) im Bauwesen zu erarbeiten. Gleichwohl es sich nicht um ein neues Feld der Wissenschaft handelt, ist in den vergangenen Jahren festzustellen, dass sowohl die Anzahl an Publikationen, wie auch die Betonung der Wichtigkeit des ökologischen Fussabdrucks im AEC-Kontext (Architecture-Engineering-Construction) gestiegen ist. Das dürfte vor allem damit zusammenhängen, dass das Bauwesen als einer der größten Energieverbraucher einerseits, und einer der größten Emittenten von klimaschädlichen und umweltbeeinträchtigenden Substanzen andererseits identifiziert wurde. Um die grundsätzlich sehr mächtigen Werkzeuge der Ökobilanzierung auch für diejenigen Stakeholder zu erschließen, die in Planung von Neubauten und Sanierungen tätig sind, ist es erforderlich einen Überblick über die komplexe Landschaft der Richtlinien und Vorgaben zu erarbeiten. Besteht ein einfacher Zugang zu dem Wissen in dieser Domäne, ist eine Berücksichtigung in der alltäglichen Arbeit einfacher möglich was den entsprechenden Zielsetzungen zur Einsparung von Ressourcen und Emissionen im Bauwesen entspricht.

Der Schwerpunkt der vorliegenden Arbeit liegt auf den aktuell gültigen normativen Dokumenten, welche sich Ökobilanzierung für Gebäude und Bauprodukte auseinandersetzen. Dabei sind die von der Internationalen Organisation für Normung (eng. „ISO“ – International Standardization Organisation) und der Kommission für Europäische Normung (eng.“CEN - Comité Européen de Normalisation;) veröffentlichten Standards die wesentlichsten: Diese Standards gelten als der valide Versuch, die Ökobilanz-Methodik im Bausektor auch über Ländergrenzen hinweg zu harmonisieren. In der Masterthese werden entsprechende Dokumente und Literatur zu den wesentlichsten gebäudebezogenen LCA-Normen der ISO und CEN zusammengefasst und strukturiert beschrieben. Darüber hinaus werden wesentliche Zusammenhänge und Aspekte der Domäne erklärt, wie z.B. gebäudebezogene Ökobilanznormen, Ökobilanzdatenbanken und Ökobilanztools innerhalb des Gebäudesektors. Ebenfalls werden Verbindungen zwischen Umweltzeichen, Gebäudezertifikaten, Designwettbewerben und gebäudebezogenen Ökobilanznormen dargestellt, die ein Bild des aktuellen Stands der Implementierung von Ökobilanzierung im Bausektor aufzeigen. Das Ziel dieser Bemühungen ist es, eine einfach zu lesende Master These anzubieten, die als Einstiegs- und

Überblicksliteratur von Personen genutzt werden kann, die sich erstmals mit der Domäne Ökobilanzierung von Bauwerken befassen und für die entsprechend wichtigsten Informationen und Daten über die Anwendbarkeit von Ökobilanznormen in der Praxis zur Verfügung gestellt werden sollen. In der Schlussfolgerung der Arbeit wird letztlich zusammengefasst, welche Anstrengungen aktuell unternommen werden und welche noch unternommen werden müssen, um die Ökobilanz-Methodik im Bausektor weiter zu harmonisieren und damit eine breitere Anwendung dieser Methoden sicherzustellen.

Schlüsselwörter :

Ökobilanz, gebäudebezogene Ökobilanznormen, Internationale Organisation für Normung, Kommission für Europäische Normalisierung, Europäische Plattform zu Ökobilanznormen im Bausektor

ABSTRACT

The primary objective of this thesis is to provide a profound review onto the current state of regulations pertaining to building related Life Cycle Assessment (LCA), and to review current publications pertaining to application of these standards. Moreover, recommendations for the further development of these standards shall be provided. While ecology of the built environment and LCA is per se not a new field of science, it can be observed that the relevance of the field gained momentum, given the increasing number of publications and the integration in laws and regulations, as well as policies of different countries. Presumably this has to do with the fact that the built environment (construction as well as operation and disposal of buildings) has been identified as a major emission source of greenhouse gases and environmentally hazardous substances as well as a major consumer of energy. To increase the efficiency of life-guided design, the tools and instruments of building related life-cycle evaluation need to be become accessible for the stakeholders involved in building planning and delivery. As such, the present master thesis intends to facilitate the access to LCA terminology and standards by providing a comprehensive overview of the complex landscape of existing standards and guidelines. It can be assumed that if standards and guidelines are better understood by the majority of stakeholders within the domain, their application will be emphasized in current and future planning processes.

The focus of the contribution has been put on the current state of international and European standards in the field of life cycle assessment of buildings and building materials issued by ISO (International Standardization Organisation) and CEN (Comité Européen de Normalisation). These standards aim at the harmonization of ecology evaluation approaches amongst different countries. In this master thesis, the major building-related ISO and CEN standards on environmental evaluation are summarized in a structured fashion. Moreover, major terminology, aspects, and interdependencies within the domain are described, for instance relevant databases and recommended tools. Furthermore, eco-labels, building certificates, connections to architectural competitions, and the current deployment of different domain-relevant tools are discussed. All these efforts are intended to result in an easy-to-read introduction for people of little to no background knowledge in the field of building ecology. Based on the structured review of the existing standards, the work concluded with concepts and recommendations, how to further emphasize the harmonization and deployment of LCA-methods in the AEC (architecture-engineering-construction) domain.

Keywords

Life Cycle Assessment, LCA building related standards, International Organization for Standardization, Commission for European Normalization, European platform regarding the LCA standards in the building sector

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Dedicated to my dad.

CONTENTS

1 INTRODUCTION

1.1 Overview

Building's construction and related operations are responsible for 36% of global end-energy use and almost 39% of energy-related carbon dioxide (CO_2) emissions (IEA 2019). The building sector as such is undoubtedly one of the major polluters of the environment (IEA-UNEP 2018). Hence, improving the environmental aspects and responsibility of the building sector is becoming one of the main issues in building planning and delivery as well as in the overall construction domain.

Currently the environmental impact of products and processes has become one of the most crucial problems in the struggle with climate change (Sadler et al. 2011, UKGBC 2019). Different international organizations and policy makers are trying to find strategies and management systems to reduce their effect on the environment. Life cycle assessment has proven itself as increasingly accepted method in the analysis of the environmental impacts related to building materials and buildings (Reiter 2010, Anand et al. 2017).

Life Cycle Assessment (LCA) is a structured, comprehensive and internationally standardised method. It quantifies all relevant emissions and consumed resources and the related environmental and health impacts and resource depletion issues that are associated with any goods and services. Life Cycle Assessment considers a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste (ISO 14040 2006, ISO 14044 2006, EU JRC 2010).

Life Cycle Assessment (LCA) methods have been used for the environmental assessment of product development processes in other industries for a long time, while the use of those in the building sector is more complex due to the specific nature of buildings. Buildings are special products that distinguish radically from these mostly controlled processes. They consume a plenty of resources and energy during their lifespan, occupy land and eventually they are demolished (Buyle et al. 2013). The complexity of a building as a product is caused by multiple factors, for instance:

- long lifespan of the building resulting in less in less predictable variables
- different lifespan of various materials and components
- variety of multiple materials and processes of different nature
- the unique character and design of each building

- evolution of the functional purpose of the building overtime
- dependence of behaviour of occupants (Sartori et al. 2007, Ramesh et al. 2010, Bribián et al. 2009, Sharma et al. 2011).

The process of harmonization and standards as an outcome play an important role in any business. Primary objective of introducing the standards in a system is to solve the problems in the functioning of the work process and ensuring that the product or services that emerge from the process have an adequate quality for the user. The right application of standards reduces error probability to a minimum, saves time in operability of building functions and ensures a higher quality of a structure. Standards represent a consensus on good practice (CEN n.d.) This also applies to LCA, as standards represent the constitution of LCA. Therefore, standards contributed significantly to the transition of LCA from an academic concept towards a professional tool to support decision-making processes in public and private organizations (Finkbeiner 2012).

Development of the LCA standards in the building sector is crucial for the credibility of LCA within the field. Reason for that is the specific nature of the building as a product. An number of technical assumptions is considerably reduced with a higher level of detail of such building related standards. LCA is generally standardized by International Organization for Standardisation and standards ISO 14040 and ISO 14044 as an instrument to assess the environmental performance of products and services (ISO 14040 2006, ISO 14044 2006, EC 2011).

As life cycle concepts and ideas are gaining more importance in public policies and decision-making processes, the need for a constant improvement and ongoing research within the building related LCA standards is one of the main goals of the LCA initiative. The construction sector is currently subject to the standardization activities of the European standardization body Commission for European Normalization Technical Committee 350's, committee on sustainability of construction works. The European standards EN 15804 (2012) and EN 15978 (2011) provide general calculation rules for LCA of products and buildings (EC 2011).

1.2 Motivation

The importance of life cycle assessment in the building sector has grown rapidly in the recent years, but this growth was not accompanied by a corresponding increase of knowledge of the experts about relevant international LCA standards in this field (Klöpfer 2012). Due to constant development in the field of LCA, the amount of available information in scientific journals, books and electronic media about that development, makes it challenging for practitioners to stay up-to-date with recent activities in the field of LCA (Klöpfer 2014).

LCA's future lies not only in its need for completeness, but in its ability to present itself to users in a way where its metrics can be tracked (Klöpfer 2014). This fact represents a crucial reason for the need of the review of building related LCA standards. Review would provide all future and current practitioners of LCA within the building sector with the most important and necessary data about applicability of LCA standards in practice.

1.3 Objective of the work

The primary objective of this work is to provide an easy-to-understand review about the building related LCA standards and publications writing about applications of these standards, with the aim to become a starting point for all new users entering in the field of LCA within building sector. This review is focused on the LCA standards for the buildings and buildings products in the framework of the ISO and CEN work on the harmonisation of the LCA methodology within the construction sector.

A considerable amount of the building related LCA literature has been published in the recent years. Therefore, a unified platform would contribute to structuring and organising all building related LCA standards in a systematic way.

Even though LCA aims to be science based, it involves numbers of technical assumptions and variables. An important role is played by international LCA standardization processes, which helps to avoid arbitrariness (Guinee 2002). An important aim is to make these assumptions and choices as transparent as possible and therefore this assessment of LCA standards overviews all current gaps in their applicability in practice and points out the need for all future improvements and research requirements.

This review provides the building sector the necessary background information to make better construction decisions and contributes to further harmonization of the LCA standards.

1.4 Background

1.4.1 Overview

Climate change is not an abstract phenomenon, as the impact of climate change can be currently observed both in nature and by looking at temperature and micro- and macroclimatic records. In the next sections, scientific facts pertaining to the climate change issue are presented. The importance of the objective and scientifically based reporting about the current state of climate as well as the role of the Intergovernmental Panel on Climate Change are highlighted (IPCC 2014). A timeline of the international agreements and efforts in tackling and mitigating climate change is demonstrated. Aim of the presentation of these international platforms is the necessity of addressing the importance of the international and organised action in this particular issue. It is more than evident that in the battle against climate change only global and organized measures provide optimal results, as each country has a significant role and contributes to environmental pollution as well as the level of energy at the global level.

In addition, share of the building sector in energy consumption and its role in global environment pollution is discussed. Opportunities as the way to mitigate the impact of the climate change through building sector are reviewed. Life cycle assessment as the method of achieving sustainable and energy efficient construction is highlighted.

Chapters are organized intentionally in the direction from the wider to narrower perspective. Wider perspective starts by presenting the state of the climate change in general and the importance of international effort in tackling it. Narrower perspective indicates the share of the building sector in the climate change and its role in tackling the mentioned above problem. A timeline of the international efforts in tackling and mitigating the climate change is observed from two points, firstly as the point of the country as a unit and secondly as the point of the building sector as a part of the unit or part of the country. In this way parallel was made to emphasize the necessity of the international response to climate change, regarding if it is the case of the international or national character, state or the segment of the state. Only internationally organised, well-structured and well-thought measures provide optimal results.

The same approach should serve as a basis for future efforts and activities in the life cycle assessment in the building sector. Framework of life cycle assessment must be internationally based; International Standards should provide an excellent platform for understanding the basic elements and requirements for LCA studies.

1.4.2 International response to a climate change

The Intergovernmental Panel on Climate Change is a leading international body for the assessment of climate change. It was established by the United Nations Environment Programme and the World Meteorological Organization in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts (IPPC .n.d.). As an intergovernmental body, membership of the IPCC is open to all member countries of the United Nations and WMO. Currently 195 countries are Members of the IPCC (IPPC .n.d.). Every six years the Intergovernmental Panel on Climate Change publishes its assessment of the current state of scientific understanding regarding human-caused climate change. It is important to emphasize that IPPC does not conduct any research nor monitoring of climate related data. That assessment is prepared by hundreds of scientists from around the world through review of the peer-reviewed scientific literature relevant to understanding climate change, its inputs and future risks. It's a statement of the scientific consensus targeted at the people in government who might do something regarding climate change and options for its adaptation and mitigation (Howarth et al. 2016, Cellura et al. 2018, Pearce et al. 2018).

On the basis of its clarity and up-to-date view of the current state of scientific knowledge relevant to climate change, reports and assessments of the Intergovernmental Panel are considered to be the most objective documents about the issue of climate change (Howarth et al. 2016).

The Sixth Assessment Report (AR6) incorporates three Working Group contributions and a Synthesis Report IPPC (IPPC .n.d.). The work from the three Working Groups and The Synthesis Report was released on 9 August 2021 (IPPC .n.d.). Key factors that can be drawn from the Synthesis Report on climate change

IPPC has also published three Special Reports and Methodology Report (IPPC .n.d.). :

• Special Report: Global Warming of 1.5ºC (IPPC 2018)

• Special Report: Climate Change and Land (IPPC 2019)

• Special Report: The Ocean and Cryosphere in a Changing Climate (IPPC 2019)

• 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPPC 2019)

In an international response to climate change certainly one of the most important roles has been played by the international agreement, the United Nations Framework Convention on Climate Change. It was established in 1992 as a framework for international cooperation to tackle climate change by limiting average global temperature increase and facing with impacts of the climate change (UN 1992; UNFCCC 2006). The main goal of the Convention is stabilization of GHG concentrations while putting the weight of the leadership towards that goal on the developed countries. Since industrialized countries are the main source of current and past GHG emissions, they are expected to do the most to reduce emissions as well as to implement measures to mitigate climate change. At the moment there are 197 Parties to the Convention (UNFCCC 2006).

The Kyoto Protocol was adopted at the Third Conference of the Parties to United Nations Framework Convention on Climate on 11th December 1997 (UN 1998). The Kyoto Protocol was structured on the principles of the Convention and it sets emission reduction targets for 37 industrialized countries and the European Union (UN 1998, UNFCCC 2014).

There are two main elements of The Kyoto Protocol. First one is binding emission reduction commitments for developed country Parties. Second is the definition of flexible market mechanisms, which are based on the trade of emissions permit. Parties are obliged to meet their targets primarily through national measures, but they can also partly meet their targets through three market-based mechanisms. These mechanisms help Parties meet their targets in a cost-effective way, for example in developing countries. The Protocol's first commitment period started in 2008 and ended in 2012 (UN 1998, Douma et al. 2007, UNFCCC 2014, UNFCCC n.d.). In 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period, starting in 2013 and lasting until 2020 (UNFCCC 2014) . During the first commitment period Parties were devoted to reducing GHG emissions to an average of five percent against 1990 levels (UNFCCC 2014). During the second commitment period, it was planned that the Parties will commit to reducing GHG emissions by at least 18 percent below 1990 levels in the period from 2013 to 2020 (UNFCCC 2014). At the moment the Doha Amendment has not been put into effect due to the fact that it has not reached a required level of acceptance from member parties (UNFCCC n.d.). The Kyoto Protocol represents first important step towards the stabilization of GHG emissions and serves as the good base for future international agreements on climate change.

The latest international response to climate change would be The Paris Agreement, adopted in Paris on 12th December 2015 (UN 2015, UNFCCC n.d.). It tends to intensify the activities and investments that are necessary for a sustainable low carbon future. Ultimate goal of The Paris Agreement is keeping a global temperature rise this century below 2 degrees Celsius above pre-industrial levels and to improving the ability of countries in coping with the impacts of climate change (UN 2015, UNFCCC n.d.).

Figure 1. presents a timeline of the key milestones in the evolution of International Climate Policies.

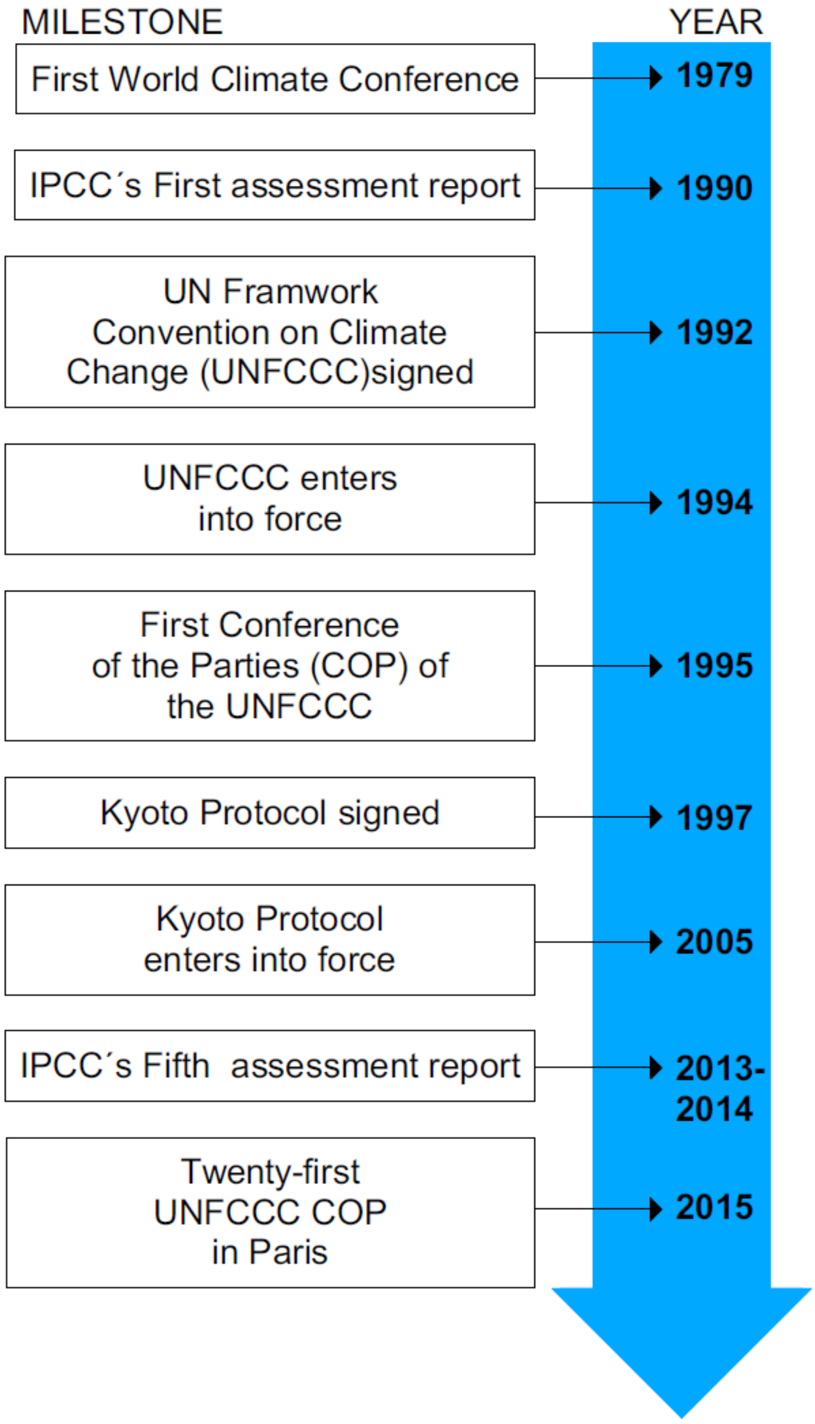

Figure 1. Timeline of the evolution of the international Climate Policies

(Adopted from UNFCC)

1.4.3 Buildings Sector Opportunities for Tackling Climate Change

Current Status of Energy consumption and Emissions in the Buildings Sector

Today building sector is considered as one of the largest energy-consuming sectors in the economy, responsible for more than 36% of global final energy use and half of global electricity consumed in general (IEA 2019). These previously mentioned factors have made buildings responsible for 19% of all greenhouse gas (GHG) emissions, about one-third of total direct and indirect energy-related carbon dioxide (CO_2) emissions (IPPC 2014; IEA 2019).

Figure 2. represents total anthropogenic GHG emissions by economic sectors. Inner circle shows direct GHG emission shares of five economic sectors in 2010. Pull-out shows how indirect CO_2 emission shares from electricity and heat production are attributed to sectors of final energy use. Emissions are converted into CO_2-equivalents based on GWP100 from the IPCC Second Assessment Report (IPPC 2014).

Greenhouse gas emissions from buildings are mainly the result of fossil-fuel based energy consumption of the buildings, conditioned by a direct use of fossil fuels or through the use of electricity, generated from fossil fuels. A significant contribution to greenhouse gas emissions was made by construction materials industry, especially insulation materials, as well as refrigeration and cooling systems (UNEP 2009).

Peter Graham (2003) used a Life Cycle Approach in his attempt to connect emissions with different stages of the life cycle of the building. It showed that the maximum amount of energy was used during the operational phase of a building. Studies have demonstrated that more than 80 percent of emissions of greenhouse gases take place exactly during this phase of the building, the operational phase. This phase includes the conduction of heating, ventilation, air conditioning (HVAC), water heating, lighting, entertainment and telecommunications. A significant increase in energy requirements, which is correlated with greenhouse gas emissions, results from improvements in wealth, lifestyle change, access to modern energy services and adequate housing, and urbanisation (IPPC 2014). It is important to highlight the fact that the energy consumption during the operational phase of a building depends on a wide spectrum of interconnected factors, such as climate and location, function and use of building, building design and construction materials as well as the level of income and behaviour of its occupants (UNEP 2009).

By 2050, the urban population is expected to have increased to 5.6 – 7.1 billion, or 64 – 69 % of world population and energy demand is projected to approximately double and CO2 emissions to rise by 50 – 150 % by baseline scenarios according to 5th IPPC report. This scenario would put a huge burden and pressure on the whole energy system and eventually result in a negative impact on the climate of the planet.

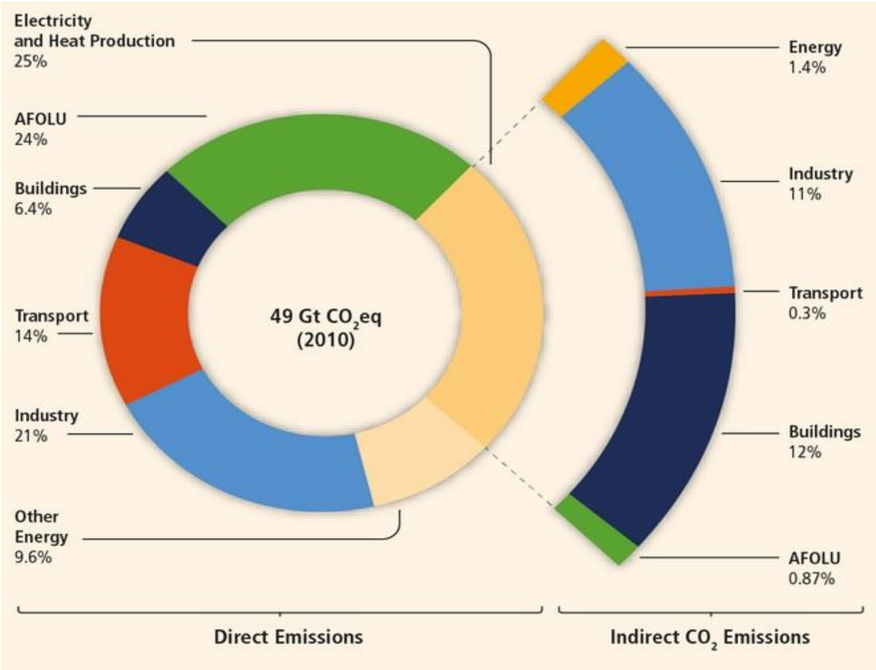

Figure 2. Total anthropogenic GHG emissions by economic sectors. (IPPC 2014).

The United Nation’s Environment Programme’s Sustainable Building and Climate Initiative

Bearing in mind a previously stated role of building sector in global annual green gas emissions and energy use, it is inevitable to come to conclusion that building sector represents a critical part of any global low-carbon future. According to the Fifth IPPC report, there is a huge possibility that the greenhouse gas emissions from buildings can double in the next 20 years if nothing is being done and the use of energy in buildings on global level could double or even triple by 2050 (IPPC 2014). Therefore, it is obvious that in order to meet the targets for the greenhouse gas emissions reduction, mitigation of greenhouse gas emissions from buildings must be treated as one of the bases of every national climate change strategy. Hence a current worldwide challenge is boasting each country´s building sector by integrating energy efficient and low-GHG emissions buildings.

United Nations Environment Programme launched the Sustainable Buildings and Climate Initiative in the year 2006. with the aim to address the challenges and needs in the building sector with the special remark to the matter of climate change (UNEP 2007, UNEP 2009). UNEP-SBCI promotes sustainable building policies and practices worldwide by providing a global platform for dialogue and collective action of the built environment stakeholders.

One of UNEP-SBCI's main objectives is to provide the parties at United Nations Framework Convention on Climate Change with a required information to support the mitigation of building-related greenhouse gas emissions. The main challenge in the implementation of sustainable construction is the lack of a unified database which would inform potential policy makers and industry innovators in building sector on the issues concerning building related mitigation of climate change. On this behalf, UNEP-SBCI has produced fundamental baseline studies including Buildings & Climate Change- Current Status, Challenges and Opportunities (2007) and Buildings & Climate Change: Summary for Decision-Makers (2009) that will be partly reviewed in this subchapter. According to UNEP-SBCI (2009), there are five main policy objectives for reducing greenhouse gas emissions from buildings:

1) Improvement of energy efficiency in new and existing buildings

This can be achieved by the use of measures such as mandatory building codes which should establish energy efficiency standards for new and existing buildings; periodic building commissioning and mandatory energy revision in order to secure that a building's systems have been designed, installed and perform as they were planned to ; loans and fundings on national basis as useful incentives to encourage the residential sector; Energy Performance Contracting as the way of guarantee of certain energy savings for a contractor over a certain time period.

2) Improvement of the energy efficiency of household and business appliances

This can be accomplished by the implementation of measures, such as appliance standards and fiscal incentives used as stimulus for consumers to buy energy efficient appliances.

3) Encouragement of energy suppliers to support emission reductions

This can be encouraged by the use of measures such as demand-side management (DSM) activities, by changing the consumers energy behaviour for example through the public information campaigns; energy efficiency obligations oblige energy suppliers legally to save energy on their customer's behalf, energy efficiency certificate schemes prove energy savings and at the public benefit charges tax charges the energy market.

4) Changes in attitudes and behaviour of society

The increase of the energy prices could encourage consumers to reconsider their energy use behaviour, green mortgages with lower interest rates and longer periods of time than other mortgages could act as additional motivation as well.

5) Substituting fossil fuels with renewable energies

Substitution can be done by implementing policies to increase the contribution of renewables in the energy market or even set them as mandatory.

International cooperation regarding all five mentioned policy objectives for reducing greenhouse gas emissions from buildings is essential. It is the true that the Convention on Climate Change secures the best framework for activity of this cooperation, but there is an urgent need to make the diversity of partnerships among national bilateral actors, and a combination of short-term and long-term strategies. There are several reasons for this necessity (UNEP 2009):

• requirement for establishment of institution for measuring, reporting, and verifying global emissions and emissions-cutting efforts in order to assure that countries that contribute their efforts as well as to prove wealthier countries support poorer countries in the manner which was planned

•need for clear strategies for supporting climate action and increased linked funding, international funds for low-carbon technology financing because institutions that backup global economic development have a great potential in promoting low-carbon mitigation of climate change and UN organizations, such as the United Nations Development Program and United Nations Environment Program, are struggling to handle large infrastructure projects but can play an important role in making relevant supplies in developing countries.

The United Nations Environment Programme (UNEP) International Resource Panel has recently published a report Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future (IRP 2020).

According to this report, G7 countries could reduce greenhouse gas emissions in the material cycle of residential buildings by 80 to 100 % in 2050, in case they adopt material efficiency strategies, including the use of recycled materials. The Panel's report suggests that, potential reductions in China could amount to 80 to 100 %, and to 50 to 70 % in India in 2050 (IRP 2020).

One of the major goals of UNEP since its foundation is to clarify the common definition of sustainable building because it often differs from nation to nation by ranking system. Therefore, the UNEP Sustainable Building Index was suggested by UNEP in 2010. as a matrix based on a life-cycle approach that would focus on measurable impacts of the building regarding GHG, water, materials, biodiversity and economics (UNEP 2010).

Idea of SB Index was to structure policies, regulations and building codes to improve sustainable buildings through common language for sustainability in building sector.

1.4.4 Introducing Life Cycle Assessment

Today's increasing environmental awareness and responsibility in society, contributed to increasing efforts of different branches of business and industry to assess the impact of their activities on the environment. The environmental impact of their products and processes has emerged as a key issue and that is why different international organizations and policy makers are exploring strategies and management systems to minimize their effects on surroundings. Life Cycle Assessment is one of the methods developed for this purpose (Curran et al. 2005, Curran 2006).

According to International Reference Life Cycle Data System Handbook (2010) Life Cycle Assessment is a structured, internationally standardised method for quantifying the emissions, resources consumed and environmental and health impacts that are associated with goods, services and products.

In ISO 14040 LCA is defined as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle''. A product's life cycle takes place into stages. The number of stages can differ, six stages normally include a distinguished product design, raw material extraction and processing, manufacturing of the product, packaging and distribution to the consumer, product use and maintenance and end-of-life management: reuse, recycling and disposal (UNEP 2005).

LCA takes into account the entire life cycle of a product, from the extraction of raw material, through the production of materials, product parts and the product itself, to use and end of life process, either by reuse, recycling and final disposal. Due to the systematic and holistic approach, the shifting of an environmental burden between life cycle stages can be recognized and possibly avoided (ISO 14040 2006, ISO 14044 2006).

Primarily, LCA method assesses the environmental aspects and potential impacts associated with a product, process, or service, by:

• Making an inventory of relevant energy and material inputs and environmental releases

• Evaluating the potential environmental impacts associated with identified inputs and releases

• Interpreting the results to help decision-makers make a more informed decision (ISO 14040 2006, ISO 14044, Curran et al 2005, Curran 2006).

LCA is used by industry and other types of business, governments at all levels, non-governmental organizations such as environmental groups and consumers organizations (UNEP 2005). The reason for application of LCA varies among the users. The most frequent use of the LCA is intended for the following purposes (Figure 3):

•Product development and improvement

• Strategic planning

• Public policy making

• Marketing

• Other (There is a variety of further LCA applications in public and private organisations. This fact does not imply that all of them are based on LCA method, but that the life cycle approach, principles and framework can be effectively applied (ISO 14040 2006)).

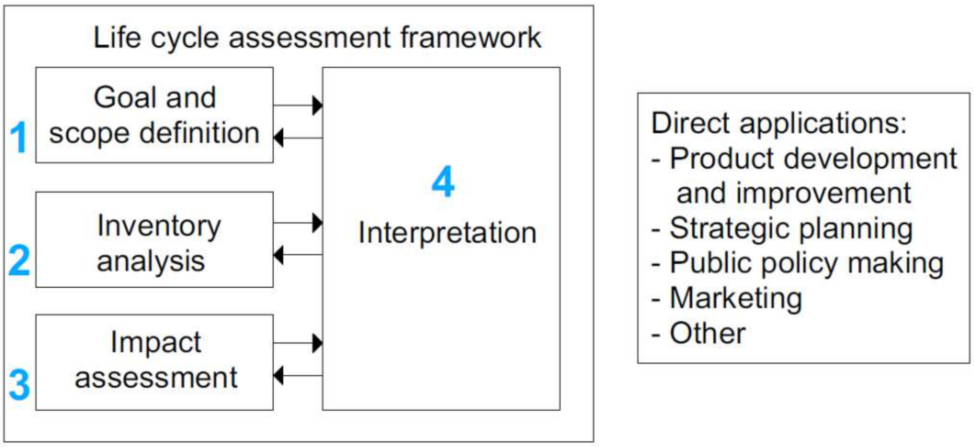

Figure 3. Stages of an LCA (Adapted ISO 14040 2006)

Life Cycle Assessment Phases

According to ISO 14040 (2006), Life Cycle Assessment contains 4 phases (Figure 3):

1. Goal and Scope definition

The first step of the LCA is definition of a goal and a scope, the initial choices which determine the working outline of the entire LCA. The goal of the study is defined by explaining the aim of the study and intended application of the results, the initiator and commissioner of the study, the practitioner and the intended users of the study results (target audience).

LCA study is identified and defined in detail during the scope definition phase. Main part of the scope definition is to derive the requirements on methodology, quality, reporting, and review in line with the goal definition. Through the derivation of the scope of an LCA study from the goal, the following items shall be clearly defined: the system or process that is studied and its function, functional unit, and reference flow; system boundaries, completeness requirements, and related cut-off rules; LCI modelling framework; LCIA impact categories; LCI data quality requirements regarding technological, geographical and time-related coverage; the required precision and maximum permitted assumptions and limitations; type of critical review; type and format of the report required for the study.

2. Life Cycle Inventory (LCI)

The Inventory analysis is the phase which involves data collection and calculations in order to quantify relevant inputs and outputs of the product system. In this context, this step includes design of flow diagrams with unit processes, data collection for each of these processes, implementation of allocation steps for multifunctional processes and completion of the final calculations. It is important to emphasize that the process of conducting LCI is an iterative, which will be later explained in more detail (Figure 6).

3. Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment is the phase, in which the relevant inputs and outputs which have been collected and notified in the inventory analysis are converted into impact indicator results related to natural environment, human health and resource depletion. Mandatory elements of LCIA are: selection of impact categories, category indicators and characterisation model; assignment of LCI results to the selected impact categories (classification); calculation of category indicator results (characterisation)(ISO 14044 2006). The results of LCIA should be seen as environmentally relevant impact potential indicators and not as predictions of actual environmental effects (EU JRC 2010).

4. Interpretation

The life cycle interpretation is the phase of the LCA where the results of the other phases are summarized and analysed with a purpose of achieving accuracy, completeness and precision of the applied data, as well as the assumptions, which have been made throughout the LCA study. It is important to highlight the iterative nature of the LCA study.

Iterative Approach of the Life Cycle Assessment

LCA is an iterative process. The goal of the study is defined as the first step and then the scope settings are derived from the goal, settings that define the requirements on the further study. More information is retrieved during the individual phases of an LCA, the initial scope settings will mostly need to be refined and sometimes also revised (ISO 14040 2006; EU JRC 2010). It is recommended to collect data in an iterative manner in order to achieve a required precision with the minimum effort (Figure 4).

Figure 4. demonstrates how LCA is carried out as an iterative process in iterative loops of goal and scope definition, inventory data collection and modelling, impact assessment, and with completeness, sensitivity and consistency checks as a managerial tool (EU JRC 2010). This kind of approach within and between the phases of the LCA contributes to the comprehensiveness and the consistency of the study.

The specifics of the construction sector in comparison with other industry sectors lies within different iterations, which are often carried out by the same practitioners. Reason for this is that the interests of different practitioners along the LCA tree usually vary. Users such as architects need tools which can be adapted to the specifics of the building project, in order to support their design decision. A complete LCA may be required at the later stage of the project. In both cases the data, method and results of the study need to be adopted in line with the goal of the study and the stakeholder requirements (EC 2011).

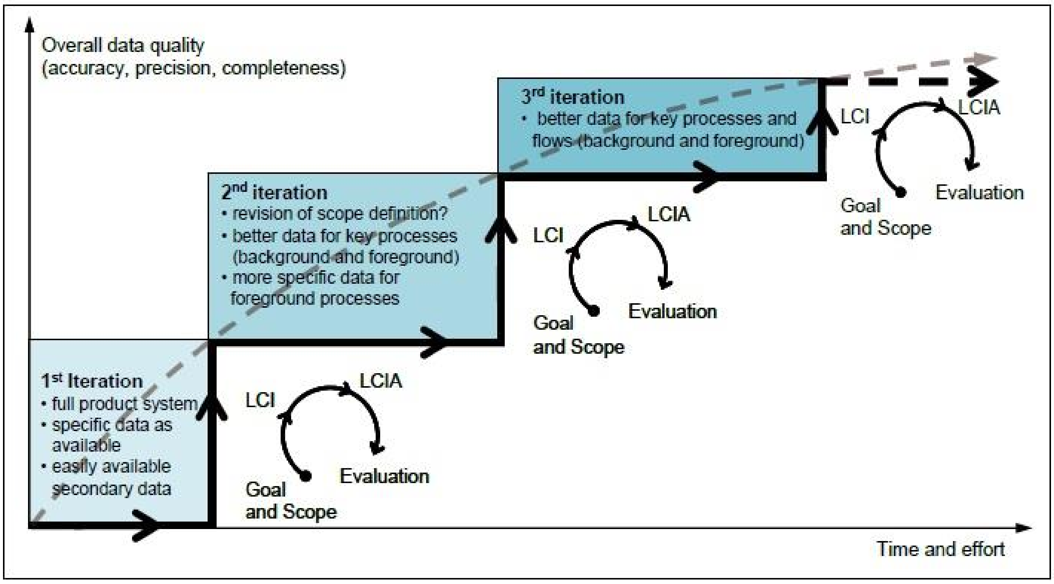

Figure 4. LCA as an iterative process (EU JRC 2010)

Variations of LCA

The scope of the LCA may include different number of stages in a product's life. Depending on the purpose of the LCA study there are two primary types of LCA:

• Process-based LCA

In a process-based LCA life cycle is designed as a series of unit processes where each unit process has inputs (materials and energy resources) and outputs (emissions and wastes to the environment) for a given stage in manufacturing a product (Hendrickson et al. 1997). Types of process-based LCA methods are (Figure 5.) (Bayer et al. 2010):

1) **Cradle-to-grave** is a full LCA method that starts from the resource extraction ('cradle') and takes into account the manufacture of the product, the use phase of the product and final disposal phase ('grave').

2) **Cradle-to-gate** is a partial LCA method, an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are not considered in this case. Cradle-to-gate assessments are often used as the basis for Environmental Product Declarations (EPDs).

3) **Cradle-to-cradle** is a specific kind of cradle-to-grave assessment, where the disposal step for the product represents a recycling process. From the recycling process derive new, identical products or different products.

4) **Gate-to-Gate** is a partial LCA that looks only into one value-added process in the entire production chain (i.e., evaluating the environmental impact of a product from the manufacture site to the construction site).

• **Economic input-output-based LCA**

The Economic Input-Output LCA method estimates the materials and energy resources that are needed and consumed in activities in our economy as well as the environmental emissions resulting from them. Simply explained, this method uses data about industrial transactions - the purchase of materials by one industry from another, as well as information about direct environmental emissions of industries to assess the overall emissions throughout the supply chain. The difference between process-based LCA and input-output-based LCA methods is the fact that input-output-based LCA methods discuss an entire sector of the economy while LCA methods focus on questioning a single process in detail (Hendrickson et al. 1998).

It is important to point out that most of the LCA methods implemented in a building sector are based on process based LCA.

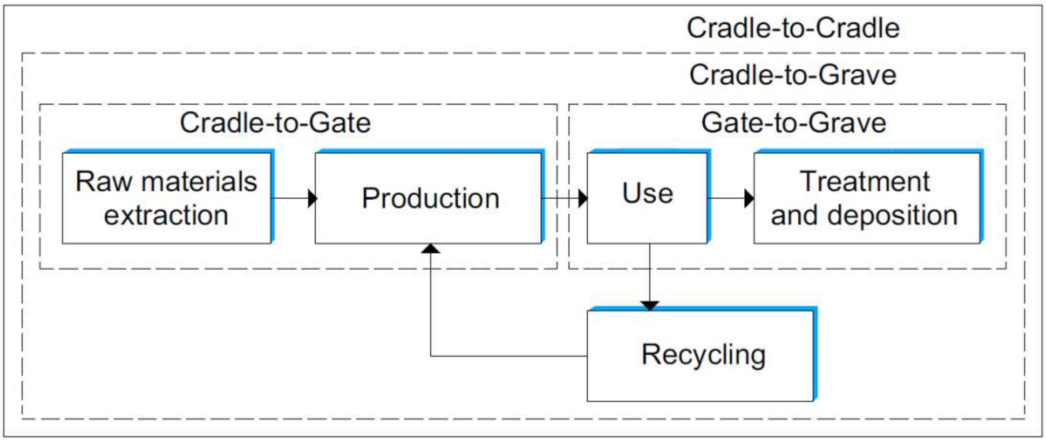

Figure 5.. Graphical representation of the life cycle phases included in each one of three variants of LCA process-based studies. (Adopted Bragança et al. 2012)

1.4.5 A Brief History of LCA

The studies of the environmental impacts of products have the history that dates back to the 1960s and 1970s. Firstly, they focused on the evaluation and comparison of consumer goods, with only a small contribution to the different life phases of the product. Studies have had mostly the comparative character. After a certain time, it was acknowledged, that for many of products, large contribution to environmental impact takes place in the use phase of the product but also in its production, transportation or disposal phase (Guinée et al. 2010).

The idea of LCA was based on the awareness about large share in environmental impact of different phases of lifespan of the product. To create a clearer picture of the gradual development of LCA throughout history as well as future steps, in the following sections were structured as a timeline through four different stages.

State of LCA from 1970 to 1990

As previously mentioned, the LCA methodology dates back to 1960s, when concerns over a limited availability of raw materials and energy resources were socially widespread and pervasive. Initially, a scope of these studies was limited to the energy analysis, which later would be expanded and taken into account resource requirements, emissions loadings and generated waste. In this period, LCA studies were mostly focused on finding alternative ways of packaging products. One of the first unpublished studies of this kind was executed by Midwest Research Institute (MRI) for The Coca Cola Company in 1969, including resources, emission loadings and waste flows for different beverage containers. These decades represent also the period when for the first-time impact assessment method was introduced, by separating water and air emissions by semi-political standards, calling them critical volumes of air and critical volumes of water (Guinée et al. 2010).

In the beginning of the 1980s, life cycle thinking appears in the building sector with a study of Bekker, with a concentration on the use of renewable resources. It was immediately acknowledged that building-related products were different from most other consumable items, in terms of LCA. The uncertainties caused by longer expected lifespan of the building were problematic, leading to complications which were difficult to solve and made accurate building-related environmental assessment very complex (Bekker 1982). As if the nature of the building itself did not represent sufficient aggravating circumstances for the implementation of LCA methodology in the building sector, others multiple obstacles were present. Early studies and research works practiced divergent methods and terminologies which would at the end lead to different results even though they were based on the same study object (Guinée et al. 1993). There was an obvious lack of communication between scientists and there was an urgent need of a platform, which would enable such communication in order to make LCA generally an accepted and widely applied method.

These first decades of LCA can be considered as the conceptual ones, decades when the idea of LCA was born but still without a common theoretical framework.

State of LCA from 1990 to 2000

During this period many life-cycle studies have been conducted, followed by a significant increase of public interest in this issue. Scientific activities were organised worldwide in the form of workshops and other forums, accompanied by a production of numerous LCA guides and handbooks (Guinée et al. 2010).

The Society of Environmental Toxicology and Chemistry (SETAC) held two LCA workshops during 1992. The first handled a topic of a life-cycle impact assessment, the second one focused on a data quality (Fava et al. 1993). Bringing the LCA practitioners together, SETAC started to play the main role in the process of harmonization of the framework of the LCA, methodology and terminology, which resulted in the SETAC 'Code of Practice' (Consoli et al. 1993). Aside from SETAC effort, some LCA guidelines which appeared during the 1990s include the publication of the Dutch guidelines on LCA authors (Lindfors 1995), from Nordic countries published Nordic Guidelines on Life-cycle Assessment (Bardy et al. 1996), 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. In this period of time also the first scientific journal papers show up in the Journal of Cleaner Production, in Resources, Conversation and Recycling, in the Journal of LCA, in Environmental Science and Technology, in the Journal of Industrial Ecology and in other journals (Guinée et al. 2010).

Besides SETAC, from 1994 the International Organization for Standardization (ISO) has been involved in LCA. Main focus of ISO was the standardization of methods and procedures of LCA. There have been many efforts to standardize the methodology of life cycle assessment. Canadian Standards Association published the first guidelines for the Evaluation of Z-760 environmental life cycle assessment of the national life cycle in the world in 1994, to in-depth information about LCA methodology (Bardy et al. 1996) but the best-known standards were those published by the International Organization for Standardization ISO. They were a part from the ISO 14040 standard series, first published in 1997. The result of this standardization was the creation of a general methodological framework, which made it easier to compare different LCAs. It is important to keep in mind that even with the consensus on the framework, ISO never aimed to define the exact methods by stating 'there is no single method for conducting LCA'(ISO 14040 2006).

This decade of LCA is a period of harmonization that is accompanied with the fact that LCA become a part of policy documents and legalisation for the first time, it is also a period of scientific questioning and researching into the foundations of LCA. It can be considered as a period of transition LCA to the present decade of LCA, considered a decade of elaboration (Guinée et al. 2010).

The Present of LCA

The beginning of 21 century, notes a sudden rise in the importance of LCA and life cycle thinking in general (Buyle et al. 2013). In the year of 2001 different national LCA networks were established, for instance the Australian LCA Network and the American Centre for LCA (ALCAS, ACLA). US Environmental Protection Agency had an important role in the initial promotion of LCA thinking and practice in the United States (Guinée et al. 2010).

The UNEP and SETAC have launched an International Life Cycle Partnership in the year 2002, also known as the Life Cycle Initiative in order to put life cycle thinking into practice and improve the supporting tools. Life Cycle Initiative contributes to the 10-Year Framework of Programmes to promote sustainable consumption and production patterns, as required at the World Summit on Sustainable Development in Johannesburg (2002). Main aims of the Life Cycle Initiative are establishment of the global network of over 2000 LCA expert members (members of industries, Government, academics that are leaders in developing and applying LCA), collecting and presenting examples of best practices and Life Cycle achievements across the world, connecting science and decision making in policy and business throughout Life Cycle approaches (UNEP/SETAC 2005; UNEP/SETAC 2011).

The European Platform on LCA was founded in 2005 with a purpose of promoting the availability, exchange and use of quality-assured life cycle data methods and studies for reliable decision support in EU public policy and business. Tools available in the European Platform on LCA include The European Reference Life Cycle Database, The International Reference Life Cycle Data System Handbook, The Life Cycle Data Network, The Resource Directory and The Life Cycle Thinking Forum. (UNEP/SETAC 2005).

1.4.6 LCA in the Building Industry

LCA method has been successfully used for decades to assess the environmental impacts of the products and processes in various industries (Kharseen et al. 2009, Buyle et al. 2013). On the other hand, the process of the adoption of the LCA within the building sector is considered complex, time consuming and challenging. Buildings represent special products that are largely different from the controlled industrial processes. Reason for this can be found in several facts:

• a **long lifetime of the building** as a product, approximately from 50 to 100 years, which results in a reduced credibility of required parameters (Satori et al. 2007, Ramesh et al. 2010, Sharma et al.2011)

• **building consists of numerous individual products**, with some of them having a shorter lifespan, as well as varying distances from the production location (Buyle et al. 2013)

• **unique character of each building and habits of its occupants**, resulting in a possible adjustment of its function regarding the needs of the occupants, maintenance and retrofit.

All the reasons mentioned above affect the credibility of the LCA results within the building sector. They require a large number of the assumptions that directly lead to a larger number of the uncertainties, affecting the validity of final LCA results at the end. Due to a current tendency toward sustainable construction and the fact that the building sector represents a major source of different environmental impacts, LCA has become an objective method to evaluate the environmental impact of the practice of the building industry. Therefore, the standardization of the LCA method specifically focuses on a building nature.

LCA method integrated into the construction sector can function on four levels: material, product, building or industry (Figure 5). It operates in a way that every larger level refers to the level under it. It can be concluded that the core of each level is represented by material level, which actually is a LCI database which is discussed later more in further detail (Bayer et al. 2010).

Material Level

Value of the calculation on this level can be achieved easily by directly accessing data from the LCI database. This material level data should not be provided by a building consultant as it has been documented by other experts and stored in a LCI database (Bayer et al. 2010).

Product / Building Level

Product level LCA is calculated as a collection of materials gathered into one final product. At the end of the calculation emissions from each component of the product are collected and summarized. For this reason, it is important to obtain detailed knowledge about the source, quantity and the manufacturing processes of each material of the finished product. In this manner building level can be seen as the product level, where the product is the building itself (Bayer et al. 2010).

Industry Level

At the building industry level, the Economic Input-Output based LCA is considered as the best solution. LCA study on this level is carried out by analyzing the industrial production and economic output data (Bayer et al. 2010).

Life Cycle Stages

The research activity in the European project REGENER (1997) led to a general framework for the application of LCA in the building sector. The life cycle of a building can be divided into several phases and connected processes with each of them (EN 15643-1 2010, Bayer et al. 2010, Reiter 2010;):

• **Production**

This is the stage, in which construction materials have been manufactured. It includes the extraction of the raw material from the earth, their transportation to the manufacturing place, production process of the materials, building product development, packaging and distribution of building products.

• **Construction**

Construction phase takes into account activities linked to construction of a building project, transport of materials to the construction site and construction process (energy used for site work, tools and equipment).

• **Use and maintenance**

This stage refers to energy and water consumption, environmental waste generation, eventually necessary replacement of building components, including the transport and equipment used in this stage.

• **End of life**

This stage covers a potential retrofit of the building, energy consumed and treatment of environmental waste produced due to a building demolition. The possible reuse and recycling of components related to demolition waste can also be included in this stage, depending on the availability of data as well on the scope of the project (*Figure 6*).

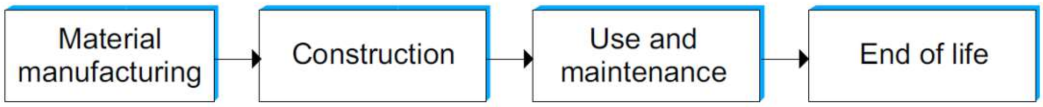

Figure 6.. Life cycle stages of the building. (Bayer et al. 2010)

Life Cycle Energy Analysis

The life cycle energy of the building implies the total energy required during the entire life of the building, from the phase of the manufacturing to the phase of the demolition. Life cycle energy of the building contains embodied and operational energy. Embodied energy represents all the energy used to extract materials, transport and manufacture them, compile them for the building and technical installations, as well as transport of the products, construction on the building site, followed by energy used for the process of the renovation and demolition of the building. Operational energy includes all activities connected to the use of the building during its life span. Energy required for preserving comfort conditions and for maintenance of the building includes system such as HVAC (heating, ventilation and air conditioning), lighting, energy needed for running appliances and for the domestic hot water (Karimpour et al. 2014).

Life cycle energy analysis is a method that calculates all energy inputs to a building in its life cycle (Ramesh et al.2010). The system boundaries of the LCEA contain the energy use of manufacturing, use and demolition phase. In other words, LCEA is an abbreviated form of LCA that uses energy as the only measure of environmental impact, in order to assist a decision-making process regarding energy efficient systems, processes and materials for the buildings during its life cycle (Huberman et al. 2008). Previous studies have claimed that embodied energy represents a very small factor in the life cycle energy of the buildings and that is why it can be neglected. However, the results of the latest reviews and analysis of the previous studies had led to a different conclusion. According to the results of the latest studies operational energy still represents a dominant parameter in LCEA of the building but when taking into account climate factors, embodied energy can represent up to 25 percentage of the total life cycle energy in milder regions. In the future, countries will continue with their efforts to achieve greenhouse emission targets. It is objectively expected that embodied energy in the life cycle energy of the building will be treated and considered with more importance (Ramesh et al.2010, Sartori et al. 2007).

Life Cycle Cost Analysis

The life cycle cost analysis is a method for assessing the total cost performance of an asset during its period of the life cycle that undergoes the study (Davis 2007). This method can include the costs of initial investment, acquisition, operation, maintenance, replacement and disposal costs (Bragança et al 2012, Davis 2007). Costs regarding potential reuse and recycling are normally not considered and the total sum is usually introduced in two forms, net present value or annual cost (Bragança et al 2012).

LCC method is used for the comparison of the buildings and building elements with the same level of the performance, in order to find option with lower costs during the life cycle period of the study and therefore represents better economical alternative (Bragança et al 2012). It is highly important to point out, when comparing LCC of two products, that it is crucial to consider the same period of each product regardless of their operational life (Mearig et al. 1999, Mistry et al 2016.)

According to the final report on Life Cycle Costs as a Contribution to Sustainable Construction that was carried out by the European Commission (2007), there are several parallels between LCA and LCC, even though they represent two distinct and separate processes in the construction. Both processes cover the evaluation of the assessment of the long-term impact of decision making, demand analysis of a diverse range of inputs, take into account maintenance and operation phases, use similar data on inputs of energy and materials and provide a platform for optimal decision making in assessing options.

Data requirements for the LCC analysis according to Schade (2009) can be categorized into five categories: cost data, occupancy data, physical data, performance data and quality data. Key factors of an early-stage building design, which are the occupancy and physical data (Schade 2009), quality and performance data are affected by the policy decisions (Kishk et al. 2003) but the key data for the

LCC analysis is the cost data found in price banks PBs (Schade 2009). In order to maintain its validity and have a proper interpretation cost data has to be in line with other data categories (Kishk et al., 2003).

Environmental Impact Categories

As previously stated, LCA is one of the methods for sustainability assessment used to support decision making processes with the aim to lower the environmental impacts of the buildings. Environmental impact category is defined as a class representing environmental issues of concern, which also includes LCA results (ISO 14050, 2009). A number and a type of the environmental impact category indicators varies through different sustainable assessment methods. This happens due to the fact that there is a wide range of the impact category indicators categorized by the endpoints or the midpoints as well as the fact that their selection depends on the purpose of the LCA. The term that is also used for endpoint is damage category. It should interpret the effect of the product in the areas of the Resources, Climate Change, Ecosystems Quality and Human Health which are considered as the areas of the protection (Consoli et al. 1993, EPA 2005, Braganca et al. 2012). Environmental impact categories have been standardized by the international organisations such as the Environmental Protection Agency, Occupational Safety and Health Administration, National Institutes of Health (Bayer et al. 2010). European Project ENSLIC (2009) provides a list of most common environmental indicators used in the building LCA methods and organised as in the shown in *Table 1*.

The selection of the environmental impact categories depends on the purpose of the research so only the relevant building related LCA projects and standards were taken into account such as ENSILC Building project by EPA in 2009, the EN 15804 (2012) and EN 15978 (2011) in order to find the most important and common in the building sector. With no specific order in their importance, they will be in next paragraphs named and described.

Table 1. A list of common environmental indicators used in the building LCA methods. (ENSLIC 2012)

Impact categories	
Resources •Depletion of abiotic resources •Cumulative energy demand (total and non-renewable) •Water consumption •Surplus energy to extract minerals and fossil fuels •Land use •Resource factor Air pollution •Global warming potential •Ozone depletion potential •Winter smog •Photochemical oxidant formation •Odours	Soil pollution and waste •Terrestrial ecotoxicity • Amount of solid waste •Amount of radioactive waste Damages, health and biodiversity •Human toxicity •Heavy metals •Carcinogenics •Disability Adjusted Life Years •Ionising radiation •Depletion of biotic resources •Impacts of land use •Potentially disappeared fraction Water pollution •Eutrophication potential •Aquatic Eco-toxicity

• **Global warming potential (GWP)**

The natural greenhouse effect needs to be differentiated from the anthropogenic greenhouse effect that is the result of the emissions caused by human activities. While the natural greenhouse effect is vital for living beings on our plant, the human emissions, also called greenhouse gases such as carbon dioxide and methane, increase the heat radiation absorption of the atmosphere which results in the increase of the earth's surface temperature (ENSLIC 2012). The potential consequences of global warming for planet Earth are already described above in the Chapter 1. The impact of the emitted gas is represented in terms of its GWP in CO_2 equivalents (see Eq. 1) (EC FP7 2009, Guinee 2002, US EPA 2014, IPPC 2007).

$$\text{Global Warming Potential (GWP)} = \sum i \, GWP_i \times m_i \qquad (1)$$

GWP_i – Global Warming Potential of substance *i* (kg of CO_2 equivalent/kg)

m_i – mass of the substance *i*, inventoried in the process (kg), the time horizon is considered for period of 20, 50, or 100 years

• Depletion potential of the stratospheric ozone layer (ODP)

The thinning of the stratospheric ozone layer as a consequence of anthropogenic emissions, such as chlorofluorocarbon (CFCs) found in refrigerators, air conditioning, aerosols and halon used for firefighting, is called the stratospheric ozone depletion. This causes the increasing breakthrough of solar UV-B radiation to the Earth's surface which results with the potential damage to human health and ecosystems (Guinee, 2002). The depletion is mostly caused by CFCs while halon has been reduced lately and soon will be phased out due to the new policies such as Montreal protocol (ENSLIC 2009). ODP is the ratio between the amount of zone destroyed by a unit of a substance x and a reference substance, usually taken as CFC-11 and the unit of the ODP is kg CFC-11 equivalent (see Eq. 2) (EPA 2014).

$$ODP(x)= \frac{Global\ loss\ of\ ozon(x)}{Global\ loss\ of\ ozone\ by\ (CFC-11)} \qquad (2)$$

• Acidification potential of land and water resources (AP)

Acid deposition in the atmosphere, mostly in the form of the rain, causes increase of the acidity of the water and land (Guinee 2002). It is considered as regional effect, in Europe effects of acidification are mostly seen in Scandinavia and middle-eastern part of Europe (EPA 2005). These potential effects are forest decadence, land acidification, damage to building materials and construction (Hoffman et al. 2005, ENSLIC 2012). It is important during the interpretation of the indicator result to take into account regional differences, because a land composite can possibly neutralise the effects (ENSLIC 2009). According to a technical report (Hoffmann 2005), the primary contributors are oxides of sulphur (SO_x), nitrogen oxides (NO_x) and ammonia (NH_3). The acidification potential can be estimated as SO_2-equivalents (see Eq. 3) (Hauschild et al ,1998).

$$AP= \sum i\ EF_i m_i \ [SO_2\text{- eq.}] \qquad (3)$$

AP – Acidification Potential

EF_i - the equivalence factor for the substance i

m_i - the emission of the substance i

• Depletion of abiotic resources (ADP)

Abiotic resources represent non-living natural resources, like oil and iron (ENSLIC 2012). Hence the most important criterion of sustainability is the efficient use of abiotic resources. Guinée (2002) and Heijungs (1992) proposed a characterisation factor called Abiotic Depletion Potential, that was based on the resource state and the extraction rate. It expressed in kg of a reference resource (see Eq. 4).

$$\text{abiotic depletion} = \sum i \; ADP_i m_i \qquad (4)$$

ADP_i - Abiotic Depletion Potential of resource *i* (kg of resource equivalent/kg)

m_i - mass of the substance *i*, inventoried in the process (kg)

• Eutrophication (EP)

Eutrophication takes a place when there is a case of the increase in the concentration of nutrients, nitrogen (N) and phosphorus (P) in a soil or water, causing a reduction in species diversity as well as changes in species composition (Guinée, 2002). It can happen naturally and as a result of human activity. Phosphate (PO_4^3),which has a eutrophication potential of 1, is the reference substance for the calculation of the eutrophication potential for each emission (Wenzel et al 1997, ENSLIC 2012). The reference unit for the inland water is grams equivalent of phosphorous per functional unit of the product (gr PO4- eq/kg) and for the marine water is grams of nitrogen equivalent of phosphorous per functional unit of the product (gr N- eq/kg) (see Eq. 5) (OECD 2005; Diakoumakou 2016).

$$EP\ (NO_{3\text{-}}\text{equivalents}) = [(c + 16f) * 62{,}0]/Mw \qquad (5)$$

Mw – molar weight of the compound

c, f - refers to the number of N and P atoms in the compound

• Photochemical oxidants

This indicator refers to the secondary air pollutants formed under the influence of sunlight by complex photochemical reactions in air which contains nitrogen oxides and reactive hydrocarbons. This ozone formation is usually known under the term *summer smog* and can cause the problems with breathing to the humans as well as with the growth to the plant species. It mostly occurs in the bigger cities with a lot of traffic. The reference substance for the assessment is the Ethylene (Guderian 1985; ENSLIC 2012). Photochemical Ozone Creation Potentials for a specific VOC is defined as the ratio between the ozone formation by an additional release of the VOC and the additional ozone formation by the same release of the reference substance eten (see Eq. 6) (Derwent et al 1998).

$$POCP_I = \frac{ozon\ increase\ from\ the\ i{:}th\ VOC}{Ozon\ increase\ from\ eten} \qquad (6)$$

2 METHOD

2.1 Overview

A systematic literature review was conducted to assess the LCA standards for the buildings and buildings products in the framework of the ISO and CEN work with a purpose of the harmonisation of the LCA methodology within the construction sector. Articles and projects that are focused on the integration of LCA building related standards into LCA practise in the construction were considered. The articles were accessed via the following databases: Science Direct (n.d.), Elsevier (n.d.) and Scopus (n.d.). These three databases were considered as the sources which offer the widest scope of research literature with well-respected sources and geographically wide coverage. Research was performed with a purpose of finding relevant articles and projects. Researched terms included “LCA in construction sector”, “LCA standards for buildings” and “LCA standards for buildings products”. One of the criteria for the literature selection was the publication date, the source had to be published not more than 30 years ago.

In recent years several different projects on the topic of LCA and buildings have been carried out. The guiding principle that connects all of these projects is the attempt to adapt the methodological rules of LCA studies in the building sector and to develop the tools that can be used by building stakeholders, without a thoroughly deep LCA knowledge (EC Seventh Framework Programme 2011). The following LCA studies, represent the foundation for the literature review in this work:

- SETAC published in 2003 a Life-Cycle Assessment in Building and Construction: A State-of-the-Art Report (SETAC 2003). This report emphasizes the difference between the general approach of LCA and LCAs of buildings.
- REGENER (APAS 1997)
- Annex 31 IEA (IEA ECES 2001)
- PRESCO (Peuportier et al. 2005)
- IMPRO-Building (EC JRC 2008)
- ENSLIC Building (EC Intelligent Energy for Europe Programme 2007)
- LoRe-LCA (EC Seventh Framework Programme. 2011).

This paper summarizes and organizes the literature sources on LCA building-related standards of the ISO and CEN through the following main tasks (Figure 7):

- LCA standards of the International Organization for Standardization (ISO), ISO Technical Committee 207 and ISO TC 59 (Buildings and civil engineering works) SC 17 (Sustainability in buildings and civil engineering works)
- LCA standards of the European Committee for Standardization (CEN) and CEN/TC 350 Sustainability of Construction Works
- Interrelation of the ISO and CEN LCA standards within the building sector
- Links between Eco labels, building certificates, design competitions and LCA standards in the building sector.
- Interrelation of the LCA databases, LCA tools and LCA standards within the building sector
- LCA ISO and CEN building related standards through LCA phases (goal and scope definition, inventory analysis, impact assessment and interpretation) and difference in provisions through this phase in ILCD Handbook (EC 2010). and EeBGuide (EC Seventh Framework Programme 2011).

Figure 7. shows the most important steps of this work where the previously mentioned topics and their interrelationships are explored

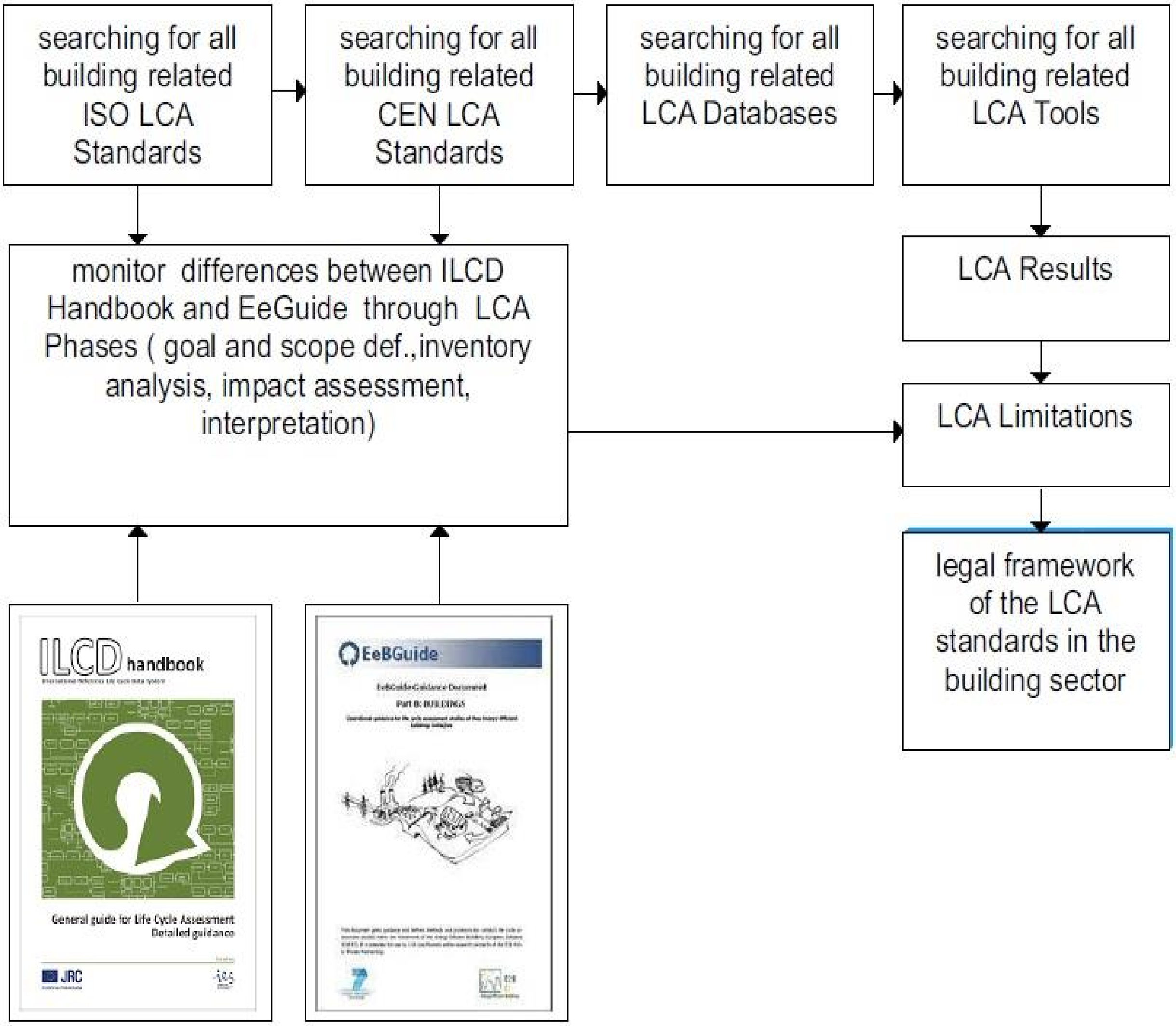

Figure 7.. Methodology flow chart

2.2 Scope

The starting point in the research for all international LCA standards related to the construction sector were the two fundamentals' standards for LCA of the products or services in general, ISO 14040 and ISO 14044 (2006). Taking them as a starting point, research is led to some of their spin-off standards, which were intentionally listed in the work (*Table 2*). It does not need to necessary mean that all of them are building related, but it is highly possible that they would be mentioned as a reference in a number of other building-related LCA standards. They are initially listed in order to, obtain a clearer picture of the standards that will be mentioned later in the scope of this work and to provide a wider review of the LCA standards in general.

Further research through the ISO work regarding the LCA harmonization has led to the Technical Committee ISO TC 59 SC 17 responsible for the process of standardisation in the field of sustainability of the built environment. Their work and aspirations towards the sustainability within the construction sector resulted in standards that have been listed in the Table 3.

The research focus is then shifted from the international to the European platform. The activities of CEN TC 350 for the Sustainability of Construction Works were reviewed and all standards, technical reports, and specifications as result of their work were listed (Table 4).

Links between Eco labels, building certificates, design competitions and LCA is researched to see the state of the European platform regarding the LCA standards in the building sector. Furthermore, it is concluded which kind of efforts are done with the aim to harmonize the LCA methodology within the building sector and which further initiatives can be suggested.

Interrelation of the LCA databases, tools and standards within the building sector is highlighted and explained.

3 RESULTS

3.1 The International Organization for Standardization (ISO)

As previously mentioned, international standards for LCA were developed since the 1990s by ISO Technical Committee 207 as part of their ISO 14000 family of environmental management standards. They represent the constitution of LCA as the only relevant international standard documents on LCA which are broadly referenced by users and other standardization processes (Finkbeiner 2012). Starting from the core standards ISO 14040-Environmental Management—Life Cycle Assessment—Principles and Framework (ISO 14040 2006) and ISO 14044-Environmental Management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044 2006), some spin-off standards, technical specifications (TS) and reports (TR) were recently developed by different secretariats (SC) within the Technical Committee 207 *List 1.* (ISO n.d., Klöpffer 2014).

Table 2.Standards, technical specifications and reports of the ISO TC 207

ISO/TC 207/ Environmental Management	
SC5/ Life cycle assessment	
ISO 14040 : 2006	Environmental Management - Life Cycle Assessment - Principles and Framework
ISO 14044 : 2006	Environmental Management- Life Cycle Assessment - Requirements and Guidelines
ISO 14045 : 2012	Environmental management - Eco-efficiency assessment of product systems -Principles, requirements and guidelines
ISO 14046 : 2014	Environmental management - Water footprint -Principles, requirements and guidelines
ISO/TR 14047 : 2012	Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TS 14048 : 2002	Environmental management - Life cycle assessment - Data documentation format
ISO/TR 14049 : 2012	Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis

ISO/TS 14071 : 2014	Environmental management - Life cycle assessment - Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006
ISO/ TS 14072 : 2014	Environmental management - Life cycle assessment -- Requirements and guidelines for organizational life cycle assessment
ISO/TR 14073 :2017	Environmental management - Water footprint - Illustrative examples on how to apply ISO 14046
SC 7/ Greenhouse gas management and related activities	
ISO/TS 14067 : 2018	Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication
SC 3/ Environmental labelling	
ISO 14025 : 2006	Environmental labels and declarations - Type III environmental declarations - Principles and procedures

3.1.1 ISO Standards for the Sustainability in Buildings and Civil Engineering Works

ISO TC 59 (Buildings and civil engineering works) SC 17 (Sustainability in buildings and civil engineering works) is aimed at standardisation in the area of sustainability of the built environment. The environmental, economic and social aspects of sustainability are included as appropriate (UNEP 2009). The work is accomplished by five working groups: General Principles and Terminology, Sustainability Indicators and Benchmarking, Environmental Declarations of Products, Environmental Declarations of Buildings and Civil Engineering Works. Efforts of these groups have resulted in the development of the following standards on sustainability in buildings and civil engineering works *Table 3.* (UNEP 2009; ISO n.d.).

Table 3. ISO Standards on the sustainability in buildings and civil engineering works

ISO TC 59/SC17/ Sustainability in building construction and civil engineering works	
ISO standard/technical specification or report	Scope
ISO 15392:2019 Sustainability in building construction - General principles	Establishes general principles of sustainability in building construction. Applicable to buildings and other construction works individually and collectively, as well as to the materials, products, services and processes related to the life cycle of buildings and other construction works. This standard does not provide levels (benchmarks) that can serve as the basis for sustainability claims. (ISO 2019)
ISO 21929-1:2011 Sustainability in building construction - Sustainability indicators - Part 1: Framework for the development of indicators and a core set of indicators for buildings	Establishes a core set of indicators to take into account in the use and development of sustainability indicators for assessing the sustainability performance of new or existing buildings, related to their design, construction, operation, maintenance, refurbishment and end of life. It does not give guidelines for the weighting of indicators or the aggregation of assessment results. (ISO 2011)
ISO/TS 21929-2 : 2015 Sustainability in building construction - Sustainability indicators - Part 2: Framework for the development of indicators for civil engineering works	Establishes a list of aspects and impacts which should be taken as the basis for the development of sustainability indicators for assessing the sustainability performance of new or existing civil engineering works, related to their design, construction, operation, maintenance, refurbishment and end-of-life. (ISO 2015)
ISO 21930:2017 Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services	Provides the principles, specifications and requirements to develop an environmental product declaration (EPD) for construction products and services, construction elements and integrated technical systems used in any type of construction works. (ISO 2017)
ISO 21931-1:2010 Sustainability in building construction - Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings	Provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of buildings and their related external works. (ISO 2010)

ISO 21931-2:2019 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 2: Civil engineering works	Provides a general framework for improving the quality and comparability of methods for assessing the contribution of civil engineering works and their related external works to sustainable development based on a life cycle approach. (ISO 2019)
ISO/TR 21932:2013 Sustainability in buildings and civil engineering works - A review of terminology	This technical report provides a compilation of terms and definitions of concepts related to both the construction and use of a building or civil engineering works, and the effect of such construction works on sustainability and sustainable development, as applied in the documents of ISO/TC 59/SC 17, Sustainability in buildings and civil engineering works. (ISO 2013)
ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance ISO/TS 12720:2014 Sustainability in buildings and civil engineering works - Guidelines on the application of the general principles in ISO 15392	This document provides an overview of design for disassembly and adaptability principles and potential strategies for integrating these principles into the design process. (ISO 2020) This technical specification provides guidance for the application of the general principles of sustainability in buildings and civil engineering works elaborated in ISO 15392. It shows the different actors involved with the construction works how to take these principles into account in their decision-making processes in order to increase the contribution of the construction works to sustainability and sustainable development. (ISO 2014)
ISO 16745-1 : 2017 Sustainability in buildings and civil engineering works - Carbon metric of an existing building during use stage - Part 1: Calculation, reporting and communication	It provides requirements for determining and reporting a carbon metric of an existing building, associated with the operation of the building. It sets out methods for the calculation, reporting and communication of a set of carbon metrics for GHG emissions arising from the measured energy use during the operation of an existing building, the measured user-related energy use, and other relevant GHG emissions and removals. These carbon metrics are separated into three measures designated CM1, CM2, and CM3. (ISO 2017)

ISO 16745-2 : 2017 Sustainability in buildings and civil engineering works - Carbon metric of an existing building during use stage - Part 2: Verification	It specifies requirements for the verification of a carbon metric calculation for GHG emissions of an existing building during the use stage, where the carbon metric calculation is performed in accordance with ISO 16745-1. (ISO 2017)
ISO 21678:2020 Sustainability in buildings and civil engineering works — Indicators and benchmarks — Principles, requirements and guidelines	This document defines principles, requirements and guidelines for the development and use of benchmarks when assessing the economic, social and/or environmental performance of buildings and civil engineering works by using sustainability indicators. (ISO 2020)

3.2 The European Committee for Standardization (CEN)

In addition to ISO standards, many efforts were undertaken during the last decade with the aim of developing LCA standards that are more building-related and focused on the building sector. The reason for this necessity is the specifics of building sector in comparison with other sectors, as well as a complex nature of the building itself as a product.

On the other hand, the CEN/TC 350 Sustainability of Construction Works has standards, for the example the EN 15804(2012), EN 15978(2011) and others listed in the Table *4.*, for the assessment of the environmental aspects of new and existing construction works and for the framework definition of environmental product declaration of construction products (Lasvaux et al, 2015).

A significant obstacle for the implementation of LCA in construction in Europe is represented by a significant difference between ILCD Handbook and CEN TC 350 standards provisions. That obstacle has been recognized by the Energy-efficient Buildings European Initiative, who set up the European research project EeBGuide in order to provide metrics and web-based operational guidance for building related projects, specifically for projects where LCA is applied as an assessment tool. The main objective of the EeBGuide is to provide a platform for research activities (EU projects, national projects), harmonization activities, supporting tools and the practical implementation of LCA in the building sector by the different parties (EC Seventh Framework Programme 2011).

Table 4 CEN standards, technical reports and specifications for the assessment of the environmental aspects of new and existing construction works and for framework definition of environmental product declarations of construction products

CEN/TC 350/ Sustainability of Construction Works	
CEN standard/technical specification or report	Scope
EN 15643-1:2010 Sustainability of construction works - Sustainability assessment of buildings – Part 1: General framework.	This standard provides the general framework for the assessment of buildings in terms of environmental, social and economic performance. The framework applies to all types of buildings over their entire life cycle. The standards developed under this framework do prescribe levels, classes or benchmarks for measuring performance. (CEN, 2010)
EN 15643-2:2011 Sustainability of construction works – Assessment of buildings – Part 2: Framework for the assessment of environmental performance	This standard provides the specific principles and requirements for the assessment of environmental performance of a building. (CEN, 2011)
EN 15643-3:2012 Sustainability of construction works--Assessment of buildings-- Framework for the assessment of social performance	This standard provides the specific principles and requirements for the assessment of social performance of buildings taking into account technical characteristics and functionality. Assessment of social performance is one aspect of sustainability assessment of buildings under the general framework of EN15643-1. (CEN, 2012)
EN 15643-4:2012 Sustainability of construction works-- Assessment of buildings--Framework for the assessment of economic performance	This standard provides specific principles and requirements for the assessment of economic performance of buildings taking into account technical characteristics and functionality. Assessment of economic performance is one aspect of sustainability assessment of buildings under the general framework of EN 15643-1. (CEN, 2012)
EN 15643-5:2017 Sustainability assessment of buildings and civil engineering works --Framework for the assessment of sustainability performance of civil engineering works	This Standard provides specific principles and requirements for the assessment of environmental, social and economic performance of civil engineering works taking into account its technical characteristics and functionality. Assessments of environmental, social and economic performance are the three aspects of sustainability assessment of civil engineering works. (CEN, 2017)

EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings - Calculation method	This standard provides the calculation rules for the assessment of the environmental performance of new and existing buildings. (CEN, 2011)
EN 15804:2012 + A2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products.	This standard provides core Product Category Rules (PCR) for all construction products and services. It provides a structure to ensure that all Environmental Product Declarations (EPD) of construction products, construction services and construction processes are derived, verified and presented in a harmonized way. (CEN, 2019)
CEN/TR 15941:2010 Sustainability of construction works – Environmental product declarations – Methodology for selection and use of generic data	This Technical Report supports the development of EPD. It assists in using generic data according to the core product category rules (EN 15804) during the preparation of EPD of construction products, processes and services in a consistent way, and also in the application of generic data in the environmental performance assessment of buildings according to EN 15978. (CEN, 2010)
EN 15942:2011 Sustainability of construction works – Environmental product declarations – Communication format business-to-business.	This standard specifies and describes the communication format for the information defined in EN 15804 for business-to-business communication to ensure a common understanding through consistent communication of information. (CEN, 2011)
EN 16309: 2014 +A1:2014 Sustainability of construction works-- Assessment of social performance of buildings--Calculation methodology	The purpose of this European Standard is to provide rules for the assessment of the social performance of new and existing buildings. In this European Standard, the method of assessment of the social performance of a building is based on a life cycle approach. The general requirements for sustainability assessment of buildings are described in EN 15643-1. The framework for the assessment of social performance is given in EN 15643-3. (CEN, 2014)
EN 16627: 2015 Sustainability of construction works-- Assessment of economic performance of buildings--Calculation methods	In this European Standard, the assessment method for the quantitative evaluation of the economic performance of the building is based on a life cycle approach. The general requirements for sustainability assessment of buildings is described in EN 15643-1. The requirements for the assessment of economic performance are given in EN15643-4. (CEN, 2015)

CEN/TR 16970:2016 Sustainability of construction works - Guidance for the implementation of EN 15804	This Technical Report provides general guidance to the users of EN 15804 and those preparing complementary Product Category Rules. (CEN, 2016)
CEN/TR 17005:2016 Sustainability of construction works - Additional environmental impact categories and indicators - Background information and possibilities - Evaluation of the possibility of adding environmental impact categories and related indicators and calculation methods for the assessment of the environmental performance of buildings	This Technical Report (TR) has been developed by CEN/TC 350/WG 1 and WG 3 to provide a clear and structured view on the relevance, robustness and applicability of a predefined set of additional impact categories and related indicators for the assessment of the environmental performance of construction works, construction products and building materials. The TR describes the evaluation criteria that are used to determine, for these impact categories, the suitability of indicators and calculation method(s) for inclusion in the standards EN 15978 and EN 15804. (CEN, 2016)

3.3 Overview of the Interaction between ISO and CEN Standards Related to LCA in the building sector

Having in mind that LCA method considers only environmental impacts and excludes the consideration of the social or economic aspects of sustainability of the product or service, as well as the difference between LCA studies on the product and building level in the building sector, the following interrelation of the current LCA standards in the construction sector was produced (Figure 8 and Figure 9).

Firstly, a framework, building and product level is differed between ISO standards, reports and specifications.

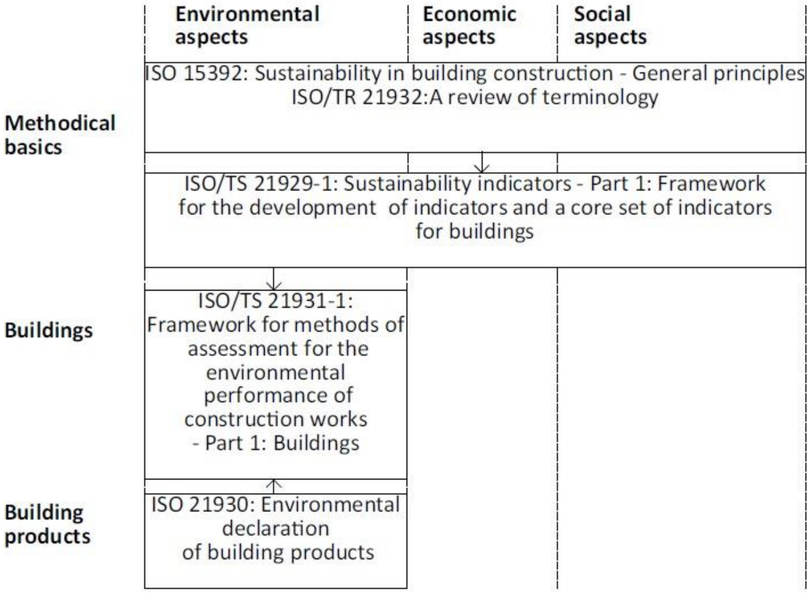

Figure 8.Suite of related International Standards for sustainability in building construction and construction works. (Adopted from ISO 21930 (2017))

Secondly, a framework, building and product level is differed between CEN standards, reports and specifications.

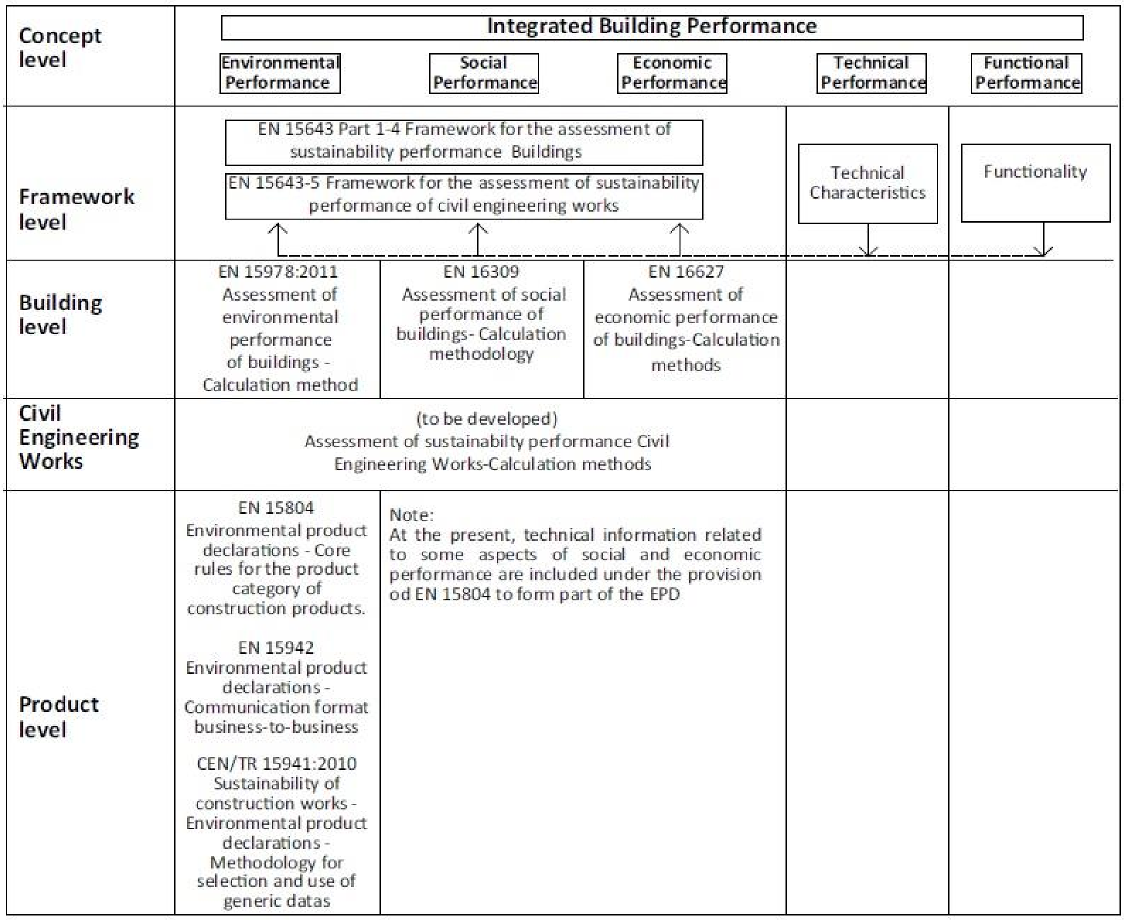

Figure 9. Work programme of CEN/TC 350. (Adopted from EN 16309(2014))

While keeping in consideration the fundamental LCA standards ISO 14040/44 (2006) and focusing only on the environmental performance among both ISO and CEN standards, the following interrelation was produced (Table 5).

Table 5.Comparison between ISO and European standards related to the building and product LCA within the construction sector

LEVEL	International standards (ISO)	European Committee for Standardization (CEN)
FRAMEWORK	• ISO 15392: Sustainability in building construction -- General principles • ISO/TR 21932: Sustainability in buildings and civil engineering works -- A review of terminology • ISO 21929-1: Sustainability indicators – Part 1: Framework for the development of indicators and a core set of indicators for buildings	EN 15643-1: Sustainability of construction works - Sustainability assessment of buildings – Part 1: General framework. EN 15643-2: Sustainability of construction works – Assessment of buildings – Part 2: Framework for the assessment of environmental performance
BUILDING	• ISO 21931-1: Framework for methods of assessment for the environmental performance of construction works – Part 1: Buildings • ISO 14040/44	• EN 15978: Sustainability of Construction works – Assessment of Environmental Performance of buildings – Calculation method
PRODUCT	• ISO 21930: Environmental declaration of building products • ISO 14040/44	• EN 15804: Environmental Product Declarations • CEN/TR 15941: Methodology for selection and use of generic data • EN 15942: Communication format business-to-business

A parallel order of the International standards (ISO) and The European Committee for Standardization (CEN) standards was produced with the aim of showing the complex interrelationships between them. Standards that belong to the framework level are applicable not only to the environmental assessment but also to the social and economic assessment as well. EN 15804:2012+A2:2019 provides the methodology for developing an EPD at the product level while EN 15978:2011 describes the assessment of environmental performance at the building level. Hence, certain interdependency exists between standards of the building and product level. Any decisions that are taken during the assessment at the product level display their impact at a later stage when this information is used for the assessment at the building-level (Kirchain et al. 2017, BRE n.d.).

3.4 Life Cycle Inventory (LCI) Database

The core of LCA analysis lies within the LCI data, since quality of the used data has a major impact on the results of an LCA. Different organizations and LCA tool developers have developed LCA databases that include not only material and energy data, but also the emission data of applied products and processes. Usually, the databases are available within an LCA tool or can be imported into a tool.

According to numerous published studies and papers (Oritz et al. 2009, Verbeeck et al. 2010; Lasvaux et al. 2012; Martínez et al. 2016), the following two databases are the most used sources in current industry practice and governmental studies around the world due to their integrity and usability :

•The Ecoinvent database

The Ecoinvent is the database by the Swiss Ecoinvent Centre, containing the inventory data of more than 2,500 products and services (Wernet et al. 2016). The data source is primarily aimed at Swiss and German industry, but can be applied in other parts of Europe as well. Besides the detailed inventory data on each product, impact assessment results based on various models can also be obtained. Thus, Ecoinvent is properly targeted for construction objectives, since every category of construction materials is included and developed with a high variety of products. Many LCA software tools, such as GaBi5, SimaPro8 and Umberto5 use Ecoinvent data (Martínez et al. 2016).

• The GABI database

GaBi Databases, created by PE International are the largest internally consistent LCA databases on the market today and contain over 10,000 ready-to-use Life Cycle

Inventory profiles (PE INTERNATIONAL n.d.). This database refers, amongst other processes, to construction materials, with a variety of products within each category.

Databases contain elementary flows (inputs and outputs) for each unit process for a product system (SAIC 2006; Bayer et al. 2010). Due to many factors, including energy sources, supply assumptions, product specifications, manufacturing differences and complications in the economic activities databases differ from one country to another (Menzies et al. 2007). Any of the above-mentioned factors can make significant variations in the environmental impact assessment. Thus, there is a need for the development of the national LCA bases.

The next list (*Table 6.*) presents an overview of international and national databases for LCA in the construction sector. The European Commission's Institute for Environment and Sustainability provides a list of available LCA databases, where those working with the construction materials are listed (European Commission 2018, Kharsen et. al. 2009). They are divided into category of those with the single aim of serving as a database only and the interdependent sources with compatible software tool.

Regardless of the significant number of the LCA databases, that have been formed after the ISO 1040/44 standards have been released in 2006, only a few of them contain data on construction materials (Martínez et al. 2016). Nevertheless, thereby several issues were noticed among, such as a lack of the harmonization between locations of the LCA data and the location of a performed study, mismatching of the data on the project conditions. All mentioned, limitations play a significant role, regardless the fact that the most of the LCA databases use the cradle to gate model, and lack of transparency in general (Rocamora et al. 2016, Bribiánl et al. 2011, Lopez et al. 2011, Reap et al. 2008) .

Table 6. List of the Construction LCA Databases

Database		Function
European databases		
Ecoinvent / Swiss Centre for Life Cycle Inventories		database
ELCD database 3.1. / European Commission		database
Gabi Database		database + tool
Plastics Europe Eco-Profils		database
American databases		
Athena database		database + tool
U.S. Life Cycle Inventory Database		database
National databases		
Base Carbone	France	database
BEDEC database	Spain	database
CPM LCA database	Sweden	database
ProBas	Germany	database
Input–Output databases	Denmark	database
BRE	UK	database + tool
IBO	Austria	Database

3.5 LCA Tools for Buildings

The LCA of a building can be executed by using the LCA general software. Nevertheless, this process is extremely time-consuming, and involves quantification of building materials and their energy use. For this reason, specific tools have been developed to facilitate an easier use of LCA in the building sector (ENSLIC Building 2007). An LCA tool can be defined as an environmental modelling software that develops and presents life cycle inventory and also life cycle impact assessment results through analytical process that cohere closely to fundamental ISO standards and other accepted LCA guidelines (Trusty et al. 2005). Their intended function may vary, they can be applied as the guidance for general building planning, for supporting the selection of building materials and components, or as an assessment tool for a complete building. There is a wide variety of such software depending on the area of application, geographic relevance, and data quality.

According to Reiter (2010) and Bayer (2010) LCA tools can be classified into two groups based on:

1) different levels of LCA application (for building-specific tools)

2) required user skill to use the tool (for all tools)

Three main types can be identified based on different levels of LCA application:

• **Building Product LCA Tools**

In building product tools, the products are the smallest element of analysis (e.g., doors) and these tools include pre-set material data in order to facilitate easy use by designers and architects.

• **Building Assembly LCA Tools**

Building assembly tools represent a group of interdependent building components that make up a system within a building (e.g., wood, plastic, glass for doors). Building assembly tools assess complete assemblies for their environmental impact by considering the combined effect of all the applied products.

• **Whole Building LCA Tools**

Whole building LCA tools evaluate the environmental impact by considering all the systems and assemblies together. These tools are helpful during preliminary design by virtue of their capability to compare several design options and iterations in a modelling software. The result is assembled for the entire building and presented in the form of environmental impacts according to different life-cycle stages or the share of the building to a particular impact (Reiter 2010; Bayer 2010).

Two main types can be identified based on different required user skill to use the tool LCA application:

- **Tools for LCA Practitioners**

Tools for LCA practitioners help within arranging the analysis, connecting unit processes, facilitating the consideration of standard transport, energy production, and other datasets, providing necessary analytical and computational frameworks. Important feature of these tools is represented by the database adjustability or the potential to be replaced by the user, which can be helpful in the LCA assessment of individual products and complex components assemblies (Kubba 2016)

- **Tools for General Users**

Tools for general users (e.g., architects and designers) have all the basic LCA work done in the background. For these tools user has to input the data and does not need to structure the analysis. Databases are locked and cannot be modified, this limits the applicability of the tools only for the building products, materials and activities, which data is already provided in the database (Trusty et al. 2005)

Table 7. represents a list of current building LCA tools. It provides us with the information about the country of the development of the software, information about the level of LCA application and the type of software (Lasvaux et al.2015, Diakoumakou 2016).

Table 7. List of currently available LCA Software tools at the market (Lasavux et al.2012; Diakoumakou 2016)

Tool name	Country	LCA level	Type of the Software
ArchiPHYSIK	Austria	Whole building	Stand alone
Athena Impact Estimator for Buildings	Canada	Whole building	Stand alone
BEES	United States	Building product	Web based
CAP'EM Compass	France	Building product	Web based
CMLCA	Netherlands	Building product	Stand alone
COCON – Excel	France	Whole building	Stand alone
COCON BIM	France	Whole building	Plug in
Eco2Soft	Austria	Whole building	Web based
ECODESIGN	Austria	Building product	Web based
Eco-Sai	Switzerland	Whole building	Stand alone
Eco-Sai Revit Plug in	Switzerland	Whole building	Plug in
e-LICCO	France	Whole building	Web based
ELODIE	France	Whole building	Web based
eToolILCD	Austria	Whole building	Web based
Eve-BIM ELODIE	France	Whole building	Plug in
GaBi	Germany	Building product	Stand alone
LeGep- LCA	Germany	Whole building	Stand alone
novaEQUER	France	Whole building	Stand alone
openLCA	Germany	Building product	Stand alone
SimaPro	Netherlands	Building product	Stand alone
Tally	United States	Whole building	Plug in
TEAM	France	Building product	Stand alone
Umberto NXT LCA	Germany	Building product	Stand alone

LCA tools also differ based on their goal (eco design or building certifications) in a way that they can use different data and calculation rules. This leads to another challenging issue: The environmental indicators in the databases differ considerably and thus LCA tool studies are not always comparable (Lasvaux et al.2015). In addition, Cole states (1996) that the fact of a limited availability of data and the existence of a large number of different building technologies makes it impossible for LCA tools to model and analyze the environmental impact of all phases of the building.

3.6 State of the LCA in the Building Industry

The European standards EN 15804 and EN 15978, which are both based on ISO 14040 and ISO 14044, define the general framework and general calculation methods for the LCA calculation of buildings and products. The links between eco labels, building certificates, design competitions, and LCA are researched to represent the state of the European stage regarding the LCA standards in the building sector. Furthermore, it is concluded which efforts are undertaken to harmonize the LCA methodology within the building sector and which further initiatives maybe suggested.

Interrelation of LCA databases, tools and standards within the building sector is discussed in the following pages (Figure 10).

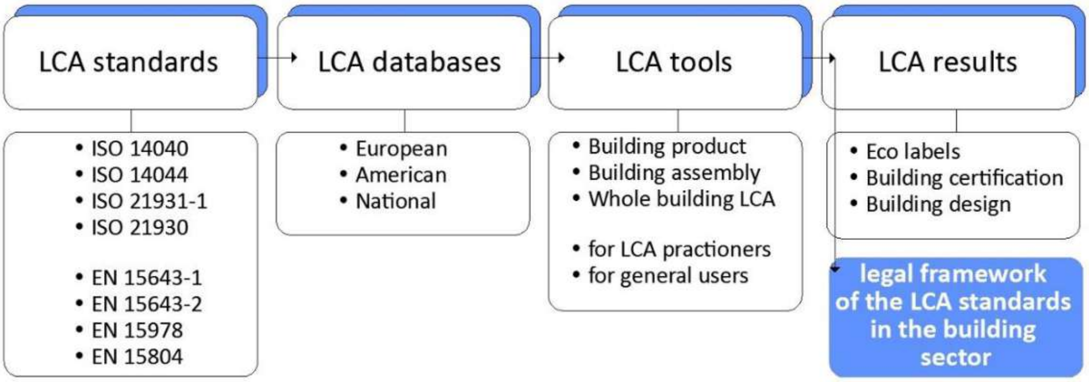

Figure 10. Interrelation of the LCA databases, tools and standards within the building sector

3.7 Type of eco labels and their relation to the LCA

Within the ISO 14000 series of environmental management standards, the ISO 14020 series precisely address the aspects of environmental labels and declarations. The International Standards Organisation (ISO) differentiates three types of eco-labels (ISO n.d.):

• **Type I environmental labelling** is a voluntary, multi-criteria based, third party program that awards a license by approving the use of environmental labels on products. This indicates the environmental effort of a product within a particular product category based on life cycle observations. Type I involves multiple attribute labels such as Blue Angel, EcoLogoTM, Green Seal and EU Eco-label (Gamage et al. 2008). Award of these labels communicates to customers that the product has passed an evaluation of criteria included in that label. Type I labels require life cycle considerations (ISO 14024, 1999).

Regardless the fact that the ISO 14024 standard says that the life cycle of a product has to be considered, it does not establish to what extent LCA methodology has to be followed (Santos 2014). Hence, its application deviates from one Type I scheme to another (Scheer et. al. 2005).

• **Type II environmental labelling** deals with self-declared environmental information. It suggests that the goal of environmental labels and declarations is to simulate the demand for products which cause less stress on the environment through the communication of accurate information. This encourages the potential for continuous environmental improvement of the market (Braganca et al. 2012). The ISO 14024 (1999) is a crucial tool for manufacturers and businesses that often claim a certain environmental performance on their products, as part of their marketing campaign.

LCA can be used to provide this scientifically based claim for the development and verification of this eco label (Santos 2013). Information is not verified by a third party (Gamage et al. 2008).

• **Type III environmental labelling** is a voluntary program that provides quantified environmental data of a product, based on life cycle assessment, under categories previously set by a qualified third party and later verified by that or another qualified third party. EPDs are Type III eco-labels (ISO 14025, 2006).

The EPD as a voluntary system provides a description of the environmental performance of products. This system is based on Product Category Rules for the presentation of environmental characteristics defined in ISO 14025 for type III environmental declarations. Depending on the type of a product, these rules may vary. ISO 21930 (2017) provides basic requirements for PCR for type III environmental declarations of building products and aligns with the European standard EN 15804 for construction products in Europe.

EPD does not imply any environmental advantage of the product itself, provided information has been verified by Product Category Rules and the General Programme Instructions. EPD is based on the party's knowledge to understand and select optimal materials and products (Braganca et al. 2012). The reference standards include ISO 14025 for type III environmental declarations and ISO 14040/14044 for the procedure to carry out a life cycle assessment (Figure 5.). In the building sector, the standard ISO 21930 complements the ISO 14025 and provides more specific requirements for the EPD of the building products, as well as for the PCR of the building products (Fores at al. 2016). It is important to highlight the fact that the ISO 21930 focuses on the environmental impacts of the product when declarations are developed, unlike its family standards for evaluating sustainability, which take into account also social and economic aspects of the product (Fores at al. 2016).

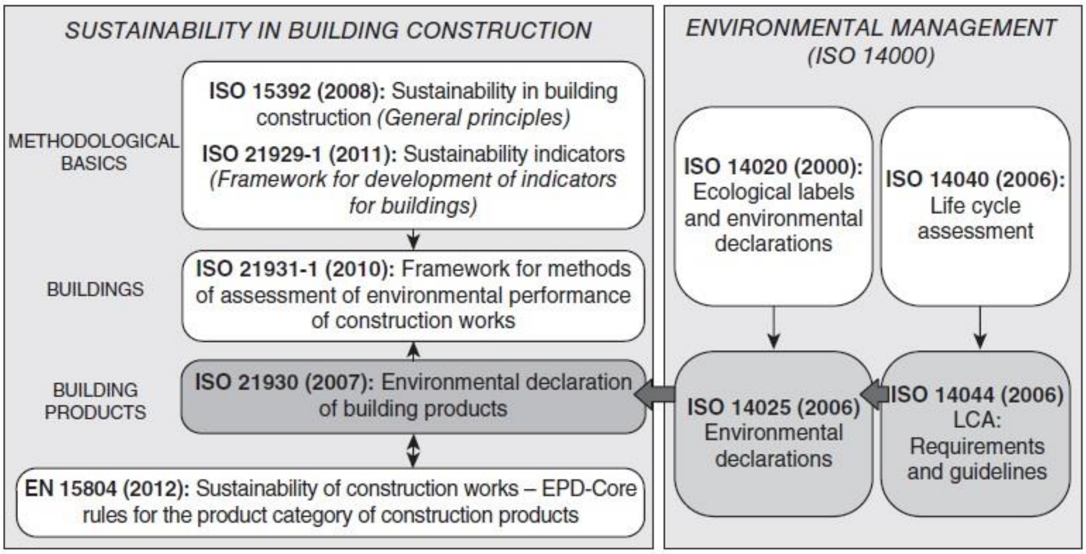

Figure 11. Regulatory framework for Type III environmental declaration of building products. (Adopted from Santos et al. 2014)

Sweden was the pioneer of public EPDs and that effort has resulted in an international EPD network, which includes three Swedish organizations. EPDs of these organisations cover products of other European nations as well (Braganca et al. 2012). According to EPD network, there are five essential steps, which have to be followed in order to create, register and publish an environmental declaration in the

International EPD System in accordance with ISO 14025 and EN 15804 (for construction products). These steps are listed in the following by the sequence of occurrence:

1.Creation of the relevant PCR documentation for the product category.

2.Carrying out LCA study based on PCR documentation

3.Summary of the environmental information according to EPD reporting format.

4.Verification,certification,registration and publication (EPD n.d.).

As previously stated, LCA may be used during the development of the required criteria for obtaining a Type I eco-label and in the case of the Type II eco-labels, they are not necessarily based on LCA results. On the other hand, Type III eco-labels (EPDs) demand that an LCA study is based on the following specific product category rules. Hence, only in the case of Type III eco-labels (Table 8.) is LCA a requirement for award of the eco-label as a method to inform the market about the relevant environmental aspects of the product throughout its life cycle (Santos 2014).

Table 8. Relation of LCA methodology to different types of eco-labels

Type of the eco label	Type I	Type II	Type III
ISO/CEN Standard	ISO 14024	ISO 14021	ISO 14025 ISO 21930 EN 15804
LCA included for defining the awarding criteria	not in all cases	no	yes
LCA included for demonstration that the product fulfils awarding criteria	no	not in all cases	yes
LCA included to provide quantitative environmental information allowing the comparison of different eco-labelled products/services	no	no	yes

3.8 Building Certification and LCA

Certainly, the most important application of the EPDs in the building sector is their application for environmental assessment of the buildings. EPD indicator results are used directly for computing on the building level in certain building assessment schemes (Fullana et al. 2008). Building certifications contribute to implementing a sustainable approach in the construction sector, as well as gaining economic and social benefits (Anand et al. 2017). They can be used as a framework for assessing the environmental performance of the building and for incorporating the sustainable aspects of the whole life cycle of the building in the design, construction and maintenance phase (Giama et al. 2012). Building rating system can be seen as a management tool in order to address and include environmental issues during all phases of the life cycle of the building such as design, construction, operation and maintenance (Giama et al. 2012). Development of the building rating systems is promoted and encouraged by the international organizations such as the Green Building Challenge (Todd et al. 2001) and World Green Building Council (WGBC n.d.).

Expertise and knowledge in the field of environmental methodology from other sectors is integrated in the building rating systems (Sartori et al 2021). Among them is a well-know LCA method (Giama et al. 2012). As previously stated, some of these schemes sometimes need environmental quantitative information about the product that can be provided by the direct use of its EPD. On the other hand, life cycle information is mainly being used for defining the criteria for rewarding the green building certificates and LCA methodology is being used in some schemes and not in all of them (Santos 2014). In Table 9. in order to detect which of the building certificates scheme integrate LCA methodology in its ratings, most popular certification schemes based on the number of accredited certifications are reviewed (Giama et al. 2012; Vibha et al 2021; Sartori et al 2021).

Based on the carried-out review of the building rating systems in the Table 9., it may be concluded that, in spite of their mutual differences regarding structure, evaluation methodology, and rating, all systems emphasize the same environmental aspects in respect to energy and water consumption, material use and building operational management (Sartori et al 2021).

It may be seen that there are certain building schemes such as DGNB, LEED, HQE and BREEM that include the LCA in different levels. Specific set of rules is applied to the calculation of the building LCA, which may refer to EN 15978 (Anand et al. 2017; Wittstock et al. 2012). Integration of the LCA into building rating systems is a relatively new idea. Further efforts must be undertaken in the direction of international harmonization and a development of international standards in a long perspective, which will play an important role in the integration of the LCA in the building certificates schemes (Bribian et al. 2009; Lessard et al. 2015; Trusty at al 2009.; Giama et al. 2012).

Table 9.List of Building Rating Systems

Rating system	Scope
Building Research Establishment Environmental Assessment Method (BREEAM)	•created in UK in 1990 by The British organization BRE, also available and applicable to any other country •assesses the performance of buildings using environmental aspects such as energy efficiency, water consumption, internal environment, pollution, transportation and materials •awarding credits in each area according to buildings' performances (Anand et al 2017; Vibha et al 2021; Sartori et al 2021)
U.S. Green Building Council (LEED)	•developed in USA in 2000 by the US Green Building Council, also used around the world •assesses the overall performances of buildings using environmental aspects such as energy efficiency, water consumption, indoor air quality, pollution, transport and sustainable sites selection •awarding credits for each environmental criterion according to the building's performance •LEED has evolved over the years to now include LCA in LEED V.4 (Khasreen et al. 2009; Anand et al 2017; Giama et al.2012; Vibha et al 2021; Sartori et al 2021)
High Environmental Quality (HQE)	• developed in 1994 in the France •certification is based on 14 target areas grouped into four themes: environmental construction, environmental management, comfort and health •the choice of construction products and materials is based on EPDs that include LCA data (Anand et al 2017; Giama et al. 2012)
Deutche Gesellschaft fur Nachhaltiges Bauen (DGNB)	•developed by the German Sustainable Building Council and the German Government, in 2009 and adopted for several countries •based on several criteria grouped into six topics, among which are ecological quality, economic quality and technical quality • for the ecological quality topic, LCA data are required (Anand et al 2017; Giama et al. 2012; Vibha et al 2021: Sartori et al 2021)
Comprehensive Assessment System for Building Environmental Efficiency	•launched in 2001 by the Japanese Sustainable Building Consortium •LCA is used in determining quantitative assessment indicators for typical building environmental loads (Anand et al 2017; Giama et al 2012; Vibha et al 2021; Sartori et al 2021)

Green Globes	•developed in Canada in 1996 and based on BREEAM •special focus is on the design of new buildings, where points are given in the resource section for conducting an LCA of building assemblies and materials (Anand et al 2017; Giama et al 2012; Vibha et al 2021; Sartori et al 2021)
Green Star	•developed in 2003 by the Green Building Council of Australia, based on LEED and BREEAM. •most popular assessment system in Australia, New Zealand and South Africa •it does the assessment of the building environmental performance based on the nine environmental impact categories •it does not have a real inclusion of LCA for the construction materials that have been used (Anand et al 2017; Giama et al 2012; Vibha et al 2021; Sartori et al 2021)

3.9 Design phase and LCA

Terminology of the embodied and operational energy within the life cycle energy of the building was previously discussed. The focus of the discussion in this chapter is shifted ratio of operational energy to embodied energy in last years (Herren et al. 2015).

It is reported in various LCA studies (Sartoril et al. 2007; Sharma et al.2011; Verbeeck et al. 2010) of conventional building types that an operational phase of a building life cycle has a high impact. In these particular cases, embodied energy is irrelevant and may even be neglected. However, the measures that have been performed in order to reduce the operational energy demand have created a shift of the ratio of operational energy to embodied energy in the last years (Herren et al. 2015). As a result, the share of embodied energy was increased, while operational an energy demand was successfully reduced (Hollberg et al. 2019).

On the other hand, in case of low energy buildings, such as those with the Passivhaus standard label, the embodied energy contributes up to 30 % of the full life cycle primary energy demand (El Khouli et al. 2014; Passer et al. 2012; Takano et al. 2015). Starting from 2021, the situation became even more complex regarding the contribution of the embodied energy to the life cycle primary energy demand (Hollberg et al. 2019). This complication is based on a new limitation that nearly zero-energy buildings are allowed to be constructed (EU 2010). According to

Weissenberger et al. (2014), nearly zero-energy buildings are buildings that produce the same amount of energy, which is consumed on average on an annual basis. In other words, the operational energy demand of nearly zero-energy buildings is close to zero, hence the proportional contribution of embodied energy will be almost 100 % (Hollberg et al. 2019). This is the main reason of the shift of the focus from operational to embodied energy in case of the nearly zero-energy buildings. Hence, the consideration of the LCA in the design building phase is essential (Heeren et al. 2015). Unfortunately, European regulations until now address only the operational energy, while embodied energy is still considered as an insignificant factor (Szalay and Zöld 2014).

There are several reasons for the fact that LCA has not been widely applied in a very complex building design process (Wittstock et al. 2009; Bribián et al. 2009; Hollberg et al 2019):

• Nature of architectural design

6 phases are normally distinguished in the design process, as per *Figure 5.* (Hegger 2007; El Khouli et al.2014). Hollberg and Ruth (2016) describe these as follows:

1) The design process starts with the preliminary phase, which usually includes research about the context of the building, functional analysis and feasibility studies. These research aspects are mostly defined by the initiator of the architectural competitions.

2) The second phase is the phase of the architectural design, when such decisions as building orientation, number of storeys, function and volumes are made. These decisions have a fundamental impact on further design steps. Due to this fact, LCA could be seen as a useful tool for the environmental assessment of the suggested design already in this phase (Fuchs et al. 2013).

3) In the next phase, elaboration of the design is carried out, primary constriction material and building envelope are defined in a low level of details without any precise data on quality and characteristics. This phase is usually followed by the application for building permission.

4) The fourth phase, phase of a technical description, is the first phase of the building design, where the information required for a complete LCA is available and where EPDs, if available, can be applied.

5) Next phase is the construction phase, which is followed by a handover of the building to the client.

6) The last phase, operational phase, contributes significantly to the energy consumption of the building. It must be taken into account hat the decisions taken in the second phase of the design, such as thermal characteristics of the building envelope, the choice of heating and ventilation systems, have already had an impact on the operational phase of the building.

In the design process, the main difficulty of LCA application lies within the fact that the information, the precise summary of quantities and product-specific properties, required for conducting the LCA at the second design stage is firstly available later in the fourth stage. As a consequence, changes of the main design at this stage might turn to be too expensive, in case LCA results demonstrate a need of those (Hollberg et al. 2019).

• Designers' lack of knowledge about LCA

One of the major barriers in the application of LCA in practice is the designers generally poor understanding of the methodology (Byule et al. 2013). Baitz et al. (2012) explained the demand for a simplified, more time efficient LCA approaches as the response to the general gap between the application of LCA in theory and practice. Hollberg et al. (2016) suggest that the additional effort of conducting the LCA can be minimized by incorporating such a simplified LCA into the design process.

• LCA initiatives

Performing LCA in the design process is an expensive and time-consuming task (Weissenberger et al. 2014). Hence, this could be seen as a one of the reasons why LCA is mostly carried out by larger companies that have a better financial status normally by an LCA expert and not by the architect (Bribián et al. 2009). In a case study, which included seven different architectural companies (Buyle et al. 2013), architects suggest the integration of the monetary incentives as a solution. Integration of subsidies and tax would expand the use of the green building products and facilitate LCA calculation in the building design. In that way companies would be encouraged to perform LCA, educate their designers about LCA methodology and consider the calculation results in architectural design solutions.

3.10 Limitations and problems of LCA in BS by Phase

Various studies have shown that two LCA studies based on the same building can yield different results (European Commission FP7 2011). LCA studies of buildings and building materials require methodological assumptions on several different aspects, which can lead to different results by applying different methodologies (EU JRC 2010; European Commission FP7 2011; Rooning et. al 2014).

In the following sub-chapters, possible reasons of such differences in LCA results through the different four phases is considered.

Special emphasis is placed on ISO 14040 (2006) and EN 15978 (2010) standards as well on publications about their provisions, ILCD Handbook (EU JRC 2010) and EeBGuide Guidance Document Part B: BUILDINGS (European Commission FP7 2011).

3.10.1 Goal and Scope Definition

The goal of the LCA study is defined as the first step. It is a key LCA requirement as it affects and guides all aspects of the scope definition, which then set LCI and LCA. That is why special attention should be placed in this first step of any LCA study due to the fact that it will influence the study results and determine their applicability. The goal definition of the study includes six different aspects: intended application of the LCA results; reason for carrying out the study; the targeted audience; whether the results are intended to be used in comparative assertions and intended to be disclosed to the public; method, assumptions and impact limitations; commissioner of the study and other influential actors (ISO 14040, 2006).

According to EN 15978 (2010) the goal of the assessment is to quantify the environmental performance of the object of the assessment by means of the compilation and summation of the environmental information. Object of the assessment in this case is a building over its life cycle (or it is restricted to a part of the building, part of an assembled system or a part of the life cycle). Object should be addressed by its physical and time dependent characteristics, one of the first identified limitations of the LCA standards in the building sector. Issue of the time dependence of the representativeness, completeness and precision of the LCA results is a highly sensitive issue in the LCA in the building sector. It is considered in next subchapter in further detail.

As soon as the goal of the study is defined, the next step includes deriving the scope from the defined goal. First concern of the scope definition is a clear description of a product system, its function, functional unit, and reference flow (ISO). Some complexities shall be stated regarding the function of the building. Very common phenomenon is the change of function of the object during its lifecycle. Often, this may happen even several times due to a variety of users' needs and market demands over time. This leads to the conclusion that a good solution for the building design considers its adaptability over time. This fact complicates the process of a scope definition of the LCA study due to the fact that future scenarios of its adaptability cannot be precisely planned and considered in detail. In addition to these aspects related to adaptability (redesign, changes in use pattern and functionality), Rooning et. al (2007) define sustainable building as the structure, which functions optimally for its purpose over time, while using the optimal sum of resources. In more detail, a sustainable building should function optimally in order to fulfill the users' needs effectively, be convenient for its use in the way that it corresponds to state-of-the-art of the construction industry, be flexible to adapt to the needs for redesign and user requirements over time and to have optimal resource use, i.e., low energy consumption and carbon emissions (Rooning et. al 2011). Taking all the mentioned aspects into account, a legitimate description of the function of the system or product in qualitative and quantitative terms seems almost impossible, as it means that we should be able to anticipate future needs of the end users and future environmental impacts as a result .

Functional unit names and quantifies the qualitative and quantitative aspects of the performance of a product system along the questions ,,what'', ,,how much'', ,,how well'' and ,,how long ''. It is used as a reference unit for LCA and any comparative assertion (ISO 14040, 2006; ISO 14044, 2006; EU JRC 2010). Having in mind a specific and unique nature of the building as a product, CEN EN 15 978 (2012) introduces the functional equivalent, a representation of the required technical characteristics and functionalities of the building. Thus, this standard, functional equivalent of a building or an assembled system shall include information on the following aspects: building type, relevant technical and functional requirements, pattern of use. and a required service life.

Reference study period determines the maintenance phase of the assessed building or a product and it is defined as the time period for the analysis of the time-dependent characteristics of the object under the assessment (CEN EN 15 978, 2012). According to the CEN EN 15 978 (2012), the default value of the reference study period should be a required service life period (SLP) and all possible deviations should be clearly stated and explained. In this view, a time factor has crucial importance for the calculation of the environmental impact of the object of the assessment. It would influence the required life service period and further have an impact on the development of the future scenarios. In fact, the SLP has a significant influence on a system boundary. It defines which stages of life cycle of the building (product) are taken into account for the assessment.

The range of the SLP is considered to be in the range from 20 to 100 years (Happioo et. al 2008; Rooning et. al 2014). If SLP lasts during the whole life of building, then no special attention has to be placed on the adaptability and all its consequences, such as changes due to new technologies, use patterns, re-design and functionality). In case SLP differs from the whole life of the building, aspects related to adaptability should not be neglected in LCAs, as they have a direct impact on the maintenance phase of the building (Rooning et. al 2014). Some studies describe the operation phase in terms of the use of the energy for the cooling and heating (Blengini et al. , 2010). Others take into account lighting, as well as use of technical equipment and appliances (Scheuer *et al* ., 2003). As such, the credibility of LCA results could be challenged in both cases. In the first case, it is questioned whether it is possible to estimate required energy in a reliable manner.

It is important to note that LCAs are often based on technical service of a product, provided by the producers (Rooning et. al 2014). SLP does not always represent the real life. According to the Bribrian (2009), many studies have proven that the SLP in practice differs considerably from the SLP assumed by the producers. Hence, this represents the basis for the scenario development of the operation phase of the object and has the direct impact on the credibility of LCA results.

3.10.2 Life Cycle Inventory

The aim of this phase is to decide which actual data collection and modelling of the system or product is to be carried out. This is done in a line with the goal and the scope requirements. According to ILCD (EU JRC 2010) and ISO 14044 (2006), the inventory phase includes the collection of the required data for elementary, product and waste flows, as well as other data, which was identified in the scope definition phase as a relevant information for the study. Results of the LCI serve as feedback for the scope of the study, as they indicate the need for the potential adjustment of the initial scope definition. Limitation of the scope of the LCA approach has to be noted: it is exclusively linked to the impacts that are potentially done by interventions between the analysed system and the ecosphere. They are also caused during normal and abnormal conditions of the included processes, while excluding accidents and other similar unpredictable scenarios (EU JRC 2010).

On the other hand, the results of the LCI represent the input for the following LCIA phase of the study. Hence, the burden of the credibility of the LCI results is even greater, especially regarding their consistency and representativeness and the validity of final LCA study itself.

Hence, the first task to be undertaken is to decide which data has to be collected regarding the upstream and downstream processes (amin). The data collection planning step is also iterative and hence it is advisable to clarify some fundamentally different options before this step (EU JRC 2010). Two different methodologies can be differed: top-down, which is based on input–output life cycle assessment and bottom-up, based on process life cycle assessment. As previously mentioned in the second chapter (Variations of LCA), most of the LCA methods implemented in a building sector are based on process-based LCA.

The results of the input–output life cycle assessment represent the impacts from a change in demand for an industry sector and as such can be treated as an accurate holistic information only if the data describes a specific industry and if this industry is representative of the sector. In the opposite case, this methodology may yield relatively unreliable results, taking into account the fact that industry sector consists of several different types. Circumstances in this modelling case are further complicated by the fact input-output data are not modelled annually and only a limited number of countries obtain statistical data available in this format. The issue usually arises when certain country uses a source as a data background not totally comparable to their data formats.

Process based life cycle assessment is explained in first chapter in a more detailed manner (Variations of LCA). This modelling is based on a traditional mass and energy balance approach. However, it is not common that projects in a building sector are evaluated on a mass basis, but rather in economic terms. This is one of the reasons why data selection and collection represent a difficulty. Second reason lies within a fact that not all materials which are included in a construction phase are well-documented. The last reason is a general lack of availability of environmental data for building materials, which is explained in more detail further in this work.

Hybrid LCA is based on these two approaches. In the third approach, a collected process information and the life cycle inventories are linked with monetary flows and economic models. Hybrid LCA represents a complementary tool for traditional inventory methods and LCA to overcome the lack of data and to include embodied emissions (Guggemos and Horvath, 2016; Sharrard et al. 2008).

According to the EeBguide (European Commission FP7 2011) all data used in any LCA study should be modelled within a consistent methodology. This can be normally achieved by using a public or commercially available background data bases and modelling the foreground systems. In general, LCA practitioners should use consistent data form a single source such as ecoinvent, GaBi, ELCD or ESUCO. The combination of different sources should be avoided. However, in practice, mixing the background data sources can happen. For example, this can occur when the background data sets are more representative of the study context rather than the main database or in the case of EPD databases, where no mandatory background database is provided. The issue occurs sometimes in the adaptation of data in terms of methodology and cut off rules. When combing data from different sources, in case specific datasets are lacking, practitioners must decide whether it is more relevant to use consistent but roughly estimated or a more representative data set . In this case, the usability of the quality indicators can be a possible solution for the assessment of the consistency of the methodology and the representativeness of the data (European Commission FP7 2011).

This all leads to the most important issue of the LCI phase of the LCA study, which is the data quality. Although it is crucial for any LCA study, usually it is not possible, in building sector practice to choose the datasets for quality reasons, but rather for the reasons of availability. Nevertheless, the current situation is much better in comparison with the past decades, as it is possible to differ the generic, average and specific industry data regarding the screening, simplified and complete LCA in the construction sector. Altogether, process data gaps and missing data still remain a major challenge .

3.10.3 Life Cycle Impact Assessment

According to the ISO 14044 (2006) and ILCD (EU JRC 2010), life cycle impact assessment is the phase of the LCA study, when the inputs and outputs of the elementary flows, which were collected and reported in the life cycle inventory phase, are translated into impact indicator results related to natural environment, human health and resource depletion. Aim of this phase is to identify which impact assessment methods are to be used, the type and the number of indicators which should be taken into account in LCA or LCI studies in order to avoid burden shift (European Commission FP7 2011).

It is important to note that LCA study and the impact assessment is the analysis of a potential environmental impact on humans and natural environment. Hence, the results of the LCIA should be seen as environmentally important impact potential indicators and not as predictions of an actual environmental effect (EU JRC 2010). LCIA phase prepares inputs for the interpretation phase of the LCA and contains mandatory and optional steps (ISO 14044 (2006)).

First step is the *classification* of the elementary flows of the inventory phase, in a way where one or more impact categories is assigned to each of the flows. This step clarifies which emissions contribute to certain impact categories. Note that the impact categories were selected in the scope definition of the study. Second step represents the *characterisation* of elementary flows in a manner of the quantitative characterisation for each classified elementary flow, which contributes to the impact categories. This characterisation factor indicates how much certain flow contributes to the impact category indicator or category endpoint indicator (ISO 14044 (2006), EU JRC 2010).

According to EeBguide, the operational guidance for the environmental indicators can be broken into two main aspects:

• the number of the selected indicators depend on the study type

• the calculation rules for environmental indicators by CEN TC 350 standards and ILCD.

In order to avoid burden shift, the set of indicators in any LCA study should be as comprehensive as possible (European Commission FP7 2011). Required environmental indicators for the building sector are given by EN 15804 and EN 15978 standards. The issue arises due to the fact that the choice of impact categories is made in the goal and scope phase, as later several other environmental impacts are detected during the LCA study (Rooning et. al 2014). These difficult circumstances can be further complicated by the fact that most international and national environmental policies are centrally focused on the climate change and its mitigation. Hence, LCA are often focused on a limited number of the impact categories which further results with the focus in only one direction. As a consequence, this can lead to some impact categories being excluded, even though they can be extremely crucial for the LCA study.

Optional steps of the LCIA are *normalisation* and *weighting*. The decision about their inclusion must be made in the scope definition phase and shall not be changed later. The weighted and normalised LCIA results are used to implement the cut off criteria. When assigning the normalised LCIA results to the different impact categories, it can be shown which impact category is impacted more by an analysed system. (European Commission FP7 2011).) The representation of the impact of several impact categories of the study, as well as it is comprehensiveness is one of the main advantages of the LCA study (Rooning et. al 2014).

Another difficulty involves the number of various methods, which are available for the calculation of LCIA indicators. They are mentioned in CEN TC 350 standards, but they require specialised knowledge in order to select the appropriate standard and apply it correctly. The ILCD handbook has released the report ‘Characterization factors of the ILCD-Recommended Life Cycle Impact Assessments Methods’ (2013). This report discusses several methods, which are recommended for each impact category.

It has to be noted that a further harmonization of the LCIA indicators and methods is urgently required for the LCA international building related standards. This represents the essential step for improvement of the credibility of the LCA studies.

3.10.4 Intepretation

The primary goal of the interpretation phase is to identify and explain the most crucial issues and questions in the LCA study. The answers can often be complex, since LCA modelling allows significant variations in the calculation methods and therefore the results obtained can be very different, even for calculations based on the same building (European Commission FP7 2011).

Several studies conclude that following limitations can impact the results: the intended application of the study, which phases are excluded in the system boundaries, cut-off criteria, the availability and quality of the data, the assumptions made, the intended audience, the influence of the building design on its energy use (Byule et al. 2013; Rooning et. al 2014; Guggemos 2016; Horvath, 2016).

,,LCAs are too case-specific with respect to functional unit, system boundaries, specific scenarios for a specific type of building, etc. Thus, an LCA cannot be replicated, and general conclusions are not transferable to other building projects. On the other hand, the flexibility of LCA enables a large number of different analyses. Often the results are intended to be communicated to a wide audience. Thus, the results and outcome of the LCA have to be presented with a certain transparency and clear interpretation to ensure that the audience understands that figures and results may vary depending on the intended use of the LCA.”
(Rajagopalan et al .2012).

4 CONCLUSION

The primary objective of this work is to provide an overview of the state of the building related LCA standards on the international level that could be useful to the new users entering in the field of LCA within Building Sector.

The starting point in the research for all international LCA standards related to the construction sector were the two fundamental standards for LCA of the products or services in general, ISO 14040 and ISO 14044 (2006).

Further research through the ISO work regarding the LCA harmonization has led to the Technical Committee ISO TC 59 SC 17 responsible for the process of standardisation in the field of sustainability of the built environment. Their work and aspirations towards the sustainability within the construction sector resulted in standards that have been listed in the Table 3.

The research focus is then shifted from the international to the European platform. The activities of CEN TC 350 for the Sustainability of Construction Works were reviewed and standards, technical reports, and specifications resulting from their work were listed (Table 4.).

A parallel consideration of the International Standards (ISO) and The European Committee for Standardization (CEN) standards could show the complex interrelationships between them. Standards that belong to the framework level are applicable not only to the environmental assessment but to the social and economic assessment as well. EN 15804:2012+A2:2019 provides the methodology for making EPD at the product level while EN 15978:2011 describes the assessment of environmental performance at the building level. Hence, certain interdependency exists between standards of the building and product level while any decisions that are made during the assessment at the product level have impact later when this information is taken for the assessment at the building-level (Kirchain et al. 2017, BRE n.d.).

The core of LCA analysis is the LCI data since quality of the used data has a major impact on the results of an LCA. Regardless of the significant number of the LCA databases, that have been formed after the ISO 1040/44 standards have been released in 2006, only few contain data on construction materials (Martínez et al. 2016). Thereby, several problems exists, such as a lack of the harmonization between locations of the LCA data and where the study was performed, mismatching of the data to the project conditions, limitation regardless the fact that the most of the LCA databases use the cradle to gate model, and lack of transparency in general (Rocamora et al. 2016, Bribiánl et al. 2011, Lopez et al. 2011, Reap et al. 2008).

An LCA tool can be defined as an environmental modelling software that develops and presents life cycle inventory and also life cycle impact assessment results through analytical process that cohere closely to fundamental ISO standards and other accepted LCA guidelines (Trusty et al. 2005).

LCA tools differ based on their goal (eco design or building certifications) in a way that they can use different data and calculation rules depending on what they are supposed to do, which leads further to another challenging issue the fact that the environmental indicators are not the same and thus LCA tool studies are not comparable (Lasvaux et al.2015).

The European standards EN 15804 and EN 15978, which are both based on ISO 14040 and ISO 14044, define the general framework and general calculation methods for the buildings and products LCA methodology. Links between Eco labels, building certificates, design competitions and LCA were researched to see the state of the European platform regarding the LCA standards in the building sector.

Within the ISO 14000 series of environmental management standards, the ISO 14020 series precisely address aspects of environmental labels and declarations. The International Standards Organisation (ISO) differentiates three types of eco-labels (ISO n.d.): Type I environmental labelling, Type II environmental labelling and Type III environmental labelling (EPDs). LCA may be used during the development of the criteria that need to be fulfilled in order to receive a Type I eco-label and in the case of the Type II eco-labels, they are not necessarily based on LCA results. On the other hand, Type III eco-labels (EPDs) demand that an LCA study is set following specific product category rules. Hence, only in the case of Type III eco-labels (Table 8.) is LCA a precondition for award of the eco-label as a method to inform about the relevant environmental aspects of the product throughout its life cycle (Santos 2014).

Building certifications help in achieving the implementation of the sustainable thinking into construction sector, as well as in gaining the economic and social benefits (Anand et al. 2017). Expertise and knowledge in the field of environmental methodology from other sectors is integrated in the building rating systems (Sartori et al 2021), among them is the LCA method as well (Giama et al. 2012). Some of these schemes sometimes need environmental quantitative information about the product that can be provided by the direct use of its EPD. On the other hand, life cycle information is mainly being used for defining the criteria for rewarding the green building certificates and LCA methodology is being used in some schemes and not in all of them (Santos 2014). In the Table 9. in order to detect which of the building certificates scheme integrate LCA methodology in its ratings, most popular certification schemes based on the number of accredited certifications are reviewed (Giama et al. 2012; Vibha et al 2021; Sartori et al 2021).

Performing LCA in the design process is time and money consuming (Weissenberger et al. 2014). Hence, that could be seen as a one of the reasons why even when LCA is performed it is done mostly by larger companies that have better financial status and, in that case, mostly by an LCA expert, not by an architect (Bribián et al. 2009). A case study that included seven different architectural companies (Buyle et al. 2013), suggests the integration of the monetary incentives in terms of subsidies and tax benefits for the use of the green building products and performing LCA for the design of the building. In that way companies would be encouraged to perform LCA, educate their designers about LCA methodology, and include its results in their design.

Several studies conclude that following limitations can influence the LCA results: the intended application of the study, which phases are exclude in the system boundaries, cut-off criteria, the available data and the quality of the data, the assumptions made, the intended audience, not considering the influence of the design of the building on its energy use and the amount of the materials that will be used, and not including transport activities related to the use of the building (Byule et al. 2013; Rooning et. al 2014; Guggemos 2016; Horvath, 2016).

Development of the standards for LCA for the building sector is crucial for the credibility of LCA within the sector. The reason for this is the specific nature of the building as a product and the number of difficulties that this fact brings with itself. If building related standards are more detailed, the number of the technical assumptions and value choices will be reduced.

LCA’s future lies not only in its need for completeness, but in its ability to present itself to users in a way where its metrics can be tracked (Klöpffer 2014). This fact represents a crucial reason for the need for the review of building related LCA standards. Reviews can assist future and current practitioners of LCA within the building sector with information about the applicability of LCA standards in practice.

5 INDEX

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5.3 List of Formulas

5.4 List of Abbreviations

ADP	abiotic depletion potential
ADPE	abiotic resource depletion potential for elements
ADPF	abiotic resource depletion potential of fossil fuel
AP	acidification potential
BREEAM BRE	Environmental Assessment Method
CEN	Commission for European Normalization
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	global warming potential (climate change)

ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardisation
LCA	Life Cycle Assessment
LCC	Life Cycle
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment Costing
PCR	Product Category Rules
RSP	reference study period
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Programme

LITERATURE

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APPENDIX

A. The Fifth Assessment Report (AR5)

Human influence on the climate system is clear, and recent anthropogenic emissions of green-house gases are the highest in history, the report quotes (2014). The atmospheric concentration of key greenhouse gases, carbon dioxide, methane, and nitrous oxide, is the highest in at least the last 800.000 years, the report warns, and our increasing population and fossil-fuel driven economic growth are main cause (*Figure 1.*) (2014). Figure 1 shows cumulative emissions of CO_2 from these sources and their uncertainties are shown as bars and whiskers, respectively, on the right-hand side.

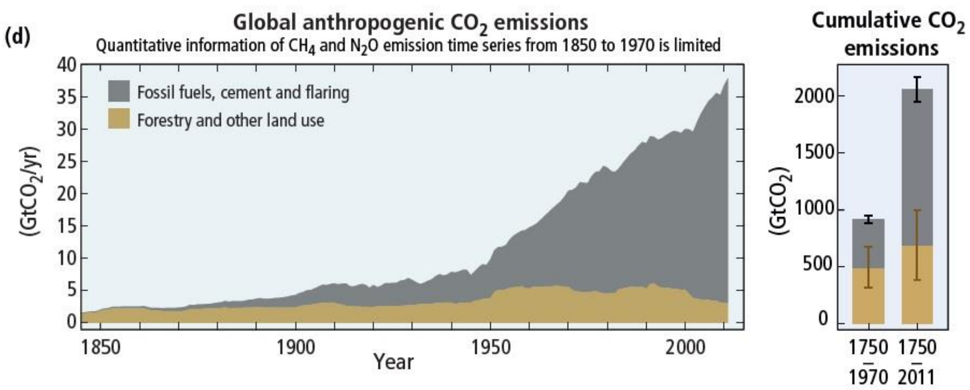
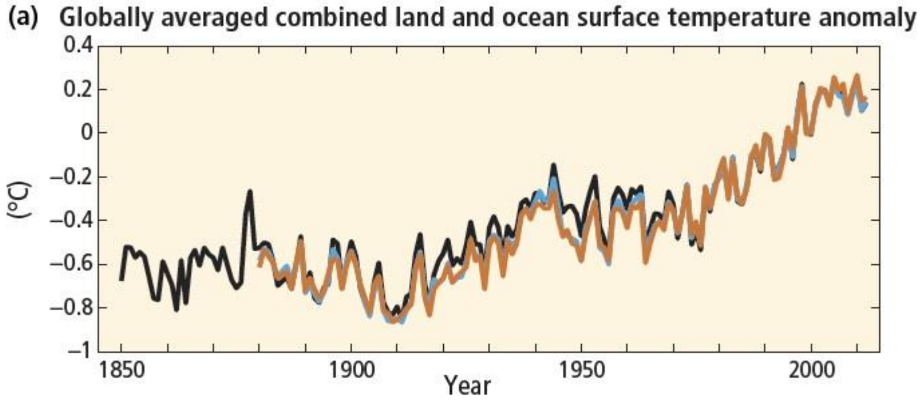


Figure 1. *Global anthropogenic CO_2 emissions from forestry and other land use as well as from burning of fossil fuel, cement production and flaring. (IPPC 2014)*

The reality of climate change is undeniable, it is already happening. Report asserts that the atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. According to the report each of the past three decades has been warmer than the last, and warmer than any decade since 1850 (2014). The report states that the globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 (0.65 to 1.06) °C over the period 1880 to 2012 (*Figure 2.*) and that over the period 1901 to 2010, global mean sea level rose by 0.19 (0.17 to 0.21) m (*Figure 3.*) (2014). The report claims that since 1971 almost 90 percentage of the energy that goes into the climate system went into the ocean with only about 1 percentage stored in the atmosphere (2014). The ocean is also becoming more acidic due to the fact that ocean has absorbed about 30 percentage of the emitted anthropogenic CO2 (2014). In the term of impacts, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Arctic ice cover is shrinking, crop yields are changing, storms and heat waves are getting more intense (2014). Some of



these extreme changes that have been stated in the report have been linked to human influences, including a decrease in cold temperature extremes and an increase in warm temperature extremes.

Figure 2. *Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. (IPPC 2014)*

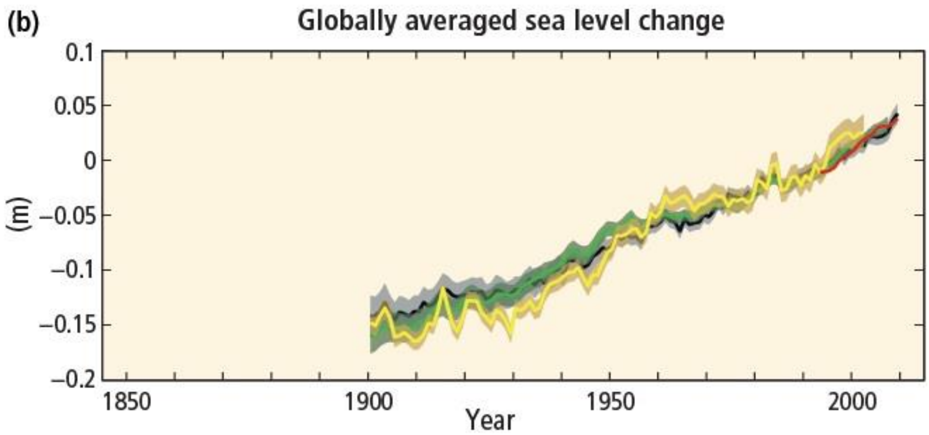


Figure 3. *Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset (IPPC 2014)*

Regarding future climate changes and scenarios report does not have positive remarks. It states that there must be generally switch to renewable energy sources by 2050 and phase out fossil fuels by 2100 in order to avoid most damaging and potentially irreversible impacts of climate change as well greenhouse gas emissions should be severely cut (2014). Aim should be near zero emissions of CO2 and other long-lived GHGs by the end of the century, according to the report (2014).

After taking into account all mentioned facts in the report, a conclusion is reached that humanity needs to tackle climate change immediately. This raises the question what prevents that action. The answer is simple, only a good will to act. In 21st century all necessary technologies are available, and economic growth will not be strongly affected if we take action, the report argues (2014). It highlights the fact that this action must be united act of international cooperations in order to achieve effective mitigation (2014).