BIM-led LCA: Feasibility of improving Life Cycle Assessment through Building Information Modelling during the building design process

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BIM-led LCA: Feasibility of improving Life Cycle Assessment through Building Information Modelling during the building design process

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EXTENDED ABSTRACT (eng)

The Architecture, Engineering and Construction sector is responsible for a significant proportion of the world's environmental impact. Several tools have been developed and are now applied to calculate the sustainability level of buildings. Life Cycle Assessment (LCA) is widely recognized to be a suitable and holistic method to evaluate the environmental impact of the construction, maintenance, operation, and demolition stage of buildings. However, LCA is currently hindered by a number of limitations in the construction industry. Building Information Modelling (BIM) has gained attention as it provides opportunities to manage a large amount of data in a common data environment. As such, BIM makes it possible to overcome some specific issues of the LCA. Several studies have developed BIM-based LCA frameworks, and researches acknowledge the integration of LCA in BIM as a way of improving the environmental performance of buildings. The focus of the thesis is the development of a method to perform the LCA throughout all the building design process phases. Furthermore, the thesis provides a method for identifying and coding all the relevant variables involved in the LCA calculation, which can be implemented into the building information model as BIM parameters.

From an analysis of the literature review, two different trends are identified. Current BIM-LCA approaches use complex models in detailed design phases, when it is late for major changes, or simplified approaches only applicable in early design stages. As such, none of them provide the way for conducting a BIM-led LCA throughout the entire building design process. Furthermore, most of the existing approaches only use BIM as storage of materials and components quantities information, without providing a way to implement all the relevant LCA data within the BIM.

In this context, the thesis proposes a method for applying continuous LCA over the entire building design process by using the data from BIM with as much accuracy as possible in each design stage. The method uses different LCA databases with different levels of detail for the specific Level of Development (LOD) of the BIM elements. Since the building elements are not modelled with identical LODs in each design phase, the LCA is conducted by consistently mixing the databases, which is possible as long as the databases use identical background data. The method is tested on a multi-family house. The framework helps to provide information for decision-making throughout the whole design process, both in the early design phases and later phases with a more detailed BIM. Nevertheless, a full LCA requires further information, which is not only related to the materials and components quantities. To this end, the thesis provides a framework to map all the variables responsible for the environmental impacts, which can be employed as BIM parameters. A flow-chart is proposed in order to structure the design parameters responsible of the environmental impacts throughout the lifecycle stages of buildings. The proposed parameters, which are tested on a case study, are found to be sufficient for conducting the LCA. Hence, the identified parameters, when implemented in the BIM environment, could potentially improve the reliability and consistency of the sharing information process between the building information model and the LCA tool.

key words

Life Cycle Assessment (LCA); Building Information Modelling (BIM); Design process; Levels of Development (LODs); Sustainability.

EXTENDED ABSTRACT (ita)

Il settore delle costruzioni, è ormai noto, contribuisce fortemente al problema ambientale. Le attività antropiche di tale comparto producono modificazioni sempre più significative e diversificate sull'ecosistema, molto spesso di tipo irreversibile. In uno scenario siffatto, gli ultimi anni sono stati investiti dallo sviluppo di numerosi strumenti in grado di valutare il livello di sostenibilità degli edifici. Tra tutti, il metodo Life Cycle Assessment (LCA) rappresenta un approccio olistico per la valutazione degli effetti ambientali degli edifici con riferimento al loro intero ciclo di vita. LCA, infatti, è orientata al prodotto ed è una metodologia idonea a valutare tutte le fasi del processo edilizio, quali la costruzione, la manutenzione, la fase d'uso e di demolizione di un edificio. Tuttavia, allo stato attuale, l'approccio LCA per gli edifici possiede alcune limitazioni connesse alla natura stessa del processo edilizio. Il Building Information Modelling (BIM), quale innovativo approccio alla progettazione, consente in alcuni casi di superare suddette limitazioni. Tale potenzialità è garantita dalla possibilità, tra le altre, di poter gestire un'ingente mole di dati in un unico common data environment. Diversi studi hanno sviluppato work-flows utili alla conduzione di analisi LCA basate sul BIM ed è dimostrato come l'integrazione BIM-LCA sia sinonimo di miglioramento della performance ambientale degli edifici. La tesi fornisce un metodo per effettuare analisi LCA in tutte le fasi del processo progettuale. Inoltre, la tesi identifica e codifica tutte le variabili ambientali proprie della metodologia LCA implementabili in ambiente BIM per diventarne parte integrante del corredo informativo.

Recenti applicazioni LCA basate sul BIM si riferiscono a modelli complessi applicabili solo a stadi avanzati del processo progettuale, laddove la raggiunta inflessibilità si traduce nella impossibilità di utilizzare le previsioni fatte in supporto dei processi decisionali. Ulteriori studi propongono approcci semplificati che, seppur utili nelle fasi iniziali della progettazione, risultano essere di difficile applicazione in quelle finali. È evidente la difficoltà nel condurre analisi LCA basate sul BIM in maniera coerente in tutte le fasi progettuali di un organismo edilizio. Inoltre, la maggior parte degli approcci impiega il modello BIM solo come un database utile a estrarre dati di carattere geometrico e quantitativo, omettendo, difatti, informazioni rilevanti nella conduzione di una LCA.

La tesi fornisce un metodo per l'applicazione della LCA nel corso dell'intero iter progettuale mediante l'impiego di dati BIM quanto più accurati in relazione alla fase progettuale di riferimento. Il metodo proposto prevede l'utilizzo di differenti database LCA che riflettono i diversi livelli di sviluppo (Levels of Development, LODs) degli elementi BIM. Poiché, nelle prassi progettuali, gli elementi del modello non sono realizzati tutti al medesimo LOD in una determinata fase, le valutazioni LCA sono effettuate adoperando differenti database in maniera coerente. Il metodo è testato su un edificio residenziale multipiano. Il framework proposto fornisce informazioni sulla performance ambientale degli edifici utili nel processo di decision-making durante l'intero iter progettuale. Tuttavia, una LCA completa richiede informazioni aggiuntive rispetto ai soli dati quantitativi e geometrici. Pertanto, la tesi codifica tutti i parametri concorrenti all'impatto ambientale che possono essere impiegati nel modello BIM come parametri progettuali. Essi, dapprima strutturati all'interno di un flow-chart, sono testati su un caso di studio atto a definirne la completezza con riferimento alle necessità informative di una LCA. I parametri così strutturati migliorano l'affidabilità e la coerenza del flusso informativo condiviso tra modello BIM e strumenti LCA.

key words

Life Cycle Assessment (LCA); Building Information Modelling (BIM); Processo di progettazione; Livelli di Sviluppo; Sostenibilità.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

The first chapter provides a brief overview of the thesis. It defines the research background and the problem statement. The research goal and the research approach are also described. The chapter concludes with the outline for the thesis.

Research background

The Architecture, Engineering and Construction (AEC) sector is one of the major carbon emitters and energy consumers. Over the last decades, greenhouse gas (GHG) emissions from the building sector have more than doubled (IPCC, 2014). Reducing embodied and operational energy and the resulting environmental impacts of buildings has increasingly become a hot topic amongst governments and organisations. Embodied energy (EE) can be described as the energy used during the lifecycle of materials, upstream or downstream of the building development. Thus, it includes the energy used for extraction, transport and processing of raw materials, manufacturing of building components, on-site processes, storage, performance, deconstruction and disposal of materials (Sartori and Hestnes, 2007). These activities lead to harmful greenhouse gases including CO_2 (Häkkinen et al., 2015). Operational energy (OE) is the energy consumed to operate the building (e.g. heat, cool, ventilate and light) and running the equipment and appliances. Operational CO_2 is the CO_2 emission induced from the operational energy. The share between EE and OE can vary as a function of geographical location and building's level of efficiency (Abanda et al., 2017). The embodied energy of a conventional residential buildings accounts for a share of 4-20% of the entire life cycle energy demand, 11- 33% for passive residential buildings, 26- 57% for low energy residential buildings, 74-100% for net zero energy buildings. Building energy research so far has focused more on OE than EE, and as a result, the OE of buildings is gradually decreasing (Dixit, 2017). Moreover, the European Directive on the energy performance of buildings requires that Member States shall ensure that all new buildings will be Nearly Zero-Energy Buildings by 31 December 2020. This means that the embodied energy will became more relevant. For the purpose of this thesis, only the embodied impact is of interest.

Problem statement

The environmental impacts of buildings need to be reduced in order to improve the sustainability of the construction industry. Several tools and methodologies have been developed to evaluate the environmental impact of buildings and their level of sustainability. There is growing interest in integrating Life Cycle Assessment (LCA) into building design decision-making, due to LCA's comprehensive and systemic approach to the environmental evaluation. Life Cycle Assessment evaluates the environmental impact of processes and products during their life cycle. However, when applying LCA, there are many challenges that practitioners may encounter, and several limitations could be found. Further limitations could be highlighted in the context of LCA of buildings due to the specific nature the construction sector, such as the large amount of data required and the lack of data at the early design stage. Today's approaches and tools could overcome these issues. Building Information Modelling (BIM) can assist the building community in accomplishing the sustainability objectives. BIM is both a methodology and a tool able to manage building's data during its life cycle (Eastman et al., 2011).

Existing studies show the possibility of conducting a BIM-based LCA and by that overcoming some limitations (Chong et al., 2017; Eleftheriadis et al., 2017; Kylili et al., 2015; Soares et al., 2017; Soust-Verdaguer et al., 2017; Wong and Zhou, 2015). It is recognized that BIM can significantly reduce data input and the time-consuming nature of the LCA. Although the BIM-LCA integration is widely recognized to be a powerful approach for improving the environmental performance of buildings, some methodological challenges arise.

The nature of the building design process leads to the LCA dilemma. On the one side, LCA is recognized to have the greatest influence in early design stages, but the information available is scarce. On the other side, LCA could be fully performed in the later phases of the design process when complete information are available, but in those stages it is too costly to make changes (Hollberg and Ruth, 2016). As a result, LCA is scarcely employed as a decision-making throughout the building design process. Two different general approaches are usually adopted to perform the BIM-based LCA of buildings. The first methods concerns performing detailed LCA with refined processes at the end of the building design process. The second approach involves simplified methodologies for early design stages with uncertain data.

There is also a knowledge gap on how to match information from the BIM with data needed to conduct the LCA. This implies the use of BIM mainly to model the building and store materials and components geometrical data. Nevertheless, the complex LCA calculation requires further information, such as the reference service life of products, the type of transport used to convey materials and products, the energy required for on-site equipment, and others (Cavalliere et al., 2018).

Research goal

The goal of the thesis is two-sided. First, the thesis intends to provide a framework for performing BIM-based LCA during the entire building design process. Second, it aims at defining all the variables involved in the LCA calculation that could be implemented into the BIM as buildings parameters. According to the objectives of the thesis, on the one hand a number of LCA limitations are found to hinder the BIM-based application. The thesis faces the following limitations:

- the project-based nature of the construction industry, which means that each project has its specific characteristics,
- the large amount of information required, and
- the lack of data at the early design stages.

On the other hand, BIM can assist the LCA application for buildings. For the purpose of the thesis, the following BIM key concepts are employed to meet the goals:

- BIM software functionalities, and
- Levels of Development of BIM elements.

Research approach

The first objective is to apply the LCA over the whole building design process by using project data as accurate as possible in each stage. This allows LCA to be employed as a continuous decision-making tool during the entire design process. To achieve this goal, the Level of Development (LOD) concept is employed. LODs identify the minimum content requirement for each digital model element at different progressively detailed levels of completeness. As such, LCA can be performed from the early design stages to the detailed ones based on lower to higher level of accuracy. The method consists of three main parts and it is applied to a building case study. The first part aims at defining the LODs progression of the different BIM elements since they evolve asynchronously during the design process depending on to the goal of the specific design phase. The second part consists in providing a framework to combine different LCA databases, while the third part of the method provides a framework to link LCA databases to the LODs previously defined. According to the method, each LOD involves the use of different databases. Therefore, since the design phases refer to a digital model where the different objects are modelled at different LODs, LCA calculations are based on mixing the databases in every design phase. The results show a general coherence throughout the entire design process. The shift from the use of average LCA data in the early design phases to detailed values in the last phases reduces the environmental impacts throughout the building design process. Moreover, the use of increasingly detailed data cuts the range of variability (min values and max values) from the early phase to the final ones. The consistency of the method is demonstrated by the fact that the environmental impact at one specific phase is continually within the variability of the previous phase. This outcome enables practitioners to approximately predict the final impacts of the late phases from the early stages of the building design process. The application of the proposed method to a real case study demonstrates that it is possible to continuously perform the BIM-based LCA during the entire design process, providing consistent information for decision-making both in the early design phases and later phases with a more detailed BIM. Components and materials quantities are extracted from the 3D model and they are used to calculate the LCA results here. However, in order to perform a full LCA, more information needs to be defined and implemented into the BIM. This is the second side of the research goal.

The second objective of the thesis is to map all the variables responsible for the environmental impacts that could be implemented in a BIM environment. To meet this goal, it is proposed a flow-chart to structure the design variables throughout the lifecycle stages of buildings. The building design processes are identified and the related input and output variables are shown from the raw materials extraction phase to the end-of-life of buildings. Finally, the variables are decomposed into parameters, which are defined as the relevant BIM parameters needed to perform an LCA. The framework is tested on a building case-study. First, the LCA is conducted for the reference building. Second, it is proved that all the data required for the LCA are identified amongst the proposed BIM parameters. The results show that the life cycle inventory requirements are covered by the BIM parameters proposed. The variables and parameters are firstly defined in an inclusive way to fully detail the LCA information during the entire building lifecycle. However, it is demonstrated that data can be streamlined because of some redundancies and only few parameters are required to characterize each BIM object/material from a LCA perspective as well as the means and tools necessary for its construction. Also, the presented approach demonstrate that the proposed parameters could improve the data consistency when sharing information from the BIM to the LCA tools.

Outline

The thesis consists of six chapters. The first three chapters provide the scientific background for the proposed methods. Chapter four describes the framework to improve the BIM-led LCA. The highlights of each chapter are provided. The thesis ends with a discussion and a concluding chapter.

Chapter one introduces the concept of sustainability and provides an overview of methods to evaluate the environmental sustainability.

The second chapter introduces the scientific background for the Life Cycle Assessment. After an introduction and a brief history, an overview of the LCA methodology is provided in the fourth section. Here, the sub-sections are structured according to the four stage of the LCA according to the international standard ISO 14040:2006, namely: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The last section of this chapter defines the key aspects of the LCA for buildings.

Chapter three provides an overview of Building Information Modelling. It consists of four main sections. After the highlights of the chapter, the second section provides an overall introduction to the BIM, BIM uses, BIM dimensions, and BIM benefits. The third section defines the current adoption of BIM across different markets. An overview of the international BIM standardization is also shown. The last section presents the most important key aspects for increasing BIM benefits.

The fourth chapter describes a framework to improve the BIM-LCA integration. After the highlights of the chapter, the second section provides a brief introduction and identifies the challenges addressed by the thesis. Then, the methodological challenges of BIM-LCA integration that arise from the literature are defined. A comprehensive literature review of previous studies focusing on BIM-LCA integration is described here. The third and the fourth section describe the method and the application to the case-studies according to the BIM-based LCA challenges previously defined. In particular, the third section presents a method to perform a continuous BIM-based LCA throughout the building design process. The fourth section provides a framework to structure all the relevant BIM parameters needed for LCA calculation.

Finally, the last two chapters presents the overall discussion, conclusion and outlook of the thesis.

1. ENVIRONMENTAL SUSTAINABILITY

1.1 Highlights of the chapter 1

The threefold interpretation of sustainability suggests that environmental, social and economic aspects have to be considered. This thesis focuses on the environmental dimension. A number of tools to evaluate the environmental sustainability have been developed and are widely applied, such as the Green Building Rating Systems (GBRSs) and the Environmental Systems Analysis Tools (ESATs). Life Cycle Assessment is used as ESATs in this thesis since it is the most suitable tool for evaluating the environmental impacts of buildings. In fact, LCA considers both inputs and outputs and takes into account the potential environmental impacts and natural resources throughout the whole lifecycle of buildings. Also, standards exist for the application of LCA to the building sector. Furthermore, LCA is employed by building certification systems, such as LEED and BREEAM. Further strengths of LCA for buildings are described in the chapter 2, such as the range of available LCA data sources and LCA tools.

1.2 The environmental problem

Nowadays the environment is not able to withstand the natural resources demand and the pollution caused by human activities.

> *“Overshoot can lead to two different outcomes. One is a crash of some kind. Another is a deliberate turnaround, a correction, a careful easing down.*
> *The three causes of overshoot are always the same, at any scale from personal to planetary. First, there is growth, acceleration, rapid change. Second, there is some form of limit or barrier, beyond which the moving system may not safely go. Third, there is a delay or mistake in the perceptions and the responses that strive to keep the system within its limits. These three are necessary and sufficient to produce an overshoot”* (Meadows et al., 2004).

Although the concept of “going green” and “environmental sustainability” has been around in the construction industry for many years, the building sector is recognized as the most important natural resources and energy consumer (Wong and Zhou, 2015). It is recognized that there are harmful effects associated with the construction industry, such as the impact of building energy use on greenhouse gas emissions, the depletion of non-renewable resources, the effect on land use and biodiversity of increasing urbanization, and the consequences for human health (Zuo et al., 2017). Globally, the building sector consumes 32% of resources and 40% of energy (Yeheyis et al., 2013). Furthermore, it is the main waste producer generating one third of European waste (European Commission, 2011). Alongside these issues, the need to assess the sustainability of buildings has risen.

1.3 The concept of sustainability

The concept of sustainability was introduced at the UN Conference on the Human Environment in 1972 (ONU, 1972), although the objective of *sustainable development* was clearly defined in 1987 with the publication of the Brundtland Report (Brundtland Commission, 1987). With the UN Conference on Environment and Development in 1992 (ONU, 1992), sustainable development has become the new paradigm of the development itself. The most common definition of sustainability as a paradigm of development was given by the Bruntdland Commission in the UN Report Our Common Future:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (Brundtland Commission, 1987).

The definition introduces two key concepts: the concept of "needs" and the idea of limitations imposed by technology and social organization on the environment's ability to meet the present and future needs.

The concept of sustainability has undergone an evolution reaching a more global meaning. In addition to the environmental dimension, it also takes into account the economic and the social aspects (Elkington, 1994). The term Triple Bottom Line coined by Elkington (1994) is tipically employed as a synonym for sustainability (Milne and Gray, 2013). It is illustrated using three circles representing the environmental, economic, and social dimension, where their intersection forms the sustainability dimension. Based on the same concept, sustainability can be presented by three identical pillars, which denotes the identical relevance of the three dimensions. The three dimensions of sustainability are also seen as a relationship of concentric rings. In that case, the economic prosperity and human well-being are reliant upon the resources provided by a healthy planet. It means that ecosystems support societies, which create economies. (WWF, 2014).

However, sustainability could be defined as a dynamic concept, since the relationships between the ecological and the anthropic system can be influenced by the technological scenario, which could ease some relative constraints (for example, to the use of energy sources). In practice, assuming sustainability as a paradigm of the development implies the adoption of evaluation systems that determines the sustainability of activities, processes, and products.

1.4 Evaluating the environmental sustainability

Integrating environmental aspects into planning, policymaking, and programming activities has become a key issue for decision-makers across public and private sectors (Ahlroth et al., 2011; EEA, 2005). A number of different tools for analysing the environmental impact and sustainability level of buildings have been developed and are now widely applied (Ahlroth et al., 2011; Al-Ghamdi and Bilec, 2015; Finnveden and Moberg, 2005; Shan and Hwang, 2018). These can be grouped in two main categories: the Green Building Rating Systems (GBRSs) and the Environmental Systems Analysis Tools (ESATs). Generally, GBRS is a comprehensive framework developed by construction authorities, international organizations, or private consultancy companies for assessing and verifying the sustainability level of buildings. GBRSs consist of performance thresholds that buildings must meet in order to be certified, as well as guidelines that can help designers to meet or exceed those thresholds (Shan and Hwang, 2018). GBRSs consider a wide range of environmental aspects also involving qualitative features, which are not included in ESATs. Nowadays, various GBRSs have been developed to evaluate the sustainability of buildings. Most of them are tailored to serve the specific needs of the country where they are developed. Shan and Hwang (2018) conducted a comprehensive review of prevailing GBRSs used around the world focusing on their timeline in effect, particular versions, essential evaluation criteria, and scoring systems. They found that the most important evaluation criterion is “energy”, followed by “site”, “indoor environment”, “land and outdoor environment”, “material”, “water”, and “innovation”.

For the purpose of this thesis, only ESATs are of interest. However, prevailing GBRSs from Shan and Hwang (2018) are reported in Table 1. Others GBRSs are also added to the table.

Table 1 – Prevailing GBRSs identified by Shan and Hwang (2018)

GBRS	Issuers	Country
ASGB	Ministry of Housing and Urban-Rural Development of People's Republic of China	China
BREEAM	Building Research Establishment	UK
BEAM	Hong Kong Green Building Council and the BEAM Society	Hong Kong
CASBEE	Ministry of Land, Infrastructure, Transport and Tourism	Japan
CEPAS	Buildings Department of Hong Kong Special Administrative Region of the People's Republic of China	Hong Kong
CSH	Department for Communities and Local Government	UK
Minergie-Eco*	Minergie and Eco-bau association	Switzerland
EPRS	Abu Dhabi Urban Planning Council	Abu Dhabi
GBI	GBI Innovation Sdn Bhd	Malaysia
GG	ECD Energy and Environment Canada	Canada
GM	Building and Construction Authority	Singapore
GS[1]	Green Building Council Australia	Australia
GSAS	Gulf Organization for Research & Development	Qatar
ISBT	International Initiative for a Sustainable Built Environment	non-profit organization
IGBC	Indian Green Building Council	India
HQE*	HQE association and CSTB	France
LEED	US Green Building Council	USA
ITACA Protocol*	Institute for innovation and transparency in government procurement and environmental compatibility (ITACA)	Italy

* Not included in the study by Shan and Hwang (2018)

ESATs are designed to assess the environmental impacts of the systems studied using accepted scientific approaches. They could be described in relation to a number of different characteristics. According to Finnveden and Moberg (2005) the two key aspects of the decision context determining the choice of tools are the object of the study and the impacts of interest. Table 2 shows an overview of ESA tools

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[1] A comprehensive list of rating tools that are administered by the Green Building Councils can be found at: http://www.worldgbc.org/rating-tools (accessed September 13th 2018)

based on the review from Finnveden and Moberg (2005) and Ahlroth et al. (2011). The table shows the types of impacts considered and the objects of the tools.

Table 2 – Overview of ESA tools, based on Finnveden and Moberg (2005)

Impacts **Objects**	Natural resources	Environmental Impacts	Natural resources and Environmental Impacts
Policy, Plan, Programme and Project	EF, EN, MFA	RA-accidents	**SEA**, **EIA**
Region and Nation	TMR, DMI, DMC		SEEA incl. IOA
Organisation			**EMS with Environmental Auditing**
Product/Function	MIPS		LCA
Substance		RA-chemical	SFA

NOTE: Procedural tools are written in bold text.

Abbreviations: **DMC**, Direct Material Consumption; **DMI**, Direct Material Input; **EF**, Ecological Footprint; **EIA**, Environmental Impact Assessment; **EMS**, Environmental Management System; **EN**, Energy Analysis; **IOA**, Input-Output Analysis; **LCA**, Life Cycle Assessment; **MIPS**, Material Intensity Per unit Service; **MFA**, Material Flow Assessment; **RA-accidents**, Risk Assessment accidents; **RA-chemical**, Risk Assessment chemical; **SEA**, Strategic Environmental Assessment; **SEEA**, System of Economic and Environmental Account; **SFA**, Substance Flow Analysis; **TMR**, Total Material Requirement.

Life Cycle Assessment (LCA) is suitable for assessing the environmental impacts of buildings and it is used as environmental assessment tool in this thesis.

LCA is a tool to assess both the potential environmental impacts and resources used throughout the whole lifecycle of products or services. Since LCA considers the entire lifecycle, it avoids shifting a problem from one part of the lifecycle to another (Bueno and Minto, 2018). Furthermore, LCA deals with both inputs and outputs in a holistic perspective. In fact, LCA is defined as a compilation and evaluation of inputs, outputs, and the potential environmental impacts of a product through its lifecycle (ISO 14044, 2006).

Different methods focus only on inputs, such as Material Flow Accounting (MFA) tools. MFA is a family of different methods, including Total Material Requirement (TMR), Material Intensity Per unit Service (MIPS) and Substance Flow Analysis

(SFA). They focus on material flows, especially on the input side (Finnveden and Moberg, 2005). TMR aims at calculating all the material inputs including direct and hidden inputs, while related concepts such as DMI (Direct Material Input) and DMC (Direct Material Consumption) focus on the direct inputs, excluding hidden flows (Finnveden and Moberg, 2005). As can be seen in Table 2, only LCA takes into account natural resources and environmental impacts while focusing on products or services. For example, MIPS focuses on product or service but it considers natural resources only. Conversely, Substance Flow Analysis (SFA) takes into account natural resources and environmental impacts while focusing on substances. Ecological Footprint (EF) and Energy Analysis (EN) only consider natural resources as well. EF has mainly been used on regions, nations, and projects to compare the world's biocapacity with humanity's demand for natural services and the results are presented in terms of area used (Global Footprint Network, 2018). These approaches do not cover all types of environmental impacts, but pick a few ones that are judged to be important. EN focuses only on the inputs in physical measures and it can be used as evaluation tool for different types of objects (Finnveden and Moberg, 2005).

Different ESA tools come from the field of economics and focus on Region and Nation. IOA defines trade between industries using a nation or a region as the object of the study. The Input-Output Table (IOT) states how much the sector buys from each of the other sectors, for each unit produced in the sector (Finnveden et al., 2009). An IOT becomes a powerful tool for Life Cycle Assessment (LCA), when information on resources use and environmental emissions from each sector are added to the table (Finnveden et al., 2009). Systems for Economic and Environmental Accounts (SEEA) use environmental IOA for assessing environmental impacts from different sectors and TMR and MFA could be used as indicators (Finnveden and Moberg, 2005).

Others ESATs are not analytical tools. Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) are both procedural tools. For this reason, analytical tools may be used in the processes, such as the LCA. EIA is mainly employed for assessing the environmental impacts of projects, while SEA is used at the early stage in the decision-making process for policies, plans, and programmes (Finnveden and Moberg, 2005). Also Environmental Management System (EMS) with Environmental Auditing is a procedural tool. ISO 14001:2015 specifies the requirements for an environmental management system that an organization can use to enhance its environmental performance.

LCA is employed to evaluate the environmental sustainability of buildings within the European framework (EN 15643, 2010). Standards for its application exist in the building sector, such as EN 15804 (2012) and EN 15978 (2011). Moreover, there are many GBRSs that use LCA to achieve environmental goals, such as LEED and BREEAM (Al-Ghamdi and Bilec, 2015). In the last years LCA has increasingly been applied in the building sector, especially in the academic context, where studies on building LCA have gained a rapid growth over the past 15 years (Geng et al., 2017).

2. LIFE CYCLE ASSESSMENT

2.1 Highlights of the chapter 2

Life Cycle Assessment (LCA) is a method defined by ISO 14040/44:2006 and involves the analysis of the environmental aspects throughout a product's life cycle. According to ISO standards, LCA consists of four stages: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. It is crucial to keep in mind that LCA is not able to predict absolute values of environmental impacts but only potential ones. A key aspect of LCA is defining the functions of the product system under study and the functional unit (fU), which outlines the quantification of the identified functions (performance characteristics). They are crucial when comparing different products or processes. Further key characteristic of the LCA is the definition of the system boundary, which describes the unit processes to be included in the system. LCI phase involves data collection and calculation procedures to quantify inputs and outputs of a product system over its lifecycle according to the fU. In order to facilitate this phase, several databases have been developed. Indeed, LCA of buildings is typically performed using predetermined LCI datasets. The purpose of the third phase (LCIA) is to interpret the inventory results according to the environmental significance. It is composed by mandatory and optional elements. The Interpretation phase allows understanding the meaningfulness of the environmental impact results, explaining limitations, and providing recommendations.

LCA of buildings is defined by the technical committee CEN/TC 350 within the EN 15643:2010. EN 15978:2011 represents a methodological guide for the LCA of buildings. It is structured according to the lifecycle stages of buildings. Simplifications could be adopted according to the goal and scope of the analysis. EeB Guide Project identifies three LCA study types with increasing level of data quality, time and effort: Screening LCA, Simplified LCA, and Complete LCA. They are defined in relation to the life-cycle modules and building elements to be considered.

Broadly speaking, limitations of the LCA are the lack of available environmental information, environmental problems knowledge, technical and methodological choices to be adopted, and uncertainties. As regards the LCA of buildings, further challenging aspects are the uniqueness of each building that results in difficulties for comparative analysis, the lack of data at the early design stage, the interoperability between LCA tools and CAD/BIM-based software, and the lack of practitioners' knowledge. Moreover, the high RSL of buildings and the long-life terms of its products and materials imply a lower predictability of the exact environmental impacts.

2.2 Introduction to LCA

Life Cycle Assessment (LCA) is a method defined by the international standards ISO 14040:2006 and 14044:2006[2] to analyse environmental aspects of product systems. In the introduction part of the international standard ISO 14040:2006, LCA has been defined as follows:

> *"LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of life treatment, recycling and final disposal (i.e. cradle-to-grave)."*

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[2] ISO 14044:2006/Amd 1:2017 has superseded ISO 14044:2006, which has been withdrawn.

The ISO standards depict the general methodological framework of the LCA, without defining the exact method. Thus, a range of assumption needs to be considered when conducting an LCA. After a brief history in the next section of this chapter, the fourth and the fifth section introduces the basic concepts of the LCA method. A detailed discussion on the LCA is beyond the scope of this chapter. The aim of this chapter is to introduce the necessary background on the LCA.

2.3 Brief history

Life cycle assessment is often called "cradle-to-grave" analysis as it evaluates the environmental aspects and potential impacts of a product, process or service over its whole life (Cabeza et al., 2014). The first studies on environmental impacts date from the 1960s and 1970s. One of the first studies was carried out by the Midwest Research Institute (MRI) for The Coca Cola Company in 1969, including resources, emission loadings, and waste flows for different beverage containers (Guinée et al., 2011). The early researches applied diverging methods, approaches, terminologies and results. There was a lack of scientific discussion and consensus and the technique was often used for market claims with doubtful results, which prevented LCA from becoming a generally accepted and applied method. The efforts for standardizing the LCA began to take shape in the 1990s with the publication of several specific manuals and scientific papers (Guinée et al., 1993; Perriman, 1993). During that period, the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading role by harmonizing the framework, methodology, and terminology. This process culminated in 1993 with the publication of the *Guidelines for the Life Cycle Assessment: A Code of Practice*, a result of the SETAC workshop in Sesimbra, Portugal (SETAC, 1993). In the same year started the standardisation of the LCA by the International Standard Organization (ISO) as well, resulting in the ISO 14000 standard series, first published in1997. To date, the structure developed by SETAC has essentially been maintained by ISO with the exception of the *Improvement Assessment* phase, which was replaced by the *Interpretation* phase. The first series of the international LCA standards was as follows:

- ISO 14040: LCA – principles and framework; international standard 1997.
- ISO 14041: LCA – goal and scope definition and inventory analysis; international standard 1998.
- ISO 14042: LCA – life cycle impact assessment; international standard 2000.
- ISO 14043: LCA – interpretation; international standard 2000.

A revision of these international standards led to restructuring without technical changes. The standard containing principles and framework continues to be called ISO 14040 (ISO 14040, 2006), while the directives have been summarised in a new standard called ISO 14044 (ISO 14044, 2006). Recently, ISO 14044:2006 has been supersedes by ISO 14044:2006/Amd 1:2017.

From the start of the 21st century, the interest in LCA has been increasing rapidly. The number of publications related to the LCA grew steadily during the past 15 years, and more rapidly since 2010 (Geng et al., 2017). Life cycle thinking is also growing in importance within the European Policy as demonstrated by the Communication from the European Commission on Integrated Product Policy (IPP) (Buyle et al., 2013). A result of the IPP's actions is the International Reference Life Cycle Data System Handbook (ILCD), a practical guide for LCA according to the best practice, complementary with the ISO 14040 series (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). In addition to the practices and standards, the European Community has been actively promoting LCA through a range of funding programs. In 2002 the Life Cycle Initiative was launched by the United Nations Environment Program (UNEP) & SETAC (Jolliet et al., 2005). Further to the ISO standards, there have been also some developments addressing specifically the construction sector. In 2003, SETAC published a state-of-the-art report on Life Cycle Assessment in Building and Construction, which is an outcome of the Life Cycle Initiative. The ISO and the European Committee for Standardization (CEN) have continued this standardisation (Buyle et al., 2013). The CEN Technical Committee

(CEN/TC 350 Sustainability of Construction Works) is developing standards for assessing the three aspects of sustainability (environmental, social, and economical).

2.4 LCA methodology: An overview

Life Cycle Assessment method focuses on products in a life-cycle perspective through the analysis of the potential environmental impacts from raw material acquisition, via production and use phase, to waste management (ISO 14040, 2006). LCA deals with product systems, which are subdivided into a set of unit processes. The centre is a product, a process, a service, or in the widest sense, a human activity (SETAC, 1993). Products can be compared with services as long as they have the same function (Klöpffer and Grahl, 2014). Unit processes are linked to one another by flows of intermediate products, to other product systems by product flows, and to the environment by elementary flows. The comprehensive scope of LCA is useful in order to avoid problem-shifting from one phase of the lifecycle to another, from one region to another, or from one environmental problem to another (Finnveden et al., 2009). ISO 14040:2006 divides LCA into four stages: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (Fig. 1). These stages are described in the following sub-sections.

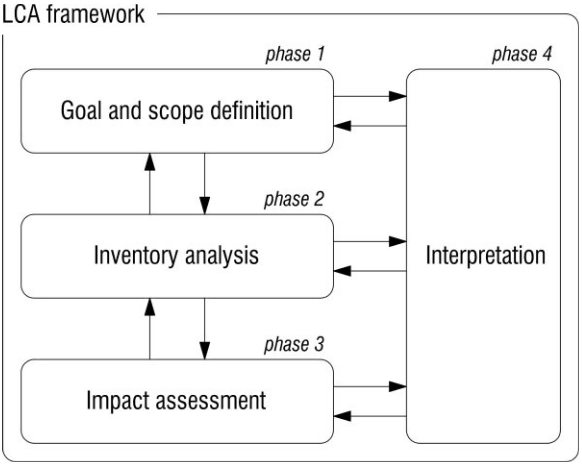

Fig. 1 – Phases of an LCA, based on ISO 14040:2006

2.4.1 Goal and Scope Definition

The first phase of an LCA is the Goal and Scope Definition (G&S). The Goal states the intended application, the aims for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions to be disclosed to the public. The scope should be well defined to ensure that the breadth, the depth, and the details of the study are compatible and sufficient to address the stated goal. The Scope includes, *inter alia*, the function and functional unit (fU), system boundary, data quality requirements, assumptions, and limitations.

First of all, the function of the product system needs to be defined. A system may have a number of functions depending on the G&S of the LCA. The definition of the functional unit (fU) is critical when different systems are being assessed in order to ensure that such a comparison is meaningful and made on a common basis. Thus, the expected performance of the product, which is the fU, must be defined. According to the ISO 14040:2006, the fU "*defines the quantification of the identified functions (performance characteristics) of the product*". As an example, for comparing a wood fibre insulation board (WFIB) and a thermal insulation in Expanded Polystyrene Sintered (EPS), the function could be the thermal resistance. The fU could be 1 m^2 of the insulation panel with 2.5 m^2K/W of thermal resistance. Finally, in order to fulfil the intended fU, the reference flow in each product system, which is the amount of products, needs to be determined. Therefore, it is not possible to compare 1 kg of EPS with 1 kg of WFIB without defining the fU.

The system boundary defines the unit processes to be included in the system. There are three types of system boundaries (Finnveden et al., 2009):

- between technical system and the natural environment;
- between significant and insignificant processes;
- between technological system under study and other technological systems.

It can be noted that an LCA should cover the entire lifecycle. In that case the system boundary is called "cradle-to-grave". Partial LCAs could also be performed with “cradle-to-gate” studies, considering all the processes until the factory gate. Different types of partial LCAs are “gate-to-gate”, taking into account only the processes of the factory (ecobalance of the enterprise), and “gate-to-grave”, considering all the processes from the factory gate to the end-of-life (EoL) scenario. “Cradle-to-cradle” analysis include the reuse, recovery and/or recycling. For example, the cradle-to-cradle perspective in LCA of construction materials is necessary to create a cyclic metabolism. Closing material loops can be achieved by the design for deconstruction or developing building products that can be dismantled (Silvestre et al., 2014). System boundaries could be further defined by the cut-off rules, which quantify the amount of materials, the energy flows, and the level of environmental significance associated with unit processes or product systems to be excluded from the study.

2.4.2 Life Cycle Inventory

Life Cycle Inventory phase involves the data collection and calculation procedures to quantify the relevant inputs (resources) and outputs (emissions) of a product system over its lifecycle in relation to the fU. An LCI requires a lot of data and setting up inventory data could be one of the most labour intensive task of an LCA (Finnveden et al., 2009). The database is the core of the inventory. National and regional databases provide data for the most important products and services that are needed for an LCA, such as raw materials or complex products, electricity generation, transport processes, waste services, etc. Data for each unit process within the systems boundary can be classified under major headings, including:

- energy inputs, raw material inputs, ancillary inputs, other physical inputs,
- products, co-products and waste,
- emissions to air, discharges to water and soil, and
- other environmental aspects.

Actually, few industrial processes yield a single output. Most industrial processes yield more than one product, and they recycle intermediate or discarded products as raw materials. In that case, the inputs and outputs need to be partitioned and assigned to the different products through allocation procedures[3]. For example, allocation could be based on physical causation[4], mass[5], or economic value[6]. According to the ISO standards, allocation should be avoided and the use of system expansion[7] should be preferred. Following the collection, data need to be validated, related to unit processes, and related to the reference flow of the fU in order to generate the results.

2.4.3 Life Cycle Impact Assessment

The purpose of the Life Cycle Impact Assessment (LCIA) phase is to interpret the inventory results according to the environmental significance. According to the ISO 14040:2006 and ISO 14044:2006/Amd 1:2017, the LCIA is composed by mandatory and optional elements (Table 3).

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[3] Consideration should be given when systems involve multiple products. Few industrial processes yield a single output or are based on a linearity of raw material inputs and outputs. The major task is to fairly allocate the environmental loads, which is for example, inputs and outputs to the product A and B. This means that a strict scientific solution cannot be provided.

[4] Scientific-technical arguments could be a reason for allocation procedures. Allocation based on physical causation is not always possible, since there is not always a physical causation involved (Finnveden et al., 2009).

[5] Allocation per mass is the oldest allocation rule and is commonly used with multi-output process. As LCA is primarily based on mass flow-analysis, the allocation proportional to mass lends itself as an arbitrary though simple and universal rule (Klöpffer and Grahl, 2014).

[6] Allocation on the economic value is based on prices. It is primarily an allocation per mass although averaged by price. Problems with price-proportional allocations are often considerable with market-dependent price fluctuations. In order to avoid this problem, average values for longer periods or for reference period of the LCA should be considered (Klöpffer and Grahl, 2014).

[7] System expansion is illustrated by Klöpffer and Grahl (2014). A comparison of product A and C is made, where A is formed together with co-product B. It is evident that the benefit of the system 1 (A+B) and 2 (C) is not identical. In order to achieve comparability, the fU is changed by a system expansion to A+B and C+B. As an alternative for expansion, a comparison between A and C could be maintained if the environmental loads related to B are subtracted from A (credit).

Table 3 – Mandatory and optional elements of an LCIA and their significance

Elements		activity
Mandatory	Selection	Selection of impact categories, category indicators, characterization model
	Classification	Assignment of LCI results to the impact categories
	Characterisation	Calculation of category indicator results
Optional	Normalisation	Calculation of the magnitude of impact category indicator result relative to reference information
	Grouping	Sorting and ranking of impact categories
	Weighting	Converting indicator results of different impact categories by using numerical factors based on value-choices and possible aggregation into a single point indicator

The *impact category* represents the environmental issue of concern to which LCI results may be assigned. The *category indicator* is the quantifiable representation of an impact category, while the *characterization factor* derived from a *characterization model* which is applied to convert an assigned LCI result to the common unit of the category indicator. Table 4 shows an early list of impact categories.

Table 4 – List of impact categories, based on Klöpffer and Grahl (2014) after Udo de Haes (1996)

Categories	List of impact categories
Input-related	Abiotic resources
	Biotic resources
	Land
Output-related	Global warming (renamed as Climate Change)
	Depletion of stratospheric ozone
	Human toxicological impacts
	Ecotoxicological impacts
	Photo-oxidant formation
	Acidification
	Eutrophication
	Odour
	Noise
	Radiation
	Casualties

ISO standards do not prescribe an impact category list. Nevertheless, they recommend that impact categories, category indicators, and characterization models are to be internationally accepted, based on international agreement or recognised by an authorised international board. The section of the impact categories depends on the G&S and on the authors of the LCA. Table 5 shows two lists for a selection of *impact categories* that can be assigned to the results of the inventory (*midpoint categories*), which can be further bundled into *damage categories* (*endpoint categories*).

Table 5 – Lists for a selection of impact categories, based on Klöpffer and Grahl (2014)

Impact category	**Impact category**	
	Mid-point categories	**Damage categories**
Human toxicity Ecotoxicity Eutrophication (aquatic) Eutrophication (terrestrial) Land use Ozone formation (near-surface) Resources demand Ozone depletion (stratospheric) Greenhouse effect Acidification	Human toxicity	Human health
	Impact on respiration	
	Ionising radiation	
	Ozone layer destruction*	
	Photochemical oxidation	
	Aquatic ecotoxity	Quality of ecosystems
	Terrestrial ecotoxity	
	Aquatic acidification	
	Aquatic eutrophication	
	Terrestrial acidification and eutrophication	
	Land use	
	Global warming	Climate change
	Non-renewable energy	Resources
	Mining of minerals	

*The impact category ‘ozone layer destruction’ was erroneously only assigned to the Damage Category ‘human health’ because of a proven correlation between skin cancer illnesses and short-wave UV radiation; however there are also correlations to quality of ecosystems’ and particularly to ‘climate change’ which is classified here as Damage Category, which deviates from ISO 14044 definition.

The so-called midpoint categories represent a problem-oriented approach as they relate to the environmental problem fields shown in Table 4. The damage categories are often called endpoint; they translate the environmental impacts into issues of concern, such as human health, integrity of ecological systems, and resources, usually called *areas of protection.* The ISO standard allows the use of impact category indicators that are somewhere between the inventory result (i.e. emission) and the endpoint. Indicators that are chosen between the inventory results and the endpoints are sometimes referred to as indicators at midpoint level. In general, indicators that are chosen close to the inventory result have a lower uncertainty, as only a small part of the environmental mechanism needs to be modelled, while indicators near the endpoint level can have significant uncertainties. However, indicators at endpoint level are much easier to be understood by decision makers than indicators at midpoint. Fig. 2 shows the distinction between midpoint and endpoint. Several methods for classifying the LCI data have been developed in the past; among them the CML-2001, Eco-Indicator 99, EDIP 2003, ReCiPe, LIME, EPS 2000, Ecological Scarcity Method, TRACI. Some methods have both mid and endpoints, such as ReCiPe and LIME.

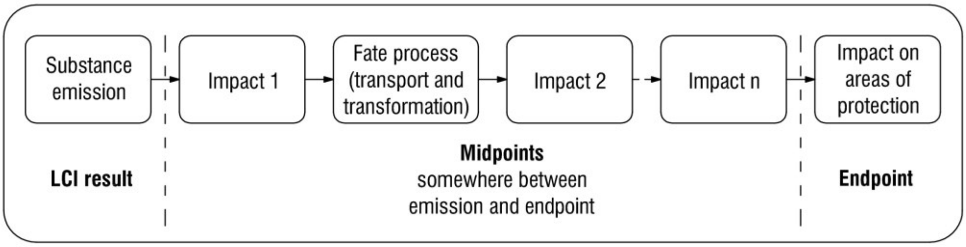

Fig. 2 – Schematic presentation of an environmental mechanism, based on Finnveden et al. (2009)

Classification in the LCIA phase provides the way for assigning the elementary flows from the inventory to the impact categories according to the substances' ability to contribute to the different environmental problems. Each substance contributes differently to the environmental problem in an impact category. The characterization factors (CFs) are employed to determine this different contribution. The CFs are multiplied to the substance in consideration and allow having a common category indicator. Fig. 3 depicts the principle of classification and characterization.

Normalisation, grouping, and weighting are optionally applied to the LCI result (Table 3). Normalisation means that category results are divided by selected reference value. It is employed to facilitate the interpretation of results, since it expresses the relative magnitude of the impact on a scale that is common to all the impact categories. Grouping provides options to summarize the results of the preceding elements of the LCIA by sorting (on a nominal basis) or ranging (in a given hierarchy) the impact categories. Weighting converts indicator results of different impact categories by using numerical factors based on value-choices. Thus, the possibility of ecopoints and similar aggregations is implicitly suggested. These are also called single point methods because in the context of weighting the impact categories are quantitatively taken into account but only a highly aggregated result is documented (Klöpffer and Grahl, 2014).

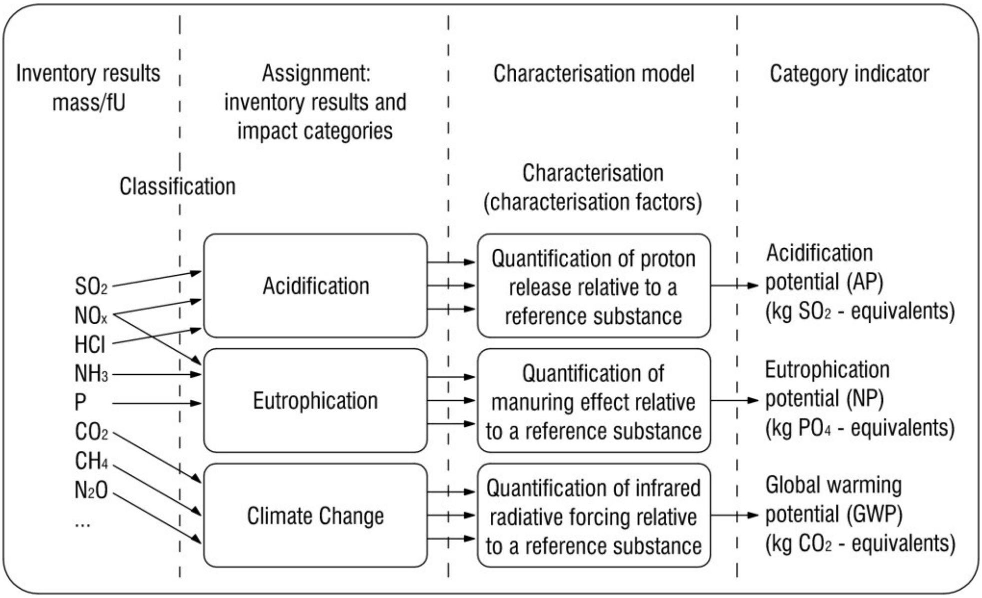

Fig. 3 – Principle of classification and characterisation of LCIA, based on Klöpffer and Grahl (2014)

2.4.4 Life Cycle Interpretation

The Interpretation phase of the LCA allows understanding the meaningfulness of the environmental impact results, drawing conclusions, explaining the limitations of the results obtained, and providing recommendations to decision-makers. The results of the previous phases are critically analysed and the components of the system in which changes can be made are identified in order to reduce the environmental impact of the processes considered. In addition, it should include completeness, sensitivity, and consistency checks.

2.5 LCA of buildings

Life cycle assessment of buildings has been a widely research area over the past decade because of the high environmental impact of this sector. The AEC sector is one of the major carbon emitters and energy consumers. Since 1970, greenhouse gas (GHG) emissions from the building sector have more than doubled, accounting for 19% of the total emissions in 2010 (IPCC, 2014). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), direct and indirect CO_2 emissions from buildings accounted for 8.8 $GtCO_2/a$ in 2010 with a projection to 13-17 $GtCO_2/a$ in 2050. The manufacturing of building materials alone, for example, represents 5-10% of the global CO_2 emissions (Habert et al., 2012). The number of publications related to buildings LCA has more than doubled in the last years: about 14 review papers have been published in the research area of LCA for buildings from 2009 to 2014, and 10 review papers in 2015-2016 at least (Anand and Amor, 2017). In 2015 alone, more than 250 papers focusing on LCA for buildings were published (Anand and Amor, 2017).

LCA for buildings is defined by the technical committee CEN/TC 350 within the EN 15643:2010, which consist of four parts. The first part of the standard describes the general framework, while the last three refer to the environmental, social, and economic aspects (Fig. 4). Within the framework for the environmental performance of buildings, the standard EN 15804:2012 provides the product category rules (PCRs) for Environmental Product Declarations (EPDs). *"An EPD communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market-driven continuous environmental improvement"* (EN 15804, 2012).

EPDs will be essential for the assessment of the environmental performance of buildings, since they state the environmental performance of construction products and services, based on reliable and verifiable information (Passer et al., 2015).

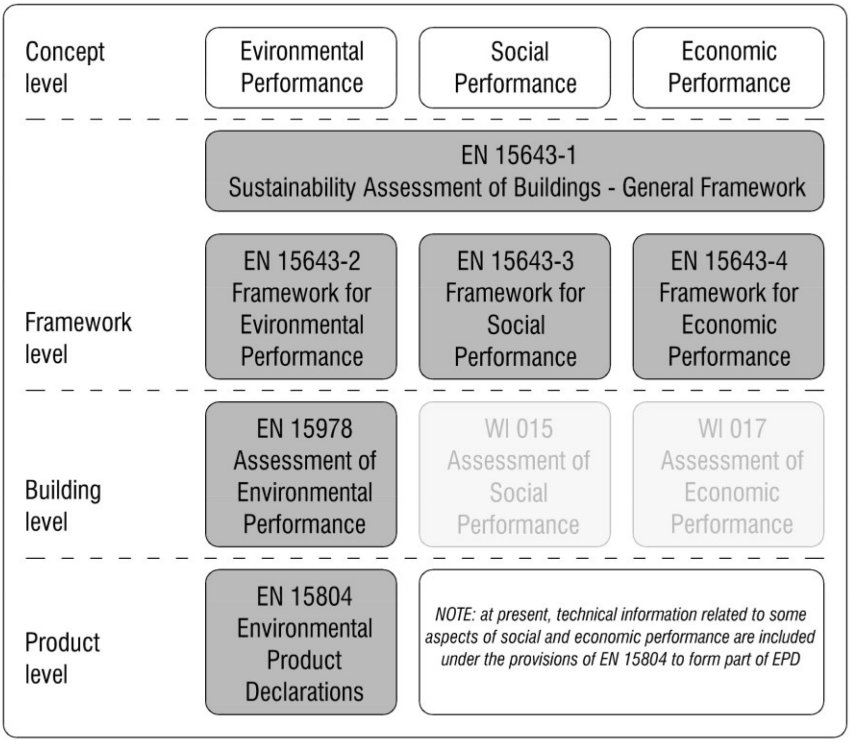

Fig. 4 – Work program of CEN/TC 350, based on EN 15643:2010-1

EN 15978:2011 represents a methodological guide for the quantification of environmental impacts of buildings. It is structured according to the “life-cycle modules” of buildings, including four stages: Product, Construction process, Use, and End of Life. The modules are shown in Fig. 5. The “product stage” (A1-A3) concerns the cradle-to-gate analysis. Environmental information for the product stage is defined in the product EPD, since the modules A1-A3 are mandatory for EPDs (EN 15804, 2012).

Scenarios for the “construction process stage” (A4, A5) cover the processes that occur from the factory gate of products to the completion of the construction work. The module A4 refers to the distance between the factory and the building site. It is related to the transportation processes of products, materials, services, and equipment. The module A5 includes the processes that take place within the building site, such as ground works and landscaping, transportation processes within the site, construction processes and products installation, temporary works, and waste management. For example, the construction processes may also include the energy for on-site equipment, such as cranes, scissor lifts, scaffolding elevators, etc.

The "use stage" is identified with the modules B1-B7. Scenarios of this stage should be based on the existing regulations, client's requirements, or accepted code of practice. The module B1 includes the impacts related to the characteristics of the products in their application (e.g. emissions depending on pattern of use, humidity, air velocity, and temperature). The modules B2-B5 cover measures to restore the functionality of the building or its components, as well as to adapt them to the new standards of the sector or to increase the performance of the building. The module B2, B3 and B4 take into account the client's requirements, service life of products and materials, requirements issued from EN 15804, manufacturers' information, and pattern of use. Maintenance (B2) refers to the actions during the service life of the building or its parts in order to retain them in a state in which they can perform the required functions. Repair (B3) can include partial replacement and it refers to the corrective actions to address the loss of performance of building parts. Thus, the complete replacement of building components is addressed within the module B4. The environmental impacts of the upstream processes (raw material acquisition, production, transport of a new product), installation, and waste processing of a removed product, are assigned to the assessment results of this module. Refurbishment (B5) refers to the modification of the building in order to bring it up to an acceptable condition. The module B6 takes into account the energy consumed by technical systems for heating, cooling, ventilation, lighting, and control the building. The processes related to the use of domestic hot water are included in this module. The operational water use (B7) refers to the water use for operating the building. Additional energy and water uses not included in modules B6 and B7 shall be documented separately.

The “end of life stage” (EoL) is defined by the modules C1-C4. The module C1 describes the activities for dismantling and deconstruction. The module C2 refers to the type of transport used, the distances travelled, and the fuel consumption required to convey materials and products from the building site to the final treatment plant. The module C3 specifies all waste treatment processes (e.g. sorting, preparatory processes for reuse, recycling, energy recovery, etc.) up to the moment where the output from dismantling, deconstruction or demolition of the building or construction works ceases to be waste. The last module of the EoL stage (C4) includes any processes or activities necessary before the final disposal where not covered in modules C1-C3, as well as the final disposal itself.

The supplementary information is addressed by the module D. Hence, benefits and loads outside the system boundary could be defined, such as benefits for waste management which can be used for energy production.

It can be noted that the LCA of buildings is based on current scenarios and technologies (Fig. 5). The modules A4-C4 are based on the collection of assumptions and information concerning the expected sequence of possible future events. Hence, although the LCA results are based on realistic scenarios, they may not fully reflect the actual and future performance of the building. This is due to the fact that buildings usually have a very long lifespan.

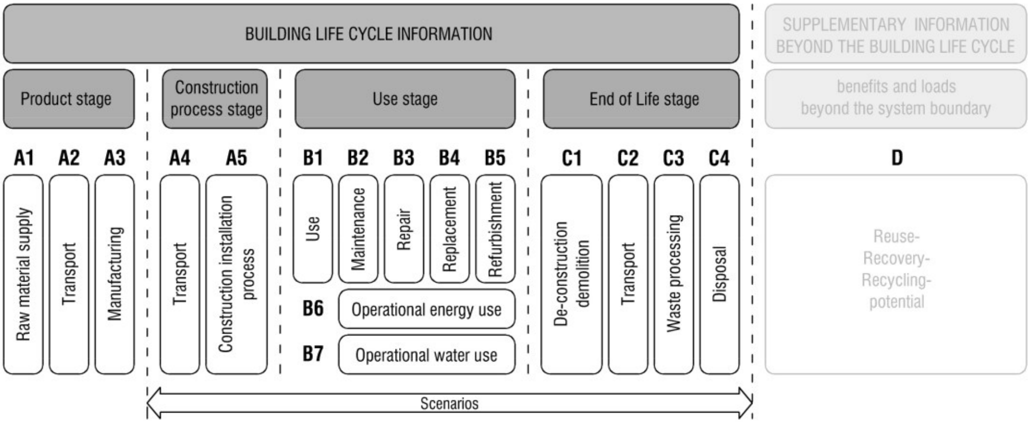

Fig. 5 – Life cycle modules of buildings, based on EN 15978

2.5.1 Functional unit, reference study period, and system boundaries

According to the EN 15978:2011, the functional equivalent defines the required technical characteristics and functionalities of buildings or building components. Comparisons between the LCA results are made on the basis of the functional equivalency. The functional equivalent includes information about the object of the assessment, such as the definition of the building type, technical and functional requirements, pattern of use, required service life, etc. A variety of functional units is used in LCA of buildings (Cabeza et al., 2014). Meter square and the whole building are reported as the most used fU in case of residential buildings (Abd Rashid and Yusoff, 2015; Islam et al., 2015). Several studies consider the complete building as a fU and in other cases the fU is a part of the building, such as the envelope, windows, roof, and shading (Soust-Verdaguer et al., 2016). However, the use of the fU based on building elements, such the weight of materials, could lead to ignore the impact of the building as a whole or the impact of the building based on its other functions (Anand and Amor, 2017). Depending on the scope of the assessment, for example, 1 m^2 of heated area and one year of operation could be used as a reference unit. In that case the Reference Study Period (RSP) needs to be selected for the assessment.

EN 15978:2011 defines the Required Service Life (RSL) of the building as a default value for the Reference Study Period. However, the RSP may differ from the RSL given for the object of assessment depending on the intended use of the assessment, or on regulatory requirements or national guidance. The simplest approach for defining the RSL of buildings consists in attributing a fixed values without referring to a calculation method (Mastrucci et al., 2017). For new building, for example, typical chosen values range of RSL are from 50 to 100 years (Mastrucci et al., 2017; Moschetti et al., 2015; Sartori and Hestnes, 2007). For existing buildings, a residual service life is considered instead. Values depend on the building type and a range from 20 up to 50 years could be adopted (Famuyibo et al., 2013; Nemry et al., 2010). Furthermore, since buildings are made up of various elements with varying lifetimes, service lives of products must be defined. In reality, the lifetimes of buildings vary significantly and the use of standard assumptions may have incorrect results (Grant et al., 2014). In addition, the typical service life turns out to be inappropriate for some materials because of their exposure to the agents of degradation or pattern of use. In order to overcame this issues, reliable service lives of products could be estimated using the factor method according to the ISO 15686-8:2008.

LCA of buildings involves the definition of two levels of system boundaries, since a building consist of different products. Hence, in addition to the system boundaries at the product/material level described in 2.4.1, the system boundary at the building level must be defined. This last determines the processes that are taken into account for the object of the assessment. According to EN 15978:2011, for a new building, the system boundaries shall include all the life cycle modules as shown in Fig. 5; for an existing building all stages representing the remaining service life need to be considered instead. Nevertheless, depending on the task, some life cycle modules could be not taken into account (Soust-Verdaguer et al., 2016).

2.5.2 Environmental data sources and LCA tools

LCA of buildings requires a lot of data. In order to facilitate the data compilation, many databases have been developed in the last decades. Therefore, LCA of buildings is typically performed using predetermined LCI data. These could be public national or regional databases, industry databases, and consultants' databases. LCA data can be defined as "background generic data", "foreground specific data", and "average data" (Silvestre et al., 2015). Background generic data are used to model upstream and downstream processes that are not under the control of the manufacturer of a building product. They can be defined as a surrogate data used if no system specific data are available. Foreground specific data (primary data) are collected at the manufacturer's plant. These are usually provided by the EPDs. An average dataset is a combination of different specific datasets that are aggregated in order to represent, for example, a product group. On the one hand, the use of generic databases can reduce significantly the amount of data, but at the same time the representativeness of data cannot be assured (EeB Guide Project, 2012). On the other hand, when regional LCI have not been available, data used from generic databases has been adapted to reflect regional characteristics (Soust-Verdaguer et al., 2016). In general, the mix of different databases has to be carefully carried out when performing an LCA. In fact, datasets are based on different PCRs, cut-off and allocation rules, background data of the electricity mix, etc. Although the comparison of different databases could show similar trends in the assessment results, numerical differences have been found (Takano et al., 2014). Furthermore, the mix of EPDs calculated with different background data may not be appropriate (Lasvaux et al., 2015).

There are various multi-sectorial generic LCI databases, such as *ELCD database*[8], *Ecoinvent database*[9], *GaBi database*[10], or *U.S. Life-Cycle Inventory Database*[11]. Islam et al. (2015) presented a list of LCI databases around the world. The EeB Guide website lists further databases, including those that are out of date. Databases developed specifically for the construction industry have also been published in the last years. Table 6 lists the most used generic LCA databanks for the construction sector.

LCA databases are often included within LCA software tools. The development of tools in the building sector has been active in the past years. A variety of different tools exist for the building components and the whole building. The tools cover different phases of a building's lifecycle and take into account different environmental issues (Haapio and Viitaniemi, 2008). Hollberg et al. (Hollberg and Ruth, 2016) listed a multitude of LCA tools by identifying four categories: generic LCA tools, spreadsheet-based tools, component catalogues, and CAD-integrated. Generic LCA tools have

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[8] ELCD has been discontinued the 29th of June 2018. The ELCD database is not available anymore online, but is still downloadable as a zip package. See http://eplca.jrc.ec.europa.eu/ELCD3/ (accessed July 5th 2018).

[9] Ecoinvent is provided by the Ecoinvent Swiss Centre. See https://www.ecoinvent.org/ (accessed July 5th 2018).

[10] GaBi is a commercial database provided by thinkstep. See http://www.gabi-software.com/databases/ (accessed July 5th 2018).

[11] US LCI is provided by the U.S. National Renewable Energy Laboratory. See https://www.nrel.gov/lci/. (accessed July 5th 2018).

been developed for the LCA of product and process. However they require extensive background knowledge and therefore are suitable for LCA-experts. Spreadsheet-based tools are based on the input of bill of quantities (BOQ) in a spreadsheet, and the LCA is calculated by multiplying the mass of materials with the respective environmental impact factors. Usually the calculation refers to the embodied impact, but some tools, such as *LEGEP* and *Elodie*, can calculate the operational energy as well. Component catalogues facilitate the LCA of building components, as typical components are predefined and can be quickly modified. Over the last years, a number of plug-ins for BIM software has been developed. In most cases the BOQ is automatically generated from the BIM and the plug-in provide the LCA calculation. As such, BIM-based tools do not require manual input of materials and components quantities since this information is already available into the BIM environment. Table 7 gives an overview on the currently most used LCA tools.

Table 6 – Generic LCA databases for the construction sector

Database	**Country**	**Focus**
The Athena Institute database[12]	Canada	Database for building materials and products, including wood, steel, concrete and structural products.
Bauteilkatalog[13]	Switzerland	The database is provided by the LCA data of the construction sector according to the KBOB/eco-bau 2009/1 recommendation, which were developed by the EMPA Dübendorf and are based on Ecoinvent.
DIOGEN[14]	France	The database gives the environmental impacts for materials used in the implementation of civil engineering works.
KBOB[15]	Switzerland	The database contains data for building materials and building technology (production, disposal), energy and transport (operation, vehicle, and infrastructure) for Switzerland.
IBO LCA database[16]	Austria	The Internet platform is a comprehensive info-communication hub for energy-efficient and ecological construction.
Ökobau.dat[17]	Germany	Generic data sets and specific data sets of construction materials and the construction and transport processes.
Minnesota Building Materials Database[18]	USA	Information on sustainable materials, products, systems, and services for the commercial and residential building construction industry in Minnesota.
ICE database[19]	Global	Embodied energy and carbon coefficient for building materials.

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[12] http://www.athenasmi.org/our-software-data/overview/ (accessed July 5th 2018).

[13] It is based on the project presented by Holliger Consult in 2002 and was developed as part of the building technology research program. See http://www.bauteilkatalog.ch (accessed July 5th 2018).

[14] Following a working group it gives the environmental impacts of the NF P 01-010 standard. See http://www.diogen.fr/ (accessed July 5th 2018).

[15] https://www.kbob.admin.ch/ (accessed July 5th 2018).

[16] https://www.baubook.info/ (accessed July 5th 2018).

[17] ÖKOBAUDAT is considered as a binding database within the federal building assessment system (BNB). See http://oekobaudat.de/en.html (accessed July 5th 2018).

[18] http://www.buildingmaterials.umn.edu/materials.html (accessed July 5th 2018).

[19] Developed by Hammond, G. P. and Jones, C. I. See http://opus.bath.ac.uk/12382/ (accessed July 5th 2018).

Table 7 – Most used LCA tools, based on Hollberg and Ruth (2016)

Classification	**Name**	**Country**	**Website**
Generic LCA tools	Gabi	Germany	www.gabi-software.com
	SimaPro	Netherlands	www.simapro.com
	OpenLCA	Germany	www.openlca.org
	Umberto	Germany	www.umberto.de
	TEAM™ *	France	www.ecobilan.pwc.fr/en/boite-a-outils/team.html
	EIO-LCA*	US	http://www.eiolca.net/
Spreadsheet-based tools	Envest	UK	www.clarityenv.com.au/envest/
	SBS Building Sustainability	Germany	www.sbs-onlinetool.com
	Ökobilanz Bau	Germany	www.oekobilanz-bau.de/oekobilanz/
	eTOOL	Australia	http://www.etoolglobal.com/
	Athena Impact Estimator	Canada	www.athenasmi.org/our-software-data/impact-estimator/
	Legep	Germany	www.legep.de
	Elodie	France	www.elodie-cstb.fr
	GreenCalc+	Netherlands	www.greencalc.com
	LCAbyg*	Denmark	www.lcabyg.dk
	BeCost*	Finland	www.virtual.vtt.fi/virtual/proj6/environ/
Component catalogues	Ecosoft	Austria	www.ecosoft.com.br
	Bauteilkatalog	Switzerland	www.bauteilkatalog.ch
	eLCA	Germany	www.bauteileditor.de
	BEES	US	www.nist.gov/services-resources/software/bees
	NovaEQUER*	France	www.izuba.fr
CAD-integrated LCA tools	Impact	UK	www.impactwba.com
	Cocon-BIM	France	www.eosphere.com
	Lesosai	Switzerland	www.lesosai.com
	360optimi	Finland	www.360optimi.com
	Tally	US	www.choosetally.com
	CAALA*	Germany	www.caala.de
	One Click LCA*	Finland	www.oneclicklca.com

* Not included in the LCA tools list of Hollberg et al. (2016)

2.5.3 Environmental indicators used for LCA of buildings

The quantified environmental impacts of buildings during their whole life cycle could be described by a number of environmental impact indicators. EN 15804:2012 identifies the “indicators describing environmental impacts” (output related indicators) and “indicators describing resource use” (input-related indicators). These indicators are shown in Table 8 and Table 9 and should be applied to the LCA of buildings according to EN 15978:2011.

Table 8 – Indicators describing environmental impacts (EN 15804:2012)

Impact Category	**Indicator**	**Abbreviation**	**Unit**
Global Warming	Global warming potential	GWP	kg CO_2-equiv.
Ozone Depletion	Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 equiv.
Acidification for soil and water	Acidification potential of land and water	AP	kg SO^2-equiv.
Eutrophication	Eutrophication potential	EP	kg $(PO_4)^3$-equiv.
Photochemical ozone creation	Formation potential of tropospheric ozone photochemical oxidants	POCP	kg Ethene equiv.
Depletion of abiotic resources-elements	Abiotic Resource Depletion Potential for elements	ADPe	kg Sb equiv.
Depletion of abiotic resources-fossil fuels	Abiotic Resource Depletion Potential of fossil fuels	ADPf	MJ, net calorific value

NOTE 1: The indicator describing the depletion of abiotic resources is subject to further scientific development. The use of this indicator might be revised in the next version of EN 15804.

NOTE 2: Parameters describing emission of ionising radioactive radiation and its impact on human health and/or ecosystems on the LCA level might be revised in the next version of EN 15804.

Table 9 – Indicators describing resource use (EN 15804:2012)

Indicator	**Unit**
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ, net calorific value
Use of renewable primary energy resources used as raw materials	MJ, net calorific value
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials), PERT	MJ, net calorific value
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	MJ, net calorific value
Use of non-renewable primary energy resources used as raw materials	MJ, net calorific value
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials), PENRT	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ, net calorific value
Use of non-renewable secondary fuels	MJ, net calorific value
Net use of fresh water	M^3

The choice of the environmental indicators varies from study to study. The selection depends on the specific goals and regional interests of the research. Most of the LCA studies only refer to a limited number of the environmental indicators listed by EN15804:2012 and EN 15978:2011. According to Soust-Verdaguer et al. (2016) most of the selected papers considered GWP as environmental impacts indicator. According to Islam et al. (2015) the greenhouse gas (GHG) emissions and CED[20] (Cumulative Energy Demand) are the indicators most often selected in some studies. A CED cannot be an indicator since it does not correspond to an impact category (Klöpffer and Grahl, 2014). However, it represents a useful characterising figure that can be determined with small uncertainty. It is therefore an ideal supplement to the information provided by the impact categories but it is not suitable as the sole criterion. Further indicators could be useful to describe additional information. EN 15804:2012

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[20] The primary energy total demand (Primary Energy Total, PET) is composed by the Primary Energy Renewable Total (PERT) and Primary Energy Non-Renewable Total (PENRT). The Primary Energy Demand is also called Cumulative Energy Demand (CED).

and EN 15978:2011 define other environmental information describing different waste categories (Table 10) and output flows (Table 11).

Table 10 – Other environmental information describing waste categories (EN 15804:2012)

Indicator	**Unit**
Hazardous waste disposed	kg
Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

Table 11 – Other environmental information describing output flows (EN 15804:2012)

Indicator	**Unit**
Components for re-use	kg
Materials for recycling	kg
Materials for energy recovery	kg
Exported energy	MJ per energy carrier

As can be seen in Fig. 6, LCA intends to consider all the environmental impacts, which include the resources input, emissions, and wastes output of a building during the lifecycle (Chau et al., 2015). The basic principle of the LCA consists of multiplying each product and service in a life cycle module of the building with its respective value for any environmental indicator. It can be represented mathematically by:

$$EP_i = \vec{a}_j \ x \ M \tag{1}$$

Where:

EP_i is the indicator value of the module i of the building;

$\vec{a}_j$ is the vector containing the gross amounts of all products and services used in the module j of the building;

M is the matrix containing in its columns the environmental indicator values per unit of all products and services used in the module i of the building.

Equation (2) exemplifies the resulting calculation routine for the quantification of the GWP of stage i. The same calculation routine applies to all the environmental indicators listed above.

$$GWP_i = a_{1,i} \ x \ GWP_{a1,i} + a_{2,i} \ x \ GWP_{a2,i} + \ldots + a_{aN,i} \ x \ GWP_{aN,i} \quad (2)$$

Where:

GWP_i	is the global warming potential quantified for the module i of the building;
$a_{N,i}$	is the gross amount of product or service n used in the module i of the building (n = 1, 2, 3, …, N);
$GWP_{aN,i}$	is the global warming potential of product or service n used in the module i of the building (n = 1, 2, 3, …, N).

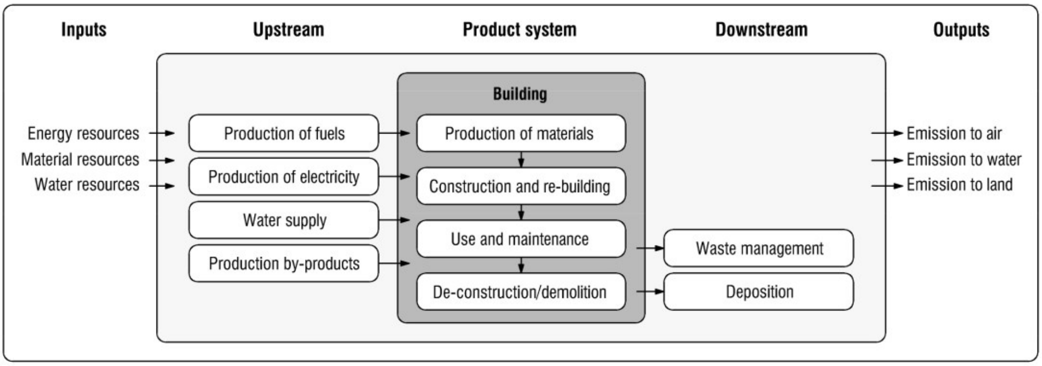


Fig. 6 – LCA of buildings, based on Kulahcioglu et al., 2012

2.5.4 Simplifications in LCA of buildings

LCA is widely recognized as the most complete tool for assessing the environmental impacts of buildings. Nevertheless, it is not widespread because of many difficulties. Some of them are the extensive and exhaustive amount of information required, as well as the required experience of the practitioner for calculating impacts (Zabalza Bribián et al., 2009). During an architectural competition, a screening LCA could be needed for supporting the design alternative, whereas a complete LCA might be required at a more advanced stage of the building project.

Simplifications could be adopted at the LCI level by considering the main elements and processes, and the impact assessment phase can be simplified to a few impact categories (Soust-Verdaguer et al., 2016). Zabalza et al. (Zabalza Bribián et al., 2009), for example, proposed a simplified LCA of a building focusing on the calculation of operational energy consumption and CO_2 emissions. In the last decade, several studies have focused on the BIM-based LCA. Some of them employed the BIM as a strategic tool for the time-reduction of data acquisition (Basbagill et al., 2013). Malmqvist et al. (Malmqvist et al., 2011) proposed guidelines for simplifying the LCA method of buildings. Strategies to overcome some of the existing barriers for the LCA could be: (1) reducing the data acquisition phase focusing on larger building elements; (2) simplifying inventory analysis focusing on the most important substances that contribute to a certain impact category; (3) simplifying the calculation by focusing on a few impact categories; (4) reducing the time-efforts by using CAD applications (Malmqvist et al., 2011). EeB Guide Project determines three different LCA study types with increasing level of data quality, time and effort:

- Screening LCA,
- Simplified LCA,
- Complete LCA.

As shown in Fig. 7, a complete LCA involves all the life cycle modules defined in EN 15978:2011 with the use of specific LCA data. As regards the Screening and Simplified LCA, several modules are optional depending on the relevance of the study. For Screening LCA only the modules referring to the product stage (A1-A3) are compulsory together with B6 and B7. For simplified LCA, in addition to the modules considered for the screening, the use and end of life stages are also partially included.

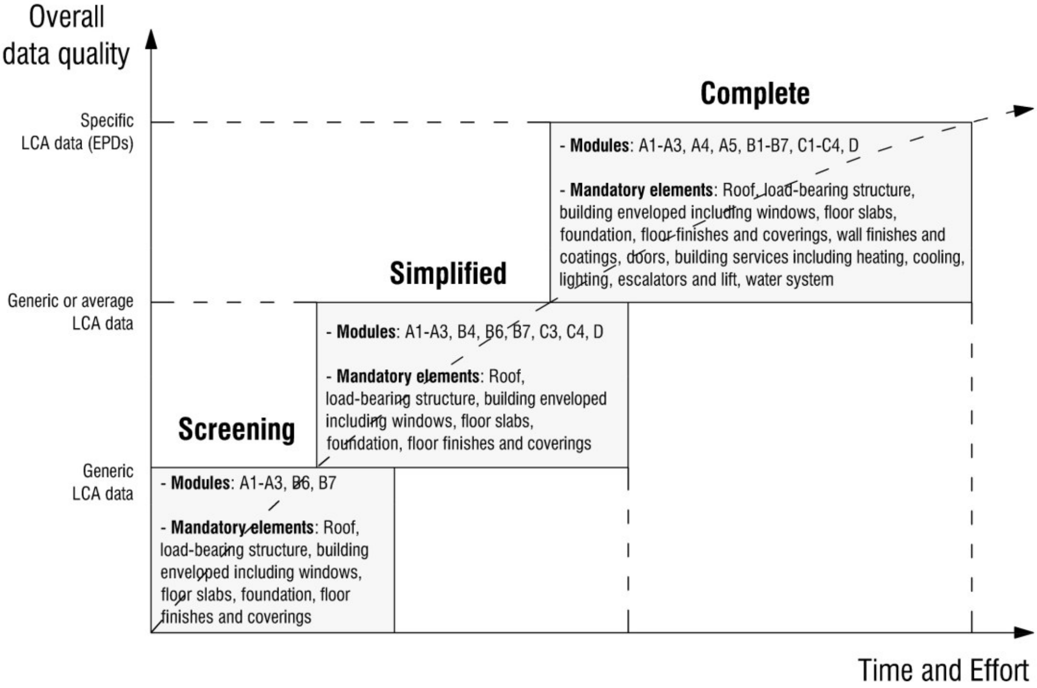


Fig. 7 – LCA study types, based on EeB Guide Project (2012)

2.5.5 Limitations of LCA

LCA is an holistic approach aiming at forecast future materials/energy fluxes on regional and global scales (Ayres, 1995). This could be the strength and limitation at the same time. Furthermore, ISO standards (ISO 14040, 2006; ISO 14044:2006/Amd 1:2017, 2017) define the principles and framework for LCA without describing the detailed technique and the methodologies for the individual phases of the LCA. This leaves room for assumptions. Several discussions about limitations of LCA could be found in literature. They are mainly summarized as follows.

- **Lack of data**: LCA is very data intensive, and lack of data can limit the conclusions that can be drawn from a specific study (Finnveden et al., 2009). However, as discussed in sub-section 2.5.2, several LCA databases and tools have been developed in last decades. However, only a few LCIs have been developed in certain countries. Some researches presented workflows and data conversion methods which makes use of non-local LCI to evaluate the environmental impact of local construction materials (Lu et al., 2017). Also, EPDs are crucial to reduce this limitation, since they state the environmental performance of products and services, based on reliable information (Passer et al., 2015).

- **Limitations of environmental problems knowledge:** The employed impact categories address a wide range of environmental problems. However, not all types of impacts are equally covered in a typical LCA (Finnveden et al., 2009). According to Klöpffer and Grahl, a list of the environmental problem is always lacking since it correspond to the present knowledge and reception (Klöpffer and Grahl, 2014).
- **LCA assumptions:** Despite the science-based nature and the general framework proposed by ISO and EN standards, LCA can include several technical and methodological choices. Assumptions are uncertain and may potentially influence the results. Examples include allocation methods, time limits for the inventory analysis, and choices of characterisation methods for the impact assessment (Finnveden et al., 2009).
- **Uncertainties and variability:** LCA are affected by a certain level of uncertainty and variability. This issue is widely addressed in the literature from different standpoints. Lloyd and Ries (2007) considered three types of uncertainty, which are parameter uncertainty, scenario uncertainty, and model uncertainty. Parameter uncertainty includes data uncertainty regarding process inputs, environmental discharges, and technology characteristics. Scenario uncertainty could include choices regarding the functional units, valuation and weighting factors, time horizons, geographical scales, natural contexts, allocation procedures, waste-handling scenarios, use of environmental thresholds, and expected technology trends. Model uncertainty concerns models for deriving emissions and characterization factors. Williams et al. (2009) identify five types of uncertainty in compiling LCIs:

    - Data: collection errors in input parameters;
    - Cut off: arises due to processes left out of analysis;
    - Aggregation: different processes lumped into sectors/superprocesses;
    - Geographic: inter/intranational variations in process implementation;
    - Temporal: products and processes evolve over desired time scale.
- **Assessment of potential environmental impacts:** ISO 14040:2006 defines LCA as a method to address "*the environmental aspects and potential environmental impacts throughout a product's life cycle*". This means that LCA is unable to predict absolute or exact values of the environmental impacts. LCA does not identify the actual environmental impact, but indicate that there is a potential linkage between the product or process lifecycle and the impacts.

Additionally, in the context of LCA for buildings, further limitations could be highlighted. They are due to the specific nature of the building, the construction sector, and the practitioners involved. The main limitations that could be found in literature are presented as follows.

- **Project-based nature of the construction industry:** As opposed as standardized/industrialized products, each building project is unique and has its own characteristics, for example, related to specific conditions, individual needs of the client, special locations (Antón and Díaz, 2014). Thus, to compare the lifecycle performance of different buildings, ranges of similar assumptions need to be adopted to draw conclusions (Soares et al., 2017).
- **Amount of data:** Due to the large amount of data required to perform an LCA, it is recommended the use of software application that makes the studies much more efficient (Zabalza Bribián et al., 2009). There are various tools that allow LCA studies to be carried out at various degrees of detail. LCA of buildings can be performed using general LCA software, but identifying and quantifying all the required data involves a lot of time (Zabalza Bribián et al., 2009). Therefore,

specific applications have been developed to facilitate the use of LCA in the building sector (see sub-section 2.5.2), but they also presents limitations.

- **Long-life terms of buildings:** The total building service life is uncertain and can vary from 50 up to 100 years as shown in sub-section 2.5.1. Additionally, buildings incorporate multiple construction materials and products that have their specific RSL. As a consequence, the schedule and the nature of maintenance activities (corrective, preventive or predictive) can highly influence the lifespan of buildings. This implies a lower predictability of the exact environmental impacts. Furthermore, products or active systems could be replaced by more efficient ones, which is hardly predictable and make the end-of-life scenario very uncertain (Soares et al., 2017).
- **Lack of data at the early design stage:** The buildings design process consists of several phases, which are defined similarly in most industrialized countries. The dilemma of the LCA during the design process is that decisions taken in early design stages have the greatest influence, but the information available is scarce and uncertain. The complete information are available at the end of the design process, but by then the project has already lost most of its flexibility and the results are less useful because it is too costly to make changes (Hollberg and Ruth, 2016).
- **Interoperability:** Further developments concerning interoperability between LCA tools and CAD/BIM software are needed. There is a lack of interoperability between the different software systems and this lead to difficulties in the adoption of LCA in construction industries (Díaz and Antón, 2014). However, in recent years BIM-based LCA methods have been developed in order to overcome this issue (Soust-Verdaguer et al., 2016).
- **Practitioners' knowledge:** In general, designers lack the knowledge and experience necessary to carry out an LCA. Therefore, simplified approaches are needed which include the knowledge of LCA experts and allow the designers to focus on designing the building (Hollberg and Ruth, 2016).

3. BUILDING INFORMATION MODELLING

3.1 Highlights of the chapter 3

BIM provides a paradigm shift in the construction sector. The typical 2D-based design gives way to the BIM-based consistent process. BIM is defined in many different ways: it stands for the process for leveraging building data during its lifecycle (Building Information Modelling); the digital representation of physical and functional characteristics of a building (Building Information Model); the organization and control of the building process by using the information stored in the digital model (Building Information Management). BIM does not only rely to the technology field, but it also refers to the process and policy fields. The process field relates to the stakeholders involved in the ownership, delivery and operations of buildings, while the policy field refers to the players involved in the preparation of guidelines and standards on BIM. The digital information embodied in the BIM is shared amongst the project stakeholders from the various disciplines. It allows expanding the dimensions of modelling activities from 3D to nD. The nD modelling enables project members to retrieve information through the same model and it allows for the model validation analysis (3D), time-related simulations (4D), cost estimations (5D), sustainability assessment (6D), and facility management (7D). As such, the benefits of BIM concern the entire lifecycle of buildings. Several reports and researches recognized the BIM benefits, such as, among others, the ability to produce more accurate and reliable information. It could also reduce errors, costs, and the overall project duration, while increasing the general quality of the results. BIM benefits could be increased by a number of factors. Key concepts for the BIM adoption across markets are found to be the interoperability between software applications and the BIM software functionalities. The third key aspect refers to the definition of BIM deliverables between parties. Several organizations are trying to address these aspects to offer better opportunities for adopting BIM in the design process of buildings and their whole lifecycle.

3.2 Introduction to BIM

Building Information Modelling (BIM) is a process focused on the development, use and transfer of digital information model of a building to improve the design, construction and operations of a project (Computer Integrated Construction Research Group, 2010). Eastman et al. (2011) define BIM as follows:

> *"BIM is not merely a type of software but a human activity that involves paradigmatic process changes in design, construction and facility management."*

Building Information Modelling allows connecting the building process phases that are usually managed asynchronously. The stages of the building process are closely related to each other. Nevertheless, the poor information flows, redundancies, complex methodological approaches, multidisciplinary activities, and the large number of stakeholders involved, generate unnecessary errors and inefficiencies. In this context, Building Information Modelling leads to the re-shaping of the Architecture, Engineering, and Construction (AEC) industry. Hence, Building Information Modelling stands as the natural and necessary evolution of the design approach in relation to the increasing complexity of the building process.

After the highlights, the second part of this chapter provides an overall introduction about BIM, its dimensions and benefits. The differences between the BIM-based design process and the typical design effort are also shown. Then, the level of current adoption across different markets is presented and the relations in international BIM standardization are shown. Finally, the fourth part of this chapter addresses the top three factors increasing the BIM benefits.

3.2.1 BIM uses

Building Information Modelling (BIM) is the vector whereby the AEC sector is moving towards the digital prototyping. BIM lays down the transition from unidirectional and asynchronous workflows to integrated and shared models (Succar, 2009). According to Santos et al. (2017), the term "*Building Information Model*" first appeared in 1992, in "*Modelling multiple views on buildings*" article (van Nederveen and Tolman, 1992). The authors suggested a new approach for modelling the building information according to various key aspects. The paper presents an approach in which aspect models are used to store view specific information. Since then, the research on BIM has been growing significantly and new applications have been found (Santos et al., 2017). The bibliometric analysis conducted by Santos et al. (2017) shows that over the last decade there has been an increase in published papers on BIM from 4 in 2006 to 106 in 2015, for a total 381. The Latent Semantic Analysis proposed by Yalcinkaya and Singh (2015) identified twelve principal BIM research areas among 975 research papers published from 2004 to 2014. Additionally, several literature reviews on BIM have been published.

Table 12 lists some literature reviews focusing on different fields of BIM application. Furthermore, a number of BIM areas can be identified through an examination of existing published studies and state-of-the-art advancements. There are many different tasks which can benefit from the incorporation of BIM in the different buildings stages, from planning to operation (*Building Information Modeling Project Execution Planning Guide, Version 2.1*, 2011). These tasks are documented as BIM Uses (Fig. 8).

Table 12 – Literature reviews on different fields of BIM

Authors	**Year**	**Focus**
Eastman et al.	2009	Rule checking systems
Tang et al.	2010	Automatic reconstruction of as-built models
Cerovsek	2011	Technological BIM dimension and BIM implementation in new buildings projects
Jung and Joo	2011	Computer-integrated construction (CIC) and BIM
Love et al.	2011	Design errors
Zhou et al.	2012	Construction safety and digital design
Ding et al.	2014	BIM applications in the construction industry
Volk et al.	2014	BIM for existing buildings
Ibem and Laryea	2014	Digital technologies in procurement of construction projects
Skibniewski	2014	Construction safety assurance
Abanda et al.	2015	BIM systems used in construction projects
Chen et al.	2015	As-built data collection and analysis
Negendahl	2015	Building performance simulation
Chi et al.	2015	Structural design
Cho et al.	2015	Building energy modelling and diagnostics
Shou et al.	2015	Infrastructure industry
Patraucean et al.	2015	Automatic as-built modelling
Son et al.	2015	As-built data collection and analysis
Teizer	2015	Automatic as-built modelling
Yang et al.	2015	Construction performance monitoring
Wong and Zhou	2015	Green BIM
Soust-Verdaguer et al.	2017	BIM-based LCA method to buildings
Eleftheriadis et al.	2017	Life cycle energy efficiency in building structures
Chong et al.	2017	BIM for sustainability
Bruno et al.	2018	Performance assessment of existing buildings

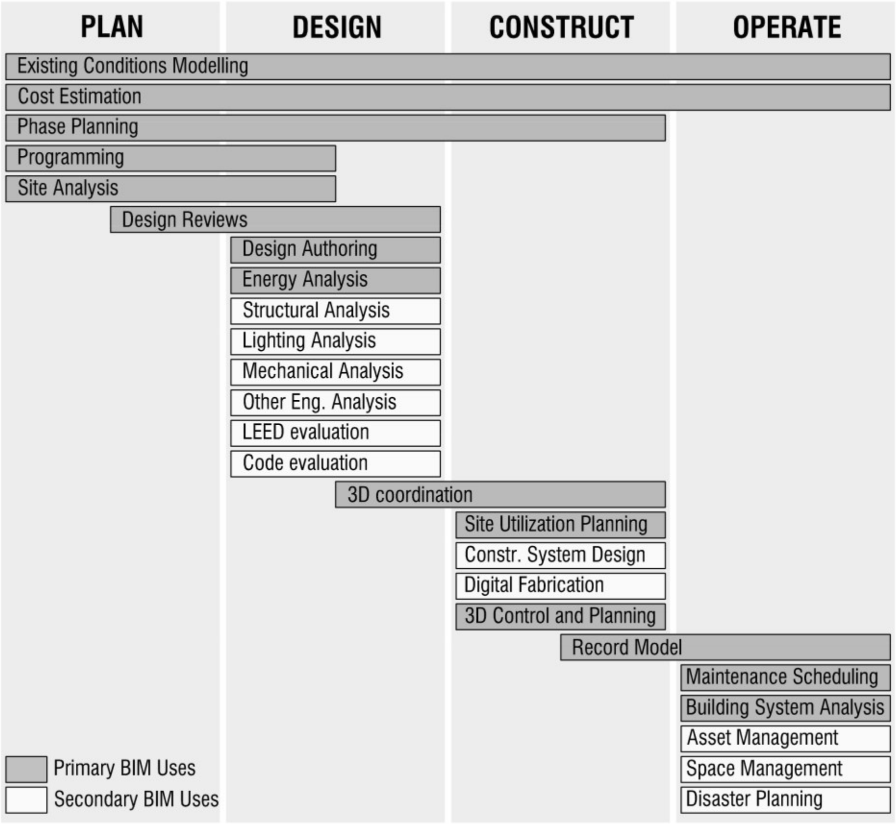


Fig. 8 – BIM Uses organized in chronological order

3.2.2 A paradigm shift in the construction sector

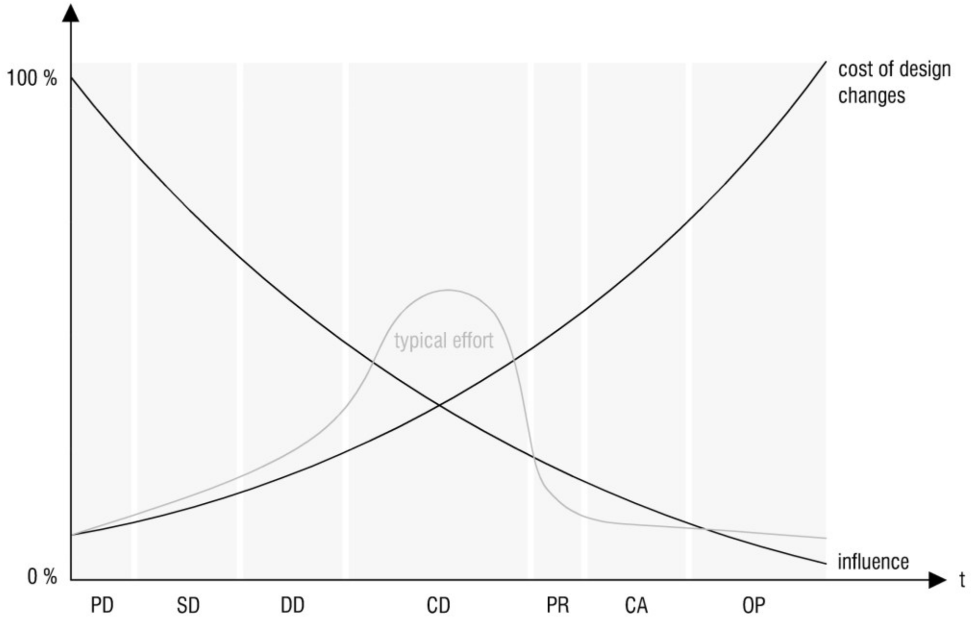
The AEC industry has long sought techniques to decrease costs, reduce project delivery time, and increase quality and productivity. Evidence of poor field productivity in the construction sector is illustrated in a study developed by the Center for Integrated Facility Engineering (CIFE) at Stanford University (CIFE 2007) (Eastman et al., 2011). The research, developed by Paul Teicholz at CIFE, shows the productivity within the U.S. field construction industry from 1964 through 2009. During this 44-year-long period, the productivity of non-farm industries is more than doubled. Meanwhile, labour productivity within the construction industry is relatively unchanged. Recent studies show that the trend of increasingly weaker construction productivity when compared with manufacturing has continued, but they also show the gap between off-site and on-site construction activities. It is clear that fabrication off-site is more productive than construction on-site (Sacks et al., 2018).

Interoperability also leads to inefficiencies in the construction sector. The National Institute of Standards and Technology (NIST) analysed the additional cost incurred by building owners as a result of inadequate interoperability (Gallaher et al., 2004). The results show that inefficient interoperability accounted for an increase in construction costs by 6.12 $\$/ft^2$ for new construction (71.57 €/m^2 updated to 2015) and an increase of 0.23 $\$/ft^2$ for operations and maintenance (2.69 €/m^2 updated to 2015), resulting in a total added cost of $15.8 billion (€17.18 billion updated to 2015) (Eastman et al., 2016).

The construction sector is typically based on 2D documentation to describe a 3D reality. Even when 3D models are generated, they are often disjointed and reliant on two-dimensional documentation (Succar, 2009). Furthermore, quantities, cost estimations and others specifications are usually neither derived from the model nor linked to documentation. Similarly, workflow is linear, asynchronous, and it is not based on collaborative practices (Succar, 2009). This leads to errors in cost estimations, scheduling, project coordination, and design.

The ability to influence the project comes out to be another key aspect when referring to inefficiencies. Decisions made in the early design stages have the greatest influence without significantly impacting on costs (Paulson Jr., 1976). The peak of the design efforts takes place in the construction documentation stage, when the project has become inflexible and the cost of design changes is higher (Fig. 9). The cost of design changes is lowest in the early design phases and simulations could support the decision-making process since they have higher influence. This is also the LCA dilemma of buildings: while decisions taken in the early stages have the greatest influence, data available are still scarce and uncertain (Hollberg and Ruth, 2016). In fact, the product specific information are available after the construction documentation stage when LCA is impractical to be used as decision-making tools since it is too costly making relevant changes at that stage.

As a result of the higher costs for changes in the later stages, various initiatives aim at shifting decisions into the early design stages. The Integrated Project Delivery (IPD)[21] is a relatively new procurement process that intends to shift the design efforts into the early design stages in order to reduce costs (AIA, 2007). MacLeamy curve (Fig. 10) shows how the greatest effort is within the schematic design and design development stages through IPD against the typical design.



Abbreviations: **PD**, Preliminary Design; **SD**, Schematic Design; **DD**, Design Development; **CD**, Construction Documentation; **PR**, Procurement; **CA**, Construction Administration; **OP**, Operation.

Fig. 9 – Paulson curve (Paulson Jr., 1976)

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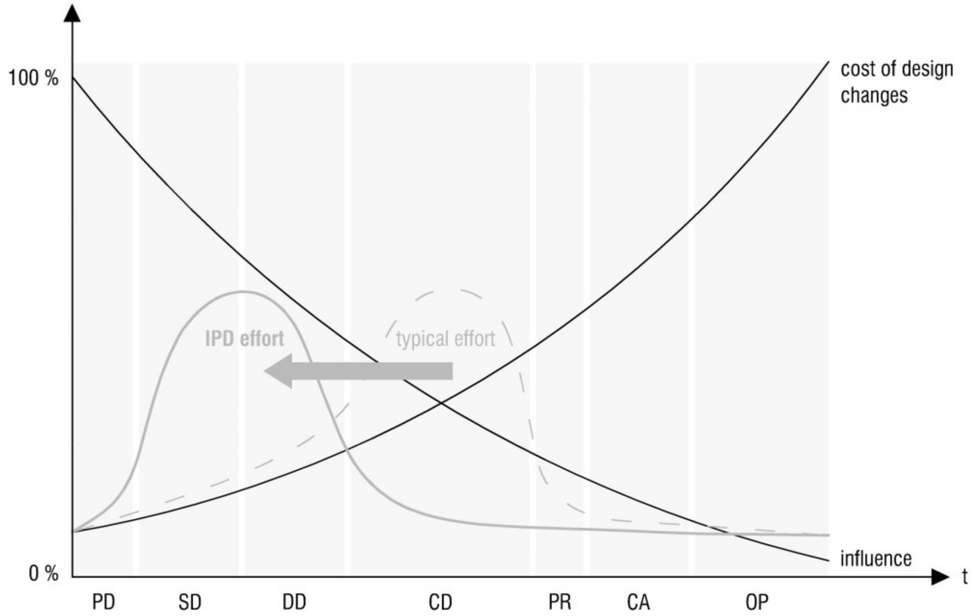
[21] Integrated Project Delivery (IPD) is a project delivery method that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction (AIACC, 2014).



Abbreviations: **PD**, Preliminary Design; **SD**, Schematic Design; **DD**, Design Development; **CD**, Construction Documentation; **PR**, Procurement; **CA**, Construction Administration; **OP**, Operation.
Fig. 10 – MacLeamy curve

It did not take long to recognize that BIM has become the catalyst for significant process and contractual changes in the AEC industry such as the growing move towards IPD (Eastman et al., 2011). Building Information Modelling can be considered as a breakthrough in the construction sector on the basis of interoperability and data management. BIM has the great potential to manage project alternatives bringing forward the design choices through the early performance design analysis (Schade et al., 2011). Moreover, BIM leads to a change in the role of project participants. This happens because BIM provides them with the opportunity of managing information in a Common Data Environment (CDE)[22]. Owners can realize significant benefits by us-

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[22] Common Data Environment or CDE Process means a combination of hardware, software and workflow that is used to collect, manage and disseminate all relevant approved files, documents and data for multidisciplinary teams in a managed process. The documents stored in a CDE contain both graph-

ing BIM processes and tools to streamline the delivery of higher quality and better performing buildings (Eastman et al., 2011). They must be able to define their needs and requirements according to the Employer's Information Requirement (EIR)[23]. Designers redefine their activities by looking at the whole lifecycle of the building. They works together with the owners, general contractors and key trade contractors, by making the best use of BIM as a collaborative tool (Eastman et al., 2011). Contractors must push for early involvement in construction projects, or seek out owners that require early participation. They cooperate with team members from the beginning of the building process and share risks and responsibilities (Ciribini, 2016).

3.2.3 The three faces of BIM

Looking at CAD and BIM, it is important not to associate CAD with 2D and BIM with 3D designs. CAD provides static 2D documents, which does not relate to the other documents created separately. While, in CAD, building elements are represented by geometrical shapes, in BIM the elements hold specifications. BIM is oriented to the modelling and to the communication of both graphical and non-graphical information, allowing the extraction of quantities, cost estimations and material properties for building, facility and infrastructures (Cheung et al., 2012). It is also a method that foster closer cooperation between the various technical teams involved in the different stages of a construction project (Grilo and Jardim-Goncalves, 2010). Currently, BIM refers to the use of shared digital representation of a built object to facilitate the design, construction, and operation processes and to create a reliable basis for decision-making (ISO 29481-1, 2016).

BIM is defined in many different ways. On the one hand, BIM is a sophisticated software, and on the other hand, it offers a framework for a paradigm shift within the

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ical and non-graphical data. This single data source facilitates collaboration amongst project team members, thus avoiding mistakes and duplication.

[23] Pre-tender document setting out the information to be delivered, and the standards and processes to be adopted by the supplier as part of the project delivery process.

construction sector. Actually, BIM is both of these extremes and everything that comes in between (Khosrowshahi, 2017). BIM has three main different meanings based on different contexts. It could be defined as Building Information Modelling, Building Information Model, and Building Information Management. The National Institute of Building Science[24] defines Building Information Modelling as a "*business process for generating and leveraging building data to design, construct and operate the building during its lifecycle*" (NIBS, 2015). Building Information Modelling allows stakeholders to have simultaneous access to the same information through interoperability between technology platforms. A different meaning comes when referring to the model: "*Building Information Model is the digital representation of physical and functional characteristics of a facility"* (NIBS, 2015). As such it serves as a shared resource for information, forming a reliable basis for decisions during the building's lifecycle. Finally, "*Building Information Management is the organization & control of the business process by utilizing the information in the digital prototype to effect the sharing of information over the entire lifecycle of an asset"* (NIBS, 2015). Building Information Management allows centralized and visual communication, early exploration of options, efficient design, integration of disciplines, site control, as built documentation, etc.

Succar (2009) defines three BIM fields of activity, which are the *Technology Field, Process Field*, and *Policy Field.* The domain players and their deliverables are identified in the BIM fields as shown in Fig. 11. The Technology Field clusters players who specialises in developing software, hardware, equipment and networking systems necessary to increase the efficiency, productivity and profitability of the AEC sector. The Process Field clusters players involved in the ownership, delivery and operations of buildings. The Policy Field groups players having key roles in the prepara-

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[24] Established by the U.S. Congress in 1974, the National Institute of Building Sciences is a non-profit, non-governmental organization. It brings together representatives of government, the professions, industry, labour and consumer interests, and regulatory agencies in order to resolve problems and potential problems that hamper the construction of safe, affordable structures for housing, commerce and industry throughout the United States. https://www.nibs.org/ (accessed September 14th 2018).

tion of regulations, guidelines and programs in the design, construction and operations process.

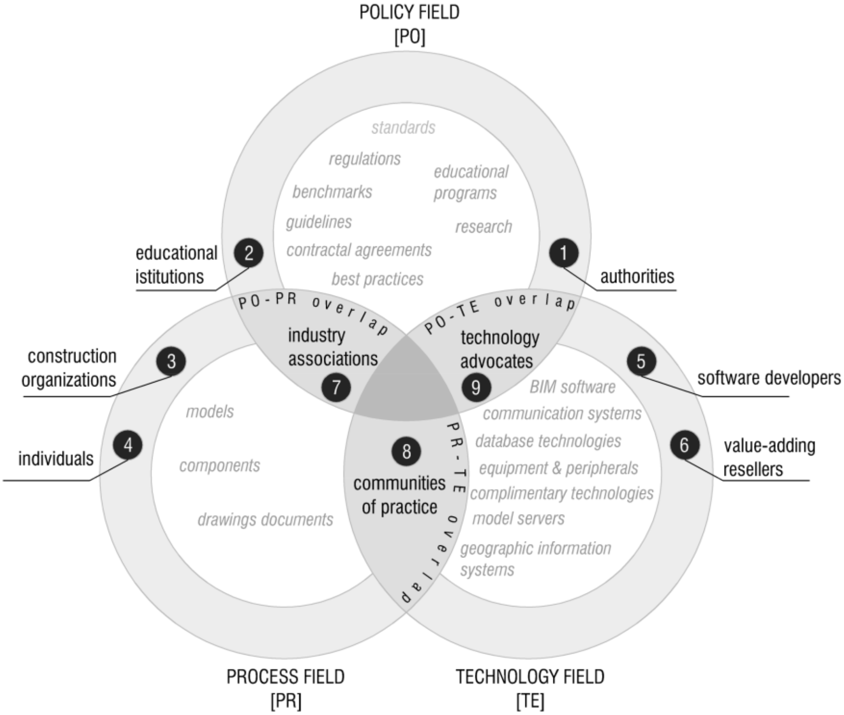

Fig. 11 – BIM fields, based on Succar (2009) and Succar and Kassem (2015)

Bew and Richards (2008) recognised that the definition and implementation of BIM is linked to levels of maturity that range from Level 0 to Level 3 (Zou et al., 2015). See Fig. 12. The maturity levels depicted by Bew and Richards are defined as follows (BIM Industry Working Group, 2011):

- Level 0: Unmanaged CAD probably 2D, with paper (or electronic) as the most likely data exchange mechanism.
- Level 1: Managed CAD in 2 or 3D format using BS1192:2007 with a collaboration tool providing a common data environment, possibly some standard data structures, and formats. Commercial data managed by standalone finance and cost management packages with no integration.

- Level 2[25]: Managed 3D environment held in separate discipline BIM tools with attached data. Commercial data managed by an Enterprise Resource Planner (ERP). Integration on the basis of proprietary interfaces or bespoke middleware could be regarded as "pBIM" (proprietary). The approach may utilise 4D programme data and 5D cost elements as well as feed operational systems.
- Level 3: Fully open process and data integration enabled by web services compliant with the emerging IFC/IFD standards, managed by a collaborative model server. Could be regarded as iBIM or integrated BIM potentially employing concurrent engineering processes.

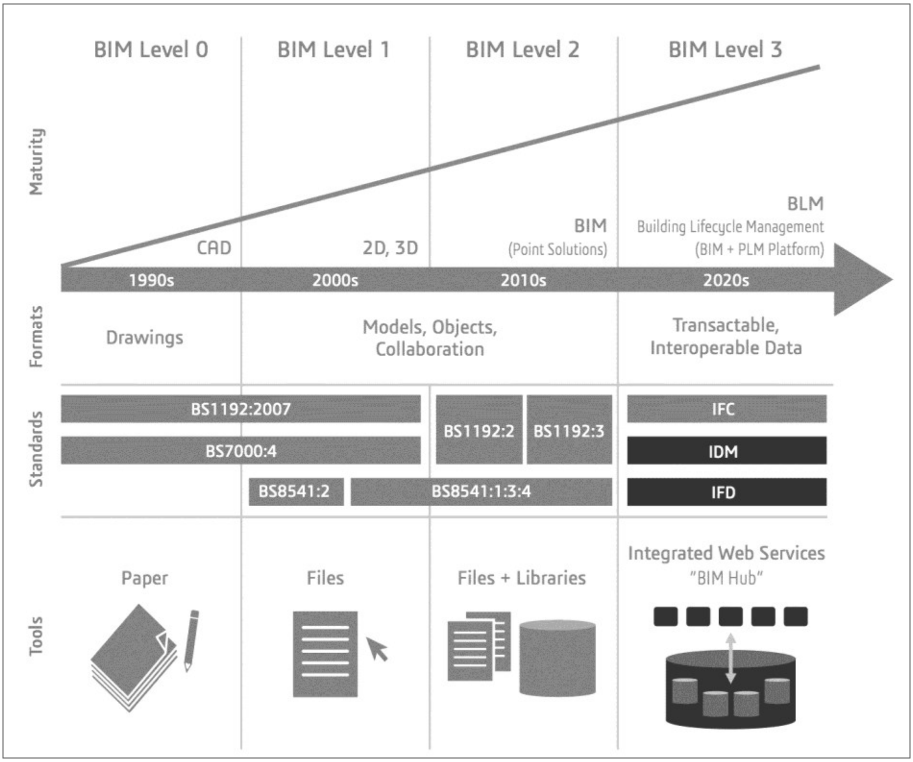

Fig. 12 – BIM maturity levels, based on Bew and Richards (2008)

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[25] BIM level 2 has become mandatory for all UK public sector projects from 2016

The maturity model has been devised to enable a concise description and understanding of the process, tools and techniques to be used. Actually, level 0 does not refer to a BIM level since it represents the use of 2D CAD drawings in conjunction with written specifications. BIM implementation starts from level 1 when BIM is used as an isolated platform without any form of collaboration, Hence, it is defined “lonely” BIM. At level 2 the coordination of different disciplines can be achieved. Integration occurs on the basis of proprietary interfaces or use of bespoke middleware. At level 3 a single project model is used as a platform for collaboration. However, reaching the BIM level 3 is a challenging task, more complex when it comes to address responsibility issues. BIM level 3 could create misperception as who is responsible and who owns the model or part thereof. Furthermore, there are potential issues about the provision of conflicting information from different models and liability for design (Khosrowshahi, 2017). BIM level 3 includes problems related to data loss due to interoperability inefficiencies (Khosrowshahi, 2017).

3.2.4 BIM dimensions

Linking extra “dimension” of data to the digital models has the potential to provide a richer understanding of the construction project - how it will be delivered, what it will cost, and how it should be maintained (McPartland, 2017a). These dimensions can all feasible occur within a BIM Level 2 workflow (see 3.2.3). Most research has agreed that BIM is a process of expanding 3D models to computable nD models (Azhar, 2011) to simulate the planning, design, construction, and operation of a facility (Fig. 8). The nD model provides a database which allows stakeholders to retrieve the needed information through the same system. This enables them to work cohesively during the whole project lifecycle (Ding et al., 2014). 3D BIM is the process of creating graphical and non-graphical information and sharing this information in a CDE. For example, it allows performing 3D visualization, Clash Detection[26] and Code

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[26] Clash Detection is the most used validation domain. It aims at identifying potential conflicts in the design and integration of models from different disciplines.

Checking[27] (Getuli et al., 2017; İlal and Günaydın, 2017; Solihin and Eastman, 2015). 4D models are needed to visualize and analyse the changing variables that occur as the construction phase proceeds. Time-related information could be added to specific BIM elements. As such, 4D BIM provides the virtual visualization of the construction process and applications for the construction management, such as scheduling (Cavalliere et al., 2017), quality control (Chen and Luo, 2014) and safety control (Zhang et al., 2013). According to Smith (2016), the fifth dimension of BIM provides opportunities for project cost management to dramatically improve the quality of the project. 5D BIM allows real-time calculation for cost estimating, and has the potential to visualise the project and its variants (Xu, 2017). Whilst there is consensus on 4D BIM and 5D BIM, there is no agreement on the 6D and onwards. Charef et al. (2018) show that 6D and 7D are still in their infancy, proven by the ambiguities on what these BIM dimensions are referring. According to Charef et al. (2018), the first consideration of 6D was in 2012, while the first journal paper found to be addressing 7D was published in 2014. The National Building Specification (NBS) defines the 6D as a dimension including information to support the facility management and operation activities (McPartland, 2017a). A different allocation to 6D was made by Yung and Wang (2014) who linked the sixth dimension to sustainability information. The seventh dimension is also still in its early stage and only two journal papers are citing the 7D (Charef et al., 2018). However, the survey carried out by Charef et al. (2018) reveals that the practitioners using BIM dimensions usually refer to Sustainability for the 6D and Facility Management activities for the 7D.

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[27] Parametric Rule Checking processes aim at validating the compliance of design proposals against codes and regulations (i.e. BIM-based Code Checking) by comparing the geometrical and alphanumerical parameters embedded within the BIM against normative requirements translated into parametric rule-sets (Getuli et al., 2017).

3.2.5 BIM benefits

The benefits of BIM are largely understood in terms of performance improvement, greater project certainty and reduced risks. Globally, several reports and researches assess the benefits of BIM. BIM is widely recognized to be able to produce more accurate and reliable information, while increasing the design workflows and the quality of products (EU BIM Taskgroup, 2016). These benefits result in financial gains. According to the EU BIM Taskgroup (2016), if the wider adoption of BIM across Europe delivered 10% savings to the construction sector then an additional €130 billion would be generated for the €1.3 trillion market. A British BIM report discloses that BIM increases competitiveness and shows that there has been an 24.6% improvement in productivity on UK Government projects using BIM (NBS, 2013). CEDR report (CEDR, 2017) describes the very high ROI[28] for investing in BIM: based on the amount of portfolio 2014, the estimated combined structural cost savings for design and construction via BIM for The Netherlands, Sweden, Finland, and Norway is on average about 378 M Euro per year as of 2020 onwards. Within 10 years, the full-scale digitalization in non-residential constructions would be capable of producing annual global cost savings of $0.7-1.2 trillion (13-21%) on Engineering and Construction and $0.3-0.5 trillion (10-17%) in the Operation phase (World Economic Forum, 2016).

Fig. 13 shows the BIM benefits on published UK commercial data (BIM Industry Working Group, 2011). The “as measured” benefits are allocated to the various stages of construction based on the RIBA stages. The prediction is that operational savings in FM is likely to be a major focus for cost saving. The main asset of BIM is not the software but rather the information and its accessibility to the whole supply chain.

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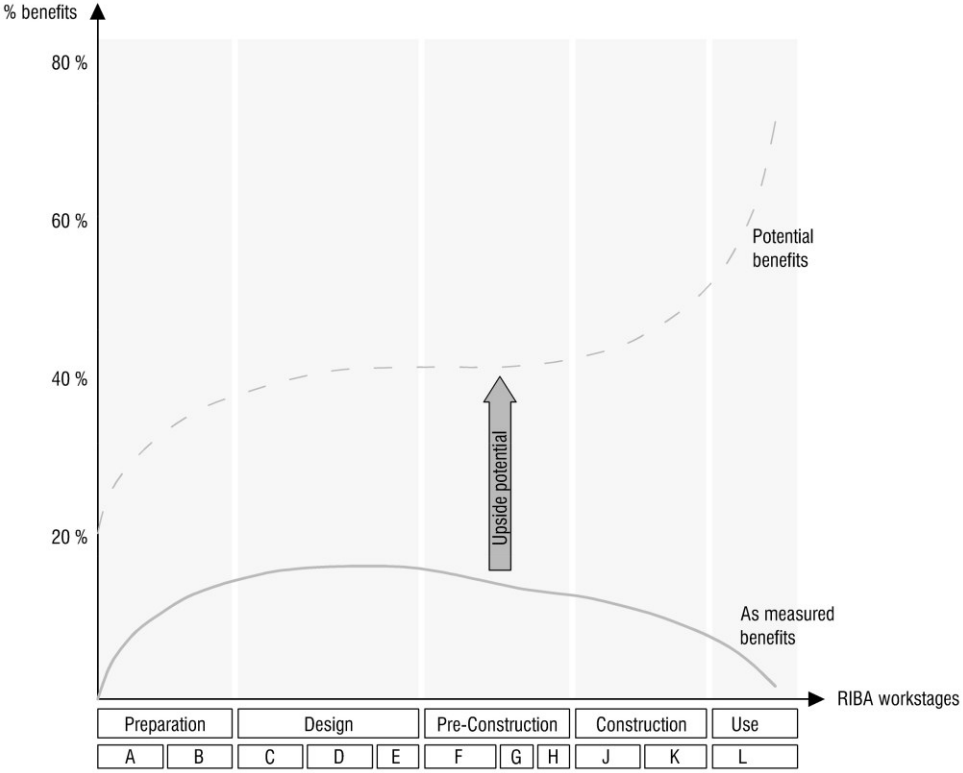
[28] The return on investment (ROI) is one of the many ways to evaluate an investment. It compares the gain anticipated or achieved from an investment against the cost of the investment, i.e. ROI = earnings/cost (Azhar, 2011).



A, Appraisal; **B**, Design Brief; **C**, Concept; **D**, Design Development; **E**, Technical Design; **F**, Production Information; **G**, Tender Documentation; **H**, Tender Action; **J**, Mobilisation; **K**, Construction to Practical Completion; **L**, Post Practical Completion

Fig. 13 – Benefits of BIM against RIBA stages

Azhar (2011) illustrates the cost and time savings realized in developing and using BIM for the project planning, design, pre-construction, and construction stages. The author presents four case studies highlighting the benefits of BIM. The case study 1 shows an overall cost saving of $200.000 attributed to the elimination of collision through clash detection. The case study 2 illustrates the use of BIM at the project planning phase to perform value analysis for selecting the most economical and workable building layout. The owner achieved $1.195.000 cost savings at the pre-design stage by selecting the most economical design option. The case study 3 shows cost benefits of $15.000 by using BIM for planning and construction documentation, while the case study 4 depicts how to improve the design quality through sustainability analysis. Furthermore, Azhar (2011) perform the BIM ROI analysis on the basis of cost data from ten project. The average BIM ROI for different projects was 634%, which clearly depicts the potential economic benefits.

Mc Graw Hill Construction[29] analysed survey data collected from construction companies that use BIM (McGraw Hill Construction, 2014). One of the key findings is the BIM ROI: three quarters of construction companies report a positive ROI on their BIM investment. Furthermore, the research examined three types of BIM benefits: internal, project, and process benefits. Fewer errors and omissions, less rework, reduced construction cost, overall project duration, and improved safety are the top five project BIM benefits cited by contractors (McGraw Hill Construction, 2014).

In addition, many researchers and practitioners have acknowledged the potential benefits of BIM. Barlish and Sullivan (2012) presented a key list of the top mentioned benefits of BIM based on the literature review. The most quantifiable benefits were: schedule, change orders, RFIs, and project or pilot cost. Ghaffarianhoseini et al. (2017) identified a wide range of clear benefits, risks, and challenges by using BIM. The authors clustered BIM benefits in different areas. BIM benefits include client satisfaction through the visualization of the model and clear expectations; enhanced collaboration in the delivery of better outcomes; improved data sharing, information control, and the delivery of green buildings. These last could be achieved through LCA, carbon foot printing, solar, wind and water analysis, etc. Other key benefits associated with BIM include: enriched performance outcomes by comparing different design options; reduced errors and omissions leading to fewer requests for information; less rework and safety risks; precise scheduling.

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[29] Since 2007, McGraw Hill Construction has been tracking the business impacts of technology advances through its Smart Market Report series, with a particular focus on how BIM is transforming the design and construction process in Asia, North America, and Western Europe.

3.3 Current BIM adoption

Given the various BIM benefits reported in the literature, it is useful to examine the current level of uptake in reality, where BIM is being used successfully, and who is supporting the use of BIM. BIM is rapidly expanding globally and its adoption has increased dramatically. To avoid confusion, this thesis refers to the terms and concepts adopted by Succar (2015). “BIM implementation” means the successful adoption of BIM tools and workflows within a single organisation, while “BIM diffusion” refers to the adoption rate of BIM tools and workflows across markets. “BIM adoption” is used to overlay the connotations of implementation and diffusion.

Many countries are investigating and developing new national BIM initiatives and protocols to facilitate BIM adoption across their respective markets. Among BIM users the US has the largest market. At 79% in 2015, US contractors lead rest of the regions for high and very high level of BIM implementation (McGraw Hill Construction, 2014). This phenomenon has largely been driven by the US governmental requirement for all major infrastructural contracts to be BIM-based. Other reasons are the existence of the major players of technologies fields and BIM in US (Autodesk, Bentley, Trimble, etc.), but also the major ICT companies with a strategic role in the construction industry, such as Amazon, Cisco, Google, IBM, Microsoft, etc. (Eastman et al., 2016). The United States can be considered as the inventors of the BIM processes and the major producers of guidelines for the BIM adoption. Among the guidelines, for istance, it is worth mentioning that of the Port Authority of New York and New Jersey (Di Giuda et al., 2017). However, the adoption of BIM in the United States took place on the basis of specific institutions initiatives (Computer Integrated Construction Research Program, 2013; GSA, 2011; NIBS, 2017; The Port Authority of NY & NJ, 2012). Conversely, the United Kingdom was the first to finalize the use of BIM in the private and public sector (AEC (UK) Committee, 2015). In particular, the British Standard Institution (BSI) has produced standards of major importance. The PAS 1192 series constitute an important reference for the application of the BIM methodology. It covers all the phases of building lifecycle, from the design phase to construction and management. The PAS 1192 framework sets out the requirements for the level of model detail (the graphical content), model information (non-graphical content), model definition and model information exchanges (McPartland, 2017b). Under the UK initiatives, the "EU BIM Task Group"[30] arose with the aim of managing the ways in which BIM will be introduced in EU public sector.

Standards, guidelines and reports are evidence of BIM adoption in different regions. In some cases BIM is mandatory (or nearly) and guidelines and standards are available, while in other cases BIM is not adopted. A more detailed description of BIM adoption in different countries can be found in *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*, *Italian version by Di Giuda G.M. and Villa* (2016). Di Giuda et al. (2017) carried out a research aimed at quantifying the number of relevant documents related to BIM for each countries. This research intends to show the direction taken by the different countries regarding the BIM. Fig. 14 shows a graphical summary of the research[31]. As shown in Fig. 14, different countries are developing or delivering a national BIM policy. Nevertheless, according to Kassem and Succar (2017) there is still a shortage of studies and methodologies for assessing the existing policies, or for assisting in the formulation of new ones. To this end, the authors proposed a “Macro BIM adoption” study. The first part of this study (*Macro BIM Adoption: Conceptual Structures*, Succar and Kassem, 2015) presents five macro BIM adoption models and defines the process behind their conceptual development. These models are developed with the aim of analysing existing national BIM policies, and aiding the development of new national BIM policies. The second part of the study (*Macro BIM adoption:*

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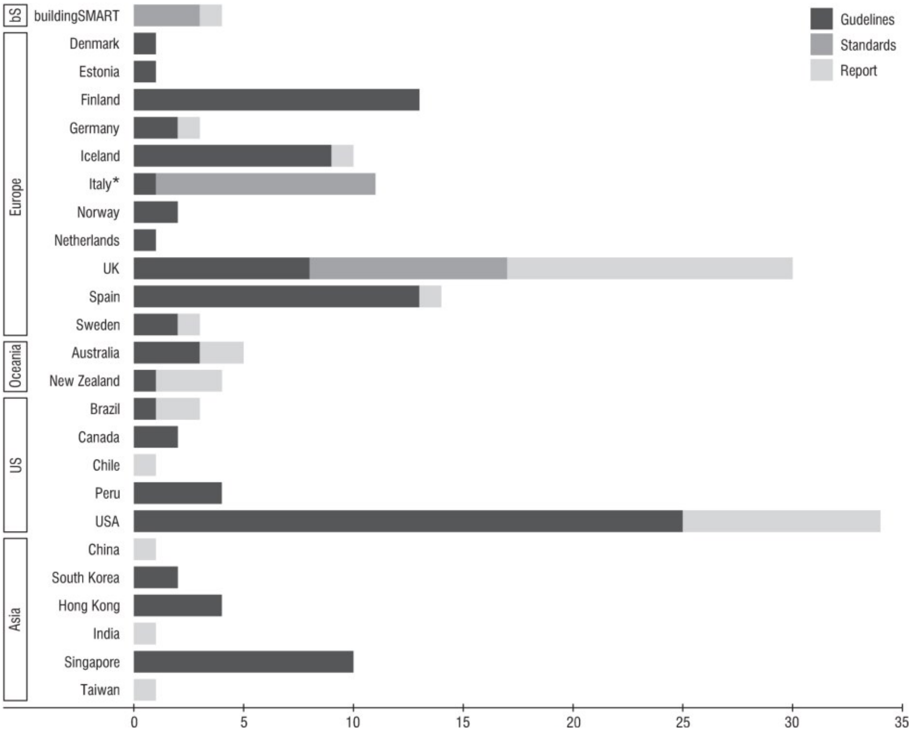
[30] The EU BIM Taskgroup is co-funded by the European Union. The Task Group’s vision is to encourage the common use of BIM, as “digital construction”, in public works with the common aim of improving value for public money, quality of the public estate and for the sustainable competitiveness of industry. http://www.eubim.eu/ (accessed August 3rd 2018).

[31] The figure shows the Italian relevant documents not included in the survey by Di Giuda et al. (2017). They are the standards UNI 11337 (currently consisting of ten parts) and ANAC guidelines. ANAC (national anti-corruption authority) provides broad indications for the gradual implementation of the changes introduced by the Ministerial Decree 560/2017 (BIM Decree).

Comparative market analysis, Kassem and Succar, 2017) clarifies how these models are validated by analysing the input of 99 experts from 21 countries; highlights the similarities and differences among countries with respect to BIM adoption; and introduces sample tools and templates for developing or calibrating BIM adoption policies.



* Not included in the survey by Di Giuda et al. (2017)

Fig. 14 – Relevant documents related to BIM for each countries, based on Di Giuda et al. (2017)

The buildingSMART International (formerly called International Alliance for Interoperability, IAI) acts as a guide across such a heterogeneous scenario. BuildingSMART (bSI) is an international body committed to create and disseminate open data standards supporting the wider spreading of BIM[32]. It is a non-profit organization with regional chapters in Europe, North America, Australia, Asia and Middle East.

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[32] buildingSMART provides the worldwide chapter network, plus the necessary technical and process support, to develop open standards that support open digital information flows across the built asset

In Europe, CEN/TC 442 operates in close collaboration with other CEN and ISO committees and with other industry standardization organizations. According to the Vienna agreement, the work programme of CEN/TC 442 includes the implementation of ISO standards - from ISO/TC 59/SC 13 and ISO/TC 184/SC 4 - as EN standards or technical specifications. The objective of CEN/TC 442 is to help the construction sector to be more efficient and sustainable by enabling a smooth information exchange and sharing between stakeholders. Formal liaison agreements have been established with other communities. There will be more liaisons in the future e.g. Energy, Environmental, Fire safety, ITS, Rail and Roads etc. Fig. 15 describe the situation in 2017.

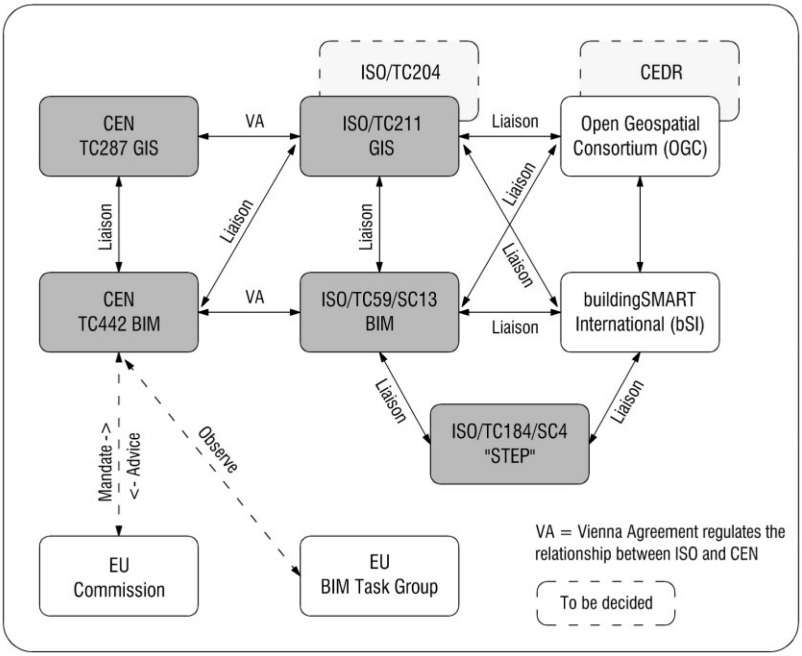

Fig. 15 – Relations in international BIM standardization, based on CEN/TC 442 Business Plan (2017)

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industry. It is engaged with other international standards bodies such as the European Committee for Standardization (CEN) and the Open Geospatial Consortium, and influencing national and client programmes across the globe. https://www.buildingsmart.org/ (accessed August 6th 2018).

3.4 Key concepts

McGraw Hill Construction (2012) analysed the most important factors for increasing BIM benefits. According to this survey, “interoperability between software applications” and “BIM software functionalities” rank first and second among the top ten factors. BIM users are still facing with file-exchange issues and challenges applying existing software to meet their needs, such as technical analysis. Emerging standards initiatives for data exchange have improved Application Programming Interfaces (API) for authoring tools to address the interoperability concerns. Software companies are also working to expand functionalities and improve ease-of-use. Business-related issues also make the top ten factors that impact BIM benefit. “Clearly-defined BIM deliverables between parties” ranks third in the survey. This indicates a persistent challenge that a number of industry organizations are trying to address, such as the BIMForum with the definition of BIM Levels of Development (LODs). Interoperability, BIM software functionalities, and LODs are analysed in the following sub-sections.

3.4.1 Interoperability

At the heart of BIM lies the way building information is managed and shared by all project team members. Interoperability becomes the core issue for transferability of information. Construction projects involve collaborative contribution of several disciplines and team members throughout the whole lifecycle of buildings. These disciplines typically use different software for simulation, calculation, operation, and management of projects (Khosrowshahi, 2017). According to the National Institute of Building Sciences (NIBS, 2017), *“Interoperability is the ability of diverse systems and organizations to work together (inter-operate). Interoperability can be used in a technical systems engineering sense, or in a broader sense, including social, political, and organizational factors that affect system-to-system performance.* This involves a wider definition of interoperability, which refers both to the exchange format allowing data transfer and to the procedures that assist the exchange of information.

Central to the subject of interoperability are standards. To this end, a global effort has been undertaken by buildingSMART International with the development of exchange standards. BuildingSMART's technical core is based around a common data schema called Industry Foundation Class (IFC)[33], which makes it possible to hold and exchange data between different software applications. The IFC data model contains geometric and semantic information of building components. It is intended to facilitate interoperability in the AEC industries.

The IFC is one of five types of open standard in the bSI portfolio, each of which exists to perform different functions in the delivery and support of assets in the built environment. Other technical principles are the development of the Information Delivery Manual (IDM)[34], Model View Definition (MVD)[35], BIM Collaboration Format (BCF)[36],

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[33] Industry Foundation Classes (IFC) BuildingSMART is all about the sharing of information between project team members and across the software applications that they commonly use for design, construction, procurement, maintenance and operations. The IFC has been implemented into ISO standards as ISO 16739:2013 under the direct responsibility of ISO/TC 184/SC 4. ISO 16739:2013 will be replaced by ISO/PRF 16739-1.

[34] IDM is a process standard providing detailed specifications of the information that a user fulfilling a particular role would need to provide at a particular point within a building project. To further support the user information exchange requirements specification, IDM also proposes a set of modular model functions that can be reused in the development of support for further user requirements. It has been implemented into ISO standards as ISO 29481-1:2016 and ISO 29481-2:2012 under the direct responsibility of ISO/TC 59/SC 13.

[35] MVD defines the subset of the IFC data model that is necessary to support the specific data exchange requirements of the AEC industry during the life-cycle of a construction project. MVD thereby represents the software requirement specification for the implementation of an IFC interface to satisfy the exchange requirements.

[36] BCF is a simplified open standard XML schema that encodes messages to enable workflow communication between different BIM software tools. Developed by Tekla Corporation and Solibri Inc, it is currently a pre-release that has been submitted to buildingSMART to become an official specification.

and International Framework for Dictionaries (IFD)[37]. Fig. 16 shows the information interoperability triangle developed by bSI.

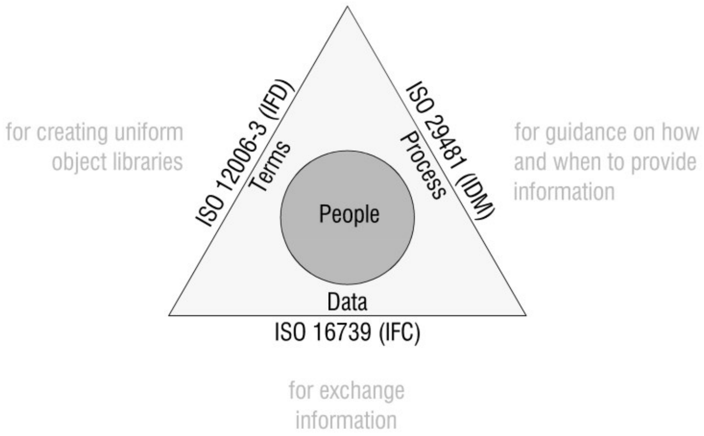

Fig. 16 – Interoperability triangle, buildingSMART

The practical definition of an IFC is "*a neutral and open specification that is not controlled by a single vendor or group of vendors*" (Lin et al., 2013). As a non-proprietary exchange format, IFCs provide a common linkage for software vendors to provide data exchanges between different BIM modelling software. IFC is used in support of "Open BIM", which is a "*universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows*"[38]. Despite the global efforts in the IFC development, the work is frequently criticised for not being complete. Interoperability & IFC is one of the most studied research area associated to BIM, with several authors testing the interoperability among BIM tools

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[37] The IFD Library, later named buildingSMART Data Dictionary (bSDD), provides the dictionary, definitions and concepts to facilitate the flow of information. The bSDD is a reference library and supports interoperability in the construction industry. It provides a flexible and robust method of linking existing databases with construction information to a bSI based BIM. It has been implemented into ISO standards as ISO 12006-3:2007 under the direct responsibility of ISO/TC 59/SC 13. ISO 12006-3:2007 will be replaced by ISO/WD 12006-3.

[38] https://www.buildingsmart.org/standards/technical-vision/ (accessed August 8th 2018).

for different applications (Santos et al., 2017; Yalcinkaya and Singh, 2015). Some studies found that IFC schema lacks entities and property sets, and pointed out the inability of some applications to read some information within the objects (Ma et al., 2015; Sacks et al., 2010). Other authors looked at the IFC limitations concluding that IFC language lacks a logical mathematical theory and has a limited expression range (Venugopal et al., 2012).

Alternative solutions of building product data models is CIMsteel Integration Standard Version 2, (CIS/2) - for structural steel engineering and fabrication. Another large set of exchanges are supported by XML (eXtensible Markup Language). XML is an extension to HTML, the base language of the Web. XML supports multiple handling of schemas in AEC areas, such as gbXML[39], CityGML[40], ifcXML[41], and OpenGIS[42]. XML schemas for AEC also include BACnet (Building Automation and Control networks), a standard protocol for building mechanical controls; AEX (Automating Equipment Information Exchange) for identifying mechanical equipment; AECxml, an XML version of the IFC schema (Eastman et al., 2011). A wider overview on industry standards and file formats for exchanging BIM data is presented by Sacks et al. (2018, pp. 85-129).

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[39] Green Building XML (gbXML) is a schema developed to transfer information needed for energy analysis of building. See http://www.gbxml.org/ (accessed August 7th 2018).

[40] CityGML is an open standardised data model and exchange format to store digital 3D models of cities and landscapes. See http://www.opengeospatial.org/standards/citygml (accessed August 7th 2018).

[41] ifcXML is a subset of the IFC schema mapped to XML, supported by buildingSMART. See http://www.buildingsmart-tech.org/specifications/ifcxml-releases (accessed August 7th 2018).

[42] OpenGIS has been developed by the OGC (Open Geospatial Consortium). It is an XML grammar for expressing geographical features. It defines an open set of common, language independent abstractions for describing, managing, rendering, and manipulating geometric and geographic objects within an application programming environment. See http://www.opengeospatial.org/ (accessed August 7th 2018).

3.4.2 BIM software functionalities

What differentiates the BIM from CAD is the association of parameters that can be adjusted through the program's interface to the 3D components (Kensek, 2014, p.13). BIM software is based on solid modelling, but 2D components also have parameters. Properties (BIM parameters) come into play at different stages of the building lifecycle. For example, design properties address parameters for spaces such as occupancy, activities, material specifications, and equipment performance needed for LCA and energy analysis. At the end of construction, properties provide information for handling data onto operations and maintenance phases (Eastman et al., 2011, p.58). Most of the parameter associations are defined in the objects within the software, but they can be changed, and new parameters can be added by the users. In fact, current BIM platforms default to a minimal set of properties and provide the capability of extending the set. BIM users must add parameters to each relevant object to produce a certain type of simulation, cost estimate, or analysis (Eastman et al., 2011, p.59). The properties of components can be arranged in a spreadsheet format and edited by modifying the graphic object or directly in a spreadsheet tabular view. As the model is a database, BIM parameters can be edited in different manners (both graphic and tabular) in a bidirectional way. The information is consistent across each ways because the data is stored in one location and then referenced in text or graphics or both as necessary (Kensek, 2014, p.13).

Currently, structuring such parameters is feasible in all BIM software used, but when it comes to interoperability it is a challenging task. Parameters have to be exported/imported in the right place to be useful, and a common model is required. The import/export process works with proprietary formats or common data schemes, such as IFC. Furthermore, BIM parameters can be extracted from the model to spreadsheets. The possibility to read from and write to spreadsheets enhances the level of interoperability among different design tools to perform analysis at the different stages of building lifecycle. The import/export of properties allows performing a number of analyses with the aid of dedicated design tools, building performance simulations (BPSs) tools, and Visual Programming Language (VPLs) tools. Various types of model integration could be adopted to perform buildings' analysis on the basis of BIM parameters exchange. Negendahl (2015) reviewed different ways in which design tools and BPSs could be coupled to support the design of better performing buildings, particularly for early design analysis. The author presented the "combined model", which consist of a design tool and BPS in the same environment; the "central model" that is a combination of a design tool and a BPS environment; and the "distributed model", which is a combination of a design tool, a middleware tool, and a BPS environment.

3.4.3 Levels of Development (LODs)

People involved in BIM-based projects usually face the "deliverables dilemma". Within the information exchange processes at the different design stages, it is crucial to define what information is needed, how much detailed it must be, and who is responsible of that information. Several specifications have been developed to meet these needs, such as the Model Development Specifications[43] (MDS), the Model Progression Specification[44] (MPS), the Level of Development (LOD), and the Model Element Table (MET). They are usually included within a BIM Execution Plan[45] (BEP) to assign roles and define standards, methods, and procedures for the Information Exchange Management process.

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[43] The Model Development Specification is a method for defining the amount, type, and precision of information that is to be included in Building Information Models (BIMs) for specific project milestones and deliverables as the project progresses from concept to closeout. It forms the basis of processes that clearly inform the project team about the content and timing of information required of them and available to them. It increases efficiency and reliability of the project and aims at eliminating unnecessary or redundant information (Bedrick, 2013).

[44] The Model Progression Specification defines how the design, cost, and schedule will evolve from early-stage design to the construction phase (Kensek, 2014, pp.33-34).

[45] The Building Information Modelling Execution Plan is a plan prepared by the suppliers to explain how the information modelling aspects of a project will be carried out (PAS 1192-2:2013).

The LOD acronym was originally developed by Vico Software Company indicating the level of the progressive reliability of information over a period of time. In 2008, the concept was analysed and clarified by the American Institute of Architects (AIA) within the *AIA Document E202-2008* (AIA, 2008). AIA worked on a revision of the document thereafter, which resulted in the publication of the *AIA Document G201-2013, Project Digital Data Protocol Form* (AIA, 2013a)*, AIA Document G202-2013, Project Building Information Modeling Protocol Form* (AIA, 2013b), and *AIA Document E203^{TM}-2013, Building information Modeling and Digital Data Exhibit* (AIA, 2013c). According to the AIA Document G202-2013, the Levels of Development (LOD) "*identify the specific minimum content requirement and associated Authorized Uses for each Model Element at five progressively detailed levels of completeness".* Within the document, five progressive LODs are identified, from LOD 100 to LOD 500. The higher the LOD level, the more detailed the information of the BIM elements.

In 2013, BIMForum published the *Level of Development Specification* on the basis of AIA efforts[46]. BIMForum have been working on updating the LOD Specification until now (BIMForum, 2018). According to BIMForum, LOD "*is a reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process"*[47]. BIMForum included a further Level of Development called LOD 350, while not including the LOD 500. According to the BIMForum, "*since LOD 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non-graphic information, this specification does not define or illustrate it*" (BIMForum, 2018). Table 13 shows a summary of LOD concepts from AIA (2013) and BIMForum (2018).

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[46] The LOD Specification utilizes the basic LOD definitions developed by the AIA for the AIA G202-2013 Building Information Modeling Protocol Form.

[47] https://bimforum.org/lod/ (accessed August 8th 2018).

Table 13 – Comparison between the different LOD specifications

<table>
<tr><th>LOD</th><th>AIA Document G202-2013</th><th>BIMForum (2018)</th></tr>
<tr><td>100</td><td colspan="2">Generic representation, including symbols, showing the existence of a component but not its shape, size, or precise location.</td></tr>
<tr><td>200</td><td colspan="2">Generic representation with approximate quantities, size, shape, location, and orientation.</td></tr>
<tr><td>300</td><td colspan="2">Specific representation in terms of quantity, size, shape, location, and orientation as designed can be measured directly from the model without referring to non-modelled information for the manufacture of the component.</td></tr>
<tr><td>350</td><td>Not defined</td><td>Specific representation in terms of quantity, size, shape, location, and orientation, including interfaces with other building systems and such items as support and connections.</td></tr>
<tr><td>400</td><td colspan="2">Specific representation in terms of quantity, size, shape, location, and orientation with detailing, fabrication, assembly, and installation information.</td></tr>
<tr><td>500</td><td>Corresponding to the as-built model, since it belongs to the field of the representation of the elements checked in the building site.</td><td>Not defined</td></tr>
</table>

These documents became the starting point for the development of several guidelines. Other counties developed their own variants. Bolpagni (2016) provides a comprehensive review of the LOD term and its many nuances across the world. For example, in New Zealand, LODs are defined as a sum of Level of Detail (LOD), Level of Accuracy (LOA), Level of Information (LOI), and Level of Coordination (LOC). In the UK, PAS 1192-2:2013 introduces the Level of Definition with seven levels (1-7) representing both the Level of Detail (LOD) – for graphic content, and Level of Information - for non-graphic content (Bolpagni, 2016). In Italy, UNI 11337-4:2017 provides seven Level of Development (A-G) identifying the geometric and information contents. These variations of the same concept caused a large degree of confusion. For example, the same LOD acronym refers both to the Level of Detail and Level of Development (Bolpagni, 2016). However, the meanings differ significantly: Level of Detail refers to the geometric detail, while Level of Development relates to the information embedded within the model elements (Ciribini, 2016, p.227).

It should be emphasized that the BIM objects are organized into different LODs depending on the BIM uses and the project milestone. Furthermore, as the project grows, BIM elements are modelled with more detailed geometry and semantic information in order to support more accurate analyses. Thus, it is crucial to define the LOD of each BIM element at any project milestone. To this end, AIA introduced the Model Element Table (MET) that indicates the LOD to which each model element shall be developed at each project milestone and who is the model element author (AIA, 2013b). The main aim of the MET is to ensure the reliability of the model elements, making sure that they are used only for the purposes approved by their authors.

In general, each LOD depends on the functions the model is used for and its suitability for a certain class of BIM uses. Cheng et al. (2016) identified the CIM (Civil Information Modelling)[48] uses that are supported by each LOD. In summary, according to the authors, quantities based on components and materials can be obtained from LOD 200 to LOD 500. Estimations can be performed from lower to higher accuracy based on LOD 200 to LOD 500. In particular, the LOD 500 contains lifecycle information, which can be used in the O&M phase. In new construction projects, LOD increases against the lifecycle stages depending on the refinements from draft to realization. When applied to existing buildings, LOD determines the technical specifications of data capture, processing and BIM model creation (Volk et al., 2014). According to Verdaguer et al. (2017), LODs can be considered a key point during the application of LCA. In fact, the LOD of the model elements together with the BIM software capability to model and automatically quantify several building components, materials and objects, can limit or condition the input data.

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[48] The use of BIM in civil infrastructure facilities usually refers to Civil Information Modelling (CIM)

4. BIM-LCA INTEGRATION

4.1 Highlights of the chapter 4

Over the last years, several studies have integrated BIM with the LCA methodology to investigate the environmental performance of a building element or of a whole building. On the one hand, BIM supports integrated design and improves data management and collaboration between the different stakeholders. On the other hand, LCA is a suitable method for assessing the environmental performance of buildings (Antón and Díaz, 2014). However, some methodological challenges on the BIM-based LCA could be found the literature. For example, existing studies focus on a specific stage of the design processes when conducting BIM-based LCA calculations. Hence, the lack of studies that propose methods for BIM-enhanced LCA during the entire design process is recognized as a gap in the literature. Furthermore, BIM is usually employed as a mere repository of information about quantities. In order to improve LCA applications, BIM models should include more information adapting the BIM to the LCA data structure. Also, understanding the key parameters of buildings for conducting LCA is detected as a major difficulty. The thesis faces these three aspects and proposes methods for improving the BIM-based LCA. First, a method for conducting the LCA during all phases of the design process is presented. The approach refers to the available information in the BIM model as accurate as possible in order to perform the LCA in every design phase. During the design process, each design phase refers to a BIM consisting of components that are modelled at different LODs. According to the proposed method, since each LOD involves the use of a specific database, LCA calculations are based on mixing them in every design phase. This is made possible since the databases employed are based on the same background data. Second, a framework for defining the variables involved in LCA calculations is proposed in order to enrich the BIM with all the relevant environmental parameters. An information flows matrix, called Architecture of Variables, is developed by defining the parameters responsible for the environmental impacts of buildings. Then, the identified BIM parameters have been coded to avoid redundancies. The proposed methods are tested on a building case study.

4.2 BIM-based LCA

The use of the BIM-based sustainable tools is increasing together with the studies focused on methods for the environmental impact assessment, based on digitized information models (Lee et al., 2015; Motawa and Carter, 2013; Naboni, 2017). The development of methods that integrate BIM and LCA is dramatically growing. Some of them, for example, promote the use of BIM increasing the knowledge of the model in order to facilitate the LCA (Grann, 2012). Different approaches concern the use of the embodied energy of construction products as a benchmark for assessing the sustainability level of the projects (Shadram et al., 2016). The possibility of integrating the environmental indicators in BIM comes from the opportunity of referring to available databases, such as the ICE database (Hammond and Jones, 2011), the Franklin and Andrews' Blackbook (Hutchins, 2011), and the Green Guide (Anderson et al., 2009).

This chapter describes a framework to improve the BIM-LCA integration. An overview of the challenges addressed by the thesis is provided here. Next, it is presented a wide-ranging literature review of previous studies on BIM-LCA integration. The last two section of this chapter describe the method applied to the case-studies according to the challenges previously defined. In particular, the third section describes a method for a continuous BIM-based LCA throughout the building design process, while the fourth section presents a framework for structuring all the relevant BIM parameters needed for the LCA of buildings.

4.2.1 Challenges addressed by the thesis

BIM-LCA integration is recognized to be a powerful approach to reach more sustainable construction projects. BIM creates significant opportunity to achieve more sustainable building construction processes and higher performance facilities with fewer resources and lower risk than can be achieved using traditional practices (Sacks et al., 2018). Several researches show the interactions between BIM and sustainability issues (Saieg et al., 2018), and the growing number of applications about BIM-based LCA is highlighted in recent papers (Chong et al., 2017; Eleftheriadis et al., 2017; Soust-Verdaguer et al., 2017).

The literature recognizes the advantages of BIM-LCA integration. For example, Kreiner et al. (2015) developed a methodology for the environmental assessment of buildings based on LCA, and acknowledged the integration of LCA in BIM as a way of improving sustainability performance of buildings. Soust-Verdaguer et al. (2017) demonstrated the growing use of BIM in LCA. BIM can manage the information flow by simplifying data input and implementing the environmental information into the digital model (Wong and Zhou, 2015). Indeed, BIM is a repository of information: data could be used to conduct analysis on the model once extracted. Furthermore, BIM can reduce the time-consuming nature of the LCA for collecting data as it allows performing quick quantity take-off (Ajayi et al., 2015; Houlihan Wiberg et al., 2014). Recent studies show that BIM provides an effective way to explore options for the mitigation of emissions as regards to the materials processing, delivery, and construction methods (Giesekam et al., 2014; Yuan and Yuan, 2011). As such, LCA could also be conducted at the early buildings design stages to support the decision-making process. Antón and Díaz (2014) conducted a SWOT analysis[49] to highlight the issues and

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[49] SWOT analysis is a strategic technique used to identify the *Strengths, Weaknesses, Opportunities, and Threats* related to project planning.

potentials of conducting LCA with the aid of BIM. The analysis refers to the BIM-LCA integration at the early design phases as shown in Table 14.

Table 14 – SWOT analysis on BIM-based LCA for early phases, based on Antón and Díaz (2014)

BIM-based LCA (early phases)	**Helpful** (to achieving the objective)	**Harmful** (to achieving the objective)
Internal origin	**Strengths**	**Weakness**
	- Higher capacity for accommodating the three pillars of sustainability	- Different stakeholders involved must be trained to consider environmental criteria
	- Extended use of environmental criteria by various stakeholders	- LCA process and way of presenting data are not standardized
	- Increased efficiency, easy to use, and less time consuming of activities	- Lack of environmental data for carrying out an LCA
	- Avoidance of manual data re-entry and easy access to the information	- Assumptions lead to increase uncertainties
	- More project information available during early phases	- Interoperability between BIM and LCA software must be improved
	- Higher effectiveness of environmental assessment when performed in early design phases	
	- Possibility to make comparisons and chance to learn from experience	
External origin	**Opportunities**	**Threats**
	- Efforts have been undertaken by Governments to make the environmental analysis compulsory	- Stakeholders are not aware of the importance of considering environmental aspects at an early stage
	- Increased demand for sustainable constructions in the markets	- Some stakeholders refuse to implement BIM-based LCA due to the efforts required
	- BIM-based LCA tools exists and they only need to improve synergies	- There is a lack of research and development in the construction industry
	- There is a real need of tools with such features in the market	- The variety of stakeholders in the construction industry hinders standardisation
	- Tools for early design phases could contribute to change the way of working in the construction industry	- Lack of interoperability between the different software systems
	- BIM-LCA integration make environmental assessments more acceptable for the stakeholders	

Although the BIM-LCA integration can reduce time and improve the environmental performance of buildings from the early stages of design, some methodological challenges arise from the literature. They are mainly summarized as follows.

- **Continuous BIM-based LCA throughout the design process:** The use of BIM-based sustainable design tools has proven to be effective for the late stage of design and detailed BIM models (Lee et al., 2015; Motawa and Carter, 2013). Furthermore, many studies acknowledged the great potential of BIM-based LCA to address sustainability issues at the early stages of the building design process (Antón and Díaz, 2014). However, it is difficult to identify studies that propose common strategies for BIM-enhanced LCA at different design stages. In this context, LODs became a key point for performing consistent LCAs. Indeed, LODs represents the information content of BIM objects that undergo an evolution during the entire design process.
- **Use of the BIM not only as a mere repository of information about quantities:** Data involved in the LCA cover the information about the building geometry (size, shape, quantities, materials, location, and orientation) and the environmental information about the building. Soust-Verdaguer et al. (2017) found that BIM input involves the physical data of the building, while LCA input data refer to the environmental characteristics of the building materials and elements, the life cycle scenarios, and the assumed phases. Results evidence that in order to improve BIM-based LCA applications, BIM models should include more information adapting BIM databases to the LCA method data structure.
- **Understanding the processes involved during the building's lifecycle**: BIM-LCA integration should help the end-users to obtain reliable results about the environmental performance of buildings from the early design stages. Thus, a key issue is to understand the processes involved during the lifecycle of the buildings (Soust-Verdaguer et al., 2017). As such, designers should have more control over processes and key parameters of buildings for conducting LCA, such as materials dimensions, transport, RSL of materials, etc.

- **Interoperability between BIM and LCA tools:** Interoperability is a key aspect as shown in sub-section 3.4.1. According to Díaz and Antón (2014), the use of BIM helps to avoid unnecessary waste of time and resources by eliminating the need to re-enter the same data. Indeed, data re-entry into LCA tools is one of the main drawbacks that have to be overcome (Eastman et al., 2011). Several methods for BIM-LCA have been developed in terms of data exchange, such as, for example, the development of a template including environmental data about materials (Lee et al., 2015), the development of a plug-in added to the BIM (Jalaei and Jrade, 2014), the combination of different BIM and LCA tools (Ajayi et al., 2015), and the use of VPL tools for performing Parametric LCA (Hollberg and Ruth, 2016). Nevertheless, each of them presents some limitations and leaves rooms for further improvement.
- **Visualization of the results:** It is crucial to know the environmental impact contribution of different construction options in order to inform designers about potential improvements. According to Röck et al. (2018), the visualization of results provides intuitive guidance on where to focus attention for improving the environmental performance of the building. This could lead to more sustainable design choices mainly when it is applied at early design stages.

The limitations of LCA of buildings (see section 2.5.5), BIM key factors (see section 3.4), and BIM-LCA integration challenges are summarized in Fig. 17. General limitations of LCA are also listed in Fig. 17. Nevertheless, they go beyond the scope of the thesis. The thesis faces three of the BIM-LCA integration challenges above described and depicted in Fig. 17. Firstly, the challenge named “continuous BIM-based LCA throughout the design process” (Ch1, Fig. 18) is addressed by the thesis. Secondly, the challenges of considering “BIM not only as a repository of geometrical information” (Ch2, Fig. 19) and “understanding the processes involved in building’s lifecycle” (Ch3, Fig. 19) are analysed together afterwards. As shown in Fig. 17, on the one hand, the challenges of BIM-based LCA improvement are hindered by specific LCA limitations. On the other hand, some key factors assist the LCA based on BIM.

Fig. 18 shows the limitations that are found to hinder the Ch1 and the key factor workable to its implementation. Fig. 19 depicts limitations and key factors affecting the Ch2 and Ch3. The detection of the limitations and key factors are crucial to identify both research gaps and current strategy amongst the academic approaches.

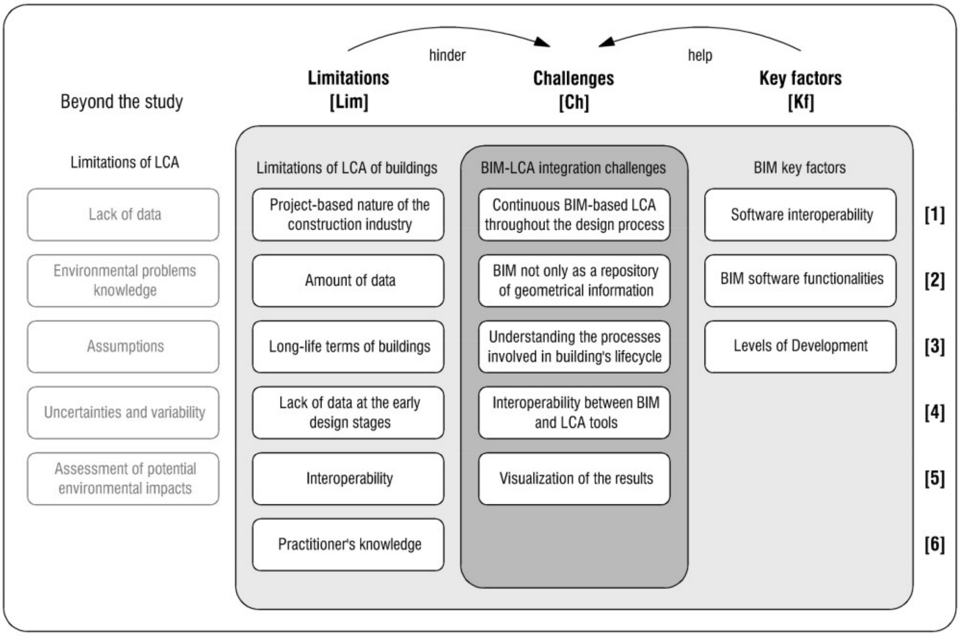


Fig. 17 – Limitations, Challenges, and Key factors for improving BIM-based LCA

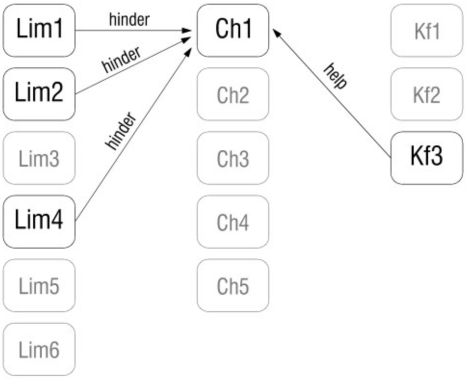


Fig. 18 – First challenge addressed by the thesis

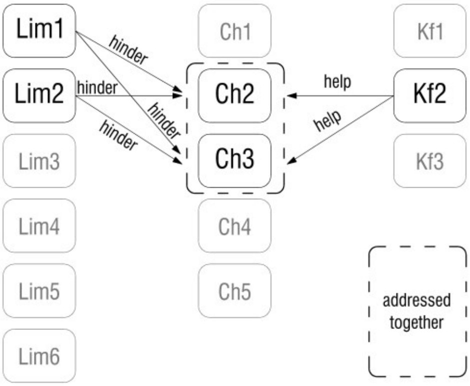


Fig. 19 – Second and third challenge addressed by the thesis

4.2.2 Academic approaches

Several studies have been conducted to enhance the dialogue between LCA and BIM to create more sustainable construction projects (Kylili et al., 2015; Wong and Zhou, 2015). Recent studies have shown that BIM supports energy demand simulations and environmental impact assessments over the building's life cycle, which provides an effective method to consider scenarios to mitigate the emissions related to material processing, delivery, and construction methods (Giesekam et al., 2014; Yuan and Yuan, 2011).

Two different general trends can be observed to perform the LCA of buildings based on BIM. The first trend concerns performing detailed LCA with refined processes and specific building performance simulation tools. This approach clearly provides benefits for performing detailed LCA. However, it requires linking LCA with a detailed BIM and can only be applied in the advanced design stages. Furthermore, only experts can use the method, and designers find it difficult to adopt it at the early design stages. The second trend involves simplified approaches for early design stages. This simplified approach does not make use of detailed information available in complex BIM in detailed design stages. The existing literature for both trends is reviewed as follows. A comprehensive list of BIM-based LCA studies is provided in Table 15.

First trend

Several studies employed the BIM automatic calculation of materials and components quantities and exported them to Excel spreadsheets where operational and embodied emission are evaluated (Georges et al., 2015; Houlihan Wiberg et al., 2014; Iddon and Firth, 2013). Peng (2016) developed a BIM-based approach to obtain the building life cycle carbon emissions. The author employed Autodesk Revit to extract the bill of materials and Autodesk Ecotect to simulate the heating and cooling loads at the operational stage. The author states that BIM and LCA remain vastly different, since BIM cannot provide sufficient data in the early design phase. Lee et al. (2015) developed a green template using Revit that can be used for the embodied environmental impact assessment of a building. Other studies integrated different software to support automated or semi-automated process. For example, Shadram et al. (2016) set up an integrated BIM-based framework to assess the embodied energy in the design development phase of the building's life cycle. The workflow incorporates the Extract Transform Load (ETL) technology to ensure the BIM-LCA interoperability supporting an automated or semi-automated process. Shadram and Mukkavaara (2018) proposed a BIM-based method to find the optimal design solution by solving the trade-off problems between the embodied and operational energy demands through the integration of a multi-objective optimization approach. The framework consists of four main modules: (1) BIM module using the Autodesk Revit software for the 3Dmodelling and Dynamo for the input-output data interface; (2) data repository module; (3) energy performance simulation; and (4) multi-objective optimization modules using Grasshopper. Marzouk et al. (2017) proposed a BIM-based method that enables the estimation of six types of emissions. The authors employed Autodesk Revit to facilitate data retrieval from Microsoft Access and used a windows application in C#.net to calculate the overall emissions using Athena Impact Estimator. Also, Abanda et al. (2017) structured a BIM-based method to automatically compute the embodied energy and GHG emissions of buildings, which aligned the results to the UK standard of construction measurement methods. The authors developed an algorithm that can be implemented in the BIM software system to assess the embodied energy/GHG emissions of a building project. Based on the input data from a Revit model, a material database with density, embodied energy and GHG emissions is used to automatically calculate the results. Yang et al. (2018) combined different software tools and data sources to enhance the data flow between BIM and LCA models. The authors used Autodesk Revit and Glondon BIM5D to create the BIM model, compute the inputs of the on-site construction processes, and simulate the energy consumption of building operation. Finally, a detailed LCA model is developed using a China's local LCA software tool.

Second trend

Several scientific studies have acknowledged the great potential of LCA in early design stages to reduce the environmental impact of buildings. Nizam et al. (2018) state that BIM approach has the potential to generate a decision-support system in the early design phase, including the selection of building materials, spatial configuration, construction methods and building service systems. Recent studies present methods to calculate the environmental impact of different material options, dimensioning choices, and design alternatives at the building conceptual stage (Ajayi et al., 2015; Basbagill et al., 2013; Eleftheriadis et al., 2018; Hollberg and Ruth, 2016; Röck et al., 2018). For example, Basbagill et al. (2013) developed a method to apply LCA to the early design stages to inform designers about the environmental impacts of building materials and dimensioning choices. The authors proposed a computational method combining BIM, LCA, energy simulation, and sensitivity analysis software to quickly evaluate the embodied impacts of thousands of building designs. Also, Hollberg and Ruth (2016) used a parametric LCA model in Grasshopper to generate several design variants to produce the real-time optimization of environmental parameters. The presented case studies show that the parametric approach is useful to evaluate geometric variants in conceptual design stages where the required information for LCA is commonly not available. Other studies focus on methods to enhance interoperability between BIM and LCA tools for early analysis. Kulahcioglu et al. (2012) proposed a framework based on a prototype software for the environmental performance analysis of a 3D model. BIM-LCA integration is enabled using the Industry Foundation Classes (IFC) as an open standard to develop a tool that support early design decisions. Bueno et al. (2018) combined existing BIM, visual programming, and a spreadsheet application to automatically obtain decision-making environmental profiles in the early design stages. Jrade and Jalaei (2013) presented a methodology to simplify the environmental impacts calculation of buildings in the conceptual stage. Their approach involves the use of a material database stored in a BIM module linked to an LCA module, certification and cost module. Jalaei and Jrade (2014) proposed an automated BIM-based method to conceptually design and assess sustainable building projects.

A plug-in for the BIM tool is developed to compute the environmental impacts and embodied energy of the building components linking BIM, LCA, energy performance analysis, and lighting simulation with green building certification systems. Najjar et al. (2017) state that the BIM-LCA integration is an optimal solution to achieve sustainable development enabling the decision-making process in the construction projects. The authors proposed a workflow-integrating BIM and LCA at early design stages to evaluate the environmental impact of building materials. An Autodesk Revit model is implemented as a BIM tool to design the case study building, whereas Green Building Studio and Tally are used to estimate the impact and give recommendations. Shafiq et al. (2015) employed Autodesk Revit and Microsoft Excel to assess the embodied carbon footprint of a two-storey building. The authors state that, in order to define the best materials choice during the early stages of future projects, additional factors such as the cost of materials should be considered to create a design that is both environmentally and economically sustainable. An application to select the appropriate design alternatives based on LCA and Life Cycle Costing (LCC) was proposed by Shin and Cho (2015). The authors developed an automatic framework to connect LCA with LCC methods in the early phase of a construction project by manually entering data when it has been extracted using BIM software.

Table 15 – List of BIM-based LCA studies

Reference	BIM model	Tool used	Data stored in BIM	LOD	Trend		Environmental Impact indicators	fU	lifespan (years)	Database	LCA phases
					1	2					
Abanda et al., 2017	Single-ground floor house	Revit, Excel, Navisworks, Revit API	Quantities of materials	–	●		ECOE, EE	Complete building	–	ICE	–
Ajayi et al., 2015	Two-storey school building	Revit, Green Building Studio, ATHENA Impact Estimator, Excel	Quantities of materials	200		●	GWP, HH	Complete building	30	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7,
Basbagill et al., 2013	Residential building	Dprofiler, CostLab, eQUEST, SimaPro, ATHENA EcoCalculator, Excel	Location; Building type; Gross floor area; geometric parameters; Window-to-wall ratio (WWR); RSL	–		●	EIF	Complete building	30	Athena Eco Calculator	A1-A3, B1-B7
Bueno et al., 2018	Single-family social housing	Revit, Dynamo, Excel	Quantities of materials, environmental parameters (ReCiPe 2008 environmental indicators)	–		●	ReCiPe 2008 midpoint indicators	Walls and roofing systems	40	Ecoinvent	–
Eleftheriadis et al., 2018	Multi-storey reinforced concrete buildings	–	Quantities of materials, materials embodied carbon factors	–		●	ECE	1 m2 of Gross Floor Area (GFA)	–	EPD	A1-A3
Georges et al., 2015	Two-storey single-family house and office building	Revit, Excel, SIMIEN, SimaPro 7.3	Quantities of materials	–	●		ECOE, OCOE	1 m2 of heated floor area	60	Ecoinvent Version 2.2	A1-A3, B1, B4, B6
Hollberg and Ruth, 2016	Multi-family house and Single-family house	Grasshopper, Rhinoceros	Quantities of materials, RSP, material properties, energy standards, life cycle emissions	–		●	PET, PERT, PENRT, GWP, EP, AP, ODP, POCP, ADP	Complete building	50	ökobau.dat, EPDs	A1-A3, B4, B6, C3, C4

Table 15 – List of BIM-based LCA studies

Reference	BIM model	Tool used	Data stored in BIM	LOD	Trend		Environmental Impact indicators	fU	lifespan (years)	Database	LCA phases
					1	2					
Houlihan et al., 2014	Single-family house	Revit, Excel, SIMIEN, SimaPro 7.3	Quantities of materials	–	●		ECOE, OCOE	1 m2 of heated floor area	30 (solar panels)	Ecoinvent Version 2.2	A1-A3, B4, B6
Iddon and Firth, 2013	Single-family house	BIM tool (N/S), Excel	Quantities of materials	–	●		ECOE, OCOE	Complete building	60	ICE	A1-A3, B6
Jalaei and Jrade, 2014	Three-storey office building	Revit, Ecotect, IESVE, Excel, Athena Impact Estimator	Quantities of materials	–		●	AP, EP, GWP, HH, ODP, PEC, PCSP, REP, WRRU	Complete building	–	ATHENA Impact Estimator	A1-A3, B6
Jrade and Jalaei, 2013	Six-storey apartment building	Revit, Athena Impact Estimator, Excel	Quantities of materials	–		●	AP, EP, GWP, HH, ODP, PEC, PCSP, REP, WRRU	Complete building	–	ATHENA Impact Estimator	A1-A3, B1-B7
Kulahcioglu et al., 2012	–	Google SketchUp, IFC2SKP plug-in, Blender, GABI	Quantities of materials	–		●	–	–	–	Ecoinvent 2010	A1-A3, A4-A5, B1-B7, C1-C4
Lee et al., 2015	18-storey Korean apartment building	Revit, Korea LCI database	Quantities of materials, Embodied environmental information of major buildings materials	300	●		ADP, AP, EP, GWP, ODP, POCP	Complete building	40	Korea LCI database	A1-A3, A4-A5, B1-B7, C1-C4
Marzouk et al., 2017	Three-floors building with isolated footings	Revit, Revit DB link (plug-in), Microsoft Access, Athena Impact Estimator, MS Excel, Microsoft visual studio 2010	Quantities of assemblies	–	●		GHG, Ap, PM, Ep, ODp, Smog	Complete building	–	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7, C1-C4

Table 15 – List of BIM-based LCA studies

Reference	BIM model	Tool used	Data stored in BIM	LOD	Trend		Environmental Impact indicators	fU	lifespan (years)	Database	LCA phases
					1	2					
Najjar et al., 2017	Multi-story office building	Revit, Tally, Green Building Studio	Quantities of materials	–		●	AP, EP, GWP, ODP, SMP, PET, PERT, PENRT	Complete building	50	GaBi database	A1-A3, B1-B7, C1-C4
Nizam et al., 2018	Cast-in-situ concrete frame structure	Revit, Revit API, External databases	Quantities of materials	–		●	EE	Complete building	–	ICE, Chinese handbook	A1-A3, A4-A5
Peng, 2016	Office building	Revit, Ecotect, Excel	Quantities and densities of materials	–	●		COE	Complete building	50	ICE	A1-A3, A4-A5, B1-B7, C1-C4
Röck et al., 2018	Residential building	Revit, Dynamo, Excel	Quantities of materials	200		●	GWP	1 m2 of Gross Floor Area (GFA)	60	Ecoinvent	A1-A3, B4, C3-C4
Shadram et al., 2016	Semi-detached dwelling	Revit, Power Pivot, FME, Google Maps API	Quantities of materials	–	●		EE	External wall	50	EPD database	A1-A3, A4
Shadram and Mukkavaara, 2018	Semi-detached low-energy dwelling	Revit, Dynamo, MySQL, Grasshopper, Slingshot plug-in, Archsim plug-in, Octopus plug-in, EnergyPlus	Geometry and construction element properties	–	●		EE, OE	Complete building	50	ICE	A1-A3, B1, B4, B6, B7
Shafiq et al., 2015	Two-storey office building	Revit, Excel	Quantities of materials	–		●	ECOE	Complete building	–	ICE	A1-A3, A4
Shin and Cho, 2015	11-storey office building	ArchiCAD, Excel	Quantities of materials	–		●	COE	Complete building	40	Korea LCI	A1-A3, B1-B6

Table 15 – List of BIM-based LCA studies

Reference	BIM model	Tool used	Data stored in BIM	LOD	Trend		Environmental Impact indicators	fU	lifespan (years)	Database	LCA phases
					1	2					
Yang et al., 2018	Residential building	Revit, Glondon BIM5D tools, eBALANCE, Designbuilder, Excel	Quantities of materials, fuels and machine-teams using BIM5D software	300	●		GWP	Complete building	50	Chinese db, Ecoinvent, ELCD	A1-A3, A4-A5, B1-B7, C1-C4

Abbreviations: **ADP**, Abiotic Depletion Potential; **AP**, Acidification Potential; **Ap**, Acidification process; **COE**, CO2 Emissions; **ECE**, Embodied Carbon Emission; **ECOE**, Embodied CO2 Emissions; **EE**, Embodied Energy; **EFP**, Effects Potential; **EIF**, Embodied Impact Factor; **EP**, Eutrophication Potential; **Ep**, Eutrophication process; **GHG**, Greenhouse Gases; **GWP**, Global Warming Potential; **HH**, Human Health; **OCOE**, Embodied CO2 Emissions; **ODp**, Ozone Depleting particles; **ODP**, Ozone Depletion Potential; **PET**, Total Primary Energy; **PCSP**, Photo-chemical Smog Potential; **PEC**, Primary Energy Consumption; **PERT**, Total renewable primary energy; **PENRT**, Total Non-Renewable Primary Energy; **PM**, Particular Matter; **POCP**, Photochemical Ozone Creation Potential; **REP**, Respiratory Effects Potential; **Smog**, Smog; **SMP**, Smog Formation Potential; **WRRU**, Weighted Raw Resource Use.

NOTE 1: Marzouk et al. (2017) considered six types of emissions: greenhouse gases, sulfur dioxide, particular matter, eutrophication particles, ozone depleting particles and smog. The authors define the emissions considered as follows. The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Greenhouse gases (**GHG**), which are considered as the main contributor to climate change on a global scope, are estimated in terms of kg CO2-Eq. Acidification process (**Ap**) is the transformation of air pollutants into acids causing acidification of soil and water bodies. The primary constituents of acidification are: sulfur dioxide (SO_2) and nitrogen oxides (NO_x) and their corresponding acids (H_2SO_4, HNO_3). Ap is estimated in terms of kg SO_2-Eq. Particular matter (**PM**) is a mixture of very small particles and liquid droplets. Moreover, it includes: acids, organic chemicals, dust, and metal particles. PM can be divided into two main categories: inhalable coarse particles which refer to particles of a diameter larger than 2.5 μm and smaller than 10 μm, and fine particles which refer to particles of diameter 2.5 μm and smaller. PM is estimated in terms of kg PM 2.5-Eq. Eutrophication process (**Ep**) occurs when water bodies require a high percentage of nutrients such as nitrates and phosphates which facilitate the growth of algae. The growth of algae decreases the percentage of oxygen in water bodies when algae die and decomposes. The decrease of oxygen causes the death of living creatures in water bodies such as fish. Ep are estimated in terms of kg N-Eq. Chlorofluorocarbons (CFCs) destroy the ozone layer in the stratosphere. This can lead to an increase in causing skin cancer, cataracts, and destroying the immune system of human beings. Ozone depleting particles (**ODp**) are estimated in terms of kg CFC-Eq. Ground-level Ozone (O_3) is considered the primary constituent of **Smog**. Ground-level ozone is not emitted directly into the atmosphere but it is created because of chemical reaction between nitrogen oxides (NO_x) and volatile organic compounds (VOC). Smog is derived from the words smoke and fog. Smog is a type of air pollutant that is produced from vehicles and internal combustion engines. Smog can cause a serious effect on heart and lung such as emphysema, bronchitis, and inflammation to breathing passage. Furthermore, it can affect the immune system. Smog is estimated in terms of kg O_3-Eq.

NOTE 2: Hollberg and Ruth (2016) employed Grasshopper to model the building and perform the LCA. Grasshopper is not a BIM soft-ware but a VPL tool. However, since the authors propose a framework to conduct LCA at the early design phases, Grasshopper could be used as modelling software. As such, this study the study has been considered in this list.

The reviewed papers show the potential of BIM to assist the LCA of buildings. However, as can be seen in Table 15, the reviewed papers only refer to a single trend, without considering the entire design process. Moreover, only few studies set the Level of Development of BIM elements. Ajayi et al. (2015) and Röck et al. (2018) were based on a LOD 200 model to support early analysis. LOD 300 was declared only in two cases to support detailed analysis (Lee et al., 2015; Yang et al., 2018). To overcome these limitations, this thesis proposes a framework to link both trends and by that addressing the Challenge 1 defined above (see Fig. 17 and Fig. 18).

Furthermore, the reviewed studies mainly employ BIM to model the building and store materials and components geometrical information. While there are different tools trying to facilitate the BIM-based LCA, there still is knowledge gap on how to match properties from the BIM with data needed to conduct the LCA. Cerezo et al. (2014) pointed out the need of using the building properties (BP) templates through the design process stages for the buildings performance simulation workflows. To this end, the thesis aims at defining the BIM parameters responsible for the environmental impacts of buildings, and not only those related to the geometrical aspects. Such information within a building model allows performing the LCA by extracting all project data needed directly from the BIM. This could decrease the shortage of information that usually occurs in the environmental analysis and decision-making process. This second part of the thesis allows addressing the second and third challenge as defined in sub-section 4.2.1 (see Fig. 17 and Fig. 19).

4.3 Continuous BIM-based LCA throughout the building design process: a novel proposal

The goal of this section is to provide a framework which empowers LCA to be used as a consistent decision-making tool during all phases of the design process. The novel approach considers the available information in the BIM with as much accuracy as possible in each stage. This way it is possible performing continuous LCA over the entire building design process by using the data provided by BIM. Different

LCA databases are employed with regards to the different Levels of Development (LODs) of the BIM elements. Since the BIM elements are modelled with different LODs in each design phase, the LCA is performed by consistently mixing the LCA databases. This is made possible as long as the databases use identical background data.

This approach has not been considered by any method described in the reviewed literature and allows overcoming the current problem of disconnection between building LCA tools for early or late design phases. Hence, the framework helps to provide information for decision-making throughout the whole design process, both in the early design phases and later phases with a more detailed BIM.

The remainder of this section is organized as follows. In sub-section 4.3.1, the method is described for the Swiss context. The reference building is divided into eleven building elements according to the Swiss cost calculation standard. Then, the building design process is divided into five main phases according to the Swiss practice. Here, the tendering and construction phase are considered as design phases, because the decisions taken in these phases still influence the environmental performance of the building. Moreover, the LOD evolution of the BIM elements is assumed based on the typical Swiss construction practice. The framework is tested on a multi-family house, which is described in sub-section 4.3.2. The results of applying the framework are shown in sub-section 4.3.3, and the main contributions and limitations are discussed in sub-section 4.3.4.

This section is based on Cavalliere et al. (2019).

4.3.1 Method

The framework is developed for the Swiss context. However, the same approach can be applied to define frameworks for other countries as well. The approach is based on the application of different levels of accuracy of the LCA calculation depending on the available building information, respectively LOD of the BIM. The method consists of the following main parts:

1. Definition of the evolution of LOD;

2. Consistent combination of LCA databases;
3. Link between LODs and LCA databases.

These three parts are depicted in Fig. 20 and are described in the following.

Part 1. Definition of an evolution of LOD

The LOD evolution throughout the design phases involves three steps (Fig. 20):

1.A: Definition of building design phases;
1.B: Definition of LODs;
1.C: Definition of element categories.

These are matched into 1.D: LOD evolution.

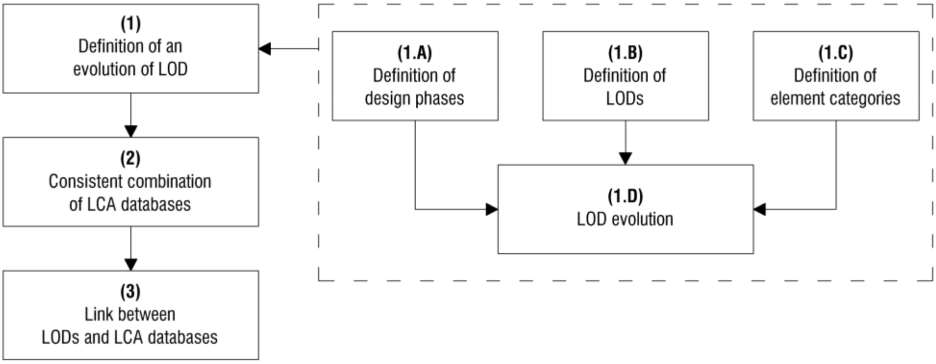


Fig. 20 – Schematic workflow of the proposed method

<u>1.A: Definition of design phases</u>

In most industrialized countries, the building design process is divided into several design phases. For the thesis, the design process is divided into five phases:

- Project Planning (PP)
- Project (P)
- Building Permit Application (BPA)
- Tendering (T)
- Construction (C)

The early design stages refer to the Project Planning (PP) and Project (P) phase. The core objectives of the early stages is to undertake feasibility studies in the PP phase, and to prepare the conceptual design in the P phase, including outline proposals for structural design, building envelope, technical equipment, and interior. The detailed design stages refer to the Building Permit Application (BPA), Tendering (T), and Construction (C) phase. The BPA and T phases aim at elaborating design documentation for the building permit and procurement. While most design decisions should be taken before tendering, specific material properties are often defined afterwards in the Construction stage. To this end, the Construction (C) stage is included as part of the design process. In fact, project information could be updated during the construction phase, as required, in response to ongoing client feedback. Table 16 lists typical objectives aligning the five stages employed in this thesis with the design phases by national regulations.

Table 16 – Design stages according to different regulations

Stages	**PP**	**P**	**BPA**	**T**	**C**	**Use***
Typical objectives	Feasibility studies	Concept design	Design documentation for building permit	Design documentation for procurement	Construction	Hand over, operation
UNI 11337-1 (Italy)	0, 1	2	3	4	5	6, 7
SIA 102 (Switzerland)	11, 21, 22	31	32, 33	41, 51	52, 53	61, 62
RIBA 2013 (GB)	0, 1	2	3	4	5	6, 7
AIA (US)	PR	SD	DD	CD, PR	CA	OP

*The Use phase is beyond the purpose of the thesis

1.B: Definition of LODs

The LODs of BIM are usually defined in five steps, from LOD 100 to LOD 500. In practice, LOD 500 is rarely achieved during the design process because the modelling effort is huge and it refers to the as-built model. In some cases an intermediate LOD, for example 350, is adopted according to the purpose of the building project. Here, four LODs are assumed, from low information content (LOD 100) to high information content (LOD 400). However, the LODs of different BIM elements do not always simultaneously evolve during the design process, but depend on the goal of the specific design phase. For example, the structure is typically defined with a higher detail in the early design stages because a structural calculation is needed, but the interior finishing is defined later. The type of paint may only be fully defined during the construction phase because the client has not decided before. Therefore, the different construction categories have a different LOD evolution.

1.C: Definition of construction categories

For the purpose of this thesis, the Swiss building element classification scheme for cost estimation e-BKP-H SN 506 511 is used to code the building parts. This scheme considers the building as composed of eleven building elements:

1. Foundation
2. Exterior wall under ground
3. Exterior wall above ground
4. Windows
5. Interior wall
6. Partition wall
7. Column
8. Ceiling
9. Balcony
10. Roof
11. Technical equipment

Each *building element* consists of *several building components*, which have different functions, and belong to different *construction categories*. The classification system marks the building components with an alphanumeric code. The alphabetic character represents the construction categories. For example, the building element *exterior wall* *above ground* is characterized by three different building components: *C2.1B exterior wall*, *E2 exterior wall finishing*, and *G3 interior wall finishing*, which belong to the construction categories *structure (C)*, *envelope (E+F)*, and *interior (G)* respectively. For this thesis, four construction categories are defined according to this scheme:

- Structure (all load-bearing parts)
- Envelope (façade and roof covering)
- Interior (non-load-bearing walls and floor finishing)
- Technical equipment

An overview of the building structure is provided in Fig. 21.

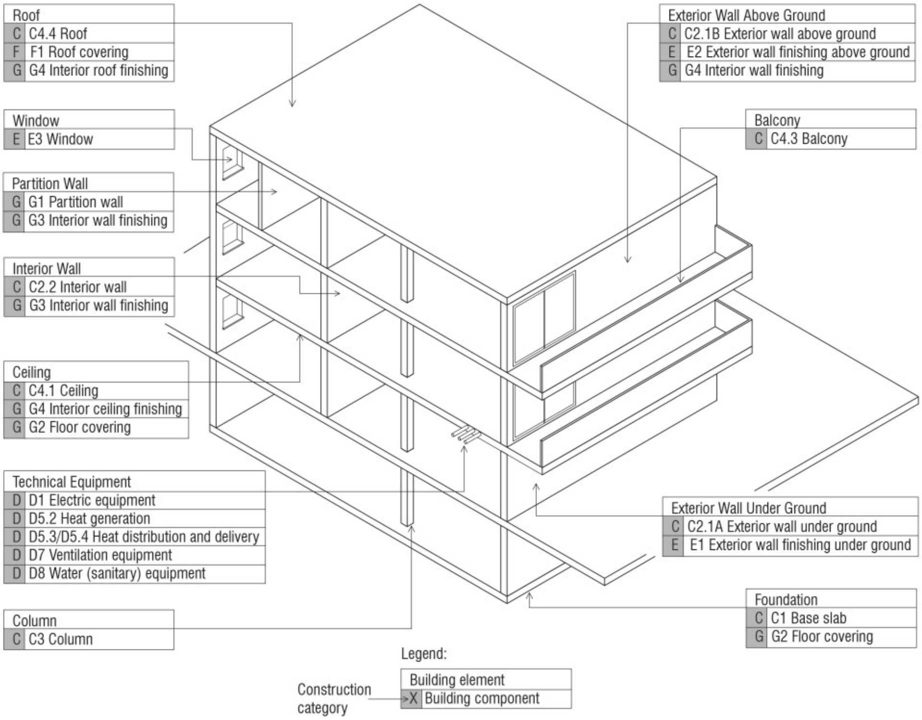


Fig. 21 – General description of the building, building element, building component, and construction categories

1.D: LOD evolution

For the purpose of this thesis, it is assumed that all building components belonging to the same construction category are developed at the same LOD at a specific design phase. For example, in the Project Planning (PP) phase, all building components belonging to the construction category *Structure* are modelled at LOD 100; in the Project (P) phase, they are modelled at LOD 300. In the following phases (Building Permit Application (BPA), Tendering (T), and Construction (C) phase), they are modelled at LOD 400. The evolution of LOD is shown in Fig. 22.

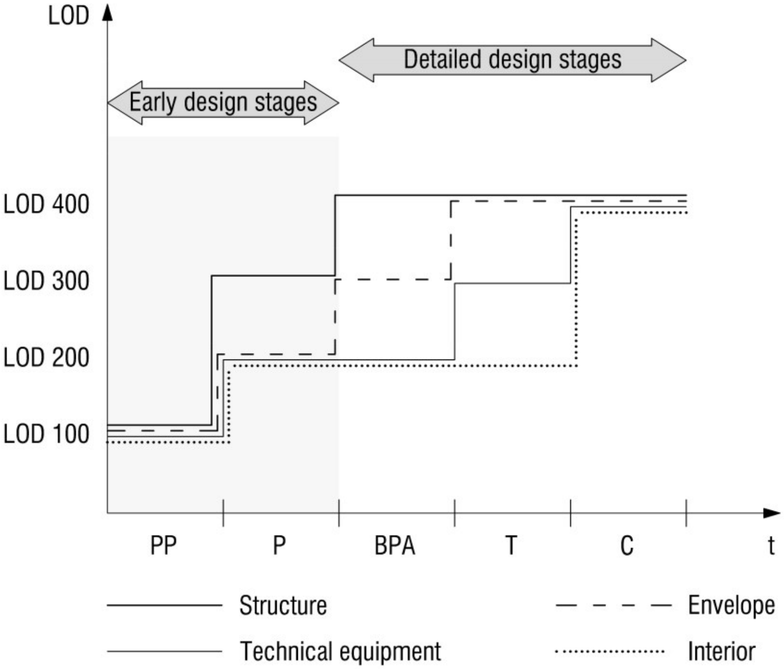


Fig. 22 – Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction.

Part 2. Consistent combination of databases

In Switzerland, LCA data for building materials are provided in a list called *KBOB Ökobilanzdaten im Baubereich*. The values are provided per mass (e.g. for metals) or per surface area (e.g. for window panes). To facilitate the application of this data, the building component catalogue *Bauteilkatalog* has been developed. The Bauteilkatalog is organised according to the Swiss building classification system, e-BKP-H SN 506 511. This database provides the environmental impact of pre-defined typical Swiss constructive solutions for building components: for example an external insulation system containing the EPS insulation, reinforcement fabric, rendering, and paint. The building component catalogue uses the materials provided in the KBOB list. Hence, both databases are based on the same background data: Ecoinvent 2.2. For that reason, they can be consistently mixed. Both databases provide values for the indicators Global Warming Potential (GWP) and Non-Renewable Primary Energy total (PENRT). In addition, a single-score indicator called *Umweltbelastungspunkte* is provided. This indicator is specifically calculated for Switzerland based on the method of ecological scarcity (Swiss Eco-Factors, 2013).

Part 3. Linking LOD and databases

The LCA databases are linked according to the LODs. Before the design process is started there is no BIM. For example in the strategic definition of the building project, only the square meters of floor area for the new building could be known. Therefore, the LOD refers to an earliest 3D sketch, and it is called pre-LOD in this thesis. At this stage, the environmental impact can be estimated using the average impact per m^2 of floor area for new buildings in Switzerland. In addition, the minimum and maximum values can be calculated based on the data from Wyss et al. (2014). At LOD 100, the type of element is not known at all. Here, the Bauteilkatalog database is employed by averaging the impact values at the building element level. In other words, the LCA is performed by taking the average of each building component and summing them at the element level to have an average building element. Also, the minimum and maximum values are calculated to show the variability of all possible constructive solutions. At level 200, it is assumed that the type of construction system is defined, for example an interior or an exterior insulation, but the exact type of material is not yet defined. For example, the insulation material could still be defined in the further design process. Therefore, average values of the building component catalogue are used. Next to the average value, the minimum and maximum values are provided to show the range of possible solutions for the element under consideration. At LOD 300, it is assumed that the type of building component is known, but the exact material quantities of each layer might not have been specified yet, such as the thickness and rendering. Therefore, the pre-defined component from the Bauteilkatalog is employed. When reaching the LOD 400, the exact quantities of each material that forms a building component are known, and the KBOB list can be used.

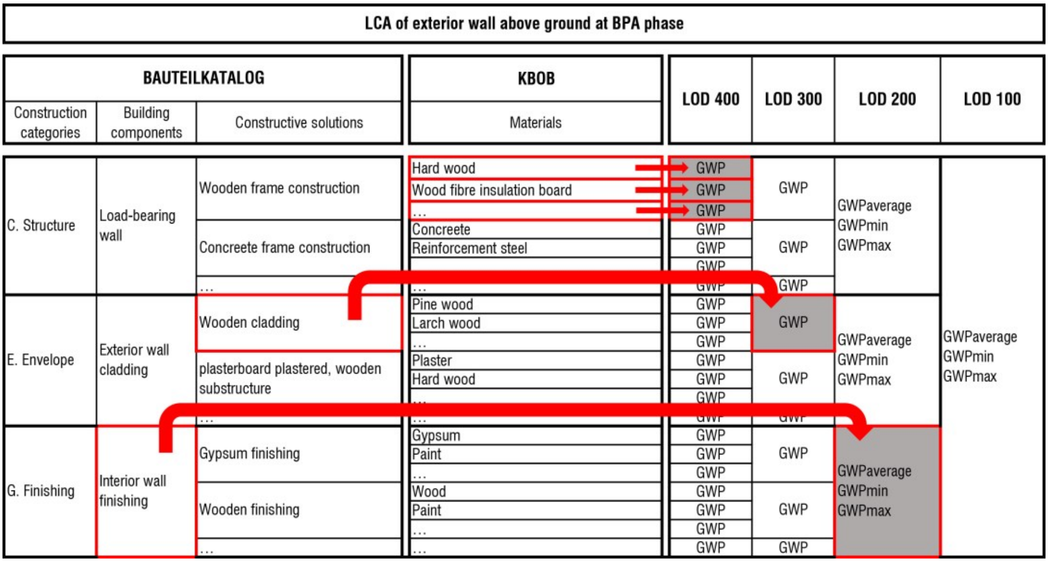
LCA calculations are made considering all the building components of a building elements until reaching the LOD 200 according to the e-BKP-H SN 506 511 scheme. In fact, LOD 100 and LOD 200 refer to a conceptual modelling where the final technical solution is not well-known yet. From LOD 300 onwards, the exact technical solution is known, and some building components could not be taken into account for the LCA calculation. For example, the building might not have the exterior wall finishing, but this shall be decided later during the detailed phases.

The linkage between LODs and LCA databased is summarized in the LOD matrix in Table 17.

Table 17 – LCA databases used for different LODs

LOD Matrix		
LOD	**Database**	**Use of Database**
Pre-LOD	Swiss Buildings Database	Average value at building level
100	Bauteilkatalog	Average value at building element level
200	Bauteilkatalog	Average value at building component level
300	Bauteilkatalog	Specific value at building component level
400	KBOB	Specific value at material level

According to the proposed method, each design phase refers to a BIM that is made of building components at different LODs. Hence, since each LOD involves the use of a different LCA database, calculations are based on mixing them in every design phase. An example of the application of the method related to the exterior wall above ground in the BPA phase is shown in Fig. 23.



LCA of exterior wall above ground at BPA phase

BAUTEILKATALOG			KBOB				
Construction categories	Building components	Constructive solutions	Materials	LOD 400	LOD 300	LOD 200	LOD 100
C. Structure	Load-bearing wall	Wooden frame construction	Hard wood Wood fibre insulation board …	GWP GWP GWP	GWP	GWPaverage GWPmin GWPmax	GWPaverage GWPmin GWPmax
		Concreete frame construction	Concreete Reinforcement steel …	GWP GWP GWP	GWP		
		…	…	GWP	GWP		
E. Envelope	Exterior wall cladding	Wooden cladding	Pine wood Larch wood …	GWP GWP GWP	GWP	GWPaverage GWPmin GWPmax	
		plasterboard plastered, wooden substructure	Plaster Hard wood …	GWP GWP GWP	GWP		
		…	…	GWP	GWP		
G. Finishing	Interior wall finishing	Gypsum finishing	Gypsum Paint …	GWP GWP GWP	GWP	GWPaverage GWPmin GWPmax	
		Wooden finishing	Wood Paint …	GWP GWP GWP	GWP		
		…	…	GWP	GWP		

Fig. 23 – Example of the proposed method for LCA of exterior wall above ground at the Building Permit Application (BPA) phase

4.3.2 Description of case study

The method is applied to a multi-family house in Hamburg. The case-study building is based on a real building called WoodCube (Fig. 24). It was built as part of the International Building Exhibition (*Internationale Bauausstellung*). The building measures approximately 15 m ×15 m with a core for the staircase and an elevator. Eight apartments are arranged around this core. Some small modifications to the geometry were made to simplify the model for the case study (Hollberg and Ruth, 2016). All material properties are obtained from a published LCA report (Hartwig, 2012). Length, area, and volume of different materials and components are extracted from the 3D model to an excel spreadsheet. These quantities are used to perform the LCA according to the method described in 4.3.1. The building elements and related building components are provided in Table 18. In addition, Table 18 lists the areas, quantities, and materials of the building components. The KBOB ID in the table identifies the exact materials used to make calculations at LOD 400.

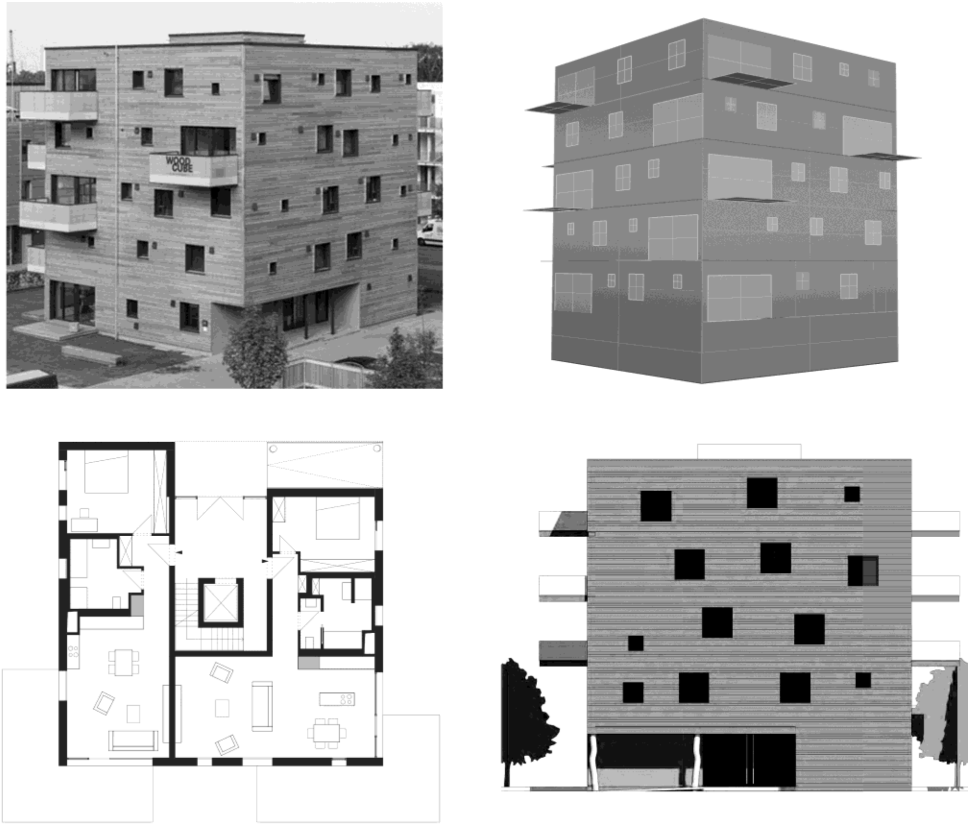


Fig. 24 – Top Left: WoodCube, north-east (www.iba-hamburg.de); Top right: simplified 3D model of the building, south-east; Bottom left: Woodcube, floor plan, ground floor (Hartwig, 2012); Woodcube, north elevation (Hartwig, 2012)

The functional unit of the performed LCA is the entire building with a reference study period of 60 years according to SIA 2032:2012 (SIA, 2012). The staircase and elevator are excluded from the analysis. Regarding the system boundaries, the LCA is performed focusing on the embodied impact including production, replacement, and end-of-life of building materials and elements. The transportation to the construction site, the operational energy use, and the operational water use are not considered for the assessment. Hence, according to EN 15978 (EN 15978, 2011), these phases correspond to the cycle modules A1-A3, B4, C3 and C4 (see Fig. 5). The number of replacement of building components and material are established according to the reference service life (RSL) of SIA 2032:2012.

Table 18 – List of material in the building organized along the Swiss e-BKP catalogue

Building element	**Building component**	**m^2**	**Material**	**KBOB ID**	**Amount per m^2 of building component**	**Unit**
Foundation	C1 Base slab, foundation	228.00	Concrete C25/30	01.002	811.2	kg
			Reinforcement	06.003	54.95	kg
	G2 Floor covering	NONE				
Exterior wall underground	C2.1A Exterior wall underground	183.00	Concrete C25/30	01.002	463.54	kg
			Reinforcement	06.003	31.4	kg
	E1 Exterior wall finishing underground	NONE				
Exterior wall aboveground	C2.1B Exterior wall aboveground	723.50	Pinewood	07.010	114.48	kg
			Hardwood	07.008	9.24	kg
			Wood fibre insulation board	10.009	4.55	kg
			Pinewood	07.010	13.28	kg
			Hardwood	07.008	1.07	kg
	E2 Exterior wall finishing aboveground		Wood fibre insulation board	10.009	5.2	kg
			Pinewood	07.010	13.74	kg
			Hardwood	07.008	1.11	kg
			Larch wood	07.008	15.86	kg
	G3 Interior wall finishing	NONE				
Window	E3 Window	200.70	Wood frame	05.005	0.1	m^2
			Double-glazing	05.001	0.9	m^2
Interior wall	C2.2 Interior wall	1368.10	Concrete C25/30	01.002	556.25	kg
			Reinforcement	06.003	37.68	kg
	G3 Interior wall finishing	NONE				
Partition wall	G1 Partition wall	391.40	Gypsum fibre panel	03.007	20	kg
			Pinewood frame	07.010	3.86	kg
			Gypsum fibre panel	03.007	20	kg
	G3 Interior wall finishing		Clay plaster	04.004	4.8	kg
			Clay plaster	04.004	4.8	kg
Column	C3 Column	NONE				
Ceiling	C4.1 Ceiling	1140.00	Pinewood	07.010	107.61	kg
			Hardwood	07.008	8.68	kg
	G2 Floor covering		Parquet	11.019	1	m^2
			Wood fibre insulation board	10.009	2.6	kg
			Separating foil	09.006	0.8	kg
			Wood fibre insulation board	10.009	2.6	kg
			Wood fibre insulation board	10.009	3.9	kg
			Perlite	10.012	60	kg
			Separating foil	09.006	0.8	kg
	G4 Interior ceiling/roof finishing	NONE				
Balcony	C4.3 Balcony	90.00	Pinewood	07.010	113.27	kg
			Hardwood	07.008	5.6635	kg
			Sealing strip	09.004	0.4	kg
Roof	C4.4 Roof	228.00	Pinewood	07.010	107.61	kg
			Hardwood	07.008	8.68	kg

	F1 Roof covering		Plastic	09.007	0.09	kg
			Gravel	03.012	80	kg
			Moisture barrier	09.002	0.28	kg
			Phenolic resin foam	10.003	5	kg
	G4 Interior ceiling/roof finishing	NONE				
Technical equipment	D1 Electric equipment	912.00* *heated floor area	Electric equipment for residential buildings	34.001	1	m^2
	D5.2 Heat generation		Heat generation (30 W/m2)	31.002	1	m^2
	D5.3/D5.4 Heat distribution and delivery		Floor heating	31.024	1	m^2
	D7 Ventilation equipment		Ventilation for kitchen and bathroom	32.003	1	m^2
	D8 Water (sanitary) equipment		Sanitary equipment for residential buildings	33.003	1	m^2

4.3.3 Results

The life cycle impact assessment provides results using the GWP in kg CO_2-equivalent as the environmental indicator amortizing the values per year. The results for each building element at different design phases are shown in Fig. 25-Fig. 34. They show the environmental impact of the building elements during the design process in relation to the LODs evolution. The results for the PP phase are provided for all the building elements since they are modelled at LOD 100. The results for the later design stages are provided for the individual components, and they are representative of the mix of databases. The results for the GWP average, minimum, and maximum value of the building elements and components at LOD 100, LOD 200, and LOD 300 are provided in appendix A. The results for PENRT are provided in the Appendix A as well.

As can be seen in Fig. 25-Fig. 34, most of the building elements show consistent LCA results during the design process. This is true for the building elements *Foundation* (Fig. 25), *Exterior wall above ground* (Fig. 27), *Window* (Fig. 28), *Interior wall* (Fig. 29), *Partition wall* (Fig. 30), *Roof* (Fig. 33), and *Technical equipment* (Fig. 34). The shift from the use of average data in the early design phases to specific values in the last phases reduces the GWP throughout the building design process. Furthermore, the use of increasingly refined data reduces the range of variability (min values and max values) from the PP phase to the C phase. The consistency of the proposed method lies in the fact that the GWP at one specific phase is always within the variability of the previous phase. This outcome enables one to roughly predict the final environmental impact of the C phase from the early phases of the building process.

However, some building elements do not show the same consistency. On the one hand, some overestimations occur in the early design phases. On the other hands, inconsistencies are due to the lack of the LCA databases. For example, the *Exterior wall under ground* (Fig. 26) shows some inconsistencies throughout the design process. In the BPA phase, the building component *E1 Exterior wall finishing under ground* should be modelled at LOD 300, while it should be modelled at LOD 400 in the following phases. Nevertheless, it is not taken into account from the BPA phase onwards because the case-study building has no finishing (see Table 18). In fact, according to the method, it is assumed to know if a building component is part of the final solution only when the modelling reach the LOD 300 since before the modelling activity refers to the conceptual. As such, the result of the BPA phase does not fall within the variability of the previous ones. Therefore, in the early phases, the impact is overestimated compared to the final results. The same type of overestimation occurs for the *Ceiling* because the building component *G4 Interior finishing* is not considered in the C phase (Fig. 32). Furthermore, the assessment of the building component *G2 Floor covering* using the KBOB list in the C phase results in a much lower GWP than that in the T phase when the Bauteilkatalog database is used, which causes a further impact overestimation in the early design phases. Regarding the building element *Balcony* (Fig. 31), the environmental impact in the PP phase is significantly higher than those in the following phases. This is due to the lack of data of the Bauteilkatalog database, which provides only concrete frame solutions, whereas the balcony of the case-study building is made of wood. In fact, to overcome the lack of data, from the LOD 300 the balcony is modelled using the wooden solution for the component *C4.1 Ceiling*, which causes the inconsistencies of the LCA results.

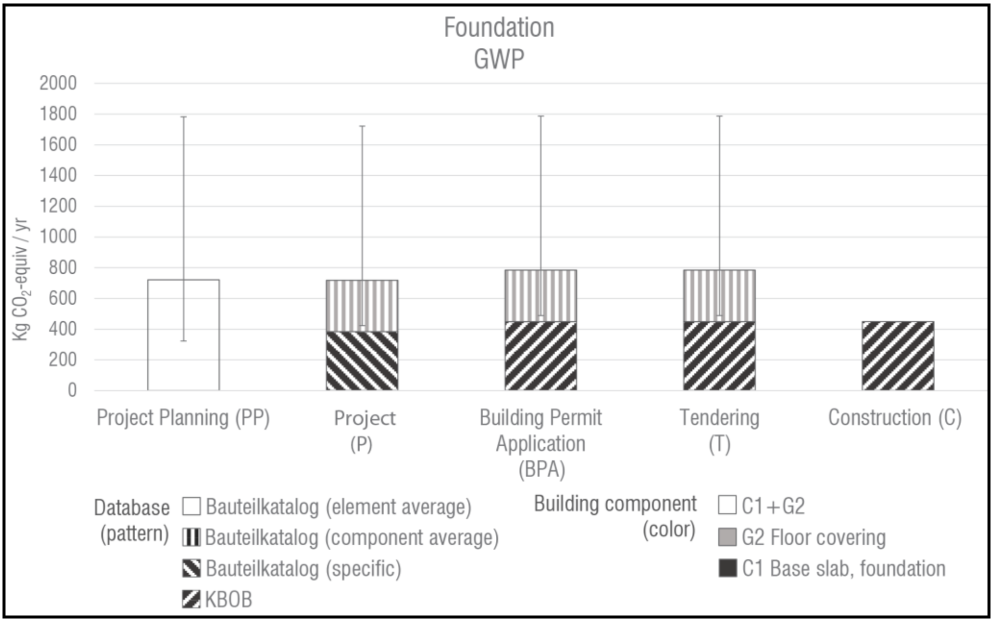


Fig. 25 – Contribution to the GWP of Foundation during the design process

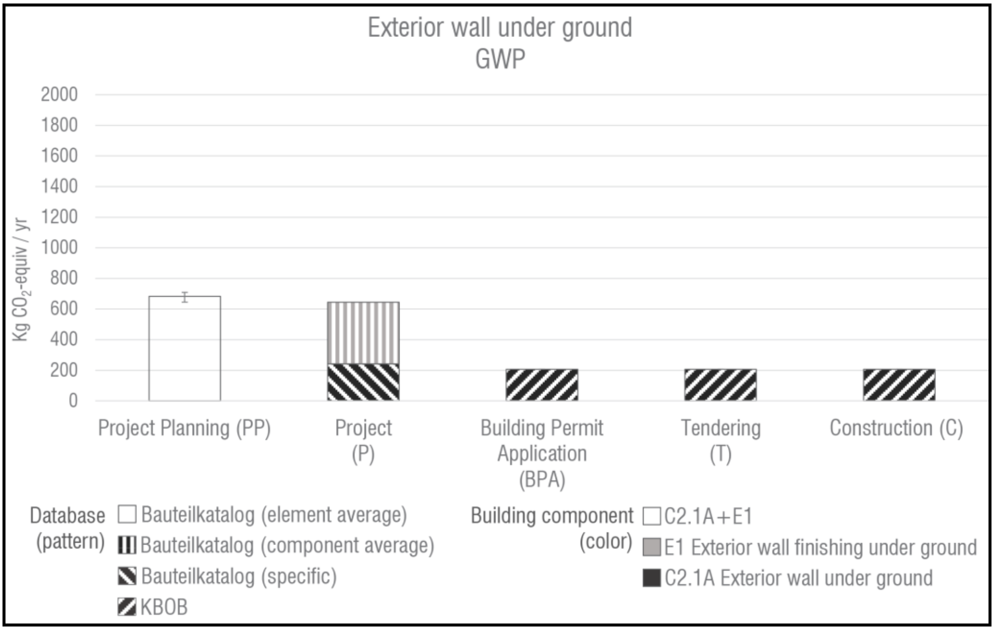


Fig. 26 – Contribution to the GWP of External wall under ground during the design process

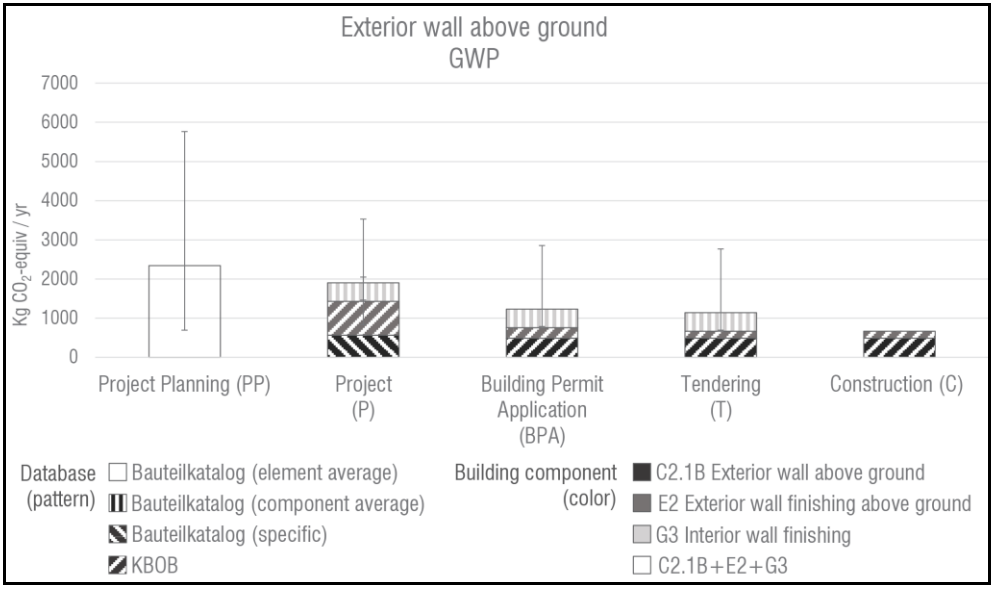


Fig. 27 – Contribution to the GWP of External wall above ground during the design process

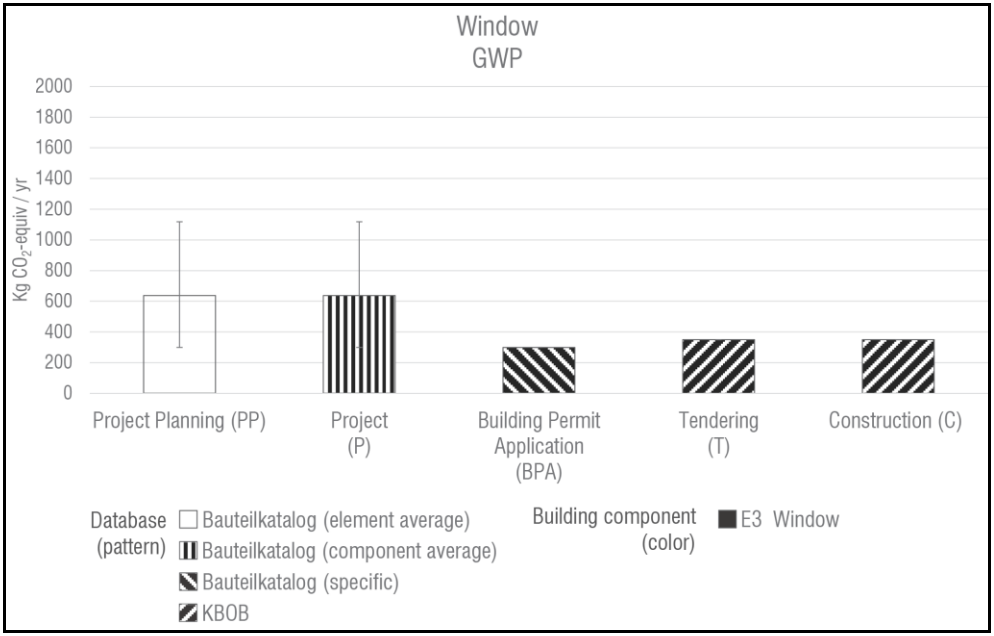


Fig. 28 – Contribution to the GWP of Window during the design process

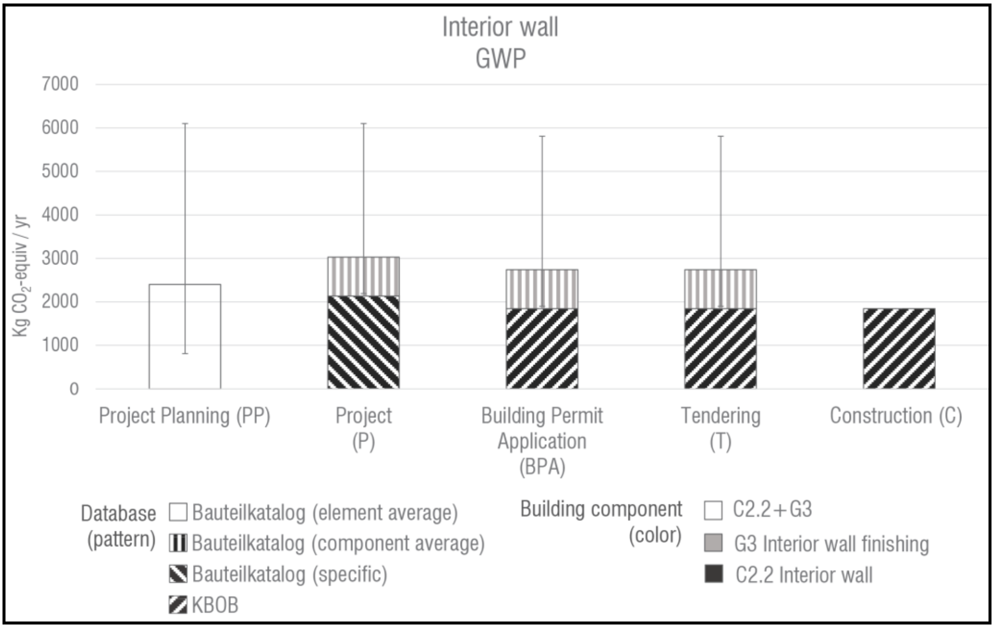


Fig. 29 – Contribution to the GWP of Interior wall during the design process

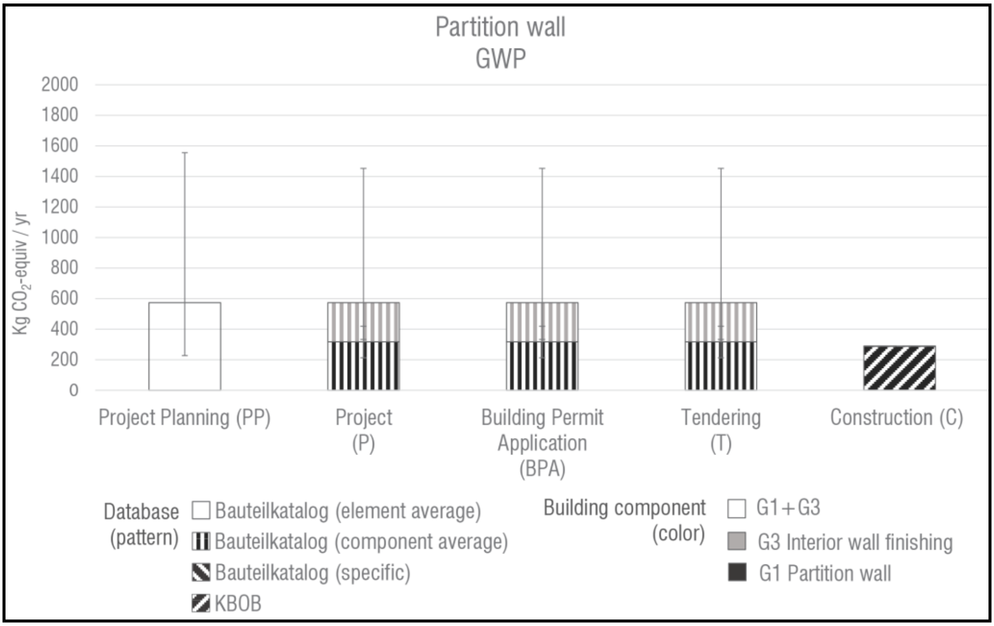


Fig. 30 – Contribution to the GWP of Partition wall during the design process

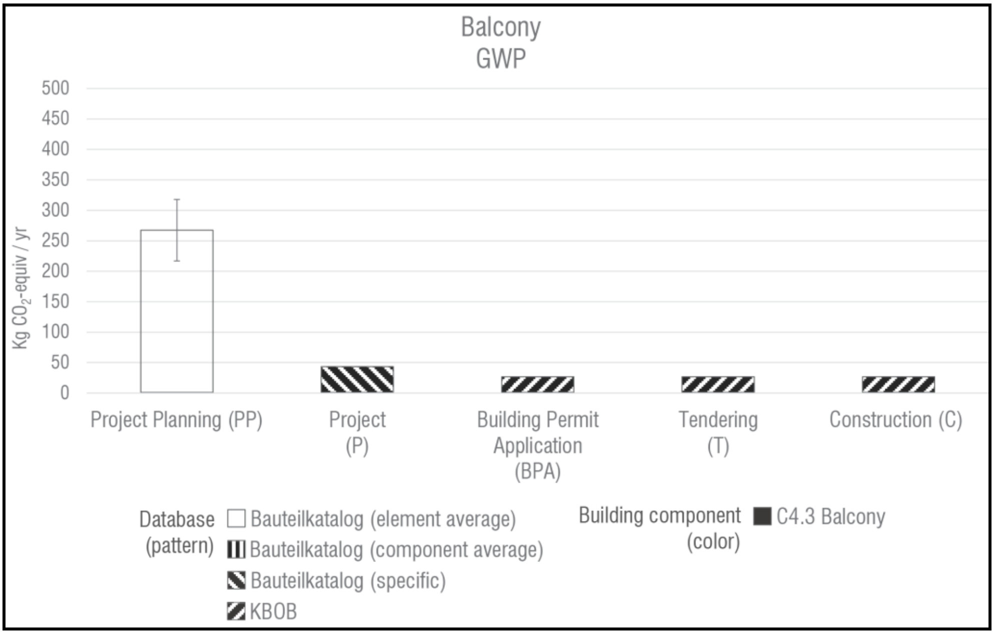


Fig. 31 – Contribution to the GWP of Balcony during the design process

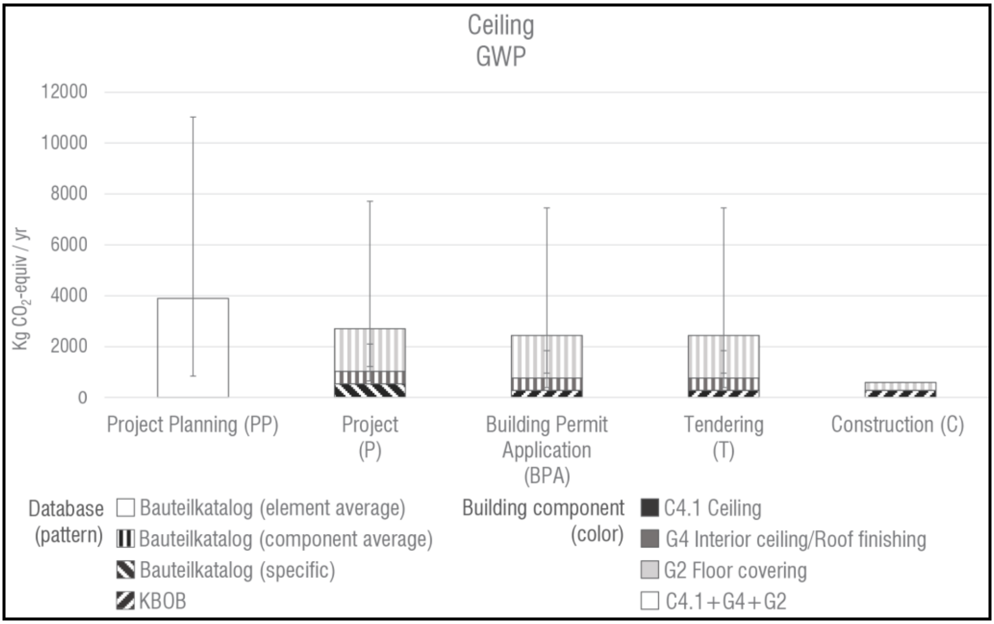


Fig. 32 – Contribution to the GWP of Ceiling during the design process

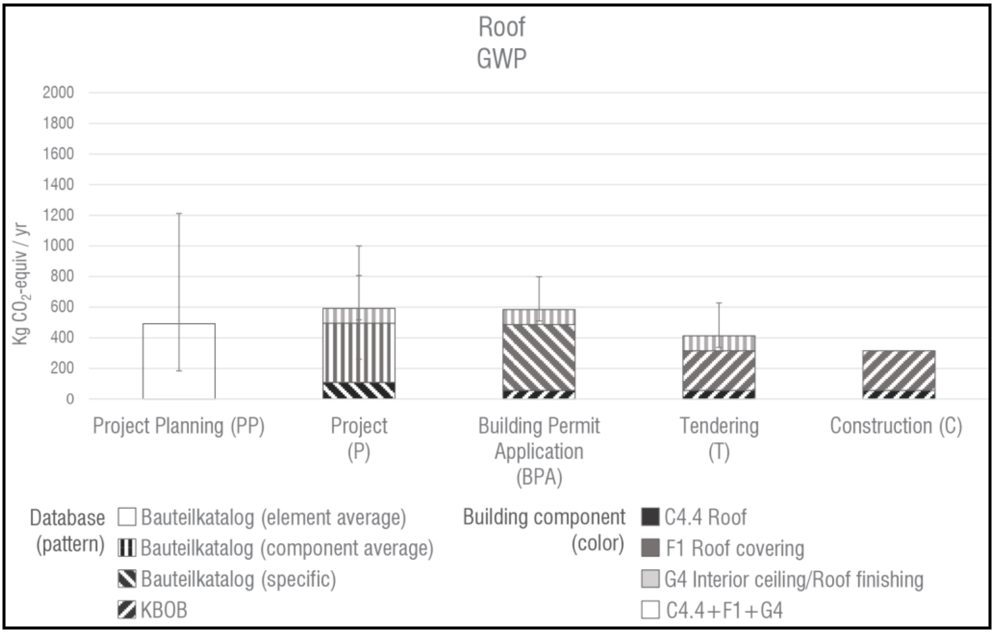


Fig. 33 – Contribution to the GWP of Roof during the design process

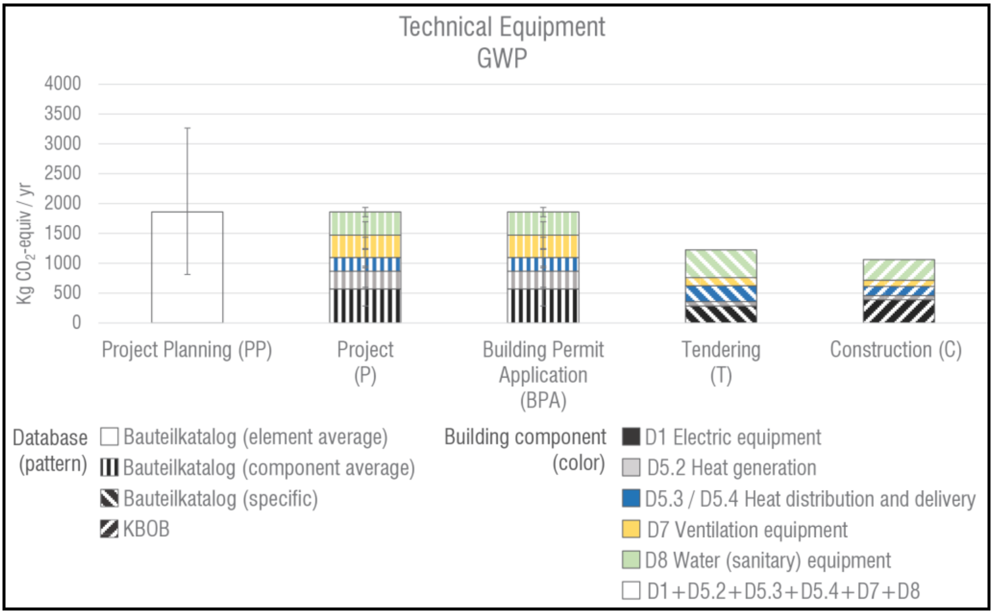


Fig. 34 – Contribution to the GWP of Technical equipment during the design process

By aggregating the results of all building elements and performing the analysis at the building level, the LCA results show a general coherence throughout the entire design process (Fig. 35). From the PP phase to the C phase, the GWP in each design phase is within the variability of all the previous phases.

In the Pre-Design phase, the results are based on the Pre-LOD. The use of the Swiss buildings database at the Pre-LOD leads to a consistent result until the BPA phase. In fact, the results in the T and C phases do not fall within the variability of the Pre-Design phase. This is due to a lack of the Swiss buildings database because it provides LCA results based on only fifteen residential buildings, which results in a limited range of variability.

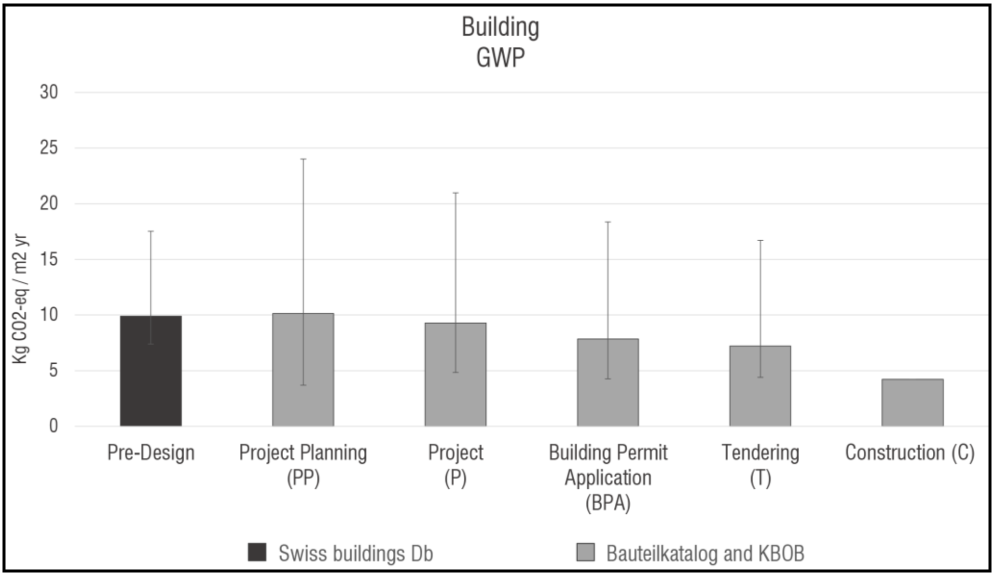


Fig. 35 – GWP of the building during the design process

As noted above, these results come from the adoption of the LOD evolution of building elements based on the typical Swiss architecture practice (scenario 1). However, different scenarios concerning the LOD evolution have been considered and the results at the building level are provided in Appendix B. This allows testing the proposed method according to different assumptions since design teams could adopt various LOD evolutions according to different design practices. Data from Appendix B once again show a general coherence throughout the design process phases as for the scenario 1 previously discussed. Furthermore, since the LCA databases employed provide values for GWP and PENRT, results are provided according to both indicators.

The operational impact is not taken into account for this thesis since it is not the focus of the study. Nevertheless, it was calculated for the construction phase to provide a relation of the share of embodied to operational impact. According to the report on the building (Hartwig, 2012), the building has a final energy demand for heating and hot water of 43.5 kWh/(m^2_{AE}·a). The electricity demand (including auxiliary energy, ventilation, lighting and equipment) is 22.2 kWh/(m^2_{AE}·a). The heating is provided though a wood chip boiler, and the photovoltaic modules on the roof produce the required electricity. The annual electricity demand can be fully covered by the building itself. Excess energy fed into the grid as well as hourly variations are not considered. The results for the operational impacts are provided in Table 19.

Table 19 – Results for the operational impact of the building case study

	Final energy demand kWh/(m^2_{AE}·a)	**KBOB ID**	**KBOB Name**	**GWP kg CO_2-e/(m^2_{AE}·a)**
Heating	43.50	41.011	Wood chip boiler	0.48
Electricity	22.16	46.003	Photovoltaic flat roof	1.80
Sum				**2.27**

4.3.4 Discussion

The application of the proposed method to a case-study building shows that it is possible to continuously perform the LCA throughout the design process. Fig. 35 shows consistent LCA results. The variability of GWP decreases from the early design phases to the final ones for most building elements because more refined data are used at higher LODs. The GWP in a certain design stage is within the variability of the previous one. This confirms the reliability of the proposed method. The main contribution of the research is to predict the GWP during the entire design process. Thus, the method helps to provide reliable information for decision-making during the entire design process, already from the first building concept.

Despite the overall consistency, the results of few individual building elements do not follow the general trend because of two main issues. First, the method considers all building components when modelling at LOD 100 and LOD 200, since it is unknown which ones will be part of the final solution. This approach causes an overestimation of the environmental impact in some cases because some building components (e.g. the interior finishing) may be excluded from the LOD 300 onwards. To solve this issue, the option of not having a certain component can be added to the building component database. Second, sometimes the limited number of datasets affects the consistency of the results, such as in the case of the balcony (Fig. 31). This issue can be solved by extending the building component database with more typical constructive solutions. Another potential issue is that the building catalogue refers to standard constructive solutions. Consequently, because the method depends on the databases, it is limited in terms of performing the environmental potential of innovative constructive solutions that are not part of the catalogue. However, it should be noted that the building catalogue employed covers the available solutions on the market. Thus, the proposed method is useful for mass construction but not the few ground-breaking solutions.

These individual inconsistencies are not visible when summing the results of all building elements to calculate the LCA of the entire building. The results for the whole building in a specific design phase comply with the forecast from the variability range of the previous stages (Fig. 35). Only the variability of the GWP in the Pre-Design stage does not match the GWP of the last two design phases. This comes from the limited number of buildings assessed in the database that is linked to the Pre-LOD. This issue can be solved by extending the dataset of the database. The same issues and considerations arise when considering the different scenarios provided in Appendix B.

Other aspects arise from the application of the method. When making calculation at LOD 100 and 200, all the possible solutions for building components have been combined to form the building elements. In some cases, this may result in an impractical solution, since not all combinations are technically feasible in practice. In addition, all minimum values at the element level are summed up to indicate the minimum value of the GWP. Thus, the minimum values should be considered as the indication of a potential and not as a benchmark. However, the final result of the real case study is notably close to the minimum value in the PP phase (Fig. 35), which implies that it can be achieved in practice.

The proposed framework should be evolved in the future. First, the method currently only includes the embodied impact of the building. Depending on the building, the environmental impact that results from the use phase can be a major part of the overall life cycle impact. However, for this specific case-study building, the operational impact is about 50% of the embodied impact. As such, it is responsible for one third of the environmental impact during the life cycle of 60 years. This confirms the findings of recent publications stating that the embodied impact of very energy efficient residential buildings often exceeds the impact from the use phase (Azari and Abbasabadi, 2018). In addition, a recent publication shows that the embodied and operational impacts of residential buildings in France are not correlated (Hoxha et al., 2017). This is due to the fact that the drivers for the embodied impact are mainly the structural elements. Currently, the insulation materials typically do not contribute very much to the embodied energy. To ensure that the solutions from the component catalogue comply with current regulations, all components that form the envelope have a U-value of approximately 0.2. This means that the final operation energy demand is not affected regardless of the specific solution. For commercial buildings the relation between embodied and operational impact might be very different. However, the method can be extended to include the operational impact in the future. Second, despite the evaluation of different scenarios regarding the LODs evolution (see Appendix B), the method is applied on a single case study. LCA results depend on the case-study building adopted. The GWP decrease when the design phases advance because of the specific building selected for the case study, which is composed of materials with a low impact compared to the average solutions. To confirm the validity of the proposed method, it should be applied on further case studies in the future. Moreover, the method is tested for the Swiss context, by using Swiss databases and standards.

The method can be applied using any databases based on identical background data to allow for mixing. The use of the method in other national contexts should be investigated in the future.

4.4 LCA data structure for BIM

The assessment of the environmental impacts related to the building lifecycle is a very complex issue because of the high number of variables involved. The previous section provides a method to perform the LCA throughout the building design process based on the LOD of BIM. In that case, LCA data extracted from the simplified 3D model only refer to the materials and components geometrical information. However, further LCA information should be stored into a BIM to provide a more complete level of information.

The aim of this section is to structure the information content into the BIM framework in order to conduct a Life Cycle Assessment. The methodology is described in sub-section 4.4.1. In sub-section 4.4.2, an information flows matrix is developed through the investigation of the parameters responsible for the environmental impacts of buildings. Such information content is tested on a case study in sub-section 4.4.3 after implementing the proposed parameters into a BIM. The purpose is to verify that the identified parameters, implemented in the BIM environment, are sufficient to conduct the LCA. In sub-section 4.4.4, the results show that the proposed parameters could potentially improve the data reliability and consistency in the process of sharing information from the digital model to the LCA tools. The main contributions and limitations are discussed in sub-section 4.4.5.

This section is based on Cavalliere et al. (2018).

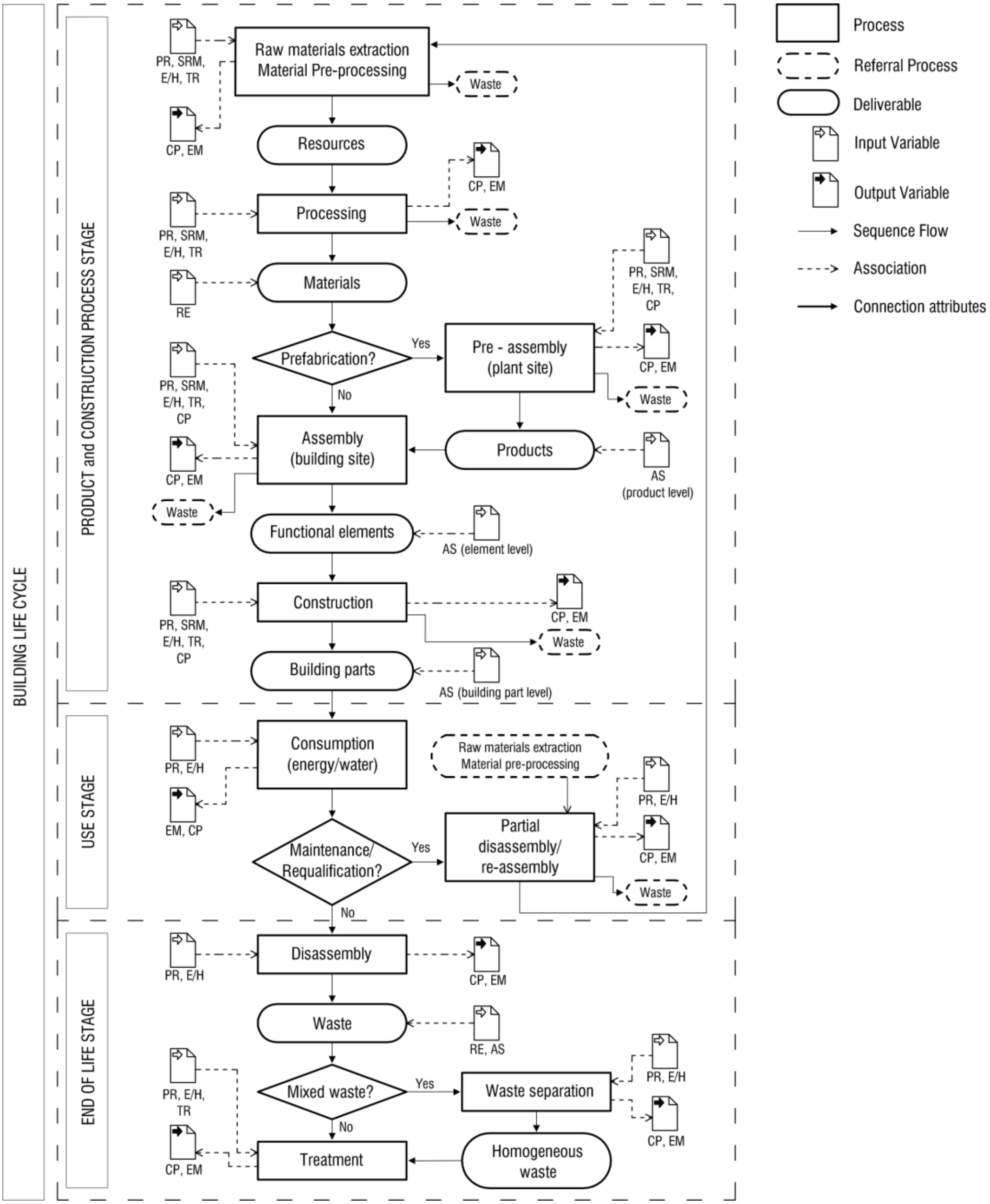
4.4.1 Methodology

The buildings lifecycle oriented analysis refer to the impacts related to the product and construction stage (from raw materials extraction to construction installation processes), use (consumption flows, maintenance, reconfiguration), and end of life stage (demolition or disassembly, transportation to the treatment site and end of life scenario) (Ramesh et al., 2010). In this context, it is possible to identify several variables competing on the environmental impact of buildings.

This section proposes a flow-chart for mapping the design variables responsible for the environmental impacts of buildings. Each variable consist of a number of parameters, which could characterize the Building Information Model. BIM default to a minimal set of properties while at the same time providing the way to include additional data. To this end, the parameters coming from the proposed flow-chart are added to the object of the Autodesk Revit model, and they are made available in the property browser. As such, the information needed to perform the LCA is made available and exportable directly from the model. The identified parameters (BIM parameters) could be visualized in schedules and divided into categories for a better visualization. They could be modified both within the schedules or the parametric objects, and each change iteratively affects the objects semantic contents. Finally, the BIM parameters could be exported to external databases for their manual or automatic management. The proposed framework aims at identifying the BIM parameters needed to perform the LCA and testing it on a case-study building. Hence, the research intends to propose neither a tool for the automatic BIM-LCA integration nor a tool for a parametric LCA.

4.4.2 The Architecture of Variables

The proposed flow-chart, called *Architecture of Variables* (AoV), shows the design variables that contribute to the environmental impact of a building throughout its lifecycle (Fig. 36). The AoV is made by a process breakdown structure that retraces the building lifecycle according to the standard on the sustainable constructions (EN 15978, 2011). Hence, the AoV consist of a number of building *processes*. These processes lead to the production of physical objects that are called *deliverables*, such as materials, building elements, and building components. They are also identified within the flow-chart. The AoV refers to the building production processes and does not cover the ancillary processes (e.g. the impacts related to the construction equipment use, temporary works, etc.). The building processes are defined in a consequential sequence. However, in some cases they need to be linked to different processes. Therefore, the AoV introduces the concept of *referral process* whenever a certain process needs to be linked to another process or deliverable. The *variables* are identified within the AoV as input and output of processes and deliverable. Finally, the identified variables are decomposed into parameters (Table 20), which are the parameters to be implemented into the BIM environment. Two types of parameters could be identified: parameters with direct implication on the environmental impacts and those acting indirectly (Table 20). On one side, the direct parameters lead to a direct change of the LCA results. The *Weight* parameter is taken as an example: the weight gain (e.g. resulting from the installation of additional building components) directly increases the environmental impact due to the increased request for resources. On the other side, the indirect parameters must necessarily be made available in the BIM, although they do not seem to have an environmental impact. The *Reference Service Life (RSL)* parameter, for instance, does not directly lead to the environmental impact, but it characterizes the maintenance/replacement of the building elements. Low RSL values imply several replacements over the building's lifespan. Hence, the RSL has indirect implications on other parameters because, for example, it leads to the increased request for resources, electricity, and transport. However, it should be emphasised that a lower service life certainly drives to a more frequent maintenance increasing the environmental impacts, but these latter are related to the technology employed, which could change during the lifespan of the building.



Abbreviations: **AS**, Assembly; **CP**, Co-Products; **EM**, Emission; **E/H**, Electricity/Heat; **PR**, Primary Resources; **RE**, Recyclability; **SRM**, Secondary Raw Materials; **TR**, Transport.

Fig. 36 – The Architecture of Variables (AoV)

Table 20 – Variables and related parameters

VARIABLES	**DIRECT PARAMETERS**	**INDIRECT PARAMETERS**
Primary Resources (PR)	Dimension (Volume, Area, Length), Weight, Nature of the Resource (allocable to recycle, reuse, incineration, landfill)	Reference Service Life
Electricity/Heat (E/H)	Source, Power, Time of Use, Georeference	
Transport (TR)	Type of transport (wheel, rail, ship, etc.), Weight of transported material (depending on the design specifications, the supply method or the site construction, etc.), Distance, Capacity, Class, Dimension (Volume, Area, Length)	
Co-Products (CP), Secondary Raw Materials (SRM)	Dimension (Volume, Area, Length), Weight, Nature of Co-Products/Secondary Raw Materials, Time of Use	Residual Performance, Economic Residual Value
Emission (EM)	Nature of the Emission, Amount	
Recyclability (RE)	Nature of the Resource	Residual Performance, Georeference
Assembly (AS)		Connection type (Dry or Wet-assembly)

Table 21-Table 23 show the parameters belonging to each variable identified in the AoV. The parameters are uniquely coded for better identifying the information into the BIM once they are implemented. However, many of them may have the same information. For example, consider all the *Nature of the Resource* parameters related the different *Primary Resources* variables of the construction phase: the information associated to these parameters is the same used for the Use stage and End-of-life stage for characterizing the material/product to be maintained/disposed. To this end, many parameters are related to each other and the information is redundant within the BIM.

Table 21 – Variables and related parameters of the Product and Construction Process stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
Product and Construction Process (C)	Raw material extraction (ME)	Waste	Primary Resources - (PR)	C.ME.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.ME.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.ME.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.ME.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products - (CP)	C.ME.CP	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.ME.EM	NoE, Am
	Processing (PG)	Waste	Primary Resources - (PR)	C.ME.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.PG.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.PG.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.PG.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products - (CP)	C.PG.CP	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.PG.EM	NoE, Am
	Materials (MT)	–	Recyclability - (RE)	C.MT.RE	NoR, RP, Geo
	Pre-Assembly (plant site) (PA)	Waste	Primary Resources - (PR)	C.PA.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.PA.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.PA.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.PA.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products (inflow) - (CPi)	C.PA.CPi	RP, Dim, We, NCP, TU, ERV
			Co-Products (outflow) - (CPo)	C.PA.CPo	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.PA.EM	NoE, Am
	Products (PRD)	–	Assembly - (AS)	C.PRD.AS	CT
	Assembly (building site) (AS)	Waste	Primary Resources - (PR)	C.AS.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.AS.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.AS.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.AS.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products (inflow) - (CPi)	C.AS.CPi	RP, Dim, We, NCP, TU, ERV
			Co-Products (outflow) - (CPo)	C.AS.CPo	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.AS.EM	NoE, Am
	Functional Elements (FE)	–	Assembly - (AS)	C.FE.AS	CT
	Construction (C)	Waste	Primary Resources - (PR)	C.C.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.C.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.C.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.C.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products (inflow) - (CPi)	C.C.CPi	RP, Dim, We, NCP, TU, ERV
			Co-Products (outflow) - (CPo)	C.C.CPo	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.C.EM	NoE, Am
	Building Elements (BE)	–	Assembly - (AS)	C.BE.AS	CT

Abbreviations: **Am**, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **NSRM**, Nature of Secondary Raw Materials; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

Table 22 – Variables and related parameters of the Use stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
Use (U)	Consumption (CO)	–	Primary Resources - (PR)	U.CO.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	U.CO.E/H	So, Pw, TU, Geo
			Emissions - (EM)	U.CO.EM	NoE, Am
			Coproducts - (CP)	U.CO.CP	RP, Dim, We, NCP, TU, ERV
	Partial disassembly (PD)	Raw materials extraction Waste	Primary Resources - (PR)	U.PD.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	U.PD.E/H	So, Pw, TU, Geo
			Emissions - (EM)	U.PD.EM	NoE, Am
			Coproducts - (CP)	U.PD.CP	RP, Dim, We, NCP, TU, ERV

Abbreviations: **Am**, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

Table 23 – Variables and related parameters of the End of Life stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
End of Life (EoL)	Disassembly (DI)	–	Primary Resources - (PR)	EoL.DI.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	EoL.DI.E/H	So, Pw, TU, Geo
			Emissions - (EM)	EoL.DI.EM	NoE, Am
			Coproducts - (CP)	EoL.DI.CP	RP, Dim, We, NCP, TU, ERV
	Waste (WA)	–	Recyclability - (RE)	EoL.WA.RE	NoR, RP, Geo
			Assembly - (AS)	EoL.WA.AS	CT
	Waste separation (WS)	–	Primary Resources - (PR)	EoL.WS.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	EoL.WS.E/H	So, Pw, TU, Geo
			Emissions - (EM)	EoL.WS.EM	NoE, Am
			Coproducts - (CP)	EoL.WS.CP	RP, Dim, We, NCP, TU, ERV
	Treatment (TT)	–	Primary Resources - (PR)	EoL.TT.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	EoL.TT.E/H	So, Pw, TU, Geo
			Transport - (TR)	EoL.TT.TR	ToT, We, Dis, Cap, Class, Dim
			Emissions - (EM)	EoL.TT.EM	NoE, Am
			Coproducts - (CP)	EoL.TT.CP	RP, Dim, We, NCP, TU, ERV

Abbreviations: **Am**, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

4.4.3 Case study

The proposed parameters are tested on the exterior walls of a new multi-dwelling building located in Bari, Italy. The building is shown in Fig. 37 while Table 24 provides the main features of the whole building. The LCA performed allows verifying if the LCI requirements are covered by the proposed parameters. That way it would make it possible to verify the completeness of the LCA information stored into the building model, providing the basis for the BIM-LCA integration. The test on the case study has two steps. The LCA is performed first. Second, it is verified that all the data required for the LCA are identified amongst the proposed BIM parameters. In other words, the study does not start extracting data from the BIM and then using them for the analysis: in that case, the flow-chart would be implicitly verified.

The performed LCA follow the steps defined by ISO 14040:2006 (Fig. 1). The remainder of this sub-section provides information related to the Goal and Scope definition of the LCA, the description of the functional unit and system boundaries, and the inventory analysis for the LCI. Results of the LCIA phase are shown in the sub-section 4.3.3. The LCA results are slightly discussed in the same-subsection to cover the Interpretation phase of the LCA, and comparative analysis against other technical solutions is not provided. In fact, the focus of this study is not the environmental impacts of the case study, but it is rather the analysis of the proposed BIM parameters.

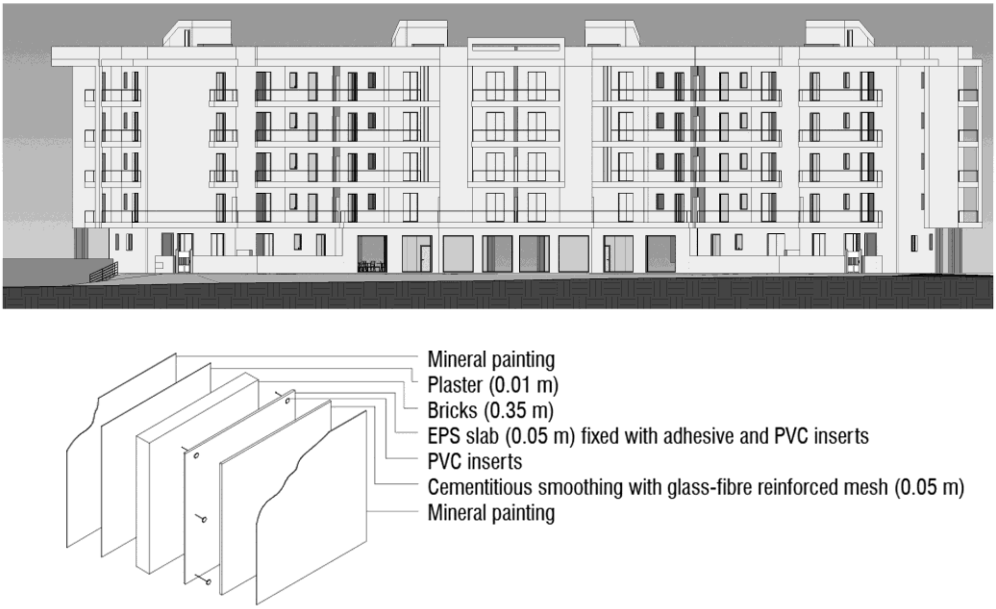


Fig. 37 – Top, 3D model of the reference building; bottom, exterior wall as case study for LCA

Table 24 – Main features of the reference building

FEATURES	**REFERENCE BUILDING**
Type	Multi-dwelling building
No. of stairwells	4
No. of floors	4 + high floor
Apartments per floor	2 (per each stairwells)
Elevation per floor	2.74 m
Structure	Reinforced concrete
External wall	Bricks with thermal insulation in Expanded Polystyrene Sintered (EPS) slabs (5 cm), fixed to the wall with adhesive and PVC inserts
Base slab	Insulation of the first floor with EPS slabs (10 cm), placed at the bottom of screed plants system (7cm) and parquet or tile flooring, fixed with adhesive/mortar
Intermediate slab	Stratification of the intermediate floor with a screed plants system (7 cm), PE sound-absorbing layer (0.8 cm), screed for the partition of loads (5 cm) and flooring (same types above mentioned)
Roof	Flat roof with a PE vapour barrier, XPS slabs layer (8 cm), PE sheets, screed slope (7 cm) and bitumen sheet
Windows	Double glazing (4-16-4 mm), cavity of argon air and PVC frame

Goal and scope definition

The LCA aims at evaluating the environmental impact of the external walls of the reference building depicted in Table 24 throughout its whole lifecycle. The lifespan of the whole building is assumed to be 50 years according to the most of the published studies (Mastrucci et al., 2017; Moschetti et al., 2015; Sartori and Hestnes, 2007). The LCIA is performed with the IMPACT 2002+ method by SimaPro 8.0.4.30 software. LCA results are normalized using midpoint impacts indicators.

Functional unit and system boundaries

The functional unit is the external wall of the reference building defined in Table 24. The external surface area of the external wall is equal to 2484.20 m^2 with a U-value of 0.213 W/m^2K. The wall is layered as follows. It is made up of bricks with a thickness of 0.35 m. They are placed with cement mortar of 1800 Kg/m^3 density and thickness of 0.007 m. A thermal insulation in Expanded Polystyrene Sintered (EPS) slab (thickness 0.05 m) is installed with the adhesive and PVC inserts. A cementitious smoothing with a drowned glass fibre-reinforced mesh is applied on the insulating slab. The external finishing completes the technological solution.

As regard the system boundaries, the LCA covers the Product and Construction, Use, and EoL stage in 50 years. The extraction of raw materials, the production of building materials, the on-site assembly processes of building components, and transports are considered in the Product and Construction process stage. The Use phase only refers to the maintenance (the demolition and disposal of building elements to be replaced and the production and assembly of new products), while neglecting the operational energy use and the operational water use. According to the RSL of the building components, the external finishing is replaced every 10 years. Therefore, four maintenance activities occur during the lifetime of the building. The EPS slabs, cement mortar for gluing and skimming, PVC inserts, and plaster are replaced twice over the building's lifespan, since their RSL is 20 years. Because of technical aspects, the replacement of the EPS slab implies the replacement of the glass fibre-reinforced mesh, although its RSL is 50 years. The EoL phase covers the demolition and disposal of the external walls as well as the transportation of materials to the landfill site or recycling sorting plant. Technical equipment embedded in the walls are left out of the analysis. Considering the life cycle modules according to EN 15978:2011, these phases correspond to A1-A3, A4, A5, B2, B4, and C1-C4 (see Fig. 5).

Inventory analysis

The Ecoinvent v3 database with its system model allocation at the point of substitution is employed for the LCA. The Italian electricity mix is used to characterize the energy flows for the installation of materials, their assembly, and their removal or dismantling. The inventory of the construction phase covers the materials and energy flows. The transports of materials and the electricity supplies for powering the machinery for assembling and installing are taken into account. Transports are defined according to the total volume of the materials involved. Hence, the type of transport and the number of trips are related both to the volume and the weight of the materials needed for the installation of the external walls. The distance between the construction site and the bricks factory is 100 km, while it is assumed an average distance of 5 km from the factories of others materials. This assumption is employed to simplify the calculation since it does not affect the validity of the BIM parameters to be tested. The inventory of the Use stage considers the new materials for the replacement and the energy for powering the construction machinery. The energy for heating, cooling, and hot water production is not considered since the Use phase only refers to the maintenance issues in this study. The transports of the new materials (from the factory to the construction site) and the disposed ones (from the construction site to the disposal site or recycling sorting plant) are taken into account. The EoL scenarios refer to two different options: disposal without recycling and recycling. Bricks, plaster, and mortar are recycled since they can be reused as inert materials. The other materials are sent to the disposal site. As for the previous phase, the transports to convey the demolished material to the treatment plant are considered. In particular, the insulating materials are conveyed to a disposal plant that is 80 km far from the construction site. The other construction materials are conveyed to a disposal plant 15 km far.

4.4.4 Results

The LCA results are shown in Fig. 38-Fig. 40 with reference to the processes involved. Each process is identified through a numerical code. The logarithmic scale is used to better visualize the graphs. Fig. 38 shows the processes and related environmental impact in the Product and Construction stage. As previously defined, each process is characterized by a number of variables, which consist of different parameters. As such, the processes involved in the Product and Construction stage and modelled in SimaPro are identified by the related variables and parameters according to the AoV. They are shown in Table 25. As can be seen, all the processes involved can be represented by the variables identified within the AoV and they can be characterized by the related parameters. This means that the proposed parameters define the information flows required to perform the LCA. Hence, each BIM element can be characterized by the information identified in Table 25. It should be emphasised that in Table 25 some variables do not refer to any process as they rely on the deliverables, according to the AoV (Fig. 36).

The variables and parameters are defined in an inclusive way to fully detail the information throughout the entire building process. However, data can be considerably streamlined because of some redundancies. For example, the *We* parameter of the *C.ME.PR* variables is equal to the *We* parameter of *C.AS.TR* variables, since the materials used for the external walls are equal to the materials to be transported (apart from the packaging that is left out of the assessment). Other redundancies refer to the *Geo* parameter of the *C.C.E/H* variables: once the type of energy supply is fixed for the construction site, it is going to be the same. For the case study, the materials are transported on wheels with a EURO 4. Therefore, the *ToT* and *Class* parameters can be simplified as the parameters previously discussed. Hence, it is possible to streamline the amount of information. As a result, the parameters shown in Table 26 would be sufficient to perform the LCA of the Product and Construction stage. As regards the others lifecycle stages, Fig. 39 and Table 27 show the parameters related to the Use stage, while Fig. 40 and Table 28 those linked to the EoL phase.

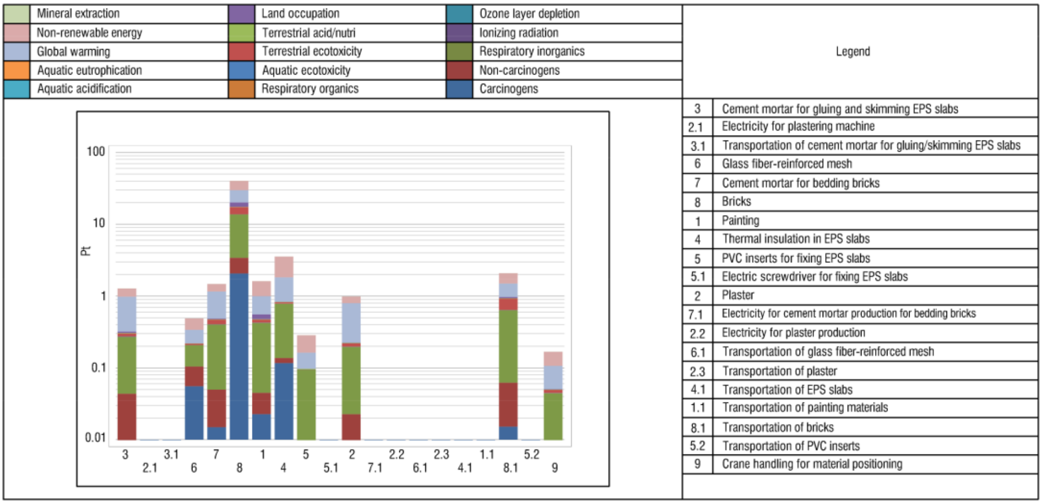


Fig. 38 – LCA of the Product and Construction Process stage

Table 25 – Processes, Variables, and parameters of the Product and Construction Process stage

PROCESSES	VARIABLES	BIM PARAMETERS
3	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
2.1	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
3.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
6	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
7	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
1	C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
4	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
5	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
5.1	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h; **Geo**: IT
2	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
7.1	C.C.E/H	**So**: Electricity; **Pw**: 1.4 kW; **Tu**: 31.30 h; **Geo**: IT
2.2	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h; **Geo**: IT
6.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.3	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2

1.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
8.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 630365.75 kg; **Dis**:100 km; **Cap**: >32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.2	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
9	C.C.E/H	**So**: Electricity; **Pw**: 16.16 kW; **Tu**: 57.14 h; **Geo**: IT
–	C.MT.RE	**NoR**: (see PR); **RP**: Yes; **Geo**: IT
–	C.PRD.AS	**CT**: Wet-assembly
–	C.FE.AS	**CT**: Wet-assembly
–	C.BE.AS	**CT**: Wet-assembly
Total parameters		**100**

Table 26 – Processes, Variables, and parameters of the Product and Construction Process stage with simplifications

PROCESSES	VARIABLES	BIM PARAMETERS
3	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
2.1	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
3.1	C.AS.TR	**ToT**: Transport on wheel; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4
6	C.ME.PR	**We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
7	C.ME.PR	**We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8	C.ME.PR	**We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
1	C.ME.PR	**We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
4	C.ME.PR	**We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
5	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
5.1	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h
2	C.ME.PR	**We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
7.1	C.C.E/H	**So**: Electricity; **Pw**: 1.4 kW; **Tu**: 31.30 h
2.2	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h
6.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
2.3	C.AS.TR	**Dis**: 5 km; **Cap**: > 32 metric ton
4.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
1.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
8.1	C.AS.TR	**Dis**: 100 km; **Cap**: >32 metric ton
5.2	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
9	C.C.E/H	**So**: Electricity; **Pw**: 16.16 kW; **Tu**: 57.14 h
–	C.MT.RE	**NoR**: (see PR); **RP**: Yes; **Geo**: IT
–	C.PRD.AS	**CT**: Wet-assembly
–	C.FE.AS	**CT**: Wet-assembly
–	C.BE.AS	**CT**: Wet-assembly
Total parameters		**64**

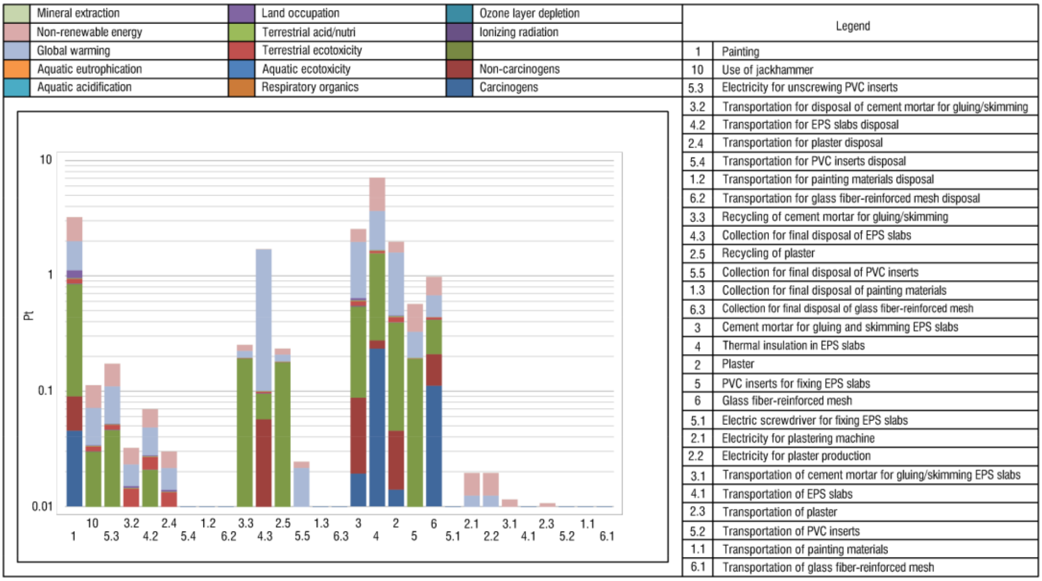


Fig. 39 – LCA of the Use stage

Table 27 – Processes, Variables, and related parameters of the Use stage

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
1	–	C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
10	U.PD.E/H	EoL.DI.E/H	**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	U.PD.E/H	EoL.DI.E/H	**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT
3.2	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.2	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 80 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.4	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.4	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
1.2	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
6.2	–	EoL.TT.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
3.3	–	EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
4.3	–	EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
2.5	–	EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
5.5	–	EoL.TT.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
1.3	–	EoL.TT.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
6.3	–	EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
3	–	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
4	–	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years

2	–	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
5	–	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
6	–	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
5.1	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h; **Geo**: IT
2.1	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
2.2	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h; **Geo**: IT
3.1	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.1	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.3	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.2	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
1.1	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
6.1	–	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
Total parameters			**140**

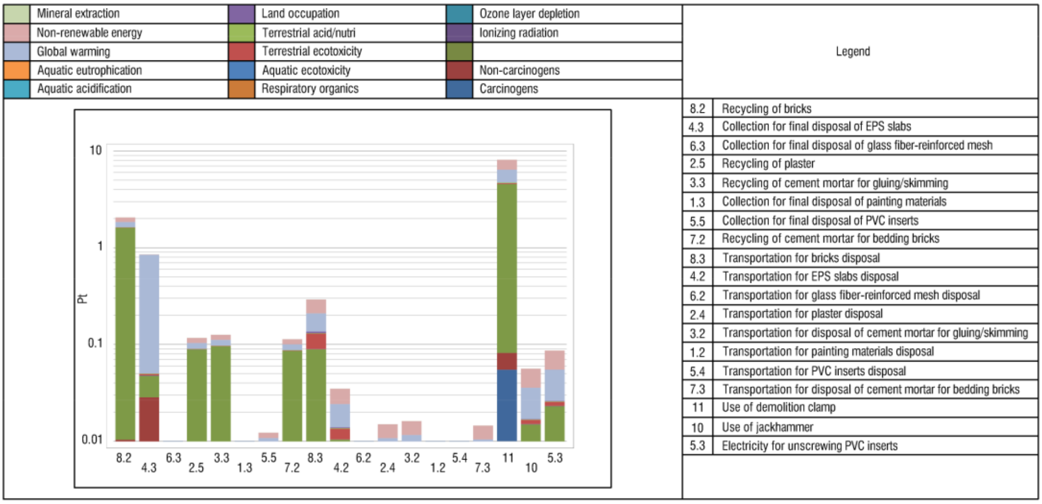


Fig. 40 – LCA of the End of Life stage

Table 28 – Processes, Variables, and related parameters of the End of Life stage

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
8.2	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
4.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
6.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
2.5	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
3.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
1.3	EoL.TT.PR	C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
5.5	EoL.TT.PR	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
7.2	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8.3	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 630365.75 kg; **Dis**:15 km; **Cap**: >32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 80 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
6.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.4	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
3.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
1.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
5.4	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
7.3	EoL.TT.TR	–	**ToT**: Transport on wheel; **We**: 31300.92 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
11	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 200 kW; **Tu**: 248 h; **Geo**: IT
10	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT

–	EoL.WA.RE	–	**NoR**: (see PR); **RP**: None; **Geo**: IT
–	EoL.WA.AS	–	**CT**: Wet-assembly
Total parameters			**96**

As can be seen in Table 27 and Table 28, a total of 236 parameters are needed to perform the LCA of the Use and the EoL phase of the case study. However, as previously defined, several parameters have some correlations. The Use and EoL phases necessarily refer to the materials flow required for the Product and Construction phase, and the related information have already been defined. This occurs when assuming that the maintenance activities are based on the same technology and materials involved in the Construction phase. In the Use and EoL phase, additional parameters can be modelled in BIM. They mainly refer to the transport and disassembly/demolition activities. As proof of this, the columns called "reference" in the Table 27 and Table 28 show the reference variables from which information is derived for modelling the parameters. The process 8.2 in Table 28 is taken as an example: according to the AoV, the parameters related to the *EoL.TT.PR* variable are the same parameters modelled for the *C.ME.PR* variable of the process 8 of the Construction phase. This means that these parameters have already been modelled and, for this reason, are redundant. Hence, the *C.ME.PR* variable is defined as a reference for the *EoL.TT.PR* variable. It should be noted that most of the processes only refer to the “reference" column for defining the variable in Table 27. This is due to the fact that the Use phase involves referral processes when the information refers to different life cycle phases than the one under consideration (see Fig. 36). The process 1 in Table 27 is taken as an example: the parameters refer to the paint that is to be restored, and they are the same as those of *C.ME.PR* variable of the Construction phase. Therefore, according to the "reference" columns in Table 27 and Table 28, it is possible to clear the redundant information. All the parameters of the Use phase are related to the variables of the Construction and EoL phase (see the "reference" column, Table 27). Thus, they can be removed from the BIM. In the case study shown, with reference to the Use phase, no additional parameters are required to perform the LCA. This happens since this study does not cover the operational energy use and the operational water use. In the EoL phase, some correlations are identified. The parameters not related to any reference variable, however, are not redundant. Furthermore, the parameters belonging to the *EoL.TT.TR* variables in Table 28, referring to the *C.AS.TR* variables, are not all redundant. On the one hand, the data related to the *ToT*, *We*, *Cap*, *Class*, and *Dim* parameter is the same used to define the parameters in the Construction phase. On the other hand, the *Dis* parameter is different in the EoL phase. In fact, while it refers to the distance between the construction site and the materials factory in the Construction phase, in the EoL phase it defines the distance between the construction site and the final treatment site. In addition, only few redundancies affect the parameters related to the *EoL.TT.TR* variable of the process 7.3. This comes from the fact that the cement mortar is not moved from the production site but it is produced directly on-site. For that reason, the redundancies only affect the *We* and *Dim* parameters. Table 29 shows the parameters of the EoL phase without correlations.

Table 29 – Processes, Variables, and related parameters of the End of Life stage with simplifications

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
8.3	EoL.TT.TR	C.AS.TR	**Dis**:15 km
4.2	EoL.TT.TR	C.AS.TR	**Dis**: 80 km
6.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
2.4	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
3.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
1.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
5.4	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
7.3	EoL.TT.TR	C.ME.PR	**ToT**: Transport on wheel; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4
11	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 200 kW; **Tu**: 248 h; **Geo**: IT
10	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	EoL.DI.E/H	–	**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT
–	EoL.WA.RE	–	**NoR**: (see PR); **RP**: None; **Geo**: IT
–	EoL.WA.AS	–	**CT**: Wet-assembly
Total parameters			**27**

4.4.5 Discussion

The proposed flow-chart identifies the relevant BIM parameters needed for performing the LCA. According to the case study, the proposed parameters are sufficient for conducting the LCA of the external wall. The storage of this information into the

BIM during the design process makes it possible to have LCA data when needed. The analysis shows that it is possible to provide the BIM with a non-too high number of parameters, since most of them are correlated. Table 30 shows the BIM parameters needed to conduct the LCA, clearing the interconnections found in the proposed case study. As previously discussed, each BIM object is defined by a number of parameters. Hence, with reference to the modelling activities, Table 31 shows the BIM parameters required to characterize each object/material of the case study as well as the means and tools necessary for its construction. The rows of the table refer to the instances modelled within the BIM. They are related to the single layer/material of the external wall as well as the equipment for its implementation. Each material is linked to one or more processes that have a number of parameters.

Table 30 – BIM-LCA parameters

Lifecycle stages	**Complete parameters**	**Parameters with simplifications**
Product and Construction Process	100	64
Use	140	0
End of Life	96	27
Total parameters	**336**	**91**

Table 31 – BIM parameters related to each BIM element, with simplification

BIM ELEMENT	**PROCESSES**	**BIM PARAMETERS**	**TOTAL PARAMETERS**
Painting	1; 1.1; 1.2	C.ME.PR.**We/NoR/RSL**; C.AS.TR.**Dis/Cap**; EoL.TT.TR.**Dis**	6
Plaster	2; 2.1; 2.2; 2.3; 2.4	C.ME.PR.**We/NoR/RSL**; C.C.E/H.**So/Pw/Tu/Geo**; C.C.E/H.**So/Pw/Tu**; C.AS.TR.**Dis/Cap**; EoL.TT.TR.**Dis**	13
Cement mortar for gluing/skimming	3; 3.1; 3.2	C.ME.PR.**Dim/We/NoR/RSL**; C.AS.TR.**ToT/Dis/Cap/Class**; EoL.TT.TR.**Dis**	9
EPS slab	4; 4.1; 4.2	C.ME.PR.**We/NoR/RSL**; C.AS.TR.**Dis/Cap**; EoL.TT.TR.**Dis**	6
PVC inserts	5; 5.1; 5.2; 5.3; 5.4	C.ME.PR.**Dim/We/NoR/RSL**; C.C.E/H.**So/Pw/Tu**; C.AS.TR.**Dis/Cap**; EoL.DI.E/H.**So/Pw/Tu/Geo**; EoL.TT.TR.**Dis**	14
Glass fibre-reinforced mesh	6; 6.1; 6.2	C.ME.PR.**We/NoR/RSL**; C.AS.TR.**Dis/Cap**; EoL.TT.TR.**Dis**	6
Cement mortar for bedding bricks	7; 7.1; 7.3	C.ME.PR.**We/NoR/RSL**; C.C.E/H.**So/Pw/Tu**; EoL.TT.TR.**ToT/Dis/Cap/Class**	10
Bricks	8; 8.1; 8.3	C.ME.PR.**We/NoR/RSL**; C.AS.TR.**Dis/Cap**; EoL.TT.TR.**Dis**	6
Crane	9	C.C.E/H.**So/Pw/Tu**	3
Jackhammer	10	EoL.DI.E/H.**So/Pw/Tu/Geo**	4
Demolition clamp	11	EoL.DI.E/H.**So/Pw/Tu/Geo**	4

Table 31 does not include the parameters of the deliverables shown by AoV as they do not refer to any process and, therefore, to no BIM element. The information related to the parameters of the deliverables is not part of the information flow of a specific BIM element, but it is included among the information of the model or a group of BIM elements. Table 31 shows that each BIM element is characterized by few parameters, which are sufficient to conduct the LCA of the case study. However, the study does not comply with the operational impact. The parameters defined could be tested at the whole building level in the future, also covering the operational impacts.

Structuring parameters is achievable in all BIM software used. However, parameters have to be implemented in the right place. Manufacturers have to be aware of it, and need to provide BIM objects with the right level of information, duly localised. Moreover, breaking BIM components as they are built in real life with real materials is another challenge, more complex when it comes to associating parameters. These topics are treated in the BIM research community and product modelling activities. Nowadays, researchers tackle the issues of how to link BIM to external databases and include BIM objects in the models. Also norms and standards are being elaborated by ISO and CEN in this direction (i.e. CEN/TC 442/WG 4).

The environmental impact of the case study is assessed with IMPACT 2002+ method. The IMPACT 2002+ methodology combines midpoint approaches and endpoint methodologies by linking the life cycle inventory results via midpoint categories (namely: mineral extraction, non-renewable energy, global warming, aquatic eutrophication, aquatic acidification, land occupation, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic ecotoxicity, respiratory organics, ozone layer depletion, ionizing radiation, respiratory inorganics, non-carcinogens, carcinogens) to four damage categories (human health, ecosystem quality, climate change, and resources). For the purpose of the proposed study, the choice of a certain impact assessment method does not affect the findings of the proposed framework, and the comparison of different impact methods does not add any benefit in testing the validity of the BIM parameters.

LCA is conducted with the use of SimaPro to generalize the method. Generic LCA tools, such as SimaPro and Gabi, have been developed for the LCA of products and processes. In the design practices, these tools are not easy to use since they require extensive background knowledge. Nevertheless, to meet the goal of the study, a generic tool is suitable to test the proposed BIM parameters in a comprehensive manner. However, in order to test the usability of the proposed parameters, future research may involve the use of different impact assessment methods as well as different LCA tools, such as spreadsheet-based tools, component catalogues, and BIM-based tools.

5. OVERALL DISCUSSION

The thesis identifies new ways of looking at BIM-led LCA by proposing a novel approach to continuously perform the LCA throughout the design process and increasing the level of knowledge of BIM information from a life cycle perspective.

Detailed discussion related to the novel proposals is presented along with the results of the thesis (see section 4.3.4 and 4.4.5), and here they are compared to the core of the methods in order to advance from information to knowledge.

The thesis faces the difficulties of coherently performing BIM-based LCA throughout the building design process since the current approaches usually apply it only within a specific design stage, which is early or late design phase. Besides, typical BIM-based LCA methods only refers to geometrical data of materials and components, which are extracted from the BIM. However, it is demonstrated that further LCA data should exist into the BIM to achieve a higher level of knowledge. To this end, the thesis identifies the relevant information to conduct the LCA of buildings, which can be used as BIM parameters. Other specific aspects arise from the application of the novel methods proposed and they should be definitely evolved in the future. These themes are closely debated in the discussion sections along with the results in sections 4.3 and 4.4.

The main challenges addressed by the thesis are:

- Ch1: Continuous BIM-based LCA throughout the design process;
- Ch2: Use of BIM not only as a repository of information about quantities;
- Ch3: Understanding the processes involved during the building's lifecycle.

The thesis proposed new ways of facing with these challenges arising from the state of the art. In order to achieve the goals, several limitations were exceeded using BIM key aspects.

Performing continuously BIM-based LCA during the entire design process deals with the project-based nature of the construction industry since each building is unique with its own characteristics, and each building project is carried out in a different way related to different conditions, individual needs, and special locations. Thus, several assumptions usually need to be adopted. Also, the amount of data for conducting a LCA of buildings and the lack of consistent information at the early stage of the building design process are additional obstacles for coherently applying BIM-led LCA during the whole design process. The thesis demonstrated how to solve this issues pointing out the "deliverables dilemma". Indeed, within the information processes at the different design stages, it is crucial to define what information is needed and how much detailed it must be. BIM objects are modelled into different LODs depending on the BIM uses and the project milestone, which usually grow reflecting the project progression. Hence, as the project grows, BIM elements are modelled with more information in order to support more detailed analyses. These issues are the core of the thesis. The proposed method and its application to a real case-study building show that it is possible to continuously perform the BIM-based LCA throughout the whole design process by mixing varous LCA databases, which is possible as long as the they use identical background data. The method has not been considered by any method described in the literature review and allows overcoming the current problem of disconnection between BIM-based LCA for early or late design phases. Consistent LCA results are shown in terms of variability of LCA results. Indeed, the variability of GWP and PENRT – used as environmental indicators, decreases from the early to the final design phases because of using more refined data at higher LODs. The GWP (and PENRT) in a specific design stage is within the variability of the previous one. This way the method provides reliable information for decision-making during the entire design process since it employs the BIM data with as much accuracy as possible in each design stage. However, when analysing the outcome of individual building elements, the results do not keep the general trend because of some issues. It is shown that some overestimations occur when some building components are excluded from the LOD 300 onwards. In fact, as a general rule of designing, the method considers all the building components when modelling at the early design stages with LOD 100 and LOD 200, since it is unknown which components will be part of the final solution at the end of the design process. Also, the limited number of LCA datasets can affect the consistency of the results since some specific construction materials are not included. However, these are evidence of minor inconsistencies since they are not visible when showing the overall results by summing the results of all building elements to perform the LCA of the entire building. In fact, the environmental impacts of the case-study building in a specific design stage fall within the variability range of the previous one.

The second main contribution of the research faced with the challenges of using BIM only as a repository of geometrical information about quantities and the difficulty of thoroughly understanding the processes involved during the building's lifecycle. Here, the project-based nature of the construction industry and the amount of data needed are found to hinder the BIM-based application once again. BIM software functionalities is a key aspect for overcoming these obstacles. For example, current BIM platforms provide the capability of extending the set of properties. BIM users can add specific parameters to each object to produce a certain type of simulation, cost estimate, or analysis as in the case of Life Cycle Assessment. Starting from this scenario, the thesis proposes a new flow-chart to identify all the relevant parameters that contribute to the environmental impact of a building throughout its lifecycle. This is made by a process breakdown structure that retraces the building lifecycle in accordance to the standard on the sustainable constructions. The thesis demonstrates that it is possible to achieve a high level of knowledge information by providing the BIM with a non-too high number of parameters. Indeed, the application of the proposed flow-chart to a building case-study demonstrate that several BIM-LCA parameters are correlated each other and they can be streamlined accordingly. Using BIM to store environmental information enables one to have LCA data when needed. However, it is highlighted that parameters have to be implemented in the right place despite structuring new information is achievable in all BIM software used. This refers to a new challenge in the field of BIM-LCA integration, also identified in the previous chapter but not addressed by the thesis, and it turn out to be a new starting point for future development.

6. CONCLUSION & OUTLOOK

BIM-led LCA is recognized to be a powerful approach to reach sustainable building projects. On the one side, Life Cycle Assessment is a suitable method for assessing the environmental impacts of buildings as it can calculate both the potential environmental impacts and resources used throughout the whole lifecycle of products or services. On the second side, BIM creates major benefits and opportunities of improving traditional practices with fewer resources and lower risk.

Although the literature recognizes the advantages of BIM-LCA integration, the debate arising from the state of the art shows that BIM-based LCA is a complex task due to several embedded LCA limitations that hinder the fully integrations of tools. Also, while it is demonstrated that the BIM-based LCA reduces time and improve the performance of buildings, some methodological challenges arise from the literature in terms of applications. They are discussed and mainly summarized in the section 4.2.1. Here, the limitations of LCA of buildings, BIM key factors, and BIM-LCA integration challenges are interconnected each other to show a general background in the field of investigation. It is shown how the challenges of BIM-based LCA improvement are hindered by specific LCA limitations, while some BIM key aspects could support the LCA based on BIM. The thesis faces three of the BIM-LCA challenges identified and shown in Fig. 17. The challenge of applying a "continuous BIM-based LCA throughout the design process" is firstly addressed by the thesis. Secondly, the challenges of using the "BIM not only as a repository of geometrical information" and "understanding the processes involved in building's lifecycle" are analysed together.

The thesis proves that it is possible to perform LCA in all phases of the building design process using BIM. Currently, it is difficult to apply the LCA during the entire building design process because the necessary data are only complete in the latest phases. The proposed approach divides the building into functional elements, which consists of several building components. Then, the building components have different functions, and belong to different construction categories because they are typically modelled at different LODs in different planning stages. The LCA is consistently performed by mixing the LCA databases according to the LOD of the building elements at different design stages. By involving the use of different databases that match the LOD of the BIM elements, LCA can be conducted with the maximum level of information accuracy available at the current design stage, providing a continuous workflow over the building design process. Hence, LCA can be performed even when information is almost missing, and the LCA results are as accurate as possible at all times. As a result, the method enables the use of LCA as a decision-making tool to reach more sustainable solutions from the early to the detailed design phases. In fact, as demonstrated by the case study, it is possible to forecast the final environmental impact from the early design stages. According to the method, the results show that the variability of the environmental impact decreases from the early design phases to the final one because estimations are performed from lower to higher accuracy based on increased LOD. The environmental impact in a certain design stage is within the variability of the previous one, confirming the reliability of the proposed method. This method refers to length, area, and volume of different materials and components, which are extracted from a 3D model. However, further LCA data should be stored into a BIM to provide a complete level of information. Usually, building information models lack of data for the LCA. To counter this lack, additional activities need to be considered to have detailed information when the BIM is finished. To this end, the thesis identifies and encodes the relevant parameters to perform the LCA of buildings, which can be implemented in the BIM environment as BIM parameters. A case study is presented to test the effectiveness of the proposed parameters for performing the LCA once extracted from the BIM. The proposed parameters are uniquely coded for better identifying the information into the BIM in a non-redundant way. This approach allows extracting information directly from the template in a consistent manner, reducing the risk of errors, approximations, and omissions due to inconsistent or missing data. Hence, the LCA can be performed as soon as the building information model is ready for the analysis. The proposed framework fills the information gap between the extracted BIM parameters and the LCA data requirements. This leads to the reduction of time-consuming activities and assumptions made.

The studies carried out in this thesis are mainly based on the embodied impact of the building. In the first case, the cycle modules A1-A3, B4, C3, and C4 are taken into account. In the second case the modules A1-A3, A4, A5, B2, B4, and C1-C4 are considered. The thesis focus on the embodied impact of buildings since it will became more relevant as demonstrated by the studies shown in the Introduction section and in the sub-section 4.3.4. Moreover, the methods refer to individual residential buildings. To further improve the proposed framework, the operational impact should be included and additional case studies should be investigated since the general approach of the methods is identical. The continuous BIM-based LCA throughout the building design process was applied to the Swiss context by using Swiss databases and standards, although different LODs scenarios were evaluated in the Appendix B. Further investigation could be integrated in the future with the reference to different national contexts by using any databases based on identical background data.

Here, it is demonstrated how the BIM-led LCA is a suitable method for achieving more environmentally sustainable buildings. The proposed framework is an additional step to reach it. The world’s resources and world’s ability to absorb emissions are limited. Designers have to be aware of it, and they need to shift their approaches towards sustainability.

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APPENDIX A

Table 32 – GWP values of foundation using Bauteilkatalog database at different LODs

Foundation									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C1 Fundament	C1 002 Flachfundation bis 4 Geschosse B 80 kg/m3, 5cm	1,24	1,69	1,94	1,24	3,16	7,81	1,41
	C1 Fundament	C1 003 Flachfundation 5 oder 6 Geschosse B 90 g/m3, 35 cm	1,68						
	C1 Fundament	C1 003a Flachfundation 5 oder 6 Geschosse B 90 kg/m3, 35 cm, waermegedaemmt	1,94						
	C1 Fundament	C1 004 Flachfundation ab 7 Geschosse B 95kg/m3, 40 cm	1,91						
G2	G2 Bodenbelag	G2.2 108a Unterlagsboden mit Trittschall, Anhydrit	0,28	1,47	5,87	0,17			
	G2 Bodenbelag	G2.2 108b Unterlagsboden mit Trittschall, Zement	0,90						
	G2 Bodenbelag	G2.2 108c Unterlagsboden mit Trittschall und Waermedaemmung, Anhydrit	1,70						
	G2 Bodenbelag	G2.2 108d Unterlagsboden mit Trittschall und Waermedaemmung, Zement	2,33						
	G2 Bodenbelag	G2.2 109a Unterlagsboden ohne Trittschall, Anhydrit	0,17						
	G2 Bodenbelag	G2.2 109b Unterlagsboden ohne Trittschall, Zement	0,79						
	G2 Bodenbelag	G2.2 110 Zementueberzug	0,44						
	G2 Bodenbelag	G2.3 113 Gussasphalt	5,87						
	G2 Bodenbelag	G2.3 118 Naturstein-Bodenbelaege einheimisch	0,73						

Table 33 – PENRT values of foundation using Bauteilkatalog database at different LODs

Foundation									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
C	C1 Fundament	C1 002 Flachfundation bis 4 Geschosse B 80 kg/m3, 25cm	12,99	18,69	22,55	12,99	29,91	43,25	15,8
	C1 Fundament	C1 003 Flachfundation 5 oder 6 Geschosse B 90 kg/m3, 35 cm	18,23						
	C1 Fundament	C1 003a Flachfundation 5 oder 6 Geschosse B 90 kg/m3, 35 cm, waermegedaemmt	22,55						
	C1 Fundament	C1 004 Flachfundation ab 7 Geschosse B 95kg/m3, 40 cm	21,01						
G2	G2 Bodenbelag	G2.2 108a Unterlagsboden mit Trittschall, Anhydrit	7,06	11,21	20,70	2,85			
	G2 Bodenbelag	G2.2 108b Unterlagsboden mit Trittschall, Zement	8,52						
	G2 Bodenbelag	G2.2 108c Unterlagsboden mit Trittschall und Waermedaemmung, Anhydrit	17,00						
	G2 Bodenbelag	G2.2 108d Unterlagsboden mit Trittschall und Waermedaemmung, Zement	18,45						
	G2 Bodenbelag	G2.2 109a Unterlagsboden ohne Trittschall, Anhydrit	3,87						
	G2 Bodenbelag	G2.2 109b Unterlagsboden ohne Trittschall, Zement	5,32						
	G2 Bodenbelag	G2.2 110 Zementueberzug	2,85						
	G2 Bodenbelag	G2.3 113 Gussasphalt	17,17						
	G2 Bodenbelag	G2.3 118 Naturstein-Bodenbelaege einheimisch	20,70						

Table 34 – GWP values of exterior wall under ground using Bauteilkatalog database at different LODs

Exterior wall under ground									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C2.1A Aussenwand unter Terrain	C2.1A 029 Betonwand bis K32, 20cm, B 90 kg/m3	1,32	1,53	1,67	1,32	3,73	3,87	3,52
	C2.1A Aussenwand unter Terrain	C2.1A 030 Betonwand ueber K32, 25cm, B 85 kg/m3	1,59						
	C2.1A Aussenwand unter Terrain	C2.1A 031 Betonwand ueber K32, 25 cm, wasserdicht, B 110 kg/m3	1,67						
E	E1 Aussenwandbekleidung unter Terrain	E1 134 Waermedaemmung unter Terrain	2,20	2,20	2,20	2,20			

Table 35 – PENRT values of exterior wall under ground using Bauteilkatalog database at different LODs

Exterior wall under ground									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
C	C2.1A Aussenwand unter Terrain	C2.1A 029 Betonwand bis K32, 20cm, B 90 kg/m3	11,99	13,95	15,63	11,99	30,67	32,35	28,71
	C2.1A Aussenwand unter Terrain	C2.1A 030 Betonwand ueber K32, 25cm, B 85 kg/m3	14,23						
	C2.1A Aussenwand unter Terrain	C2.1A 031 Betonwand ueber K32, 25 cm, wasserdicht, B 110 kg/m3	15,63						
E	E1 Aussenwandbekleidung unter Terrain	E1 134 Waermedaemmung unter Terrain	16,72	16,72	16,72	16,72			

Table 36 – GWP values of exterior wall above ground using Bauteilkatalog database at different LODs

Exterior wall above ground									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C2.1B Aussenwand ueber Terrain	C2.1B 058 Holzrahmenkonstruktion	0,78	1,39	3,02	0,55	3,24	7,97	0,96
	C2.1B Aussenwand ueber Terrain	C2.1B 060 Porenbeton	3,02						
	C2.1B Aussenwand ueber Terrain	C2.1B 061 Einsteinmauerwerk Hochlochbackstein	2,09						
	C2.1B Aussenwand ueber Terrain	C2.1B 035 Betonwand bis K32, roh, 20 cm, B 90 kg/m3	1,22						
	C2.1B Aussenwand ueber Terrain	C2.1B 036 Betonwand ueber K32, roh, 20 cm, B 105 kg/m3	1,26						
	C2.1B Aussenwand ueber Terrain	C2.1B 037 Betonwand ueber K32, roh, 25 cm, B 105 kg/m3	1,56						
	C2.1B Aussenwand ueber Terrain	C2.1B 038 Backstein BN, roh tragend, 15cm	0,64						
	C2.1B Aussenwand ueber Terrain	C2.1B 040 Backstein KS, roh tragend, 15cm	0,55						
E	E2 Aussenwandbekleidung ueber Terrain	E2 042 Waermeverbundsystem, WD, Aussenputz	0,93	1,19	2,05	0,37			
	E2 Aussenwandbekleidung ueber Terrain	E2 046 Alu-Schichtstoffverbundplatte (Alucobond), Metallunterkonstruktion	1,65						
	E2 Aussenwandbekleidung ueber Terrain	E2 047 Profilglasplatten, Metallunterkonstruktion	1,52						
	E2 Aussenwandbekleidung ueber Terrain	E2 048 Alukofferblechfassade, Metallunterkonstruktion inkl. Konsolenanker	2,05						
	E2 Aussenwandbekleidung ueber Terrain	E2 049 Natursteinplatten 30 mm einheimisch, Metallunterkonstruktion	1,05						
	E2 Aussenwandbekleidung ueber Terrain	E2 050 Betonelement 16mm vorgehaengt glasfaserverstaerkt	0,68						
	E2 Aussenwandbekleidung ueber Terrain	E2 051 Feinsteinzeugplatten	1,62						
	E2 Aussenwandbekleidung ueber Terrain	E2 053 Faserzementplatten grossformatig, Mittelwert Holz/Metallunterkonstrukti	1,64						
	E2 Aussenwandbekleidung ueber Terrain	E2 054 Faserzementschindeln Holzunterkonstruktion	0,51						
	E2 Aussenwandbekleidung ueber Terrain	E2 055 Putztraegerplatten verputzt, Holzunterkonstruktion	0,83						

	E2 Aussenwandbekleidung ueber Terrain	E2 056 Stuelpschalung Fichte, Holzunterkonstruktion	0,37						
	E2 Aussenwandbekleidung ueber Terrain	E2 057 Glasplatten vorgehaengt hinterlueftet VSG 5mm, Metallunterkonstruktion	1,41						
	E2 Aussenwandbekleidung ueber Terrain	E2 044 Vorsatzschale BN 12.5cm verputzt	1,29						
	E2 Aussenwandbekleidung ueber Terrain	E2 045 Vorsatzschale KS 12cm verputzt	1,15						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	2,90	0,65	2,90	0,04			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,04						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	0,09						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	0,07						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	0,17						

Table 37 – PENRT values of exterior wall above ground using Bauteilkatalog database at different LODs

Exterior wall above ground									
Construction categories	Building components	Constructive solutions	LOD 300	LOD 200			LOD 100		
			PENRT	PENRT average	max	min	PENRT average	max	min
C	C2.1B Aussenwand ueber Terrain	C2.1B 058 Holzrahmenkonstruktion	15,1	14,58	31,29	5,50	37,73	84,29	12,64
	C2.1B Aussenwand ueber Terrain	C2.1B 060 Porenbeton	31,3						
	C2.1B Aussenwand ueber Terrain	C2.1B 061 Einsteinmauerwerk Hochlochbackstein	20,7						
	C2.1B Aussenwand ueber Terrain	C2.1B 035 Betonwand bis K32, roh, 20 cm, B 90 kg/m3	11,1						
	C2.1B Aussenwand ueber Terrain	C2.1B 036 Betonwand ueber K32, roh, 20 cm, B 105 kg/m3	11,7						
	C2.1B Aussenwand ueber Terrain	C2.1B 037 Betonwand ueber K32, roh, 25 cm, B 105 kg/m3	14,4						
	C2.1B Aussenwand ueber Terrain	C2.1B 038 Backstein BN, roh tragend, 15cm	6,8						
	C2.1B Aussenwand ueber Terrain	C2.1B 040 Backstein KS, roh tragend, 15cm	5,5						
E	E2 Aussenwandbekleidung ueber Terrain	E2 042 Waermeverbundsystem, WD, Aussenputz	17,5	17,15	28,73	6,73			
	E2 Aussenwandbekleidung ueber Terrain	E2 046 Alu-Schichtstoffverbundplatte (Alucobond), Metallunterkonstruktion	24,2						
	E2 Aussenwandbekleidung ueber Terrain	E2 047 Profilglasplatten, Metallunterkonstruktion	21,4						
	E2 Aussenwandbekleidung ueber Terrain	E2 048 Alukofferblechfassade, Metallunterkonstruktion inkl. Konsolenanker	28,7						
	E2 Aussenwandbekleidung ueber Terrain	E2 049 Natursteinplatten 30 mm einheimisch, Metallunterkonstruktion	24,0						
	E2 Aussenwandbekleidung ueber Terrain	E2 050 Betonelement 16mm vorgehaengt glasfaserverstaerkt	9,7						
	E2 Aussenwandbekleidung ueber Terrain	E2 051 Feinsteinzeugplatten	25,7						
	E2 Aussenwandbekleidung ueber Terrain	E2 053 Faserzementplatten grossformatig, Mittelwert Holz/Metallunterkonstrukti	20,7						

	E2 Aussenwandbekleidung ueber Terrain	E2 054 Faserzementschindeln Holzunterkonstruktion	8,0						
	E2 Aussenwandbekleidung ueber Terrain	E2 055 Putztraegerplatten verputzt, Holzunterkonstruktion	9,1						
	E2 Aussenwandbekleidung ueber Terrain	E2 056 Stuelpschalung Fichte, Holzunterkonstruktion	6,7						
	E2 Aussenwandbekleidung ueber Terrain	E2 057 Glasplatten vorgehaengt hinterlueftet VSG 5mm, Metallunterkonstruktion	20,4						
	E2 Aussenwandbekleidung ueber Terrain	E2 044 Vorsatzschale BN 12.5cm verputzt	13,0						
	E2 Aussenwandbekleidung ueber Terrain	E2 045 Vorsatzschale KS 12cm verputzt	11,0						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	24,3	6,00	24,27	0,41			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,4						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	1,4						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	1,3						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	2,6						

Table 38 – GWP values of window using Bauteilkatalog database at different LODs

Window									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
E	E3 Aussenwandeinbauten (Fenster)	E3 064 Holz-Fenster 2 WS S, Rahmenanteil 25%	2,08	3,17	5,57	1,49	3,17	5,57	1,49
	E3 Aussenwandeinbauten (Fenster)	E3 065 Holz-Alu-Fenster 2 WS S, Rahmenanteil 25%	3,09						
	E3 Aussenwandeinbauten (Fenster)	E3 066 Kunststoff-Fenster 2 WS S, Rahmenanteil 25%	4,08						
	E3 Aussenwandeinbauten (Fenster)	E3 067 Alu-Fenster 2 WS S, Rahmenanteil 25%	4,91						
	E3 Aussenwandeinbauten (Fenster)	E3 068 Holz-Fenster 3 WS S, Rahmenanteil 25%	2,74						
	E3 Aussenwandeinbauten (Fenster)	E3 069 Holz-Alu-Fenster 3 WS S, Rahmenanteil 25%	3,75						
	E3 Aussenwandeinbauten (Fenster)	E3 070 Kunststoff-Fenster 3 WS S, Rahmenanteil 25%	4,75						
	E3 Aussenwandeinbauten (Fenster)	E3 071 Alu-Fenster 3 WS S, Rahmenanteil 25%	5,57						
	E3 Aussenwandeinbauten (Fenster)	E3 072 Holz-Fenster 2 WS S, Rahmenanteil 10%	1,49						
	E3 Aussenwandeinbauten (Fenster)	E3 073 Holz-Alu-Fenster 2 WS S, Rahmenanteil 10%	1,89						
	E3 Aussenwandeinbauten (Fenster)	E3 074 Kunststoff-Fenster 2 WS S, Rahmenanteil 10%	2,29						
	E3 Aussenwandeinbauten (Fenster)	E3 075 Alu-Fenster 2 WS S, Rahmenanteil 10%	2,62						
	E3 Aussenwandeinbauten (Fenster)	E3 076 Holz-Fenster 3 WS S, Rahmenanteil 10%	2,28						
	E3 Aussenwandeinbauten (Fenster)	E3 077 Holz-Alu-Fenster 3 WS S, Rahmenanteil 10%	2,69						
	E3 Aussenwandeinbauten (Fenster)	E3 078 Kunststoff-Fenster 3 WS S, Rahmenanteil 10%	3,09						
	E3 Aussenwandeinbauten (Fenster)	E3 079 Alu-Fenster 3 WS S, Rahmenanteil 10%	3,42						

Table 39 – PENRT values of window using Bauteilkatalog database at different LODs

Window									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
E	E3 Aussenwandeinbauten (Fenster)	E3 064 Holz-Fenster 2 WS S, Rahmenanteil 25%	30,85	47,50	82,11	21,41	47,50	82,11	21,41
	E3 Aussenwandeinbauten (Fenster)	E3 065 Holz-Alu-Fenster 2 WS S, Rahmenanteil 25%	44,43						
	E3 Aussenwandeinbauten (Fenster)	E3 066 Kunststoff-Fenster 2 WS S, Rahmenanteil 25%	65,25						
	E3 Aussenwandeinbauten (Fenster)	E3 067 Alu-Fenster 2 WS S, Rahmenanteil 25%	71,44						
	E3 Aussenwandeinbauten (Fenster)	E3 068 Holz-Fenster 3 WS S, Rahmenanteil 25%	41,53						
	E3 Aussenwandeinbauten (Fenster)	E3 069 Holz-Alu-Fenster 3 WS S, Rahmenanteil 25%	55,10						
	E3 Aussenwandeinbauten (Fenster)	E3 070 Kunststoff-Fenster 3 WS S, Rahmenanteil 25%	75,92						
	E3 Aussenwandeinbauten (Fenster)	E3 071 Alu-Fenster 3 WS S, Rahmenanteil 25%	82,11						
	E3 Aussenwandeinbauten (Fenster)	E3 072 Holz-Fenster 2 WS S, Rahmenanteil 10%	21,41						
	E3 Aussenwandeinbauten (Fenster)	E3 073 Holz-Alu-Fenster 2 WS S, Rahmenanteil 10%	26,84						
	E3 Aussenwandeinbauten (Fenster)	E3 074 Kunststoff-Fenster 2 WS S, Rahmenanteil 10%	35,16						
	E3 Aussenwandeinbauten (Fenster)	E3 075 Alu-Fenster 2 WS S, Rahmenanteil 10%	37,64						
	E3 Aussenwandeinbauten (Fenster)	E3 076 Holz-Fenster 3 WS S, Rahmenanteil 10%	34,22						
	E3 Aussenwandeinbauten (Fenster)	E3 077 Holz-Alu-Fenster 3 WS S, Rahmenanteil 10%	39,65						
	E3 Aussenwandeinbauten (Fenster)	E3 078 Kunststoff-Fenster 3 WS S, Rahmenanteil 10%	47,97						
	E3 Aussenwandeinbauten (Fenster)	E3079 Alu-Fenster 3 WSS, Rahmenanteil	50,45						

Table 40 – GWP values of interior wall using Bauteilkatalog database at different LODs

Interior wall									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C2.2 Innenwand	C2.2 080 Beton tragend bis K32, roh, 20cm, B 90 kg/m3	1,22	1,10	1,56	0,55	1,76	4,46	0,59
	C2.2 Innenwand	C2.2 081 Beton tragend, ueber K32, roh, 20cm, B 105 kg/m3	1,26						
	C2.2 Innenwand	C2.2 082 Beton tragend ueber K32, roh, 25cm, B 105 kg/m3	1,56						
	C2.2 Innenwand	C2.2 083a Mauerwerk tragend, BN 15cm	0,64						
	C2.2 Innenwand	C2.2 083b Mauerwerk tragend, KS 15cm	0,55						
	C2.2 Innenwand	C2.2 084 Mauerwerk tragend schalldaemmend, BN15cm, SD 4cm, BN15	1,33						
	C2.2 Innenwand	C2.2 085 Mauerwerk tragend zweischalig, KS 15cm, SD 4cm, KS 15cm	1,15						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	2,90	0,65	2,90	0,04			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,04						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	0,09						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	0,07						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	0,17						

Table 41 – PENRT values of interior wall using Bauteilkatalog database at different LODs

Interior wall									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
C	C2.2 Innenwand	C2.2 080 Beton tragend bis K32, roh, 20cm, B 90 kg/m3	11,05	10,82	14,43	5,50	16,81	38,70	5,91
	C2.2 Innenwand	C2.2 081 Beton tragend, ueber K32, roh, 20cm, B 105 kg/m3	11,73						
	C2.2 Innenwand	C2.2 082 Beton tragend ueber K32, roh, 25cm, B 105 kg/m3	14,41						
	C2.2 Innenwand	C2.2 083a Mauerwerk tragend, BN 15cm	6,83						
	C2.2 Innenwand	C2.2 083b Mauerwerk tragend, KS 15cm	5,50						
	C2.2 Innenwand	C2.2 084 Mauerwerk tragend schalldaemmend, BN15cm, SD 4cm, BN15	14,43						
	C2.2 Innenwand	C2.2 085 Mauerwerk tragend zweischalig, KS 15cm, SD 4cm, KS 15cm	11,76						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	24,27	6,00	24,27	0,41			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,41						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	1,39						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	1,28						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	2,63						

Table 42 – GWP values of partition wall using Bauteilkatalog database at different LODs

Partition wall									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
G	G1 Trennwand	G1 039 Backstein BN, roh nicht tragend, 12.5cm	1,07	0,81	1,07	0,54	1,46	3,97	0,58
	G1 Trennwand	G1 041 Backstein KS, roh nicht tragend, 12.5cm	0,89						
	G1 Trennwand	G1 104 Leichbaustaender-konstruktion < 50 dB	0,68						
	G1 Trennwand	G1 105 Leichbaustaender-konstruktion > 50 dB	1,06						
	G1 Trennwand	G1 106 Vollgipsplatten	0,61						
	G1 Trennwand	G1 107 Holzstaender-konstruktion, gedaemmt	0,54						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	2,90	0,65	2,90	0,04			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,04						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	0,09						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	0,07						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	0,17						

Table 43 – PENRT values of partition wall using Bauteilkatalog database at different LODs

Partition wall									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
G	G1 Trennwand	G1 039 Backstein BN, roh nicht tragend, 12.5cm	11,39	11,83	18,08	8,80	17,83	42,35	9,21
	G1 Trennwand	G1 041 Backstein KS, roh nicht tragend, 12.5cm	8,80						
	G1 Trennwand	G1 104 Leichbaustaender-konstruktion < 50 dB	11,87						
	G1 Trennwand	G1 105 Leichbaustaender-konstruktion > 50 dB	18,08						
	G1 Trennwand	G1 106 Vollgipsplatten	9,99						
	G1 Trennwand	G1 107 Holzstaender-konstruktion, gedaemmt	10,87						
G	G3 Wandbekleidung	G.3 043 Innendaemmung XPS, Verkleidung mit GKP, U 0.2	24,27	6,00	24,27	0,41			
	G3 Wandbekleidung	G.3 122 Wanddispersionen	0,41						
	G3 Wandbekleidung	G.3 125 Wandputze gestrichen	1,39						
	G3 Wandbekleidung	G.3 126 Wandverkleidungen aus Holz gestrichen	1,28						
	G3 Wandbekleidung	G.3 127 Wandverkleidungen aus Gipswerkstoffen gestrichen	2,63						

Table 44 – GWP values of balcony using Bauteilkatalog database at different LODs

Balcony									
Construction categories	Building components	Constructive solutions	LOD 300	LOD 200			LOD 100		
			GWP	GWP average	max	min	GWP average	max	min
C	C4.3 Balkon	C.4.3 013a Ortbeton auskragend 2.5m, d 24cm, Fe 100kg/m3 und Cn 20kg/m3	3,52	2,96	3,52	2,40	2,96	3,52	2,40
	C4.3 Balkon	C.4.3 013b Ortbeton auskragend 2.2m, d 20cm, Fe 100kg/m3 und Cn 20kg/m3	2,96						
	C4.3 Balkon	C.4.3 013c Ortbeton auskragend 1,6m, d 16cm, Fe 100kg/m3 und Cn 20kg/m3	2,40						
	C4.3 Balkon	C.4.3 014 Balkon l 5.0m b 2.5m, Stahlkonstruktion, Beton d 18cm Fe 100kg/m3	2,96						

Table 45 – PENRT values of balcony using Bauteilkatalog database at different LODs

Balcony									
Construction categories	Building components	Constructive solutions	LOD 300	LOD 200			LOD 100		
			PENRT	PENRT average	max	min	PENRT average	max	min
C	C4.3 Balkon	C.4.3 013a Ortbeton auskragend 2.5m, d 24cm, Fe 100kg/m3 und Cn 20kg/m3	35,13	30,02	35,13	24,17	30,02	35,13	24,17
	C4.3 Balkon	C.4.3 013b Ortbeton auskragend 2.2m, d 20cm, Fe 100kg/m3 und Cn 20kg/m3	29,64						
	C4.3 Balkon	C.4.3 013c Ortbeton auskragend 1,6m, d 16cm, Fe 100kg/m3 und Cn 20kg/m3	24,17						
	C4.3 Balkon	C.4.3 014 Balkon l 5.0m b 2.5m, Stahlkonstruktion, Beton d 18cm Fe 100kg/m3	31,12						

Table 46 – GWP values of ceiling using Bauteilkatalog database at different LODs

Ceiling									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C4.1 Deckenkonstruktion	C3 005 Betondecke bis 6m Spannweite B 85 kg/m3, 25 cm	1,47	1,52	2,43	0,47	3,41	9,67	0,74
	C4.1 Deckenkonstruktion	C4.1 006 Betondecke auf Waende, Spannweite 6 bis 8 m B 95 kg/m3, 30 cm	1,79						
	C4.1 Deckenkonstruktion	C4.1 007 Betondecke auf Stuetzen, Spannweite 6 bis 8 m B 100 kg/m3, 35 cm	2,11						
	C4.1 Deckenkonstruktion	C4.1 008 Betondecke auf Waenden, Spannweite ab 8 m B 100 kg/m3, 35 cm	2,11						
	C4.1 Deckenkonstruktion	C4.1 009 Betondecke auf Stuetzen, Spannweite ab 8 m B 105 kg/m3, 40 cm	2,43						
	C4.1 Deckenkonstruktion	C4.1 010a Betonelementdecke aus Hohlplatten, Spannweite bis 6 m	0,87						
	C4.1 Deckenkonstruktion	C4.1 010b Betonelementdecke aus Hohlplatten, Spannweite 6 m bis 8 m	1,30						
	C4.1 Deckenkonstruktion	C4.1 011 Decke Holzkastenelemente	0,47						
	C4.1 Deckenkonstruktion	C4.1 012 Holz-Beton-Verbunddecke	1,13						
G	G2 Bodenbelag	G2.2 108a Unterlagsboden mit Trittschall, Anhydrit	0,28	1,47	5,87	0,17			
	G2 Bodenbelag	G2.2 108b Unterlagsboden mit Trittschall, Zement	0,90						
	G2 Bodenbelag	G2.2 108c Unterlagsboden mit Trittschall und Waermedaemmung, Anhydrit	1,70						
	G2 Bodenbelag	G2.2 108d Unterlagsboden mit Trittschall und Waermedaemmung, Zement	2,33						
	G2 Bodenbelag	G2.2 109a Unterlagsboden ohne Trittschall, Anhydrit	0,17						
	G2 Bodenbelag	G2.2 109b Unterlagsboden ohne Trittschall, Zement	0,79						
	G2 Bodenbelag	G2.2 110 Zementueberzug	0,44						
	G2	G2.3 113 Gussasphalt	5,87						

	Bodenbelag								
	G2 Bodenbelag	G2.3 118 Naturstein-Bodenbelaege einheimisch	0,73						
G	G4 Decken-Dachbekleidung innen	G.4 128 Heruntergehaengte Metalldecken	1,37	0,43	1,37	0,10			
	G4 Decken-Dachbekleidung innen	G.4 129 Heruntergehaengte Gips-oder Holzdecken (Stahl 3.5 kg/m2)	0,63						
	G4 Decken-Dachbekleidung innen	G.4 129a Heruntegehaengte Gipsdecke (Stahl: 1 kg/m2)	0,33						
	G4 Decken-Dachbekleidung innen	G.4 130 Holzwolleleichtbauplatten mit Waermedaemmung	0,30						
	G4 Decken-Dachbekleidung innen	G.4 131 Holzwolleleichtbauplatten ohne Waermedaemmung	0,13						
	G4 Decken-Dachbekleidung innen	G.4 132 Einfache Akustikdecken	0,13						
	G4 Decken-Dachbekleidung innen	G.4 133 Deckenputze gestrichen	0,10						

Table 47 – PENRT values of ceiling using Bauteilkatalog database at different LODs

Ceiling									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
C	C4.1 Deckenkonstruktion	C3 005 Betondecke bis 6m Spannweite B 85 kg/m3, 25 cm	12,80	14,29	21,98	7,54	32,56	65,50	11,47
	C4.1 Deckenkonstruktion	C4.1 006 Betondecke auf Waende, Spannweite 6 bis 8 m B 95 kg/m3, 30 cm	15,94						
	C4.1 Deckenkonstruktion	C4.1 007 Betondecke auf Stuetzen, Spannweite 6 bis 8 m B 100 kg/m3, 35 cm	18,90						
	C4.1 Deckenkonstruktion	C4.1 008 Betondecke auf Waenden, Spannweite ab 8 m B 100 kg/m3, 35 cm	18,90						
	C4.1 Deckenkonstruktion	C4.1 009 Betondecke auf Stuetzen, Spannweite ab 8 m B 105 kg/m3, 40 cm	21,98						
	C4.1 Deckenkonstruktion	C4.1 010a Betonelementdecke aus Hohlplatten, Spannweite bis 6 m	7,54						
	C4.1 Deckenkonstruktion	C4.1 010b Betonelementdecke aus Hohlplatten, Spannweite 6 m bis 8 m	11,30						
	C4.1 Deckenkonstruktion	C4.1 011 Decke Holzkastenelemente	7,72						
	C4.1 Deckenkonstruktion	C4.1 012 Holz-Beton-Verbunddecke	13,57						
G	G2 Bodenbelag	G2.2 108a Unterlagsboden mit Trittschall, Anhydrit	7,06	11,22	20,70	2,85			
	G2 Bodenbelag	G2.2 108b Unterlagsboden mit Trittschall, Zement	8,52						
	G2 Bodenbelag	G2.2 108c Unterlagsboden mit Trittschall und Waermedaemmung, Anhydrit	17,00						
	G2 Bodenbelag	G2.2 108d Unterlagsboden mit Trittschall und Waermedaemmung, Zement	18,45						
	G2 Bodenbelag	G2.2 109a Unterlagsboden ohne Trittschall, Anhydrit	3,87						

	G2 Bodenbelag	G2.2 109b Unterlagsboden ohne Trittschall, Zement	5,32						
	G2 Bodenbelag	G2.2 110 Zementueberzug	2,85						
	G2 Bodenbelag	G2.3 113 Gussasphalt	17,17						
	G2 Bodenbelag	G2.3 118 Naturstein-Bodenbelaege einheimisch	20,70						
G	G4 Decken-Dachbekleidung innen	G.4 128 Heruntergehaengte Metalldecken	22,82	7,05	22,82	1,08			
	G4 Decken-Dachbekleidung innen	G.4 129 Heruntergehaengte Gips-oder Holzdecken (Stahl 3.5 kg/m2)	10,15						
	G4 Decken-Dachbekleidung innen	G.4 129a Heruntegehaengte Gipsdecke (Stahl: 1 kg/m2)	5,30						
	G4 Decken-Dachbekleidung innen	G.4 130 Holzwolleleichtbauplatten mit Waermedaemmung	5,98						
	G4 Decken-Dachbekleidung innen	G.4 131 Holzwolleleichtbauplatten ohne Waermedaemmung	1,08						
	G4 Decken-Dachbekleidung innen	G.4 132 Einfache Akustikdecken	2,41						
	G4 Decken-Dachbekleidung innen	G.4 133 Deckenputze gestrichen	1,63						

Table 48 – GWP values of roof using Bauteilkatalog database at different LODs

Roof									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
C	C4.4 Dachkonstruktion	C.4.4 015 Steildach, Sparrenlage, KVH 120x180, a 0.65m	0,03	0,03	0,03	0,03	2,15	5,31	0,80
F	F1 Dachhaut	F1 016 Kompaktdach Schaumglas, U 0.2	3,91	1,69	3,91	0,67			
	F1 Dachhaut	F1 017a Foliendach, EPS, U 0.2	1,89						
	F1 Dachhaut	F1 017b Foliendach, PUR/PIR, U 0.2	2,25						
	F1 Dachhaut	F1 018 Flachdach Kaltdach, U 0.2, Holzunterkonstruktion	0,91						
	F1 Dachhaut	F1 019 Steildach, U 0.2, Metallabdeckung	1,36						
	F1 Dachhaut	F1 020 Steildach, U 0.2, Ziegeleindeckung	0,87						
	F1 Dachhaut	G1 021 Steildach, U 0.2, Faserzementschindeln	0,67						
G	G4 Decken-Dachbekleidung innen	G.4 128 Heruntergehaengte Metalldecken	1,37	0,43	1,37	0,10			
	G4 Decken-Dachbekleidung innen	G.4 129 Heruntergehaengte Gips- oder Holzdecken (Stahl 3.5 kg/m2)	0,63						
	G4 Decken-Dachbekleidung innen	G.4 129a Heruntergehaengte Gipsdecke (Stahl: 1 kg/m2)	0,33						
	G4 Decken-Dachbekleidung innen	G.4 130 Holzwolleleicht-bauplatten mit Waermedaemmung	0,30						
	G4 Decken-Dachbekleidung innen	G.4 131 Holzwolleleichtbauplatten ohne Waermedaemmung	0,13						
	G4 Decken-Dachbekleidung innen	G.4 132 Einfache Akustikdecken	0,13						
	G4 Decken-Dachbekleidung innen	G.4 133 Deckenputze gestrichen	0,10						

Table 49 – PENRT values of roof using Bauteilkatalog database at different LODs

Roof									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
C	C4.4 Dachkonstruktion	C.4.4 015 Steildach, Sparrenlage, KVH 120x180, a 0.65m	0,5	0,52	0,52	0,52	34,25	81,95	12,10
F	F1 Dachhaut	F1 016 Kompaktdach Schaumglas, U 0.2	58,6	26,68	58,61	10,50			
	F1 Dachhaut	F1 017a Foliendach, EPS, U 0.2	35,2						
	F1 Dachhaut	F1 017b Foliendach, PUR/PIR, U 0.2	32,5						
	F1 Dachhaut	F1 018 Flachdach Kaltdach, U 0.2, Holzunterkonstruktion	15,2						
	F1 Dachhaut	F1 019 Steildach, U 0.2, Metallabdeckung	22,4						
	F1 Dachhaut	F1 020 Steildach, U 0.2, Ziegeleindeckung	12,5						
	F1 Dachhaut	G1 021 Steildach, U 0.2, Faserzementschindeln	10,5						
G	G4 Decken-Dachbekleidung innen	G.4 128 Heruntergehaengte Metalldecken	22,8	7,05	22,82	1,08			
	G4 Decken-Dachbekleidung innen	G.4 129 Heruntergehaengte Gips- oder Holzdecken (Stahl 3.5 kg/m2)	10,2						
	G4 Decken-Dachbekleidung innen	G.4 129a Heruntergehaengte Gipsdecke (Stahl: 1 kg/m2)	5,3						
	G4 Decken-Dachbekleidung innen	G.4 130 Holzwolleleichtbauplatten mit Waermedaemmung	6,0						
	G4 Decken-Dachbekleidung innen	G.4 131 Holzwolleleichtbauplatten ohne Waermedaemmung	1,1						
	G4 Decken-Dachbekleidung innen	G.4 132 Einfache Akustikdecken	2,4						
	G4 Decken-Dachbekleidung innen	G.4 133 Deckenputze gestrichen	1,6						

Table 50 – GWP values of technical equipment using Bauteilkatalog database at different LODs

Technical equipment									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			GWP	**GWP average**	**max**	**min**	**GWP average**	**max**	**min**
D	D1 Elektroanlage	D1 214 Elektroanlagen, tiefer Installationsgrad	0,31	0,62	1,04	0,31	2,04	3,58	0,89
	D1 Elektroanlage	D1 215 Elektroanlagen, mittlerer Installationsgrad	0,52						
	D1 Elektroanlage	D1 216 Elektroanlagen, hoher Installationsgrad	1,04						
D	D5.2 Waermeerzeugung	D5.2 200 Waermeerzeuger, spez. Leistungsbedarf 10 W/m2	0,03	0,33	0,95	0,03			
	D5.2 Waermeerzeugung	D5.2 201 Waermeerzeuger, spez. Leistungsbedarf 30 W/m2	0,08						
	D5.2 Waermeerzeugung	D5.2 202 Waermeerzeuger, spez. Leistungsbedarf 50 W/m2	0,13						
	D5.2 Waermeerzeugung	D5.2 208 Erdsonden, spez. Leistungsbedarf 10 W/m2	0,19						
	D5.2 Waermeerzeugung	D5.2 209 Erdsonden, spez. Leistungsbedarf 30 W/m2	0,57						
	D5.2 Waermeerzeugung	D5.2 210 Erdsonden, spez. Leistungsbedarf 50 W/m2	0,95						
D	D5.3 / D5.4 Waermeverteilung und-abgabe	D5.4 203 Waermeverteilung, Fussbodenheizung	0,18	0,25	0,42	0,06			
	D5.3 / D5.4 Waermeverteilung und-abgabe	D5.4 204 Waermeverteilung, Luftheizung	0,30						
	D5.3 / D5.4 Waermeverteilung und-abgabe	D5.4 205 Waermeverteilung, Radiatoren, spez. Leistungsbedarf 10 W/m2	0,42						
	D5.3 / D5.4 Waermeverteilung und -abgabe	D5.4 206 Waermeverteilung, Radiatoren, spez. Leistungsbedarf 30 W/m2	0,29						
	D5.3 / D5.4 Waermeverteilung und-abgabe	D5.4 207 Waermeverteilung, Radiatoren, spez. Leistungsbedarf 50 W/m2	0,06						
D	D7 Lufttechnische Anlage	D7 218 Lueftungsanlage Wohnen, Blechkanaele, inkl.	0,44	0,41	0,66	0,15			

		Kuechenabluft							
	D7 Lufttechnische Anlage	D7 219 Lueftungsanlage Wohnen, PE-Kanaele, inkl. Kuechenabluft	0,27						
	D7 Lufttechnische Anlage	D7 220 Abluftanlage Kueche und Bad	0,15						
	D7 Lufttechnische Anlage	D7 221 Lueftungsanlage Buero Blechkanaele, spez. Luftmenge 2 m3/hm2 EBF	0,41						
	D7 Lufttechnische Anlage	D7 222 Lueftungsanlage Buero Blechkanaele, spez. Luftmenge 4 m3/hm2 EBF	0,52						
	D7 Lufttechnische Anlage	D7 223 Lueftungsanlage Buero Blechkanaele, spez. Luftmenge 6 m3/hm2 EBF	0,59						
	D7 Lufttechnische Anlage	D7 224 Erdregister kurz zu Lueftungsanlage Buero (0.27 m/m2 EBF)	0,26						
	D7 Lufttechnische Anlage	D7 225 Erdregister lang zu Lueftungsanlage Buero (0.67 m/m2 EBF)	0,66						
D	D8 Wasseranlage (Sanitaeranlage)	D8 226 Sanitaeranlagen Wohnen	0,51	0,43	0,51	0,34			
	D8 Wasseranlage (Sanitaeranlage)	D8 227 Sanitaeranlagen Buero	0,34						

Table 51 – PENRT values of technical equipment using Bauteilkatalog database at different LODs

Technical equipment									
Construction categories	**Building components**	**Constructive solutions**	**LOD 300**	**LOD 200**			**LOD 100**		
			PENRT	**PENRT average**	**max**	**min**	**PENRT average**	**max**	**min**
D	D1 Elektroanlage	Elektroanlagen, tiefer Installationsgrad	5,03	10,04	16,70	5,03	32,63	58,11	13,73
	D1 Elektroanlage	Elektroanlagen, mittlerer Installationsgrad	8,39						
	D1 Elektroanlage	Elektroanlagen, hoher Installationsgrad	16,70						
D	D5.2 Waermeerzeugung	Waermeerzeuger, spez. Leistungsbedarf 10 W/m2	0,44	5,80	17,14	0,44			
	D5.2 Waermeerzeugung	Waermeerzeuger, spez. Leistungsbedarf 30 W/m2	1,32						
	D5.2 Waermeerzeugung	Waermeerzeuger, spez. Leistungsbedarf 50 W/m2	2,20						
	D5.2 Waermeerzeugung	Erdsonden, spez. Leistungsbedarf 10 W/m2	3,43						
	D5.2 Waermeerzeugung	Erdsonden, spez. Leistungsbedarf 30 W/m2	10,28						
	D5.2 Waermeerzeugung	Erdsonden, spez. Leistungsbedarf 50 W/m2	17,14						
D	D5.3 / D5.4 Waermeverteilung und-abgabe	Waermeverteilung, Radiatoren, spez. Leistungsbedarf 10 W/m2	4,25	4,03	6,89	1,00			
	D5.3 / D5.4 Waermeverteilung und-abgabe	Waermeverteilung, Radiatoren, spez. Leistungsbedarf 30 W/m2	1,00						
	D5.3 / D5.4 Waermeverteilung und-abgabe	Waermeverteilung, Radiatoren, spez. Leistungsbedarf 50 W/m2	3,03						
	D5.3 / D5.4 Waermeverteilung und -abgabe	Waermeverteilung, Fussbodenheizung	4,96						
	D5.3 / D5.4 Waermeverteilung und-abgabe	Waermeverteilung, Luftheizung	6,89						
D	D7 Lufttechnische Anlage	Lueftungsanlage Wohnen, Blechkanaele, inkl. Kuechenabluft	7,10	6,27	9,70	1,97			
	D7 Lufttechnische Anlage	Lueftungsanlage Wohnen, PE-Kanaele, inkl. Kuechenabluft	4,36						
	D7 Lufttechnische Anlage	Abluftanlage Kueche und Bad	1,97						
	D7 Lufttechnische Anlage	Lueftungsanlage Buero Blechkanaele, spez. Luftmenge 2 m3/hm2 EBF	6,65						
	D7 Lufttechnische Anlage	Lueftungsanlage Buero Blechkanaele, spez. Luft-	8,44						

		menge 4 m3/hm2 EBF							
	D7 Lufttechnische Anlage	Lueftungsanlage Buero Blechkanaele, spez. Luftmenge 6 m3/hm2 EBF	9,70						
	D7 Lufttechnische Anlage	Erdregister kurz zu Lueftungsanlage Buero (0.27 m/m2 EBF)	3,42						
	D7 Lufttechnische Anlage	Erdregister lang zu Lueftungsanlage Buero (0.67 m/m2 EBF)	8,54						
D	D8 Wasseranlage (Sanitaeranlage)	Sanitaeranlagen Wohnen	7,7	6,49	7,68	5,29			
	D8 Wasseranlage (Sanitaeranlage)	Sanitaeranlagen Buero	5,3						

APPENDIX B

Table 52 – Scenario 1: LOD evolution across design process

Construction categories		**Design phases**				
		PP	**P**	**BPA**	**T**	**C**
C	**Structure**	100	300	400	400	400
E+F	**Envelope**	100	200	300	400	400
D	**Technical equipment**	100	200	200	300	400
G	**Interior**	100	200	200	200	400

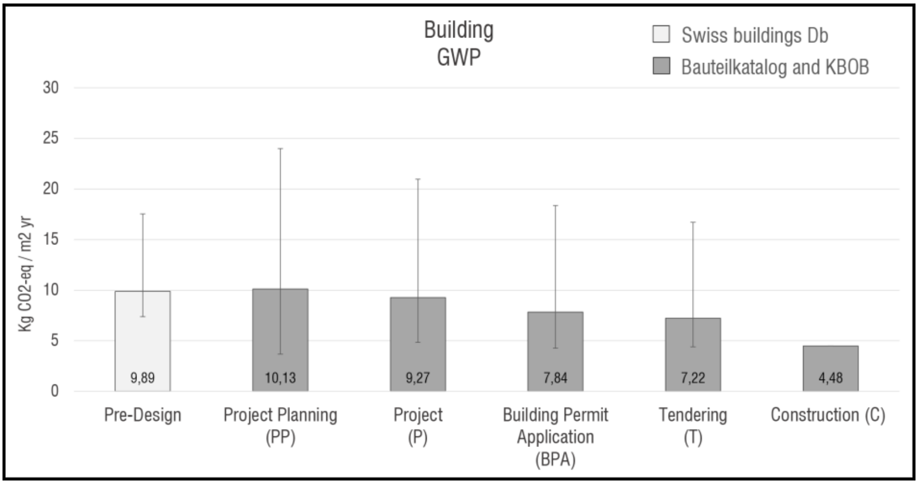

Fig. 41 – Scenario 1: GWP of the building during the design process

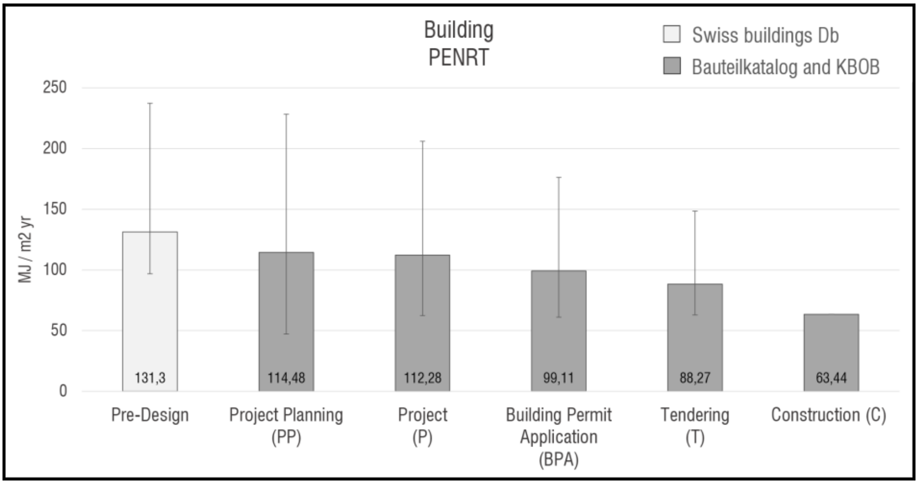

Fig. 42 – Scenario 1: PENRT of the building during the design process

Table 53 – Scenario 2: LOD evolution across design process

Construction categories		**Design phases**				
		PP	**P**	**BPA**	**T**	**C**
C	**Structure**	100	300	400	400	400
E+F	**Envelope**	100	200	300	400	400
D	**Technical equipment**	100	200	200	400	400
G	**Interior**	100	200	200	300	400

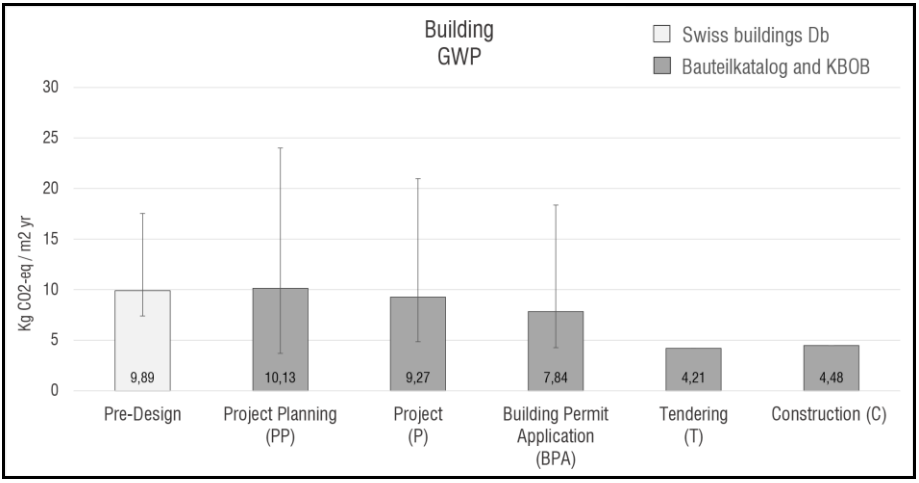

Fig. 43 – Scenario 2: GWP of the building during the design process

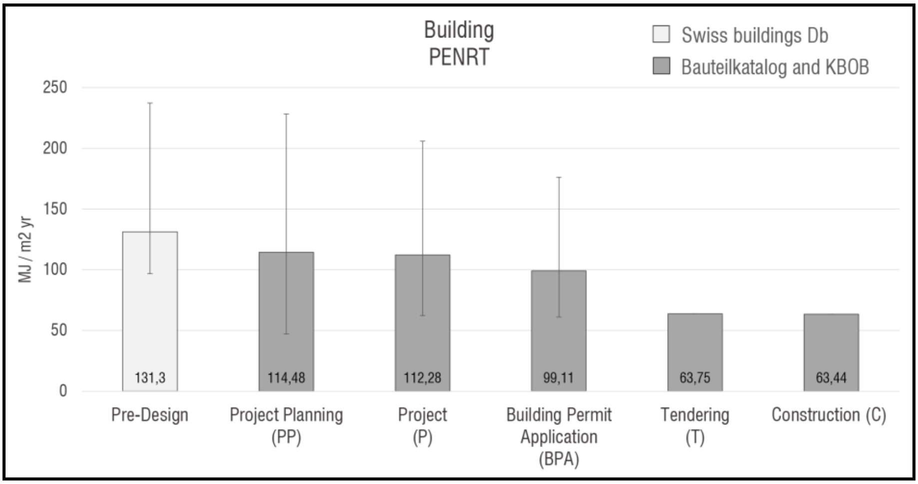

Fig. 44 – Scenario 2: PENRT of the building during the design process

Table 54 – Scenario 3: LOD evolution across design process

Construction categories		Design phases				
		PP	P	BPA	T	C
C	**Structure**	100	200	400	400	400
E+F	**Envelope**	100	200	300	400	400
D	**Technical equipment**	100	200	300	300	400
G	**Interior**	100	200	200	300	400

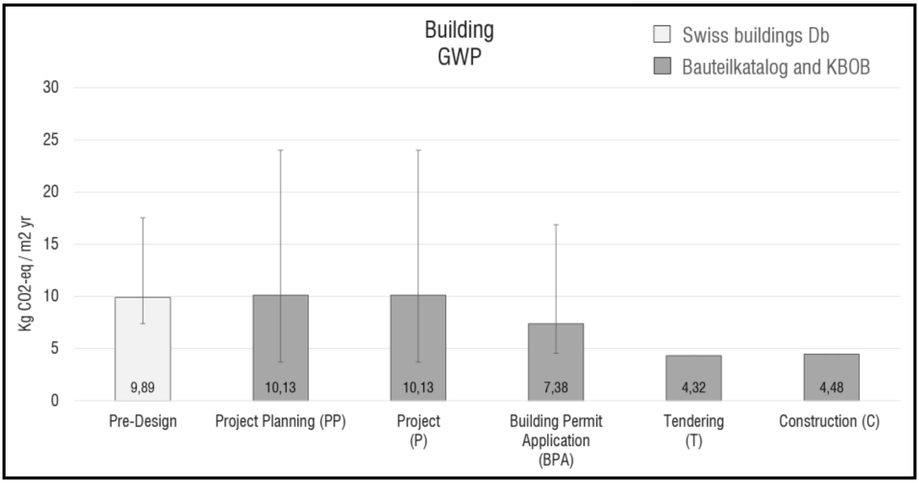

Fig. 45 – Scenario 3: GWP of the building during the design process

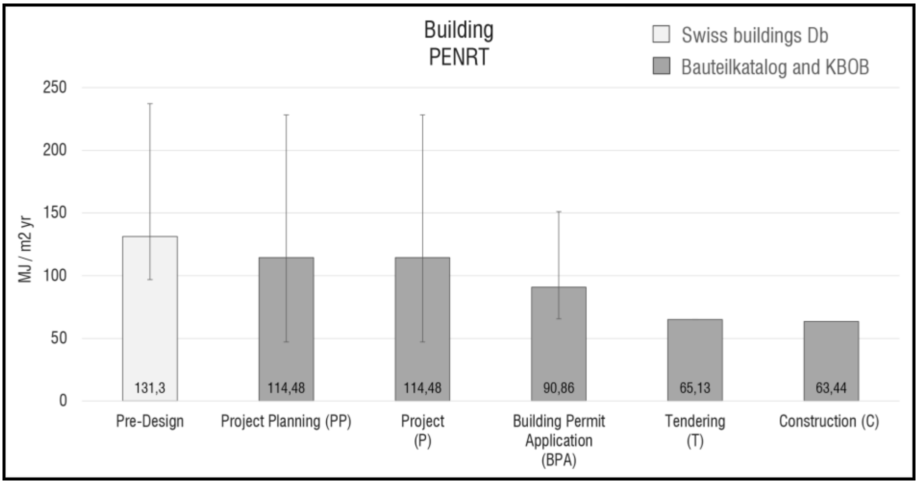

Fig. 46 – Scenario 3: PENRT of the building during the design process

Table 55 – Scenario 4: LOD evolution across design process

Construction categories		Design phases				
		PP	**P**	**BPA**	**T**	**C**
C	**Structure**	100	300	400	400	400
E+F	**Envelope**	100	300	300	400	400
D	**Technical equipment**	100	200	200	300	400
G	**Interior**	100	200	200	200	400

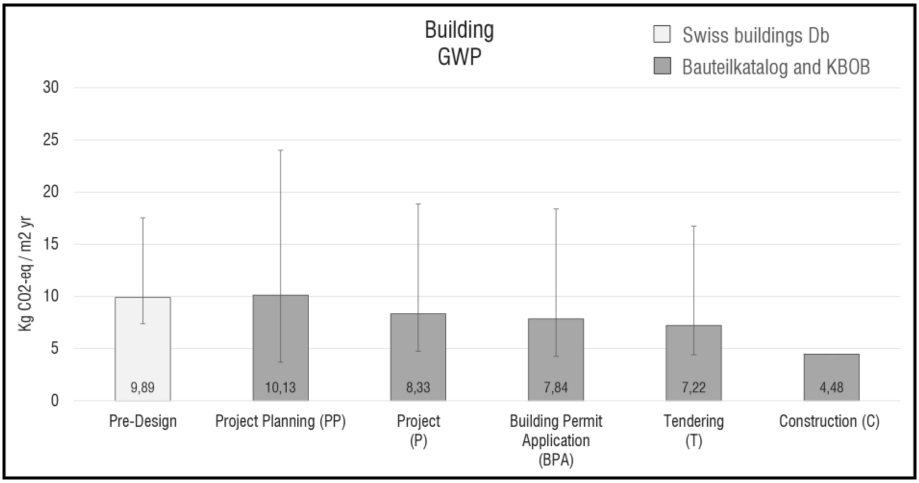

Fig. 47 – Scenario 4: GWP of the building during the design process

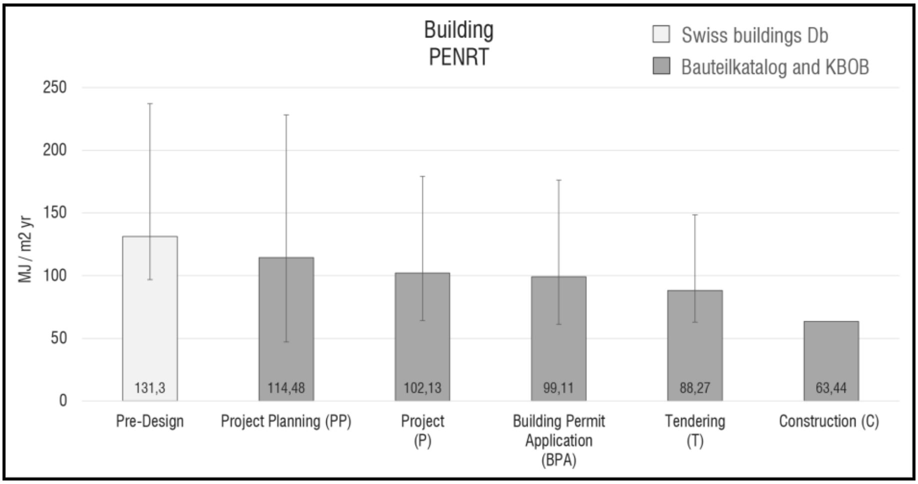

Fig. 48 – Scenario 4: PENRT of the building during the design process

Table 56 – Scenario 5: LOD evolution across design process

Construction categories		Design phases				
		PP	P	BPA	T	C
C	**Structure**	100	300	400	400	400
E+F	**Envelope**	100	300	300	300	400
D	**Technical equipment**	100	200	200	300	400
G	**Interior**	100	200	200	200	400

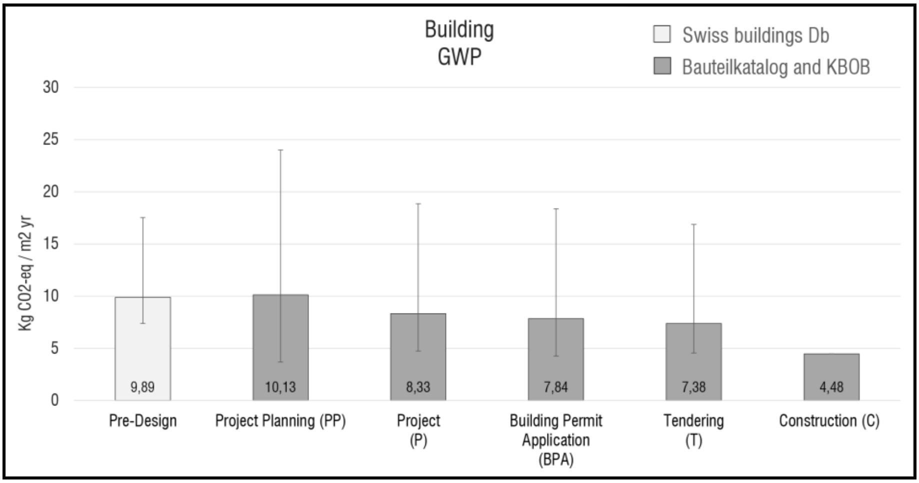

Fig. 49 – Scenario 5: GWP of the building during the design process

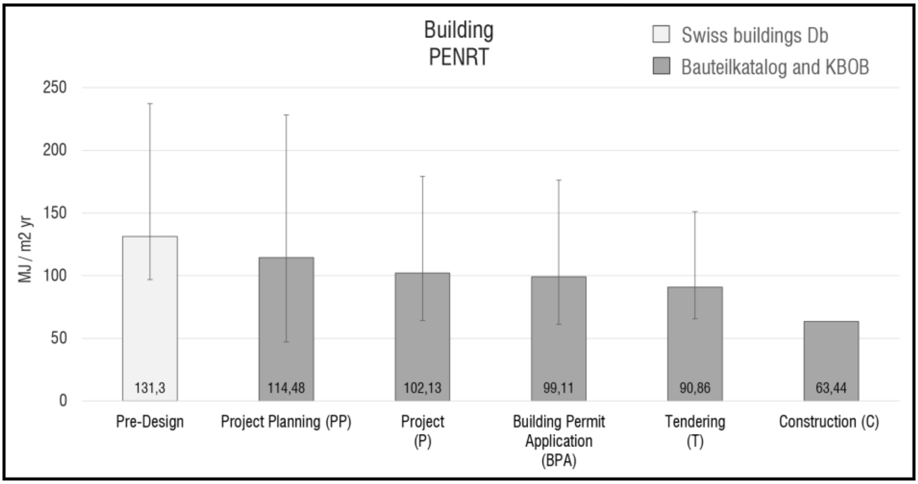

Fig. 50 – Scenario 5: PENRT of the building during the design process

Table 57 – Scenario 6: LOD evolution across design process

Construction categories		Design phases				
		PP	**P**	**BPA**	**T**	**C**
C	**Structure**	100	300	400	400	400
E+F	**Envelope**	100	300	300	400	400
D	**Technical equipment**	100	200	300	300	400
G	**Interior**	100	200	200	300	400

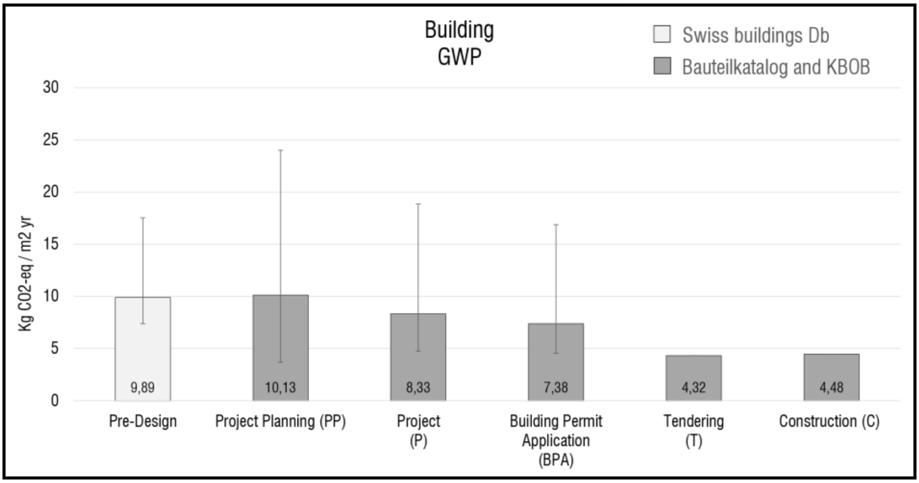

Fig. 51 – Scenario 6: GWP of the building during the design process

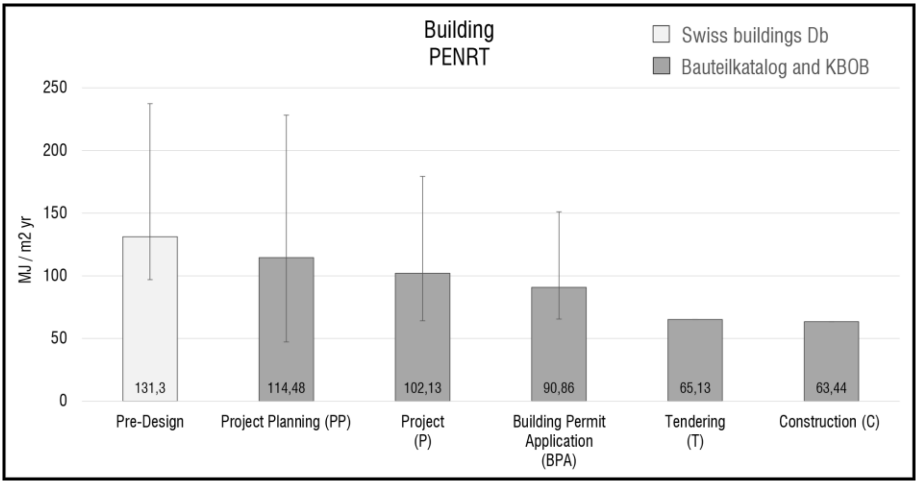

Fig. 52 – Scenario 6: PENRT of the building during the design process

SHORT CV

PERSONAL INFORMATION

Carmine Cavalliere
E-mail: carmine.cavalliere@poliba.it
Nationality: Italian
Gender: male

EDUCATION

11/2015 – 10/2018	Ph.D candidate in Risk and Environmental, Territorial and Building Development Supervisors: Prof. G.R. Dell’Osso (Polytechnic University of Bari); Prof. G. Habert (ETH Zürich) Key words: Life Cycle Assessment (LCA); Building Information Modelling (BIM); Design process; Levels of Development (LODs); Sustainability.
10/2012 – 02/2015	MEng in Building Systems at Polytechnic University of Bari Mark: 110/110 cum laude

RESEARCH PERIOD ABROAD

11/2017 – 04/2018	Visiting period at ETH Zürich – Department of Civil, Environmental & Geomatic Engineering – Institute of Construction & Infrastructure Management – Chair of Sustainable Construction. Supervisor: Prof. G. Habert

RESEARCH INTEREST

Environmental sustainability; Environmental analysis; Life Cycle Assessment; Sustainable design; Building Information Modelling; Building Information Management; Building Engineering; Building production; Project management.

PUBBLICATIONS

Journal papers

[1] Cavalliere C., Habert G., Dell’Osso G.R., Hollberg A., 2019. Continuous BIM-based assessment of embodied environmental impacts throughout the design process, Journal of Cleaner Production 211, 941-952. https://doi.org/10.1016/j.jclepro.2018.11.247

[2] Cavalliere C., Dell’Osso G.R., Pierucci A., Iannone F., 2018. Life cycle assessment data structure for building information modelling, Journal of Cleaner Production 199, 193–204. https://doi.org/10.1016/j.jclepro.2018.07.149

Conference proceedings

[3] Cavalliere C., Dell’Osso G.R., Leogrande M.A., 2017, Automatic workflow for 4D-BIM based modelling, in M.S.M. Kong & M.d.R. Monteiro (eds.), Progress(es) - Theories and Practices, CRC Press, London, pp. 405 – 409, ISBN 978-0-8153-7415-2

[4] Cavalliere C., Dell’Osso G.R., 2017, Uncertainty indicators of Life Cycle Assessment evaluations, in G. Bernardini, E. Di Giuseppe (eds.), Colloqui.AT.e 2017 Demolition or reconstruction?, EdicomEdizioni, Monfalcone, pp. 1166 – 1175, ISBN 978-88-96386-58-3

[5] Cavalliere C., Dell’Osso G.R., Iannone F., 2017, Life Cycle Assessment for Building Information Modeling, in A. Ciribini, G. Alaimo, P. Capone et al. (eds.), Re-shaping the construction industry, Maggioli Editore, Santarcangelo di Romagna, pp. 264 - 273, ISBN 978-88-916-2486-4

[6] Cavalliere C., Dell’Osso G.R., Pierucci A., 2016, LCA approach in BIM Levels of Development (LOD), in A. Guida, A. Pagliuca (eds.), Colloqui.AT.e 2016 MATER(i)A, Gangemi Editore, Roma, pp. 109 – 118, ISBN 978-88-492-3311-7

[7] Cavalliere C., Dell’Osso G.R., Pierucci A., Iannone F., 2016, LCA data structure analysis for BIM applications, in A. Ciribini, G. Alaimo, P. Capone et al. (eds.), Back to 4.0: Rethinking the digital construction, Maggioli Editore, Santarcangelo di Romagna, pp. 459 – 468, ISBN 978-88-916-1807-8. *Awarded for the “Best paper of ISTeA 2016”*

[8] Pierucci A., Dell’Osso G.R., Cavalliere C., 2015, Il management del flusso informativo delle costruzioni mediante valutazioni LCA, in G. Alaimo, P. Capone, A. Ciribini et al. (eds.), Sostenibilità ambientale, economia circolare e produzione edilizia, Maggioli Editore, Santarcangelo di Romagna, pp. 553 – 571, ISBN 978-88-916-1222-9

ADDITIONAL INFORMATION

From 2018	Reviewer of Journal of Cleaner Production and Journal of Building Engineering
From 2016	ISTeA member - Italian Society of Science, Technology and Engineering of Architecture
From 2016	Buildings sustainability certifier – Protocollo ITACA Puglia
From 2016	Certified Engineers of the province of Barletta Andria Trani, sect. A

PRIZES AND AWARDS

2018	Winner of the "Ermenegildo Zegna Founder's Scholarship" call for the support of young excellences with the potential to become leaders in their sector
2017	Finalists with AIM project in SCINTILLE2017, national contest organized by the Italian National Council of Engineers (CNI) for innovative ideas and projects
2016	Best paper of the ISTeA Congress 2016