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Buildings Embodied Impacts over the Life Cycle: an Essential Assessment Framework for the Early Design Phase

Presentata da
Stefano Politi

Coordinatore Dottorato
Prof. Annalisa Trentin

Supervisore
Prof. Ernesto Antonini

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Abstract [Ita]

Il progetto di ricerca presentato in questa tesi di dottorato è incentrato sul tema della determinazione e della valutazione dell'impronta ambientale (o profilo ambientale) associata agli edifici, a partire dalla loro progettazione fino alla dismissione.

Con riferimento agli impatti ambientali globali, infatti, all'ambiente costruito compete una quota significativa. Non tutti gli impatti, tuttavia, sono imputabili al solo funzionamento degli edifici (impatti operativi), in quanto una considerevole porzione di essi deriva anche dalle rimanenti fasi del ciclo di vita, associate quindi alla produzione di materiali e componenti da costruzione, al loro trasporto, alla loro installazione, manutenzione e al loro smaltimento (impatti inglobati).

Negli ultimi decenni, diverse iniziative di sviluppo sostenibile promosse da alcuni organismi internazionali hanno evidenziato la necessità di controllare e mitigare gli impatti relativi al settore delle costruzioni, al fine di ridurre il consumo di risorse ed energia, diminuire le emissioni climalteranti e promuovere la riduzione e il riciclaggio dei rifiuti.

La prima parte della ricerca si è quindi concentrata sullo studio degli effetti ambientali ascrivibili agli edifici, individuandone la natura ed esaminandone le cause. I principali strumenti adottati per approfondire questo tema sono i protocolli di valutazione della sostenibilità o sistemi multicriteriali a punteggio (green building rating systems) sviluppati per analizzare e valutare il profilo ambientale, sociale ed economico dell'ambiente costruito.

Una prima indagine è stata condotta attraverso un campione di sistemi a punteggio particolarmente diffusi, al fine di identificare un "nucleo" di categorie e indicatori particolarmente rappresentativi della sostenibilità degli edifici.

Questa analisi ha restituito una serie di parametri che denotano l'attribuzione, da parte dei protocolli di sostenibilità, di un peso maggiore alle fasi operative (relative, ad esempio, alle prestazioni energetiche e al benessere indoor) rispetto ai temi ambientali. In particolare, gli impatti relativi alle fasi non operative del ciclo di vita dell'edificio, ovvero gli impatti inglobati, sono risultati essere i meno rilevanti.

Tuttavia, il crescente interesse emerso da alcune politiche ed iniziative in ambito europeo nei confronti degli approcci basati sull'intero ciclo di vita degli edifici, ha portato questa ricerca ad orientarsi sulla metodologia Life Cycle Assessment (LCA), individuata come uno strumento appropriato per la misura degli impatti inglobati.

La struttura della metodologia LCA, nonché le condizioni e i metodi della sua applicazione, sono stati approfonditi attraverso una seconda analisi dei protocolli di

sostenibilità, al fine di individuarne gli aspetti più distintivi in riferimento alle applicazioni sull'ambiente costruito.

Sulla base dei risultati ottenuti dall'analisi, è stata delineata una struttura condivisa di requisiti attinenti agli edifici, con particolare riferimento alla definizione degli obiettivi e dell'ambito di analisi LCA ("goal and scope"). Sono state, pertanto, individuate una serie di caratteristiche comuni ai protocolli analizzati, in relazione a: fasi del ciclo di vita, categorie di impatto, elementi da analizzare, unità funzionali, metodi di valutazione e vita media di riferimento degli edifici.

Questo studio, pur avendo confermato alcune indicazioni riportate in letteratura relative alle possibili semplificazioni e standardizzazioni dell'approccio LCA applicato agli edifici, ha altresì sottolineato certe discrepanze nell'applicazione del metodo in contesti eterogeni e nell'interpretazione dei risultati.

L'ultima parte della tesi, quindi, partendo da una serie di considerazioni sulle criticità dell'LCA alla scala dell'edificio, affronta lo sviluppo di un approccio semplificato volto a superare i limiti emersi e facilitare le valutazioni ambientali, sia da un punto di vista metodologico che operativo. In particolare, l'approccio è stato ideato per essere applicato durante le prime fasi del processo costruttivo (progettazione), emerse determinanti nella configurazione dei profili ambientali degli edifici.

L'intersezione tra i risultati emersi dall'analisi sui sistemi a punteggio e le indicazioni contenute nel recente sistema di indicatori di sostenibilità sviluppato dalla Commissione Europea - Level(s) - ha condotto allo sviluppo di un framework LCA condiviso e semplificato adatto all'applicazione durante le prime fasi di progettazione.

In merito alle criticità operative dell'LCA, date dalla complessità dello svolgimento delle analisi per gli utenti meno esperti, è stata studiata l'integrazione del framework proposto con gli strumenti Building Information Modeling (BIM), attraverso lo sviluppo di un flusso di lavoro personalizzabile e conveniente. Questo approccio è stato elaborato, in particolare, per adattarsi alle esigenze di quei professionisti che hanno familiarità con l'ambiente BIM ma che non possiedono una esperienza consolidata in ambito LCA, né sono inclini ad effettuare costosi investimenti per l'acquisto di specifici strumenti LCA o per l'accesso a database commerciali.

La ricerca si è conclusa con l'applicazione sperimentale del metodo su un caso studio al fine di testare il flusso di lavoro proposto per l'integrazione tra LCA e BIM, mostrandone il processo operativo, individuandone e discutendone i potenziali vantaggi e svantaggi in vista di successivi approfondimenti e sviluppi.

Abstract [Eng]

The present thesis project revolves around recognition of the critical environmental footprint generated by constructions, from their conception to their disposal.

Buildings in fact are responsible for a significant share of global environmental impacts, however not all the burden can be put upon the operation of buildings, as it also results from all phases associated with the manufacturing of construction products, transport, installation, maintenance and disposal, known as "embodied impacts".

The sustainable development actions carried out over the last decades by international bodies have demonstrated the need for impact mitigation, especially within the building sector, in order to reduce resource and energy consumption, cut hazardous emissions and consolidate waste reduction and recycling campaigns.

The first part of the research therefore centered on the study of the environmental consequences arising from the construction industry and investigated the causes of such impacts. The principal tools adopted as study subjects to address this topic were sustainability assessment protocols or the green buildings rating systems (GBRSs), which have been developed to evaluate the environmental, social and economic profiles of buildings.

An initial investigation performed through a sample of GBRSs, selected from among the most common, aimed to identify a "set core" of representative categories and indicators of buildings' sustainability. This analysis highlighted the most relevant indicators which, according to GBRS protocols, mainly concern building operation, while less importance was seemingly attributed to environmental aspects. Moreover, impacts related to non-operational phases of the building life cycle, i.e. embodied impacts, were deemed to be less relevant.

Growing interest within the EU context in the life cycle approach to buildings led this research to focus on the Life Cycle Assessment (LCA) methodology, which emerged as an appropriate tool to measure embodied impacts. Knowledge of its framework, as well as the conditions and the methods of its application to buildings was deepened through a second analysis of GBRS frameworks which sought to identify the most distinctive aspects regarding building applications. Based on the results, a shared buildings LCA framework was drawn up (with particular reference to Goal and Scope definition) indicating a number of common LCA modules, impact categories, building elements to be included in the assessment, reference functional units, reference life for buildings and rating methods.

This study, despite having confirmed some evidence found in literature on a simplified and standardized approach for building applications, conversely underlined

several discrepancies in how the method is applied within a wide context and regarding the interpretation of the results.

The last part of the thesis, therefore, starting with a series of considerations about LCA weaknesses at building scale, dealt with the development of a simplified approach capable of overcoming the drawbacks that emerged in order to facilitate the environmental evaluation, from both a methodological and operational point of view, during the early phases of the process which turned out to be particularly significant stages for describing the environmental profiles of buildings.

The intersection between the GBRS analysis outcomes and the indications contained in the recent voluntary communication framework developed by the European Commission, called Level(s), led to the development and proposal of a common and simplified building LCA framework suitable for early design applications.

With respect to the operational aspects, as the complexity of the LCA assessment was an acknowledged restraint for non-expert practitioners, implementation of the proposed framework within the Building Information Modelling (BIM) environment was investigated resulting in the development of a customizable and convenient LCA-BIM integration approach. This approach was designed in particular to meet the needs of practitioners who are familiar with a BIM environment but are neither LCA experts nor inclined to make expensive economic investments in specific LCA tools or LCA commercial databases.

The research concluded with an illustrative application to a case study in order to test the proposed LCA-BIM integration, intending to demonstrate the process and, at the same time, identify and discuss the potential advantages and disadvantages of such a method with a view of future developments.

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Part 0

EXECUTIVE SUMMARY

0.1 Aim and Research Questions

Construction is one of the least sustainable economic sectors: globally, the production and operation of buildings and infrastructures are estimated to account for around 50% of greenhouse gas emissions, 40% of water pollution and 50% of waste disposal in landfills, in addition to absorbing 50% of energy, 50% of drinking water and 60% (by bulk) of materials from the ecosystem (Edwards, 2014).

In recent decades, this has led international organizations to promote - and many countries to adopt - more stringent mitigation actions and regulatory standards in order to control the negative effects resulting from the built environment (Nilsson et al., 2012).

The founding initiatives date back to the end of the 1980s with the Brundtland Report, which firstly introduced the sustainable development concept as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, *Our Common Future*, 1987, p. 37). This was followed by other important events embracing sustainable development: the Kyoto Protocol (1997) on global warming mitigation, the Lisbon Strategy (2000-2010), Europe 2020 (2010-2020) including improvement actions for greenhouse gas emissions and energy efficiency , the more recent Agenda 2030, which established a set of Sustainable Development Goals at the UN Sustainable Development Summit in 2015 (continuing the Agenda 21 action plan launched in 1992 in Rio de Janeiro) and the 2015 United Nations Climate Change Conference (COP 21) at which the Paris Agreement, a global agreement on climate change, was negotiated.

To measure the effectiveness of these actions and optimize their outcomes, it became essential to develop adequate tools to assess the environmental effects of construction activities, based on shared metrics (Lee W.L. 2013).

Starting from the 1990s, the first protocols for assessing sustainability levels were introduced (Edwards, 2014), also known as Sustainability Rating Systems or green building rating systems (GBRSs), which can be used to analyse the environmental, social and economic profiles related to processes involving the production and use of buildings (Berardi, 2015).

This comprehensive approach is based on a multidimensional and multi-criterial analysis in which single factors are separately evaluated by specific indicators and then combined in order to give a final overall rating by scores, on the basis of predefined performance levels[1] (Berardi, 2015).

[1] Excerpt from the author's paper: "Politi S., Antonini E., An expeditious method for comparing sustainable rating systems for residential buildings. Energy Procedia, 111, 41-50".

The widespread diffusion of these voluntary evaluation systems, which today are estimated to number nearly 600 globally (Doan et al., 2017), has produced a diverse and heterogeneous framework of methods since, despite sharing the same objectives, they have been developed independently and are adapted to the variety of contexts for which they have been designed, with particular respect to climate and building stock typology.

0.1.1 Research Question no. 1

This lack of homogeneity hinders the ability to perform simple and effective comparisons between assessments conducted with different protocols, significantly reducing the potential of using the Rating Systems as a vehicle to promote the sustainability of buildings and as a global market orientation element even though, individually, they are capable of raising awareness about environmental issues, helping stakeholders to go beyond the targets set in national regulations (Reed et. al, 2011).

The first research question, therefore, embraces the issue of the diversity of GBRSs, seeking to understand which aspects can be considered the most representative for building sustainability.

RQ1: ***Which shared indicators most represent sustainability for the built environment?***

In order to answer this question, in addition to a preliminary literature study, this research selected the green building rating systems as reference elements to be studied in detail.

The purpose was to identify a core set of indicators or categories of indicators, shared by the most common Rating Systems globally, as the most representative aspects of building sustainability, capable of focusing on more robust and more widely recognized sustainability objectives.

– select a number of common GBRSs on the basis of certain criteria (number of certifications issued, origin of the system, adaptability to other contexts, type of indicators assessed);

– compare, through a series of tables, all the indicators listed in the protocols as well as their weighting factors;

– define a number of generic indicator categories based on GBRS topics, such as: site environmental quality, site user comfort, indoor environmental quality, energy, water, materials and products, waste, emissions, facility management and economic aspects;

– reposition GBRS indicators within the selected generic categories;

– check which categories are more significant in terms of weighting factors.

The GBRSs used in the comparison, chosen from among home-based protocols in order to narrow the analysis boundaries, were: CSH v.2010 for the UK, DGNB v.2011 for Germany, HQE Bâtiment Residentiel v.2014 for France, Protocollo Itaca v.2012 and GBC Home[2] v.2014 for Italy and Active House v.2013, an emerging Rating System not as popular as the others but particularly appropriate for the purpose[3].

At the end of the comparison process (Fig.0.1), the most relevant categories turned out to be:

– Indoor Environmental Quality (19.30%);

– Energy (18.98%);

– Site user comfort (13.85%).

[2] GBC Home is a system developed by the Italian Green Building Council but, as a result of a partnership agreement with USGBC, GBC Italia adapted the American LEED® certification to the Italian context. For this reason, the data included within the screening analysis refers to the US market, but the assessment protocol considered is the Italian GBC Home.

[3] The protocol versions selected for comparison are presented in the last version available at the time of the research in 2016. For the majority of protocols, new versions have been released recently.

Fig.0.1 – Core set of building sustainability indicators and related weighting factors (Source: Author)

All other categories turned out to be weighted below 10%. In fact, among all the categories included in the comparison, only annual energy demand and visual, thermal and acoustic comfort indicators were the most common indicators, highlighting two significant circumstances:

- greater importance is generally given to aspects related to building operation rather than the whole life cycle, thus marginalizing upstream and downstream processes;
- less importance is given to indicators involving direct environmental impacts, such as pollutant emissions (not referable to building operation), resource depletion and waste disposal.

These observations confirm that, in recent decades, the concern expressed internationally, through sustainable development initiatives and regulations, has mainly regarded the energy efficiency of buildings (existing and new construction). Actions aimed at reducing consumption - and therefore emissions - during the operation phase, such as directive 2002/91/EC, 2010/31/EU and the recent 2018/844/EU, also support this trend (D'Olimpo D., 2017).

This consideration prompted a further in-depth analysis of the comparison outcomes, focusing on recognition of the most recurrent indicators to evaluate the environmental aspects (excluding operational energy related indicators), narrowing the scope of the research subject.

In order to appraise the relevance attributed to environmental-related indicators, a more detailed study was performed, starting with the outcomes of the first analysis.

The second part of the analysis showed that the environmental impacts category (including indicators such as: responsible sourcing of materials, pollutant emissions, material recycling, water and waste management) cover 24% of all the categories assessed, of which 14% relate to the operation of buildings while the remaining 10% relate to other phases of the life cycle (Fig.0.2).

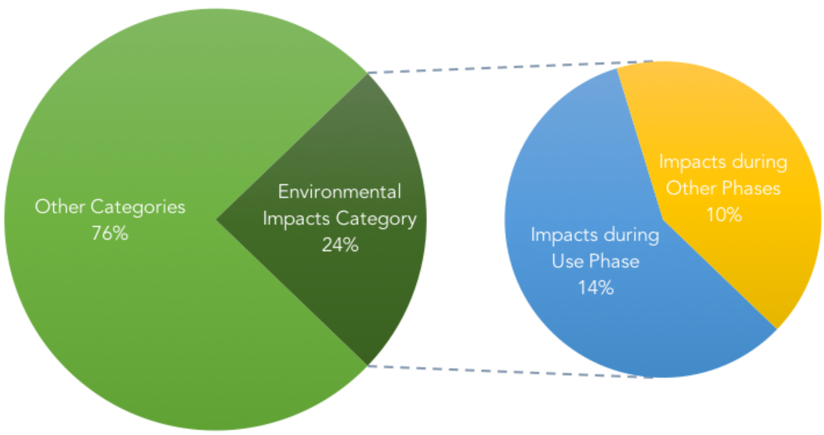

Fig.0.2 – Environmental impacts category relevance (Source: Author)

Although, according to this analysis, operation was shown to be the most significant phase, recently attention has shifted to aspects referring to the entire life cycle of buildings, with particular respect to building products (see European Regulation CPR 305/2011 and European directives 2014/23/EU, 2014/24/EU and 2014/25/EU) (Nash, 2009).

In this context, the object of interest moves, therefore, from the building scale to the scale of specific materials and components; in order to mitigate the negative effects on the environment arising from their production, transportation, assembly, maintenance and disposal (i.e. embodied impacts), it becomes necessary to rely on dependable tools capable of determining the related impacts of building processes.

The analysis conducted on the GBRS indicators suggested identification of the Life Cycle Assessment (LCA) as a comprehensive approach for this purpose. In fact, Rating Systems such as GBC Home, DGNB, CSH, HQE and Active House include assessments criteria based on an LCA analysis or LCA-based items such as Environmental Product Declarations (EPD).

This tendency is also confirmed by literature, in which the LCA is identified as the most widely used and broadly recognized method for environmental impact assessments (Röck et al., 2018).

LCA is currently acquiring much importance within the European context, supported by the European Commission which considers it a priority approach in response to the need for "*clear, verifiable, justifiable and ambitious environmental criteria for products and services, based on a life-cycle approach and scientific evidence base*" (European Commission, retrieved in March 2017).

Various actions rely on this approach, at both EU and national Italian level, such as: the EU Construction Products Regulation-CPR (July 2013); Italian law no. 221 of 28 December 2015 and Legislative Decree no. 50 of 18 April 2016, both concerning Green Public Procurement (GPP) respectively on implementation of the European directives 2014/23/EU, 2014/24/EU, 2014/25/EU and the compulsory adoption of Minimum Environmental Criteria (Criteri Ambientali Minimi - CAM) in public procurement.

Moreover, in 2005 the European Commission established, through the Joint Research Center (JRC), the European Platform on Life Cycle Assessment (EPLCA), a project developed to respond to "*business and policy needs for social and environmental assessments of supply chains and end-of-life waste management*" (European Commission, retrieved in March 2017).

Today, LCA has reached a level of international standardization (ISO 14040/14044:2006) which systematizes analysis applications. For the building sector, a series of standards, such as EN 15978:2011 and EN15804:2012, have been developed within the European Union through the CEN/TC 350 (Sustainability of Construction Works Technical Committee).

0.1.2 Research Question no. 2

The growing interest in the EU context in the life cycle approach to buildings led this research to focus on LCA methodology, deepening our knowledge of its framework.

Through a robust literature and standards review (Ding, 2004/2014; Anderson and Thornback, 2012; Simonen, 2014; Wittstock et al., 2012; etc.) the research summarized the key aspects involved in the implementation of an LCA analysis and produced a list of strengths and weaknesses from which further research developments were derived.

The evidence that emerged from the literature with respect to LCA issues, such as complexity, incompleteness, subjectivity, uncertainty and analysis inconclusiveness (Rønnin and Brekke, 2014; Simonen, 2014), prompted the second research question:

RQ2: ***Can GBRSs indicate which LCA aspects are the most suitable for buildings application?***

As for the first part of the thesis, the means adopted to address this issue were the GBRSs, since the indicators and the evaluation criteria implemented in such protocols are capable of delivering consistent information about building sustainability aspects.

If appropriately integrated with GBRSs, LCAs can have a positive impact on building design as well as on the development of environmental policies and strategies with respect, for instance, to building materials, reflecting the potential benefits for the construction products market and the built environment in general (Ganassali et. al, 2016).

For this reason, the additional aim of the thesis was to deepen knowledge about the conditions and methods of LCA application to building materials and components by investigating and tracing the GBRS indicators that employ the LCA approach as an evaluation criterion.

The methodology adopted for this second part of the research was formulated to include the following steps:

- select a number of international GBRSs that implement LCA indicators for the environmental impact assessment;
- classify the weights attributed to the LCA and EPD[4] related indicators by the selected GBRSs;
- identify a series of characteristic attributes of the LCA framework according to ISO 14040:2006 and 14044:2006;
- compare the GBRS protocols with respect to the identified LCA attributes;
- trace all similarities between the analyzed GBRSs.

For this phase, other international GBRSs were preferred considering, as a filter, inclusion within the protocols of LCA indicators for the embodied impact assessment, which resulted in the following sample: LEED v.4 (USA), DGNB Core 14 (Germany),

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[4] See section 2.4.1 for the definition of EPD.

Green Star v1.1 (Australia), BREEAM New Constructions 2016 (UK), Green Globes v.1.5 (Canada) and Active House (Denmark).

The LCA framework considered in the analysis included in particular: Goal and Scope definition (analysis boundaries, functional unit, building service life, building elements assessed, impact indicators) (Tab. 0.1) and the rating methods.

LCA Framework Analysed				Green Buildings Rating System						Sharing Extent
				DGBN	BREEAM	LEED	Green Globes	Active House	GREEN STAR	
				Core 14	International New Construction 2016	V.4 (BD+C) New Constructions	New Construction v.1.5	v.2	Design & As Built v1.1	
				Germany	UK	USA	Canada	Denmark	Australia	
Goal and Scope	Modules	Raw Material Supply	A1	●	●	●	●	●	●	100%
		Transport	A2	●	●	●	●	●	●	100%
		Manufactoring	A3	●	●	●	●	●	●	100%
		Transport	A4	×	●	●	●	×	●	67%
		Construction Install. Process	A5	×	●	×	●	×	●	50%
		Use	B1	●	×	●	×	●	●	67%
		Maintenance	B2	●	×	●	Partial	●	●	83%
		Repair	B3	●	×	●	×	●	●	67%
		Replacement	B4	●	×	●	●	●	●	83%
		Refurbishment	B5	●	×	●	×	●	●	67%
		Operational Energy Use	B6	●	×	●	Option	●	●	67%
		Operational Water Use	B7	×	×	●	×	●	×	33%
		Deconstruction - Demolition	C1	×	●	●	●	●	●	83%
		Transport	C2	×	●	●	●	●	●	83%
		Water Processing	C3	●	●	●	×	●	●	83%
		Disposal	C4	●	●	●	●	●	●	100%
		Recycling Potential	D	×	×	×	Option	×	×	0%
	Service Life			50 years (depends on the DGNB scheme adopted)	60 years	60 years	60-120 years	50 years	60 years (unless otherwise stated)	67 years
	Functional Unit			m2 of Net Floor Area (NFT)	1 m2	N.S.	N.S.	N.S.	1 m2 project Gross Floor Area (GFA) basis (Additional FU allowed)	1 m2
	Building Elements Assessed	Footing and foundations		●	×	●	●	●	●	83%
		Ground slabs		●	●	●	●	●	●	100%
		Floor Slabs		●	●	●	●	●	●	100%
		Other structural elements		×	×	●	●	×	●	50%
		Roof assemblies		●	●	●	×	●	●	83%
		External Envelope		●	●	●	●	●	●	100%
		Inner walls		×	●	×	×	●	●	50%
		Ceilings		×	×	×	×	●	●	33%
		Windows and doors		●	●	●	●	●	●	100%
		Technical installations		●	×	×	×	●	●	50%
		Finishes		×	×	●	●	×	●	50%
		Underground parking		×	×	●	●	×	●	50%
	Impact Indicators | Units	Climate Change	GWP	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq/m2 x a	kg (CO2)eq (100yr)	100%
		Water Extraction	WD	×	m3	×	×	×	m3	33%
		Mineral Resource Extraction	TMR/ADP-e	×	tonnes	×	×	×	kg Sb eq	33%
		Stratospheric Ozone Depletion	ODP	kg (R11)eq/CFC-11 eq	CFC-11 eq	CFC-11 eq	CFC-11 eq	kg (R11)eq/m2 x a	CFC-11 eq	100%
		Human Toxicity	HTP	×	kg (1.4 -DB)eq	×	×	×	○ kg (1.4 -DB)eq	33%
		Ecotoxicity to Freshwater	WTP	×	kg (1.4 -DB)eq	×	×	×	×	17%
		Ecotoxicity to Land	LTP	×	kg (1.4 -DB)eq	×	×	×	×	17%
		Nuclear Waste		×	mm3	×	×	×	×	17%
		Waste Disposal		×	tonnes	×	×	×	×	17%
		Fossil Fuel Depletion	ADP-ff	×	MJ (TOE?)	MJ	MJ	×	MJ	67%
		Eutrophication	EP	kg(PO4) eq	kg(PO4) eq	kg N2 or kg PO4	kg N2	kg (PO4)eq./m2 x a	kg(PO4) eq	100%
		Photochemical Ozone Creation	POCP	kg(C2H4)eq	kg(C2H4)eq	kg NOx, kg (O3)eq, or kg (C2H4) eq	kg (O3)eq	kg (C3H4) eq./m2 x a	kg(C2H4)eq	100%
		Primary renewable energy consumtion	PERE	×	×	×	×	kWh/m2 x a	×	17%
		Primary non-renewable energy consmption	PENRE	×	×	×	×	kWh/m2 x a	×	17%
		Acidification	AP	kg(SO2)eq	kg(SO2)eq	moles H+ or kg (SO2)	kg(SO2)eq	kg (SO2)eq./m2 x a	kg(SO2)eq	100%
		Ionising Radiation		×	×	×	×	×	○ kg(U-235) eq to air	17%
		Paticulate Matter	PMF	×	×	×	×	×	○ kg(PM2.5) eq	17%
		Land Use		×	×	×	×	×	○ m2	17%

Tab.0.1 – GBRSs LCA framework comparison (Source: Author)

The comparison provided the following outcomes:

- Different sharing extents were reported for the LCA modules: 100% sharing for Raw Material Supply (A1), Transport (A2), Manufacturing (A3) and Disposal (C4). 83% for Maintenance (B2), Replacement (B4), Demolition (C1), Transport (C2) and Water processing (C3). Greater discrepancy, instead, was reported for the remaining stages.
- For the Impact Indicators, 100% sharing was reported for Climate Change (GWP), Stratospheric Ozone Depletion (ODP), Eutrophication (EP), Photochemical Ozone Creation (POCP) and Acidification (AP). 67% for Fossil Fuel Depletion (ADP), while only minor agreement was reported for other indicators.
- The buildings elements considered by the majority of GBRSs are: ground slabs, floor slabs, external envelope, windows and doors (100%), footings and foundation, roof assemblies (83%).
- The majority of the analyzed GBRSs rate the reduction of LCA impacts with respect to a reference building (or baseline building) that must be specifically designed according to protocol requirements (usually according to national energy and thermal performance). Conversely DGNB and Active House, provide direct benchmarks for the LCA output assessment.

The results of the study on the one hand reveal some features shared by the majority of the GBRSs (in particular with respect to Goal and Scope requirements) that can therefore be considered representative of LCA applications to buildings.

On the other hand, the outcomes indicate a lack of agreement on several other aspects, confirming some of the weaknesses highlighted by the literature findings.

0.1.3 Research Question no. 3

At this point, the core issue of the research was identified: although LCA is recognized as an indispensable tool for assessing the embodied impacts of buildings, its implementation in practice is still affected by a series of limitations which hinder the widespread diffusion of this method, especially among non-expert practitioners.

In fact, the heterogeneity of the application methods, the entity and the nature of the data involved in the evaluation processes complicate its correct application, requiring time-consuming tasks and specific technical skills.

These critical issues primarily concern the early design stages in which, usually, the key variables that shape the environmental profiles of buildings are defined.

The lack of economical and effective tools with which to compare technological alternatives leads designers to consider the environmental aspects only at the end of the process when all the required information is accessible, but project variations result in significant additional costs and effort.

This situation means that LCAs cannot provide relevant feedback capable of guiding the design process and improving the sustainable aspects (Basbagill et al, 2013).

Despite being more challenging, the implementation of sustainable design has to occur in the early phases when the most decisive decisions for the environmental aspects of the project are made, at the same time carefully considering the entire building life cycle (Antón and Diaz, 2014).

These considerations inspired the third research question, as the core of the research advancement.

RQ3: ***How can LCA limitations be overcome, allowing simplified but representative applications in buildings during the initial design phases?***

The first action undertaken to approach this issue was to aggregate the weaknesses found in literature to make it easier to outline the following activities resulting in the identification of four main groups:

- Methodological inhomogeneity;
- Ambiguity of outcomes interpretation;
- Promiscuity of methods effectiveness boundaries;
- Operations complexity.

Up to this point, the research outcomes, in addition to further studies of the technical literature, suggested a series of possibilities to approach the highlighted LCA weaknesses. In particular, two elements were particularly suitable for this purpose:

- Building Information Modelling (BIM) tools for the operative issue;
- the common EU framework: Level(s), which "*provides a set of sustainability indicators and common metrics for measuring the performance of buildings along their life cycle*" (Dodd, 2017), for the remaining issues.

A scheme of the proposed approach is shown in Fig.0.3, in which the grouped weaknesses are connected with the possibilities envisaged to overcome them.

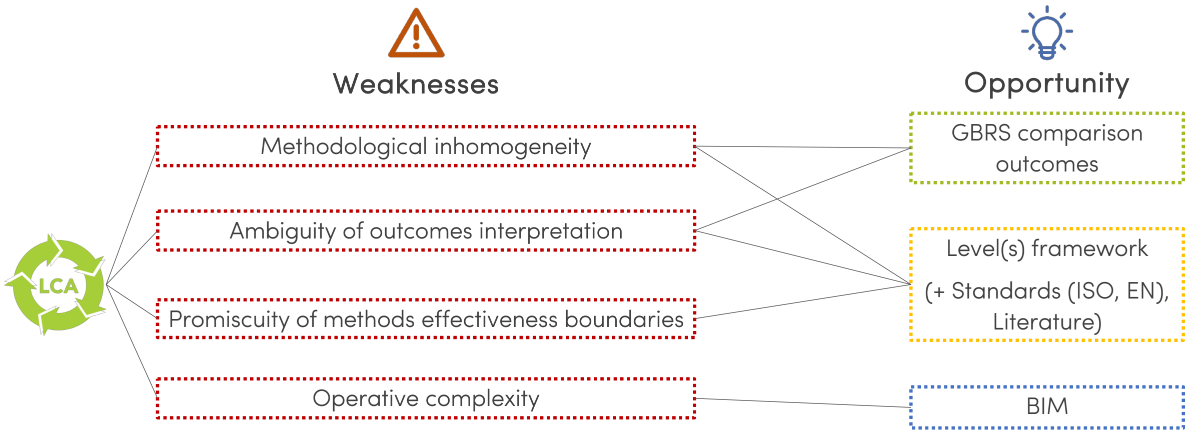

Fig.0.3 – Scheme of the proposed approach to overcome the detected weaknesses (Source: Author)

Performing LCA applications with reasonable effort can act as a driver for sustainable building projects as the consequences of decisions can be monitored as the design advances (Röck et al., 2018).

Therefore, through the outcomes of the previous analysis on GBRSs, shared LCA indicators and criteria, relying on international standards for building LCAs (such as EN 15978:2011, EN 15804: 2012) and with the support of the Level(s) framework (Dodd et al., 2017), a simplified framework for LCA application to buildings was drawn up (Tab. 0.2).

Proposed Common and Simplified LCA framework	
LCA framework parts	Description
Goal and scope definition	According to Level(s) reporting format (Part 3, section 1)
Environmental data source	Primary data source: product specific EPDs (EN15804 compliant) Secondary data source: generic LCA databases (EN 15804 compliant)
Reference Functional Unit	$1m^2$ of building useful floor area (net floor area)
LCA stages and modules	Product stage: A1, A2, A3 Use stage: B2, B4 End of Life stage: C1, C2, C3, C4
Scenarios definition	According to specific EPDs content and Level(s) scenarios guidance (Part 3, section 2.2)
LCI categories	Use of renewable primary energy excluding energy resources used as raw material*, Use of non-renewable primary energy excluding primary energy resources used as raw material**
LCIA categories	GWP, ODP, AP, EP, POCP, ADP (elements), ADP (fossil fuels)
LCIA characterization factors	CML-IA, according to EN 15804
*This LCI category is later indicated as:"PERE"(Primary Energy REnewable); ** This LCI category is later indicated as:"PENRE"(Primary Energy Non-REnewable)	

Tab.0.2 – Proposed LCA framework (Source: Author)

In order to overcome the operative complexity issue, this framework was subsequently applied to a workflow specifically designed to integrate the LCA analysis with BIM models.

The workflow, shown in Fig.0.4, was designed to implement the LCA in the early stages of the project, resulting in real-time assessment as the project level of detail evolves, thus allowing greater control over the environmental variables and design strategies.

In fact, one of the crucial tasks of integrating LCA and BIM is obtaining a convenient decision-making method suitable for designers on a day-to-day basis without the need for particular LCA expertise (Antón and Diaz, 2014).

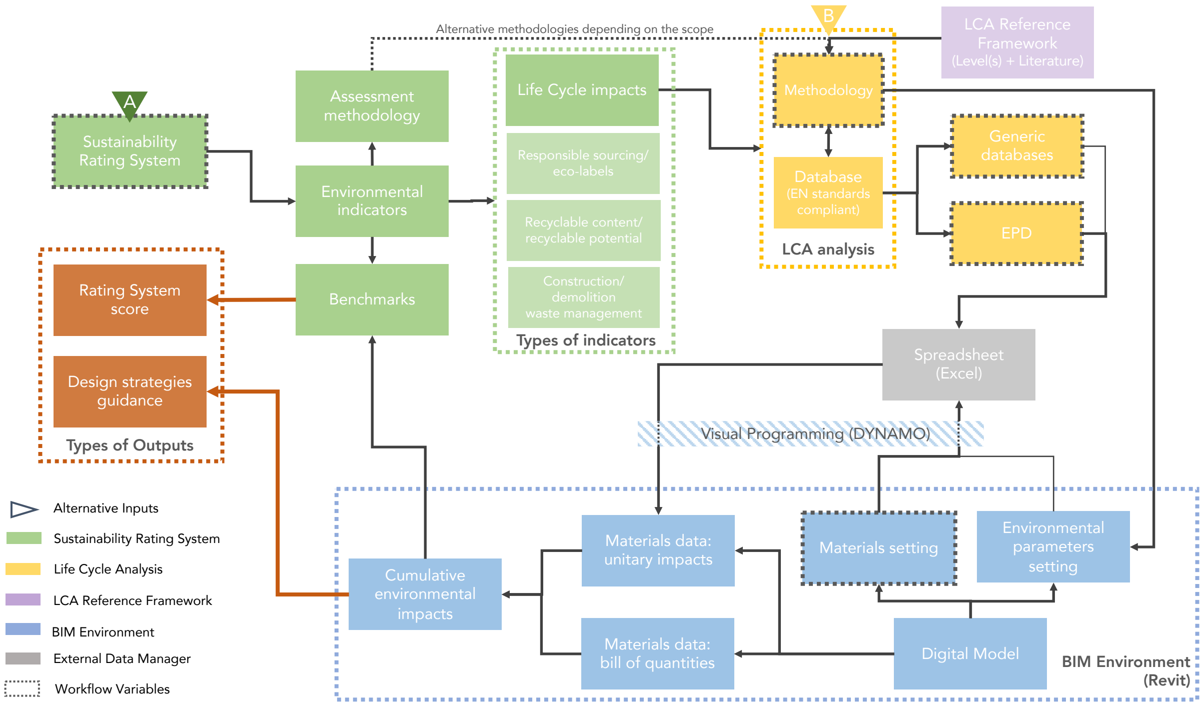

Fig.0.4– LCA-BIM integration workflow (Source: Author)

After an in-depth literature review on LCA-BIM approaches, the research proposed an original integration approach, based on two main features:

- performing an LCA analysis within a BIM platform without using external LCA tools;
- allowing users to customize the approach depending on their goal and LCA level of expertise.

Furthermore, the workflow was designed to be convenient also from an economic point of view as it does not require subscription to commercial LCA databases.

In order to test the proposed workflow, an illustrative application was performed on a case study: a model floorplan of a multi-story student residence, for which LCA indicators for the external opaque envelope were calculated.

The tools used for this were: Autodesk Revit for the BIM model management and LCA cumulative impacts calculation, Microsoft Office to manage the external LCA data, and Autodesk Dynamo to integrate the external data into the BIM model.

The workflow allows users to produce customized schedules for building materials or specific assemblies depending on the objective of the analysis.

As the illustrative application is centered on the external opaque envelope, in addition to a schedule for building materials, a schedule reporting the environmental cumulative data relating to the different external wall types was also produced (Fig. 0.5)

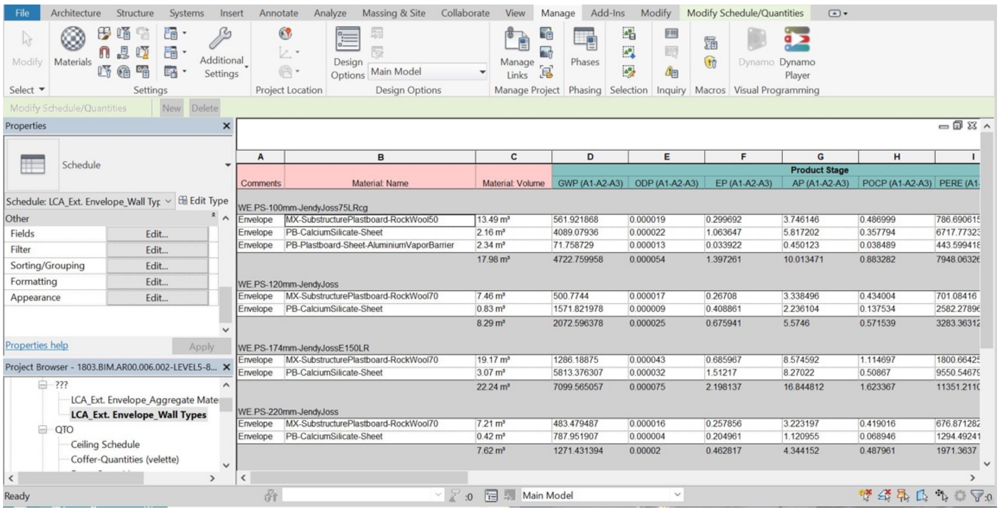

Fig.0.5– Portion of Revit schedule indicating the LCA outputs for external envelope wall types (Source: Author)

The recognized benefits of performing such an integration using the proposed method are:

- easy access to the actual quantities and attributes of construction materials and building products, thus avoiding manual data entry;
- autonomy in adapting the assessment variables (e.g. study boundaries, environmental indicators) to different analysis scopes, depending on personal expertise and evaluation goals;
- opportunity of comparing different design alternatives, especially with regard to materials and products, resulting in an effective decision-making tool;

- capacity for real-time assessment as the project level of detail evolves: from the early design stages to the conclusive ones, without re-importing the BIM model into the external LCA platform each time the model changes;
- opportunity to take advantage of a structured spreadsheet for materials and products that can be updated with new elements and environmental information and, therefore, re-employed in further analyses;

At the same time, this application also evidences certain drawbacks such as:

- producing such a spreadsheet implies a solid system for naming and classifying materials and environmental impacts, resulting in accurate but time-consuming manual data entry since it cannot be achieved by automatically importing data from EPDs or other LCA databases into the BIM models;
- collecting consistent data from certified sources, such as EPDs, is still a delicate step since, despite their certified reliability, accurate data collection depends on the availability of data for all the project materials and products;
- accuracy in performing the LCA and the representativeness of the outcomes depends greatly on the quality of the BIM model;
- the issue of calculating and automatically including aspects such as transportation information, construction techniques, materials and product maintenance, is still problematic due to the different features and locations of each project;

0.2 Research Design, Methods and Boundaries

This research was motivated by the desire to deepen our knowledge of the environmental impacts caused by building life-cycles.

The research process started by formulating a general research question about the concept of building sustainability, and it advanced by focusing on more specific topics concerning the environmental embodied impacts related to building components.

The thesis was structured specifically to achieve progressive outcomes, from which to then formulate further and more consistent questions in order to obtain a detailed framework of the circumstances and variables involved in shaping the environmental profiles of buildings.

For each question, a number of objectives were identified, and a specific research methodology was planned in order to achieve a series of outcomes in the form of different kinds of deliverables.

To advance the research process, the outcomes of each research topic were analysed and discussed and an additional narrowed research goal was identified (Fig. 0.1) (Maxwell, 2012; Creswell & Creswell, 2014).

In order to set a research boundary, progression was limited to three subsequent analyses, the last of which is considered the core of the research path.

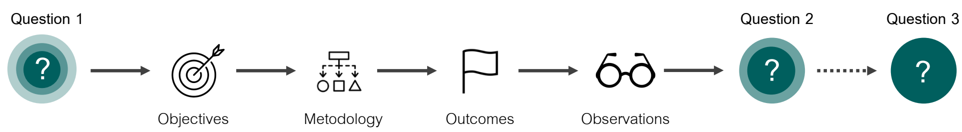

Fig. 0.6 – Progressive research process (Source: Author)

The research methodology for each group of objectives was set specifically depending on the scope and expected outcomes.

In general, the theory background was developed through a literature review of scientific journals, books, conference proceedings and national and international standards, regulations and other publications relevant for the building sector.

In order to select appropriate literature, priority was given to publications with significant Impact Factors (higher than 3) published within the last ten years (2008-2018).

However, in certain circumstances, older references were also considered, and bibliometric indices disregarded. In particular, the selection criteria were bypassed for documents or reports developed from national, international or intergovernmental organizations, which are usually not indexed or rated.

In the majority of cases, research was conducted through scientific literature databases such as: ScienceDirect, Scopus, Web of Science, Taylor and Francis Online, SpringerLink, Google Scholar, or through other specific databases for the built environment such as: ProQuest, ASCE, BUILD and RIBA.

Since the thesis premises concerns building sustainability, the principal tools adopted as references to further explore this topic were GBRSs, especially with respect to research questions 2 and 3. Different GBRSs generally propose a variety of assessment methods which can vary greatly depending on the evaluation subject.

After a preliminary literature review of the key topics in order to build a solid background of notions, the method adopted to extrapolate pieces of vital information was a direct comparison between GBRSs, which led to the recognition of interesting circumstances fit for further consideration.

Since several GBRSs are available in the market, the first step of the comparison methodology was to identify a sample of protocols by defining a series of selection criteria based on the scope of the analysis. Criteria such as international diffusion (in terms of number of certifications issued), adaptability to different building typologies and different climatic zone representativeness were adopted to narrow the sample, at the same time maintaining a good level of reliability.

Once the core of the research topic was identified, the methodology adopted to respond to the issues that had emerged was the experimental approach: the outcomes of the previous analysis were processed resulting in the definition of a workflow, which was subsequently tested on a case study for its validation.

This sample workflow, even if applied to just one case study, does not limit the consistency of the method, since the basic procedures do not depend on different buildings design processes or different building typologies.

The research considered buildings in general and did not select by specific typology. However, it was decided that for the comparison of GBRSs, only the protocols for new construction had to be considered, since LCA is a challenging method when applied to existing or historical buildings.

A similar consideration was made in the selection of the case study: as the workflow proposed was to be implemented during the initial design phases, a new construction project (not yet developed for an executive phase) was selected[5].

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[5] The case study selection and production of the BIM model were performed in collaboration with an architecture and engineering firm located in Bologna: Open Project srl, as part of a joint research project.

Since one of the research aims was to develop a simplified method for LCA applications that could suit a broad context (in terms of climatic and geo-politic conditions) in order to endorse greater diffusion of building environmental profile comparisons, the boundaries of the research were set within the European Union framework in which environmental policies, strategies and standards are shared by member countries.

0.3 Results Achieved

With respect to the three research questions investigated by the thesis, the results achieved are summarized as follows:

1. *Which shared indicators most represent sustainability for the built environment?*

   This first stage of the research, based on an analysis of a number of international GBRSs (specific to residential buildings and selected through a series of cut-off criteria) returned a core set of sustainability indicators and metrics, classified on the basis of their weighting factors. The observation of this first outcome, showing that indicators related to upstream and downstream building processes (embodied impacts) are generally considered less relevant than those related to building operation, suggested the scope of the second research question, which addressed the assessment of the environmental embodied impacts of buildings.

2. *Can GBRSs indicate which LCA aspects are the most suitable for buildings application?*

   The second stage highlighted a series of discrepancies in the application of LCA analysis to buildings. A similar comparison between other international GBRSs (selected for the inclusion of LCA indicators within their protocols) was performed in order to detect a number of LCA representative attributes for building applications. Although the comparison led to the drafting of a shared buildings LCA framework (with particular reference to Goal and Scope definition and environmental data source), it did however further underline the discrepancies in the application of the method within a broad context. This consideration, together with discernment of the fact that the environmental profiles of buildings are generally shaped in the early design stages, prompted the third research question as the core of the thesis.

3. *How can LCA limitations be overcome, allowing simplified but representative applications on buildings during the initial design phases?*

   The last part of the thesis therefore addressed the development of a sample workflow, aimed at performing simplified but representative LCA applications through the integration of the tools considered in the previous phases (GBRSs, literature findings, international standards) with two additional tools assumed to be suitable for the purpose: BIM platforms and the EU common framework on building sustainability LEVEL(s). The developed workflow (tested on a case study) aims to provide a consistent real-time LCA assessment approach as the project level of detail evolves, encouraging the feasibility of broader comparison between different building components, thus helping designers and decision-makers to shape more sustainable building profiles in terms of environmental embodied impacts.

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Part I

ENVIRONMENT VS BUILT ENVIRONMENT: THE SUSTAINABILITY CONCEPT

1.0 Research Question no. 1

Construction is one of the least sustainable economic sectors: globally, the production and operation of buildings and infrastructures are estimated to account for around 50% of greenhouse gas emissions, 40% of water pollution and 50% of waste disposal in landfills, in addition to absorbing 50% of energy, 50% of drinking water and 60% (by bulk) of materials from the ecosystem (Edwards, 2014).

In recent decades, this has led international organizations to promote - and many countries to adopt - more stringent mitigation actions and regulatory standards in order to control the negative effects resulting from the built environment.

To measure the effectiveness of these actions and optimize their outcomes, it became essential to develop adequate tools to assess the environmental effects of construction activities, based on shared metrics.

From the 1990s, specific protocols for analysing and assessing the environmental, social and economic quality of buildings were introduced to the market.

Such systems have been designed to produce an overall rating of the building quality in terms of sustainability by assigning scores to a number of building features, and for this reason they are known as sustainability rating systems or green building rating systems (GBRSs).

This comprehensive approach is based on multidimensional and multi-criterial analysis in which single factors are separately evaluated by specific indicators and then combined in order to give a final overall rating by scores, on the basis of predefined performance levels[6] (Berardi, 2015).

The widespread diffusion of these voluntary evaluation systems, today estimated to be nearly 600 globally (Doan et al., 2017), has produced a diverse and heterogeneous framework of methods since, despite sharing the same objectives, they have been developed independently, and are adapted to the variety of contexts for which they have been designed, with particular respect to climate and building stock typology.

This lack of homogeneity hinders the ability to perform simple and effective comparisons between assessments conducted with different protocols, significantly reducing the potential of using the Rating Systems as a vehicle to promote the sustainability of buildings and as a global market orientation element, even though, , individually, they are capable of raising awareness about environmental issues, helping stakeholders to go beyond the targets set in national regulations (Reed et. al, 2011).

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[6] Excerpt from the author's paper: "Politi S., Antonini E., An expeditious method for comparing sustainable rating systems for residential buildings. Energy Procedia, 111, 41-50".

The first research question, therefore, embraces the issue of the diversity of GBRSs, seeking to understand which aspects can be considered the most representative for building sustainability:

RQ1: ***Which shared indicators most represent sustainability for the built environment?***

In order to answer this question, in addition to a preliminary literature study, this research selects the green building rating systems (GBRSs) as reference elements to be subjected to a comparative analysis.

The purpose was to identify a core set of indicators or categories of indicators, shared by the most common GBRSs globally, as the most representative aspects of building sustainability, capable of focusing on more robust and more widely recognized sustainability objectives.

The GBRSs used in the comparison, chosen from among home-based protocols in order to narrow the analysis boundaries, were: CSH v.2010 for UK, DGNB v.2011 for Germany, HQE Bâtiment Residentiel v.2014 for France, Protocollo Itaca v.2012 and GBC Home v.2014 for Italy and Active House v.2013, an emerging Rating Systems not as popular as the others but particularly appropriate for the purpose[7].

Two significant circumstances emerged from the comparison:

– annual energy demand and visual, thermal, and acoustic comfort are the most common indicators, indicating that greater importance is generally given to aspects related to building operation rather than the whole life cycle, thus excluding upstream and downstream processes;

– less importance is given to indicators involving direct environmental impacts, such as pollutant emissions (not referable to building operation), resource depletion and waste disposal.

This condition led the research to shift the attention from the building scale to the scale of specific materials and components; in order to mitigate the negative effects on the environment arising from their production, transportation, assembly, maintenance and disposal (i.e. embodied impacts), it becomes necessary to rely on dependable tools capable of determining the related impacts of building processes.

[7] The protocol versions selected for comparison are presented in the last version available at the time of the research in 2016. For the majority of protocols, new versions have been released recently.

This consideration motivated a further in-depth analysis of the comparison outcomes, focusing on recognition of the most recurrent indicators to evaluate environmental aspects (excluding operational energy related indicators), narrowing the scope of the research subject in order to appreciate the relevance attributed to these kinds of indicators.

1.1 Ecological Footprint

The capacity of ecosystems to regenerate what people demand from the planet is known as Biocapacity, namely, the capacity to produce biological materials used by people and to absorb waste material generated by humans such as, for instance, carbon dioxide (*Global Footprint Network, retrieved in June 2017*).

Biocapacity is expressed in global hectares of fertile surface and, considering that the total area of the planet amounts to 51 billion hectares and that the fertile area is just 23% of the total (considering arable lands, pastures, forests, rivers, lakes and part of the oceans), the planetary Biocapacity is estimated at 12 billion hectares (Fig. 1.1).

While Biocapacity measures the fertile area available, another indicator, the Ecological Footprint, measures the fertile area necessary to sustain global consumption, which is currently estimated at 20 billion hectares.

In order to be balanced, the Ecological Footprint has to be at or below the planet's Biocapacity.

Consumption level is currently appraised to require a quantity of fertile surface 66% higher than that available (20 billion hectares against 12), producing an imbalance that overcomes the world's capabilities and results in function failures such as the environment's inability to absorb all the carbon dioxide emitted, which is consequently accumulated in the atmosphere.

It is possible to determine when the Biocapacity limit is exceeded annually by dividing the annual Footprint by the days in a year, thus identifying the so-called "Overshoot Day" which marks the beginning of consumption without the corresponding necessary fertile land. In 2018, the Earth Overshoot Day occurred on the 1st of August (*Global Footprint Network*, retrieved in September 2018).

Dividing the 12 billion hectares of total fertile area by 7 billion people, the number currently inhabiting the planet, is it possible to define the Sustainable Ecological Footprint as equal to 1.7 hectares per capita but, considering that the actual area required by humanity is 20 billion hectares, the real Footprint per capita amounts to 2.8 hectares.

Despite this average, the Ecological Footprint is not equally distributed throughout the planet. It has been proven that, among 7 billion people (100% of humanity), 3 billion (48%) benefit from less than 1.7 hectares (Sustainable Footprint), 200 million (3%) benefit from 1.7 hectares, while 3.8 billion (54%) inhabitants exceed the Sustainable Footprint limit, requiring, on average, three times more fertile land than those below the limit.

In Italy, for instance, 4.6 hectares of fertile land per capita are required, resulting in a footprint two and half times higher than the sustainable one (Centro Nuovo Modello di Sviluppo, 2016).

Among the human activities contributing to the Ecological Footprint, industries, transportation and construction (hence buildings) play a key role.

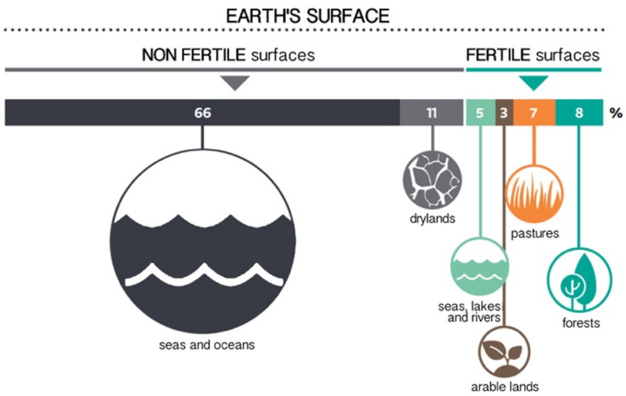

Fig. 1.1 – Earth's fertility scheme (Source: Centro Nuovo Modello di Sviluppo, 2016 – reworked by the Author)

1.2 Overview of the Environmental Impact of Buildings

Humanity has depended on buildings since the earliest civilization.

Almost all activities related to human life are linked to buildings and their content. Our planet, however, cannot handle the current level of resource consumption coupled with waste and pollution production.

About half of non-renewable resources depleted across the planet are used in the construction industry, making it one of the least sustainable sectors globally (Doan et al., 2017).

Constructions are responsible for almost half of non-renewable resource consumption across the planet (Edwards, 2014). In particular, the European economy is profoundly linked to the import of resources such as raw materials and energy, representing one of the most resource-hungry economies globally (European Commission, 2011)

The use of global materials, a significant share of which are employed in construction, has grown enormously in the last century, to unpredicted levels, and it is estimated to grow intensely over the next 30 years (Pachego-Torgal, 2014).

Resource depletion and use are strictly related to pollutant emissions and waste production, resulting in harmful impacts for the environment and ecosystems. The following tables (Tab.1.1, 1.2) provide some significant statistics:

Estimate of global resources used in buildings	[%]
Energy	45-50
Water	50
Materials for buildings and infrastructures	60
Agricultural soil	80
Timber products for constructions	60 (90% of hardwoods)
Coral reef destruction	50 (indirect)
Rainforest destruction	25 (indirect)

Table. 1.1 - Global Resources used in building sector (Source: Edwards, 2014 – reworked by the author)

Estimate of global pollution that can be attributed to buildings	[%]
Air quality	23
Global Warming Gasses	50
Drinking water pollution	40
Landfill waste	50
Ozone thinning	50

Table. 1.2 - Global pollution attributed to buildings (Source: Edwards, 2014 – reworked by the author)

1.2.1 The "embodied" issue: energy and carbon[8]

Construction materials and products can therefore generate an environmental impact through the extraction of raw materials for processing and manufacturing and during maintenance and refurbishment up to the eventual end of life and disposal (Anderson and Thornback, 2012).

The production and use of energy has been acknowledged as an emergent environmental issue since it relies on fossil fuel combustion and, for this reason, it is considered strictly connected to environmental endangerment as it affects the world's biosphere through the depletion of non-renewable sources and the global climate through the emission of pollutants such as: carbon dioxide, methane and nitrous oxide, produced during fossil fuel combustion.

Even though it is not the only characteristic to consider, energy is a good indicator to obtain a broad picture of how much each phase of a building life actually weighs in terms of its impact on the environment.

The first distinction to be made in order to describe and calculate the energy flow in building processes is between Operational Energy and a building material's Embodied Energy. Cabeza et al. (2014) define Operational Energy as the energy required to maintain indoor comfort conditions and provide ordinary building maintenance, thus it includes energy for HVAC (heating, ventilation and air conditioning), domestic hot water, lighting, and appliances.

While there is broad accordance of the definition of Operational Energy, not all authors agree on the definitions of Embodied Energy. Cabeza, et al. (2014) define the

[8] Part of this section has been excerpted from the author's scientific paper: Politi S., & Antonini E. (2017), Buildings Hidden Energy and Environmental Consequences, Sustainable Mediterranean Construction Journal, 6, 19-23.

latter as the "*Energy content of all the materials used in the building and technical installations, and energy incurred at the time of new construction and renovation of the building*" thus excluding the energy spent during the end of life phase, which they refer to as Demolition Energy.

Dixit et al. (2010) gave a more comprehensive characterization of Embodied Energy as the energy "*sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal*".

As outlined above, buildings are capable of energy and other resource depletion at each stage of their life, at the same time generating pollutant emissions (Ding, 2004).

The EeBGuide Guidance Document (Part B: BUILDINGS) (Wittstock et al., 2012), states that the energy efficiency of buildings has gained relevance in the last twenty years, especially within building planning and assessment, and it also represents a critical issue for legislation within the EU.

Through some important initiatives, the Operational Energy of new and refurbished buildings has been significantly minimized over time in the European context (Wittstock et al., 2012).

Nevertheless, a sole improvement in efficiency has been shown to be insufficient to reduce the total energy needs due to the considerable share of energy included in the upstream and downstream processes of producing building materials (Ding, 2004).

Ding (2004) supports this fact, pointing out that the energy involved in the production of building components off-site accounts for over 75 per cent of the total embodied energy in buildings.

Yet, Embodied Energy plays an important role in the building energy balance and its share within the overall energy demand therefore emerges as a crucial index to be assessed.

Chastas et al. (2016) performed a literature review regarding the Life Cycle Energy Analysis (LCEA) of residential buildings as well. The sample they analyzed consisted of 90 LCEA case studies from around the world (Europe, North America, Oceania, Asia) with a time span ranging between 1997 and 2016 and including conventional, passive, low-energy and nearly zero energy residential buildings (nZEB). They showed that the share of Embodied Energy in the total life cycle energy considering all the case studies ranges between 5% and 100% (Fig. 1.2).

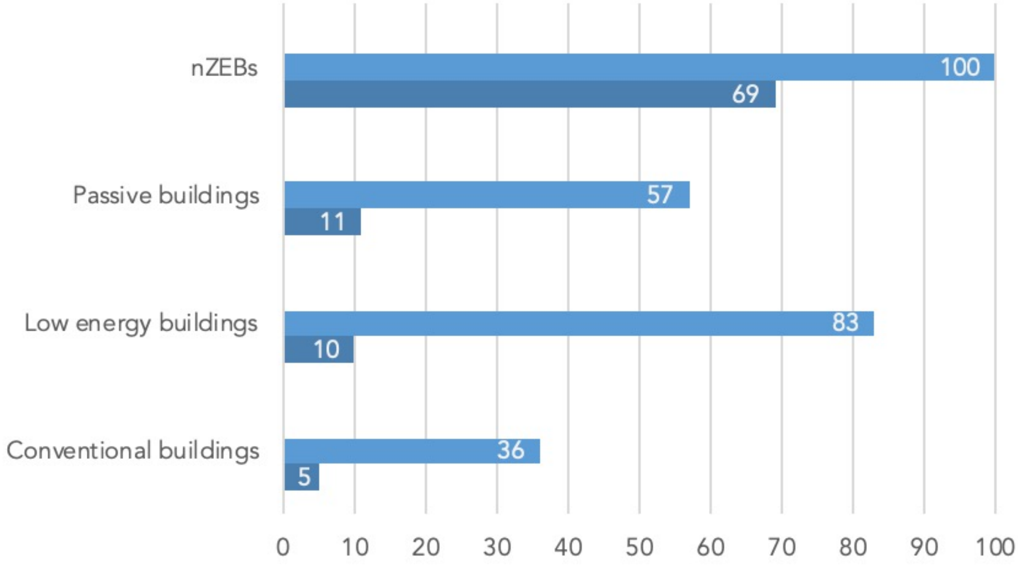

Fig. 1.2 – Embodied energy share [%] in different types of buildings (Source: Chastas et al., 2016 – Reworked by the Author)

In addition to energy consumption before, during and after the building construction process, the impact of the contribution of materials and products also affects the ecosystem through carbon dioxide (CO_2) emissions, which represents a big issue for global warming.

More recently, special attention has been paid to a particular issue parameter, namely climate change, focusing on impact measurement through carbon emissions (Anderson and Thornback, 2012). Embodied Carbon (EC) is also known as: Carbon Footprint, Climate Change or Global Warming Potential (GWP).

As for Embodied Energy, Embodied Carbon represents the emissions associated with the manufacture and use of a product or service. For construction products and materials, it is related to extraction, manufacture, transport, assembly, maintenance and disposal.

Embodied Carbon is strictly related to Embodied Energy as the latter can be converted into the former by multiplying the energy employed in a material's production by the carbon intensity of the fuel burnt.

As with energy, Operational Carbon is usually the prime cause of GHG emissions in existing buildings, with a 75-90% share of the total emissions when the share of Embodied Carbon of the building fabric ranges between 10-25% (Anderson and Thornback, 2012).

Embodied Carbon is usually expressed in units of carbon dioxide (CO_2), nevertheless the term "carbon" is often used to indicate other greenhouse gases

(GHGs) (in accordance with the Kyoto Protocol) such as: Methane (CH_4), Nitrous Oxide (N_2O), Sulphur Hexafluoride (SF_6), Perfluorocarbons (PFCs) or Hydrofluorocarbons (HFCs).

However, even though these gases are all responsible for the greenhouse effect by trapping heat in the atmosphere, a phenomenon known as "radiative forcing", their Global Warming Potential is not the same. As CO_2 is the most abundant GHG, GWP is generally expressed in units of carbon dioxide equivalent (CO_2e). Anderson and Thornback (2012) explain that this unit gives "*the relative measure of the amount of CO_2 which would need to be released to have the same radiative forcing effect as a release of 1 kg of the GHG over a particular time period*".

GWP, therefore, is an indicator for measuring the impact on climate change of a particular gas, normalized to the GWP of CO_2.

1.2.2 Environmental Impact Categories

Among the variety of environmental impacts, the one recognized as the most relevant is global warming which is a direct consequence of intensive environmentally destructive activities such as fossil fuel combustion (producing greenhouse gases - GHG), deforestation and land alterations, raising concern at international level (Khasreen et al., 2009).

Global warming is generally considered the most evident expression of environmental disruption, since extreme weather conditions such as heat waves, superstorms and floods are attributed to this phenomenon (Wallace et al., 2014).

According to the IPPC special report (2018), anthropogenic activities are estimated to have caused nearly 1.0°C (between 0.8°C and 1.2°C) of global warming above pre-industrial levels (with respect to the present level which is based on the average of a 30-year period centered on 2017 assuming the recent rate of warming continues) and it is expected to reach 1.5°C between 2030 and 2052 if the current increasing rate does not change.

In the last special report, the IPPC indicated the limit of 1.5° for the next period, illustrating the potential consequences of rising from 1.5° to 2° especially with regard to increases in mean temperature in most land and ocean regions, heat waves in the most populated regions, and violent precipitation in some regions or drought in others.

Such a goal would require quick and extraordinary changes (in terms of scale) and interventions in energy, land, urban and infrastructure management (including transport and buildings), as well as industrial systems, implying substantial emission reductions and significant mitigation actions.

For instance, according to IPCC (2018), to achieve the 1.5° target, the global net anthropogenic CO_2 emissions should be reduced by about 45% (from 2010 levels) by 2030, and they should be almost zero by 2050.

In the best scenario (1.5°), in order to cut emissions, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming.

The building industry represents one of the main contributors to the climate change issue as it is considered the single largest factor responsible for global GHG emissions (up to 50% of CO_2 emissions) (Khasreen et al., 2009), in the form of both operational and embodied emissions due to the primary energy demand over the whole life cycle of buildings (Ibn-Mohammed et al., 2013).

The same attention, however, has not been paid to the reduction of operational and embodied emissions, which has been largely neglected for a long time (Ibn-Mohammed et al., 2013).

The UK actions represent a good example of GHG reduction as they achieved an almost 14.6% cut between 1990 and 2004, (rising by about 1% since 2002), and have announced the goal to reach an 80% reduction in CO_2 emissions by about 2050 (Khasreen et al., 2009).

However, GHG emission is not the only indicator to consider with respect to environmental impacts.

According to the EN 15804:2012 standard, Anderson and Thornback (2012) have listed and described those that can be considered the most common and critical impact categories besides global warming:

– *Acidification* (Acidification for Soil and Water, Acidifying Pollution, Aquatic Acidification): this phenomenon occurs when acidic gases such as SO_2 or NO_x (usually emitted from the combustion of fossil fuels) react with water present in the atmosphere producing acid deposition, also known as "acid rain" which causes ecosystem damage.

– *Eutrophication* (Nitrification): occurs in the presence of an abnormal concentration of nitrates and phosphates in water, which favour an excessive growth of algae reducing the oxygen in the water and thus endangering the biodiversity. Constructions might contribute to this when the runoff from construction sites is not monitored, when drainage/sewerage systems are insufficiently maintained and the production of products/fuels from agricultural products is uncontrolled.

- *Stratospheric Ozone Depletion* (Ozone Degradation Potential; Ozone Depletion Potential; Depletion of the Ozone Layer). Several gases used in the building sector (such as refrigerants and blowing agents) can cause the thinning of the stratospheric ozone (O_3) layer by releasing free radical molecules, hindering the stratosphere's capability to filter ultraviolet (UV) rays.
- *Photochemical Ozone Creation* (Photochemical Oxidant Formation; Smog; Summer Smog): A low layer of Ozone or other pollutants can be generated by sunlight in atmospheres containing nitrogen oxides (NOx), a common pollutant generated by fuel combustion, and volatile organic compounds (VOCs), generally emitted from solvents contained in paints and coatings. The presence of low Ozone can be responsible for agriculture damage and health issues.
- *Abiotic Depletion - Elements/Energy* (Abiotic Depletion of Raw Materials; Abiotic Depletion Potential; Depletion of Abiotic Resources; Fossil Fuel Depletion): Abiotic depletion concerns different non-renewable resources as a result of their extraction and consumption.
- *Raw Material Use/Mineral Extraction*: these include the consumption of all renewable and non-renewable resources and all the virgin mineral material consumed in a process.
- *Toxicity* (Human Toxicity; Aquatic Ecotoxicity; Fresh Water Aquatic Ecotoxicity; Terrestrial Ecotoxicity; Marine Ecotoxicity): measures the damage to ecosystems caused by substances such as heavy (mercury or chromium) and aromatic hydrocarbons.
- *Land Use*: occurs when parts of the land change due to soil occupation by construction or as a consequence of mining and quarrying. This environmental impact category is significantly related to the construction industry.
- *Embodied Water*: the consequence of water consumption resulting from different phases of a production process. It differs from operational water which is measured during the use phase.

1.3 The Sustainable Building Concept

1.3.1 Overview of green building rating systems

In recent decades, the environmental conditions have led international organizations to promote - and many countries to adopt - more stringent mitigation actions and regulatory standards in order to control the negative effects resulting from human activities, such as the built environment. In other words: sustainability.

Sustainability is a feature that can be applied to all economic sectors and derives from a broader concept, called sustainable development, theorized for the first time in 1987 in the Brundtland Report. This document, produced by the World Commission on Environment and Development (WCED) defined sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, *Our Common Future*, 1987, p. 37).

Other important events embracing sustainable development that followed are: the Kyoto Protocol (1997) on global warming mitigation, the Lisbon Strategy (2000-2010), Europe 2020 (2010-2020) including improvement actions for greenhouse gas emission and energy efficiency, the more recent Agenda 2030, which, at the UN Sustainable Development Summit in 2015, established a set of Sustainable Development Goals (continuing the Agenda 21 action plan launched in 1992 in Rio de Janeiro) and the 2015 United Nations Climate Change Conference (COP 21) at which the Paris Agreement, a global agreement on climate change, was negotiated.

The sustainability concept usually revolves around three key dimensions: environment, economy and society, as expressed in ISO 15392:2008 (Sustainability in building construction — General principles) (ISO 15392, 2008).

When applied to buildings, the aim is to achieve sustainable development goals covering all process phases: from production to operations and disposal as, according to ISO 15392:2008, the built environment:

- Represents a key sector in national economies;
- Plays a great role in poverty reduction;
- Has a strong impact on society and the economy since it provides value and employment;
- Has significant effects on the environment as it absorbs extensive resources and interferes with the balance of natural ecosystems.

Although the ISO standards (ISO 15392:2008, ISO 21929-1:2011, ISO 21931-1:2010, ISO 21930:2017) provide solid frameworks for sustainable construction, there is still lack of agreement on a standard definition (Chong et al., 2009).

A possible reason for this is the variety of aspects pertaining to each sustainability dimension that need to be systematically addressed and ranked depending on their impact potential (ISO 15392, 2008).

This challenge was taken on by the Green Building Systems (GBS) which aimed to combine performance indicators, tools and practices to achieve sustainable buildings (Chong et al., 2009).

Since these protocols allow us to conduct quantitative assessments, providing a score representing the sustainable profile of buildings, they are also known as sustainability rating systems or green building rating systems (GBRSs) (Reed et al., 2011).

GBRSs are characterized by objective and comprehensive procedures in order to evaluate a wide range of building performances from an environmental and social-economic perspective (Bernardi et al., 2017)

This comprehensive approach is based on a multidimensional and multi-criterial analysis in which single factors are separately evaluated by specific indicators according to pre-established standards, guidelines, factors, or criteria and then combined in order to give a final overall rating by score, on the basis of predefined performance levels (Berardi, 2015).

As reported by Bernardi et al. (2017), GBRS evaluations rely on four main components:

– *Categories*: a specific set of indicators related to the different sustainable dimensions included in the protocol;
– *Scoring system*: the core of the GBRSs, which assigns a certain number of credits/points depending on predetermined performance levels for each indicator according to predefined evaluation criteria;
– *Weighting system*: every system assigns a different significance to each indicator and category, according to a weighting scale;
– *Output*: how systems display the results of the evaluation, based on predefined quality levels.

The United Kingdom was the first to develop such a system, even before this necessity was announced at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992.

In fact, at the beginning of the 1990s the British Research Establishment (BRE) started to develop a building rating system that was finally released in 1993 as a BRE Environmental Assessment Method (BREEAM).

The system, used in 79 countries, currently provides five standards: "Communities", "Infrastructures", "New Constructions", "In-use" and "Refurbishment & Fit-out" designed to be applied to nine types of buildings: "Office", "Retail", "Industrial", "Healthcare", "Education", "Residential", "Data Centers", "Mixed Use" and "Other Buildings" (Building Research Establishment, available at: https://www.breeam.com, retrieved in March 2017).

The residential protocol, initially known as Eco Homes, has been replaced by the Code for Sustainable Homes (CSH), which was adopted by the British government as a mandatory standard in certain circumstances. When it was embodied within national regulations in 2015, BRE launched the Home Quality Mark as reference protocols for residential buildings (Department for Communities and Local Government, available at: https://www.gov.uk/government/publications/code-for-sustainable-homes-technical-guidance, retrieved in March 2017).

One of the major international systems is LEED (Leadership in Energy and Environmental Design), founded in 1998 by the US Green Building Council (US GBC) but currently available also in versions for Canada, Hong Kong and Australia as well as for Africa, South America, Asia and Europe, covering over 165 countries.

It offers six different protocols: Building Design and Construction, Interior Design and Construction, Building Operations and Maintenance, Neighborhood Development, Homes, Cities and Communities. (U.S Green Building Council, available at: https://new.usgbc.org/leed, retrieved in March 2017).

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), is the tool created in Japan in 2001. The particularity of this system, based on an assessment of the life cycle of the building, is the conceptual division of the parameters into two large categories: the performance of the building and environmental loads. The first includes all the criteria such as the internal environment, quality of services and the external environment, while the second includes energy, resources, materials, reuse and recycling, and off-site environment.

The system output delivers a graph of the "eco-efficiency" of buildings with the two categories represented by the two Cartesian axes (Japan Sustainable Building Consortium (JSBC) and Institute for Building Environment and Energy Conservation (IBEC, available at: http://www.ibec.or.jp/CASBEE/english/graphicE.htm, retrieved in: March 2017).

At the end of the 1990s, through an international process called the Green Building Challenge, thanks to the coordination of iiSBE (International Initiative for a Sustainable Built Environment), the SBMethod was developed with the aim of internationalizing rating systems (International Initiative for a Sustainable Built Environment, available at http://www.iisbe.org/sbmethod, retrieved in March 2017). This method enabled implementation within several countries, through a general scheme adopted for different countries such as:

- Verde (Spain);
- SBTool PT (Portugal);
- SBTool CZ (Czech Republic);
- SBTool IT (Italy). In 2011 the Italian version became the Protocollo ITACA, available in regional versions as well as national version.

In 1996 France founded HQE (Haute Qualité Environnementale) (Cerway, available at: https://www.behqe.com/presentation-hqe/what-is-hqe, retrieved in March 2017).

In 2009 Germany released the Deutsche Gesellschaft für Nachhaltiges Bauen, known as DGNB (DGNB GmbH, available at: https://www.dgnb-system.de/en/, retrieved in March 2017).

The widespread diffusion of voluntary evaluation systems, today estimated to be nearly 600 globally (Doan et al., 2017), (while there are fewer actual GBRSs) (Fig. 1.3) has produced a diverse and heterogeneous framework of methods since, despite sharing the same objectives, they have been developed independently and are adapted to the variety of contexts for which they have been designed, with particular respect to climate and building stock typology.

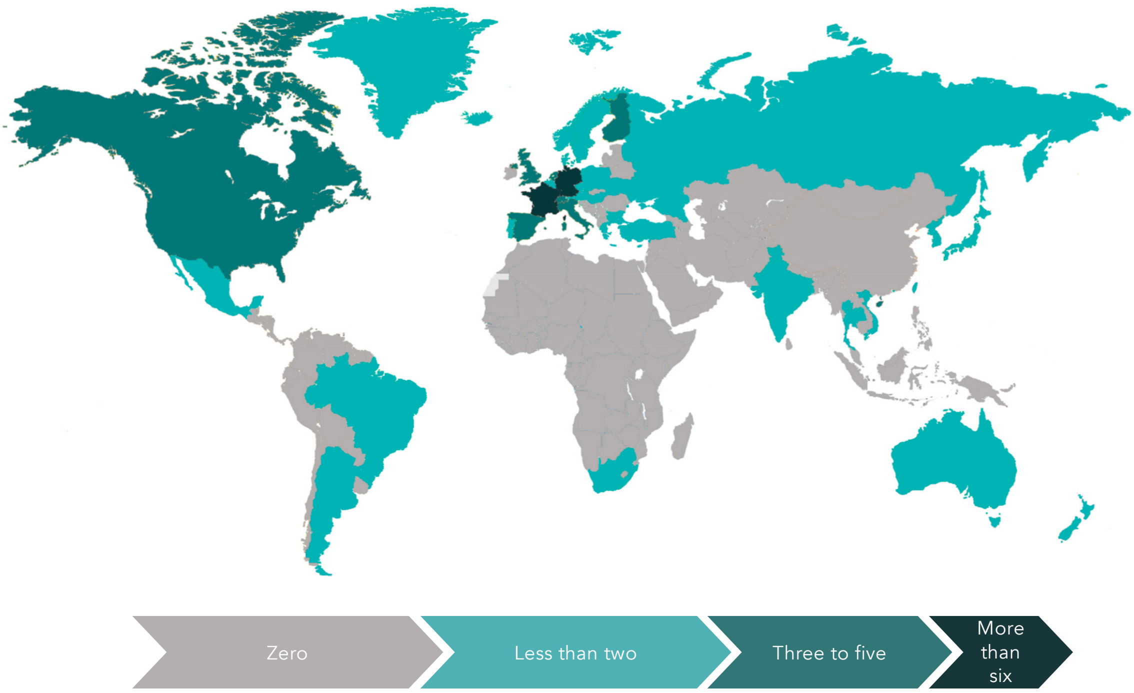

Fig. 1.3 – Global diffusion of GBRSs (Source: Bernardi et al., 2017 - reworked by the Author)

1.3.2 Comparison between the sustainable categories of GBRSs[9]

GBRSs represent a valuable means for studying the sustainability dimensions of the built environment as they provide, through evaluation categories and criteria, a detailed overview of a wide range of aspects concerning sustainability. A comparative analysis between different sustainability protocols is expected to reveal a number of common features that could be interpreted as the most representative for building sustainability. However, although the majority of GBRSs share common targets and approaches, their structures, indicators and metrics have been developed independently and are largely inhomogeneous (Awadh, 2017). For this reason, a comparison of different GBRSs will unlikely produce direct and unambiguous correspondence between their assessment categories, requiring the mediation of an external "interface" capable of providing a common structure to which the specifications of individual RS can be referred.

[9] Part of this section has been excerpted from the author's scientific paper: Politi, S., & Antonini, E. (2017). "An expeditious method for comparing sustainable rating systems for residential buildings". *Energy Procedia*, 111, 41-50.

In order to comprehend which aspects more reliably characterize building sustainability (Research question n.1), a comparison of a number of GBRSs was made, setting out the following methodology:

- a limited set of GBRSs[10] was selected on the basis of specific criteria in order to obtain a representative sample, to be subjected to the subsequent comparison stage;
- summary boards for each selected protocol were drafted, displaying the evaluation framework structured by assessment areas, indicators, evaluation criteria and relative weight for each criterion. The shared evaluation categories of the different protocols are also reported, indicating the level (as a percentage) of the shared elements between different GBRSs;
- a common platform/interface of 11 evaluation categories was identified. Then, each indicator of the analysed protocols was allocated to the common categories and the relevance (in terms of weight) of each of them was determined relying on the specific weight assigned by each protocol to the indicators;
- final considerations on the relevance of the common categories were made, identifying which can be considered the most important and hence the most representative for the built environment.

Due to the wide availability of GBRSs, starting from a number of common protocols globally and particularly in Europe, a smaller set of systems was selected to restrict the scope of the comparison. The criteria used in the selection requires protocols to:

- provide a minimum of issued certifications, set at 500 units to be sure to process the most widely used GBRSs;
- be employed within a specific geographical boundary. The selection was limited to the European continent, for both climatic and social reasons[11];

[10] The GBRSs were selected from among those available in 2016, the period in which this part of the research was conducted.

[11] Among the various systems that presented territorial adaptations in different countries, priority was given to the adaptation for the Italian territory;

– provide similarities in evaluation structures such as similar evaluation procedures and/or analogies in the final rating formulation, in order to limit the complexity in performing the comparison;

– provide a protocol for residential buildings in order to further narrow the scope, thus limiting the complexity of performing the comparison.

The screening operations performed (at the time of writing) to select the sample of GBRSs for the comparison are summarized in tables 1.3 and 1.4.

Origin	Name	Certification Data			Versions		Construction typology			
							New		Existing	
		Certifications issued	In Italy	Internationally	Residential protocol	Other countries suitability	Residential	Non-residential	As built	Refurbishment
USA	LEED	27.816 [1]	67	N.A.	YES	YES	YES	YES	YES	YES
U.K.	BREEAM	558 [2]	26	2.594	YES	YES	YES	YES	YES	YES
France	HQE	266.000	N.A.	N.A.	YES	YES [8]	YES	YES	YES	N.A.
Germany	DGNB	>1160 [3]	0	146	NO [6]	YES [9]	NO[6]	YES	YES	N.A.
Italy	ITACA	619	619	0	YES	NO	YES	YES	YES	N.A.
Italy	CASACLIMA	1689 [4]	1686	3	YES	NO	YES	N.A.	YES	N.A.
Japan	CASBEE	> 450	0	0	YES	NO	YES	YES	YES	YES
Canada	GREEN GLOBES	816 [5]	0	689	NO [7]	YES [10]	NO7	YES	YES	N.A.
Qatar	QSAS	> 128	0	0	YES	NO	YES	YES	YES	N.A.

1: only “LEED HOME” certificates were considered, out of a total of 78,379
2: only residential buildings were considered, out of a total of 7,746
3: including both certificated and pre-certificated projects
4: 618 of these are in the Bozen (BZ) province
5: 88 for residential buildings in the USA
6: under development
7: the system is however used for residential buildings
8: certifications in France are made by third party companies
9: DGNB has an international version. The adaptation of the system to specific countries depends on the technical certifier
10: system available in Canada and USA only
N.A.: Data not available

Tab. 1.3 – Screening phase - first part (Source: Author)

Name	Typology of criteria				Structure of the methodology				Certification procedure		
	Energetics	Environmental	Social	Economics	Subdivision into groups of criteria	Attribution of specific weight to criteria / group	Production of a single judgment	Levels of judgment	Internal certifier	Third party certification	Self - certification
LEED	YES	YES	YES	NO	YES	YES	YES	4	YES	N.A.	NO
BREEAM	YES	YES	YES	NO	YES	YES	YES	6	YES	YES	NO
HQE	YES	YES	YES	NO	YES	YES	YES	4	NO	YES	NO
DGNB	YES	YES	YES	YES	YES	YES	YES	3	YES	YES	NO
ITACA	YES	YES	YES	NO	YES	YES	YES	4	NO	YES	NO
CASACLIMA	YES	YES[1]	NO	NO	YES	NO	YES	3	YES	N.A.	NO
CASBEE	YES	YES	YES	NO	YES	YES	YES	5	YES	YES	YES
GREEN GLOBES	YES	YES	YES	NO	YES	YES	YES	5	YES2	N.A.	NO
QSAS	YES	YES	YES	YES	YES	YES	YES	6	YES	N.A.	NO
1: a specific version for environmental aspects evaluation is available						N.A.: Data not available					

Tab. 1.4 – Screening phase - second part (Source: Author)

At the end of the screening phase, five GBRSs were selected for the comparative analysis:

- GBC Home, based on LEED residential version and adapted to the Italian context, 2014 edition[12];
- The Code for Sustainable Homes (CSH), developed by BRE (BREEAM) and adapted for residential buildings in the UK, 2010 edition[13];

[12] Green Building Council Italia (2014) "Sistema di verifica GBC HOME ed.2014", Green Building Council Italia copyright, available at: http://www.gbcitalia.org/risorse. GBC Home is a system developed by the Italian Green Building Council but, as a result of a partnership agreement with USGBC, GBC Italia adapted the American LEED® certification to the Italian context. For this reason, the data included within the screening analysis refers to the US market, but the assessment protocol considered is the Italian GBC Home.

[13] Department for Communities and Local Government (2010), "Code for Sustainable Homes Technical Guide November 2010", Crown copyright, available at: https://www.gov.uk/government/publications/code-for-sustainable-homes-technical-guidance. The technical contents of CSH standard was managed and developed by BRE (the same

– HQE Bâtiment Residentiel, HQE Residential version, 2014 edition[14];

– DGNB[15], 2011 edition[16];

– Protocollo Itaca, Italian adaptation of SBTool, 2011 edition[17].

An additional system was also considered: Active House, an emerging European protocol initially developed for residential applications which embraces several aspects from the most common GBRSs, condensing them into 17 indicators.

Due to its peculiar characteristics, its adaptability to the European context and the simplicity of its evaluation structure, although it does not achieve the same number of certifications issued as the others, Active House was added to the sample.

After the screening phase, a final sample of six GBRSs was identified and the comparative analysis was therefore performed by comparing all the criteria and parameters included within the protocols.

In order to highlight the similarities between the evaluation structures, a number of summary boards (one for each protocol) containing a list of all the parameters considered by the sample of GBRSs was drafted (see Annex A) reporting, in addition, the weights assigned to each indicator[18] in order to identify the most shared and most relevant ones.

The approach used to make the comparison was mainly qualitative, as the correspondence between the criteria was assigned by relying on indicators and evaluation criteria similarities.

In general, correspondences between system's indicators were assigned (with a minimum margin of error) when the nomenclatures and the evaluation criteria appeared

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organization that developed the BREEAM protocol) for and on behalf of the Department of Communities and Local Government (DCLG), until the code was withdrawn by the UK Government in 2015.

14 Cerway (2014) "Assessment Scheme HQETM certified by Cerway for Environmental Performance of Residential Buildings under construction", Cerway copyright, available at: http://www.behqe.com/schemes-and-documents.

15 An exception was made for DGNB with respect to the residential dedicated version which, at the time of writing, has not yet been released. However, its evaluation structure appeared to be particularly suitable for this type of application too.

16 DGNB (2011) "DGNB Criteria", DGNB copyright, available at: http://www.dgnb-system.de/en/services/request-dgnb-criteria/.

17 Protocollo ITACA Nazionale 2011 Residenziale (2012), available at: http://www.itaca.org/valutazione_sostenibilita.asp.

18 Some discretion has been adopted to establish the weighing tables for systems whose values were not shown explicitly, or where some hypotheses were needed to assign a weight to indicators that do not have their own.

to be mostly identical[19]. Conversely, in cases where the equivalence between indicators was not immediate, correspondences were assigned relying on the final purpose of the indicators[20]. Moreover, multiple correspondences were indicated between one indicator and a plurality of other similar parameters in order to consider all possible matches.

In dealing with a multitude of indicators, characterized by different metrics and evaluation criteria, it is plausible that the outcomes of the comparison were affected by an element of uncertainty.

A graphical outcome of the summary boards drafted for each GBRS (Annex A) is shown in Fig. 1.4. Different colours indicate different sustainability categories while the amplitude of each sector indicates the relevance (as a percentage) of each indicator with respect to the whole system (100%). Each indicator has been marked with the relative identification code used in the summary boards (See Annex A) and the colour shades indicate the weight proportions within the category (e.g. the dark blue indicator denotes more relevance than light blue).

[19] For example, the "Average Daylight Factor (DF)" turned out to be the indicator used to express indoor visual comfort in 100% of the analyzed protocols.

[20] For instance, to determine the consumption of drinking water, different indicators were used such as "percentage of the volume of drinking water saved for indoor use compared to the calculated basic needs" (Protocollo ITACA) and "strategies that allow a 20-30-40% reduction of the water demand for the building, compared to a building taken as a reference" (GBCHome). In this case, since the common purpose is to save fresh water, a match was assigned.

Fig. 1.4 – Pie charts of the GBRSs summary boards (Source: Author)

1.3.3 The representative categories of sustainable buildings[21]

In order to quantitatively estimate the importance that GBRSs attribute to the individual families of indicators (Nguyen, & Altan, 2011), and thus comprehend which can be considered particularly representative for buildings, a restricted number of evaluation areas, shared by most of the systems analyzed, were identified. This activity was inspired by the study conducted by the SBA (SB Alliance, 2012) on the definition of some "Common Metrics" with the aim of establishing an assessment tool based on a shared approach.

Eleven categories were selected, aiming to include all the possible categories:

1. *Design Quality – Users*: includes indicators concerning accessibility, security, presence and proximity to services and infrastructure, assistance to building management and functionality of outdoor spaces;
2. *Design Quality – Site*: includes indicators related to environmental impacts on the project site, land reuse and management of outdoor spaces;
3. *Materials and Products*: includes indicators related to environmental impacts generated by supplied materials and products, recycled and recyclable materials, certification of raw materials and finished products;
4. *Energy*: includes indicators for energy supply and consumption, renewable energy sources, energy-saving strategies;
5. *Water*: includes indicators related to the consumption of drinking water, water-saving strategies and management of water consumption;
6. *Atmospheric Loads*: includes indicators relating to hazardous emissions on soil, water and air as well as strategies for impact reduction, during the life cycle of the buildings;
7. *IEQ*: includes indicators for visual, acoustic, olfactory, hygro-thermal comfort and air quality;
8. *Economic Aspects*: includes indicators related to Life Cycle Cost and economic sustainability;

[21] Part of this section has been excerpted from the author's scientific paper: Politi, S., & Antonini, E. (2017). "An expeditious method for comparing sustainable rating systems for residential buildings". *Energy Procedia*, 111, 41-50.

9. *Management*: includes indicators related to building operation and maintenance, monitoring and control of consumption/emissions;

10. *Waste*: includes indicators related to waste management, collection areas and measures for waste reduction;

11. *Others*: includes all the non-common criteria that are not considered in the previous categories, such as, for example, those related to integrated design and planning, site analysis or the intervention of a qualified auditor/expert in the assessment procedures.

Once the new categories were established, all the GBRSs indicators were reallocated within the new common groups.

A final board (Annex B) was then drafted, containing the reordered indicators with the original weighting factors and, in order to determine which categories might be considered the most relevant, the weighting factors were aggregated and normalized to obtain the relevance indication of the eleven common categories.

To summarize the outcomes of the reallocation operations, two graphs were produced. The first one (Fig. 1.6) shows the overall importance (%) assigned to each evaluation category, capable of revealing the weighting categories. The second one (Fig. 1.7) displays the importance (%) given to the new categories by each of the GBRSs considered in the analysis.

In order to graphically represent the outcomes, pictograms have been used for each category as shown in Figure 1.5, displayed in the same order as presented above.

Fig. 1.5 – Pictograms representing the eleven sustainability categories (Source: Author)

Fig. 1.6 – Pie chart of the final board displaying the cumulative relevance attributed to the eleven common sustainability categories by all the GBRSs analyzed (Source: Author)

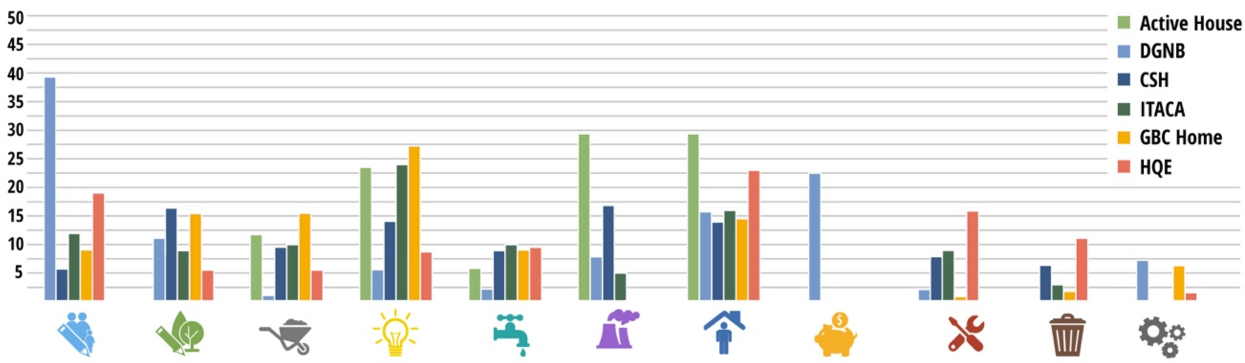

Fig. 1.7 – Bar chart of the final board displaying the relevance attributed to the eleven common sustainability categories by each GBRS analyzed (Source: Author)

The comparison performed allowed the researchers to identify to what extent a GBRS matches the basic issues involved in the sustainability assessment procedures, by means of a "core set" of the most representative indicators, spread over the eleven categories.

This makes it possible to compare the relative weight assigned to each category by each system.

At the end of the comparison process, the most relevant categories were:

- Indoor Environmental Quality (19.30%);
- Energy (18.98%);
- Site user comfort (13.85%).

All other categories were weighted below 10%.

1.3.4 A focus on non-operational environmental impact indicators

The comparative analysis results highlighted two significant circumstances:

- Annual energy demand and visual, thermal and acoustic comfort are the most common indicators, indicating that greater importance is generally associated with aspects related to building operation rather than the whole life cycle, thus excluding upstream and downstream processes; and
- Less importance is given to indicators involving direct environmental impacts, such as pollutant emissions (not referable to building operation), resource depletion and waste disposal.

These reflections are in line with the fact that the main concern expressed internationally in recent decades, through sustainable development initiatives and regulations, was formerly aimed at energy efficiency in buildings (existing and new construction) resulting in consumption - and therefore emission - reduction programs during the operation phase (see directive 2002/91/EC, 2010/31/EU and the recent 2018/844/EU) (D'Olimpo D., 2017).

The aim here was to identify which are the most recurrent non-operational environmental impact indicators (thus excluding operational energy related indicators), and a further analysis of the comparison outcomes was performed to narrow the scope of the research subject.

In order to appreciate the relevance attributed to these kinds of indicators, starting with the former analysis, a further reallocation of the GBRSs indicators related to environmental aspects such as responsible material sourcing, pollutant emissions, material recycling, and water and waste management was performed (see Annex C).

This second part of the analysis showed that environmental impact categories cover 24% of the total categories assessed by the GBRSs.

A further distinction was made, based on the difference between operational and embodied impacts addressed in Section 1.2.1, revealing that 14% of environmental impact indicators refer to the operation of buildings while the remaining 10% relate to the other phases of the life cycle (Fig. 1.8).

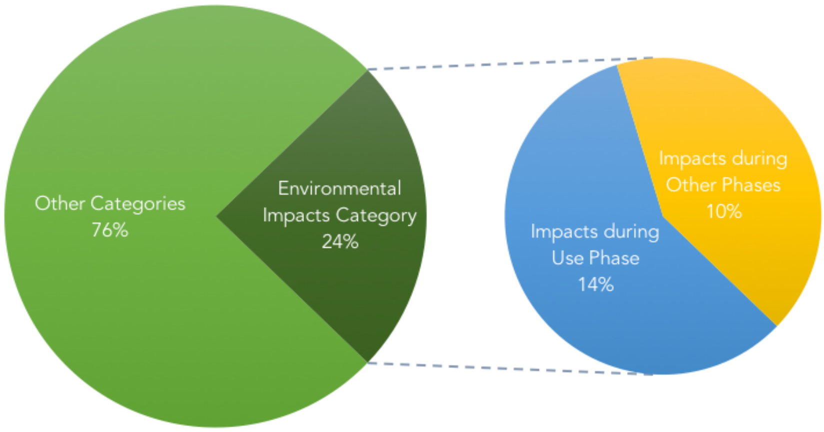

Fig. 1.8 – Pie chart displaying the relevance attributed to the environmental impact categories (left) divided into operational and embodied impacts (right) (Source: Author)

1.4 Outcomes

Several environmental dimensions are threatened by building fabrication and use, endangering natural balances and ecosystems.

The first part of the research centered on the study of environmental consequences arising from the construction industry, investigating the causes of such impacts and depicting the most important international initiatives aimed at facing this situation.

The principal tools adopted as study subjects to address this topic were sustainability assessment protocols or Green Buildings Rating Systems (GBRSs) developed to evaluate the environmental, social and economic profiles of buildings.

Their comprehensive approach is based on a multidimensional and multi-criteria analysis in which single factors are separately evaluated by specific indicators and then combined in order to give a final overall rating by score, on the basis of predefined performance levels (Berardi, 2015).

The first desktop investigation performed through a sample of GBRSs, selected from among the most common for application to residential buildings, aimed to identify a "core set" of representative categories and indicators of building sustainability.

This analysis highlighted that the most relevant indicators, according to GBRS protocols, concern building operation such as: energy, comfort of the site for users and indoor environmental quality, thus less importance is attributed to environmental aspects.

A further insight concerning the GBRS evaluation categories revealed that impacts related to non-operational phases of the building life cycle, i.e. embodied impacts, have a relevance of only 10%.

Although international initiatives and directives have typically targeted operating energy and carbon emissions (see the Energy Performance of Buildings Directives - EPBD 2002/91/EC, 2010/31/EU and the recent 2018/844/EU), recently attention has shifted towards aspects referring to the entire life cycle of buildings, with particular regard to building products (see European Regulation CPR 305/2011 and European directives 2014/23/EU, 2014/24/EU and 2014/25/EU) (Nash, 2009).

In this context, the object of interest therefore shifts from the building scale to the scale of specific materials and components; in order to mitigate the negative effects on the environment arising from their production, transportation, assembly, maintenance and disposal (i.e. embodied impacts), it becomes necessary to rely on dependable tools capable of determining the related impacts of building processes.

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Part II

ASSESSING EMBODIED IMPACTS: THE LIFE CYCLE APPROACH

2.0 Research Question no.2

As Part I shows, a great (often hidden) portion of building related environmental effects is not connected with building operation, but rather with upstream and downstream processes: this shifts the focus to the scale of materials and components.

In order to mitigate the negative effects on the environment arising from the production, transportation, assembly and disposal of products (i.e. embodied impacts), it becomes necessary to use on reliable tools capable of determining building process related impacts (Basbagill et al, 2013).

According to the European Commission, this is a priority approach, in response to the need for "*clear, verifiable, justifiable and ambitious environmental criteria for products and services, based on a life-cycle approach and scientific evidence base*" (European Commission, retrieved on March 2017).

The analysis upon the GBRSs indicators (Part I) suggested the Life Cycle Assessment (LCA) as a comprehensive approach suitable for this purpose. In fact, GBRSs such as GBC Home, DGNB, CSH, HQE and Active House include assessment criteria based on LCA analysis or LCA based items, such as Environmental Products Declarations (EPD).

Various actions rely on this approach, at both EU and national Italian level, such as: the EU Construction Products Regulation-CPR (July 2013); the Italian law n.221 of 28 December 2015 and the Legislative Decree n.50 - 18 April 2016, both concerning GPP respectively on the implementation of the European directives 2014/23/EU, 2014/24/EU, 2014/25/EU and the compulsory adoption of Minimum Environmental Criteria (Criteri Ambientali Minimi - CAM) in public procurement.

The growing interest in the EU context for a life cycle approach to buildings, led this research to focus on LCA methodology deepening the knowledge about its framework and stimulating the second research question:

RQ2: ***Can GBRSs indicate which LCA aspects are the most suitable for buildings application?***

As for the first part of the thesis, the means adopted to address this issue were the GBRSs, since the indicators and the evaluation criteria implemented in such protocols, are capable of delivering consistent information about buildings' sustainability aspects.

If appropriately integrated with GBRSs, LCA can have a positive impact on building design as well as on the development of environmental policies and strategies with respect, for instance, to buildings materials, reflecting potential benefits on construction products market and on the built environment in general (Ganassali et. al, 2016).

For this reason, the additional aim of the thesis was to deepen knowledge about the conditions and the modalities of LCA application to building materials and components through the integration with GBRSs, investigating and tracing their shared features.

An extensive deepening on LCA regulatory and methodological framework is presented in Part II, including an overview of the principal LCA-based items for buildings products such as: Environmental Product Declarations (EPD) and Products Category Rules (PCR).

In addition, a comprehensive comparison between the LCA framework included in six international GBRSs (LEED v4, DGNB Core 14, BREEAM NC v.2016, Green Star v.1.1, Green Globes v.1.5 and Active House v.2) is performed in order to identify those LCA aspects that can be considered the most characteristic for building applications from the GBRSs perspective.

2.1 LCA Overview: Background, Key Features and Phases

Various initiatives relative to sustainable development have been carried out in the last decades, leading a number of countries to develop and adopt, over the years, different kinds of regulations and standards in order to achieve specific environmental goals (Ortiz et al., 2009).

These kinds of strategies have led, therefore, to changes in the approach to design and construction, leading to the development of more energy efficient and carbon neutral buildings.

Passer et al. (2012) confirmed that all the possible actions to optimize operational energy in low-energy buildings have already been taken, having reached the maximum achievable effect.

The importance given to the operational performance of buildings has made it possible to achieve better indoor comfort conditions minimizing energy consumption but, at the same time, it has hidden some consequences (Jia e Crabtree, 2015; Copiello, 2017).

New technical solutions along with new construction approaches, indeed, have led to an increase of the environmental impacts embodied, hence hidden, inside buildings (Proietti et al., 2013).

It is not a recent discovery that processes related to buildings involve a series of environmental consequences: air, water, soil and the whole eco-system are affected, being subjected to (harmful) alterations that modify the environmental balance, jeopardizing biodiversity, contributing to climate changes thus endangering human's health (Edwards, 2014).

The challenge of improving this situation requires, primary, classification and measurement of the impacts.

It is, therefore, necessary to understand buildings and construction from a systems-based perspective (Simonen, 2014) and employ a methodology for analysing the involved variables over the entire life cycle.

Life Cycle Assessment (LCA) is a standardized method, able to address *"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)"* (ISO 14040, 2006).

The observed impacts are quantified through the tracking of the input-output flow (Fig. 2.1) of extractions from and emissions to the nature, during all the phases of a particular process such as: services, products or complex entities like buildings.

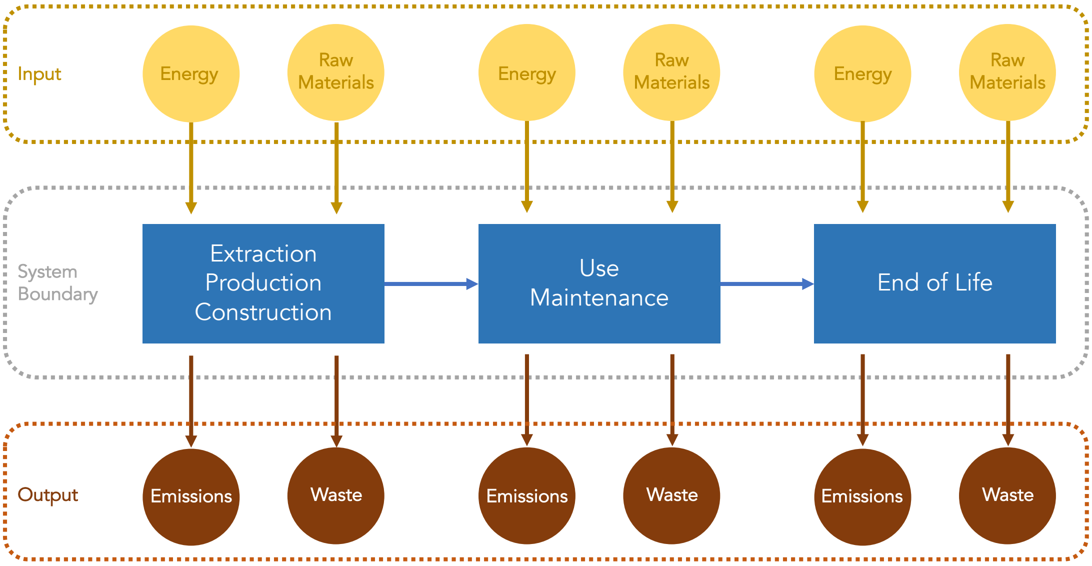

Fig. 2.1 – LCA Input-Output flow tracking (Source: Simonen, 2014 - reworked by the Author)

This necessity of accounting for resource flows led to the development of the LCA methodology which, historically was initiated in Europe and in the USA between the end of the 1960s and the beginning of the 1970s, by the Society of Environmental Toxicology and Chemistry (Hunt & Franklin, 1996).

The original intent was to enhance the reduction of resource consumption as well as the environmental impacts associated with products, processes or industrial activities (Ding, 2014), especially after the 1970s Oil Crisis (Anderson and Thornback, 2012).

One of the first assessment in the industrial sector was licensed by The Coca-Cola Company in 1969 for a business study about alternative containers (Hunt and Franklin, 1996).

Only around the 1990s, LCA raised awareness in relation to the growing environmental and energy sensitiveness of those years.

A list of the LCA related events are summarized below (European Commission, 2010):

- 1963: Early studies known as Resource and Environmental Profile Analyses (REPA).
- 1969: First comparative multi-criteria environmental study for Coca Cola, became basis for the current method for life cycle studies.

- 1991: The Society of Environmental Toxicology and Chemistry (SETAC) develops the Impact Assessment method for LCA.
- 1992: First European scheme on Ecolabels, established by the European Commission; World Business Council for Sustainable Development (WBCSD) founded by industry to address sustainability.
- 1995: SETAC develops Code of Practice for Life Cycle Assessment; first Life Cycle Assessment on a car – VW Golf.
- 1996: International Organization for Standardization (ISO) launches first standards on Life Cycle Assessment.
- 2001: European Commission releases Green Paper on Integrated Product Policy (IPP) building on Life Cycle Thinking.
- 2002: United Nations Environment Programme (UNEP)/SETAC Life Cycle Initiative launched.
- 2003: European Commission Communication on Integrated Product Policy.
- 2005: European Platform on Life Cycle Assessment established at the European Commission; EU Thematic Strategies on the prevention and recycling of waste and the sustainable use of natural resources published.
- 2006: First version of the Commission's European Reference Life Cycle Database (ELCD) goes online.
- 2007: Start of development of International Reference Life Cycle Data System (ILCD) Handbook.
- 2008: European Commission launches Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan. First public specification for carbon foot-printing published (British PAS2050).
- 2009: ISO initiates development of first international standard for product carbon foot-printing; the World Business Council for sustainable Development (WBCSD) and the World Resources Institute (WRI) start drafting a Green House Gas (GHG) Protocol Product / Supply Chain Standard and life cycle-based Scope 3 Corporate Standard.
- 2010: Launch of the ILCD Handbook by the European Commission.

Today LCA is intended to account, not only for materials and energy flows, but for all relevant environmental impacts throughout a variety of environmental issues with respect to air, water and soil quality thus including toxicity to human life and to ecosystem, climate alterations and the depletion of resource (renewable and non-renewable), water and energy (Anderson and Thornback, 2012).

Such a life cycle approach applied to the built environment, assumes the recognition of buildings not as static objects, inalterable once the construction is completed, but rather dynamic entities which evolve and change throughout their life span (Simonen, 2014).

At present, buildings LCAs can be categorised, as indicated by Simonen (2014), in four categories:

- analysis of manufacturing processes,
- development of materials and products eco-labels (see Section 2.4),
- comparison of material or technical solution alternatives,
- whole buildings assessment.

Also Ding (2014) indicates LCA approach as the only appropriate means by which it is possible to compare alternative materials, components and services and to measure environmental loads arising from buildings. Compared to other tools, LCA is capable of achieving, not only a shift of impacts but a trade-off analysis, in order to obtain an inclusive decrease of environmental impacts.

According to ISO14040, LCA framework is structured in four stages (Fig. 2.2) (further discussed in Sections 2.3):

- *Goal and Scope:* the fundamental first action to undertake in order to declare the reason for performing the analysis (the Goal) and the content of the study (the Scope). It involves the definition of the analysis objectives (e.g. product comparisons or specific building elements assessment etc.), the designation of the Functional Unit (F.U), defined as a quantified description of the performance of the product systems, to be used as a reference (Weidema et al., 2004), the delineation of the system boundary, the selection of environmental parameters and the data collection strategy;
- *Life Cycle Inventory (LCI):* considered one of the most critical stage since it involves a scrupulous and precise collection and management of data, in order to quantify materials, energy inputs and waste emissions (Fig. 2.1). This stage ends with the draft of the inventory tables including the calculation of the energy and material balance of the system.

- *Life Cycle Impact Assessment (LCIA):* this phase aims to define the importance of potential environmental consequences resulting from the LCI content. This process involves the connection between those data collected in the inventory and specific environmental impact categories and category indicators (ISO 14040, 2006).
- *Life Cycle Interpretation:* is the phase in which the findings from previous stages are observed and discussed, basing on the goal and the scope of the analysis. The interpretation can involve the explanation of outcomes and might provide specific recommendations (ISO 14040, 2006).

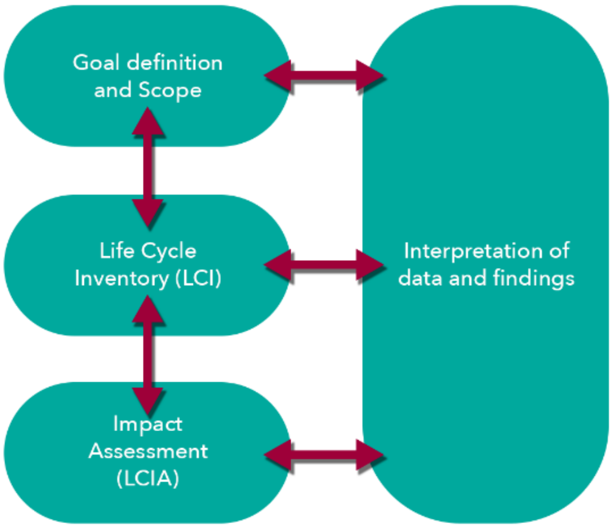

Fig. 2.2 – LCA framework stages (Source: ISO 14040, 2006 - reworked by the Author)

According to Anderson and Thornback (2012), in order to achieve a robust analysis, the LCA should comply with a number of key features such as those listed below:

- *Clear objectives and framework:* Goal and Scope have to be defined accurately in order to provide a precise explanation of the context of the study through the delineation of the boundaries, the adoption of a structured methodology including the definition of how, and to whom, the results have to be communicated.
- *Transparency:* the study must specify information on the data sources as well as it must indicate what assumptions have been made and what methodology has been implemented. Furthermore, the choice of the environmental indicators included must be listed and explained in accordance to the goal and the scope.

- *Whole Life Cycle perspective*: most of the studies are designed to cover the life of the product to the gate of the factory, for this reason this phase is called "Cradle to Gate". Nevertheless, in order to foster fair comparisons between similar products (with the same functionality), the analysis should include the transport and installation of the product, its use and maintenance program and, possibly, even the end of life scenario.
- *Comprehensive assessment*: it is important to include, in addition to the inputs and energy related to the upstream process, also the impacts occurred during the downstream process such as the waste disposal.
- *Functionality Issues:* LCA can also consider additional functionality of some processes or products, for example giving information about a specific performance of a product in respect to another (e.g. thermal insulation).
- *Enabling comparisons:* fair comparisons between LCA analysis must rely on common functionality, scope and methodology. For this purpose, the Product Category Rules (PCR) were developed and standardized within the ISO 14027:2017 and EN 15804 (See Section 2.4).
- *Compliance with standards:* all LCA standards should be critically reviewed to assure compliance with the ISO14040 series, in particular with ISO14044. When employed for buildings, LCA should rely on the standards developed by TC-350, such as EN 15978 and EN 15804.

Different studies can have different scopes, hence consider different system boundaries. The EN15804 standard identifies 17 buildings life cycle modules (A1-D) and provides clear definitions of each of them (Fig. 2.3).

The stages are further aggregated in groups in relation to different process phases:

- A1-A3: Product Stage
- A4-A5: Construction Process Stage
- B1-B7: Use Stage
- C1-C4: End of Life Stage
- D: Reuse and Recycling Stage

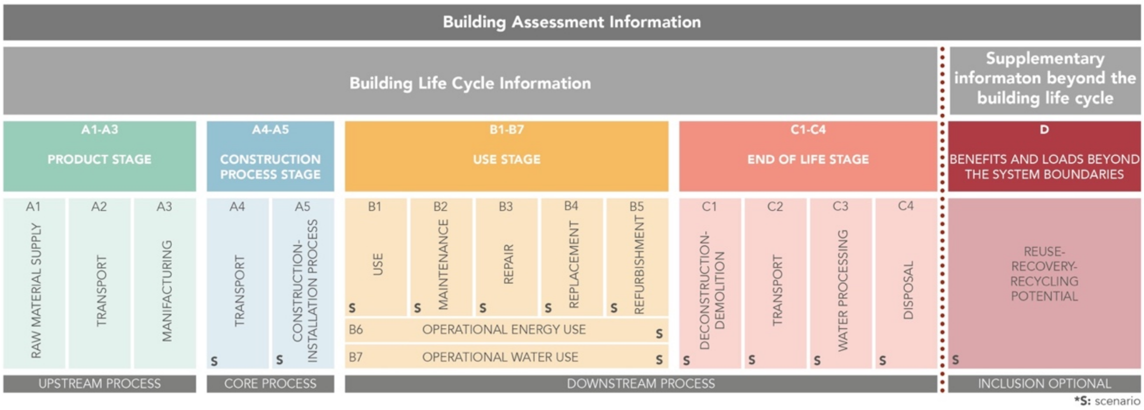

Fig. 2.3 – Building LCA modules (Source: EN 15978, 2011 - reworked by the Author)

While for the upstream process (product stage) the analysis has to rely on specific and reliable data as defined in the EN 15804 standard, for the remaining stages it is possible to perform the assessment basing on different scenarios, intended as "*a collection of assumptions and information concerning an expected sequence of possible future events*" (EN 15978, 2011).

However, scenarios have to be clearly defined and documented, describing the context in which they are expressed, and the source of information should be declared.

Based on the subdivision provided by the standards, a number of boundaries are proposed depending on the different scope of the analysis (Fig. 2.4).

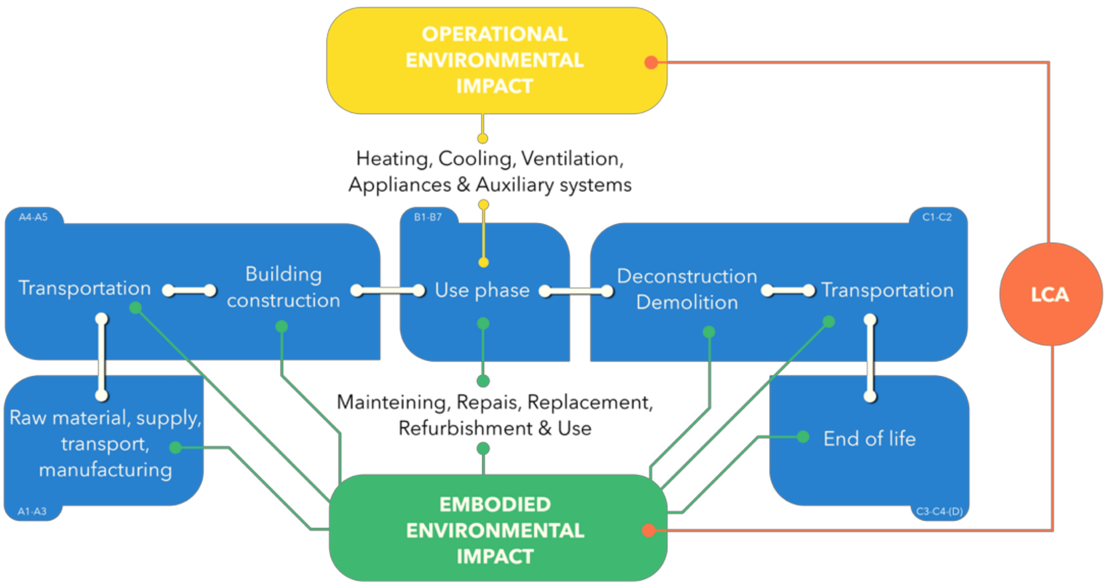

Fig. 2.4 – LCA scheme (Source: Chastas et al. 2016 - reworked by the Author)

When only the product stage is considered, the analysis is defined "Cradle to Gate", where "cradle" is intended as the primary source of raw materials (e.g. extracted from the ground), while the "gate" indicates the factory gate where manufactured products are ready to be shipped (Dixit et al., 2012).

If the transport to, and the installation of the product on a construction site is included, the assessment is known as "Cradle to Site" while, if also the use, maintenance and disposal phases are considered, then the limit of the boundary is the "Grave", i.e. the end of the building life. An additional step could be, however, included in the analysis: the reuse or recycle scenarios that make the assessment a "Cradle to Cradle" (Fig. 2.5) (Dixit et al., 2010).

The definition of system boundaries strictly depends on the comprehension of the possible limitations to the study as well as on a precise recognition of time and data availability. The knowledge of processes involved is another important aspect in shaping the analysis confines. It is, therefore, crucial to detect those processes that are not strictly relevant for the study and, consequently, setting proper "cut-off rules" defining the significance extent, possibly omitting some elements from the analysis (Simonen, 2014).

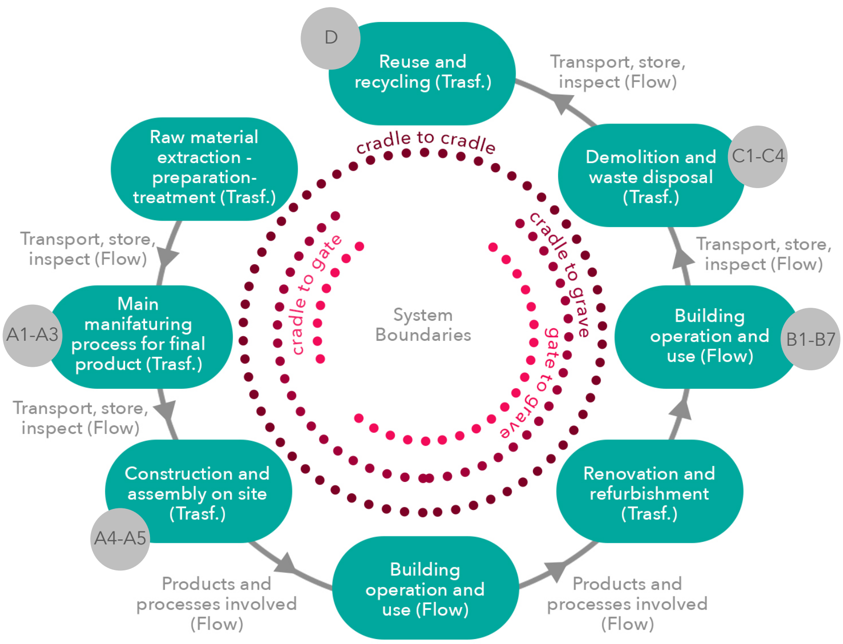

Fig. 2.5 – LCA boundaries (Source: Dixit et al., 2010 - reworked by the Author)

2.2 Environmental Assessment Regulatory Framework

The assessment of the environmental impacts related to industry processes such as construction, is regulated within international frameworks. In particular, the ISO 14000 (Fig. 2.6) which is a series of standards related to environmental management, was developed by the Technical Committee ISO/TC 207, a section of the International Organization for Standardization (ISO), in order to endorse the minimization of impacts related to industrial processes.

The ISO standards are broadly recognised as the basic reference for performing LCA analysis, as they do not provide a single method for conducting the assessment but rather a framework for guiding practitioners in choosing and documenting their own approach (Simonen, 2014).

Within the ISO 14000 family, there are two aggregation of standard specifically developed for material and products:

- ISO 14040 series, which regulate the Life Cycle Assessment procedure, describing the principles and framework for LCA including: definition of the Goal and Scope of the LCA, the Life Cycle Inventory Analysis (LCI) phase, the Life Cycle Impact Assessment (LCIA) phase, the Life Cycle Interpretation phase, Reporting and Critical Review of the LCA, Limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements[1].
- ISO 14020 series, which establishes guiding principles for the development and use of environmental labels and declarations[1].

The ISO 14040 are further organized in:

- ISO 14044:2006: specifies requirements and provides guidelines for the principles and framework contained in the ISO 14040:2006[1].
- ISO/TR 14047:2012: provides examples of current applications of life cycle impact assessment according to ISO 14044:2006[1].
- ISO/TS 14048:2002: provides the specifications of data documentation format, for producing transparent and unambiguous documentation regarding LCA and LCI data collection[1].
- ISO/TR 14049:2012: provides examples of current production of a life cycle inventory analysis (LCI) according to ISO 14044:2006[1].

- ISO/TS 14071:2014: represents additional specifications to ISO 14040:2006 and ISO 14044:2006 as it provides requirements (including prerequisites) and guidelines for conducting a critical review on LCA studies[1].
- ISO/TS 14072:2014: provides additional requirements and guidelines for the application of ISO 14040 and ISO 14044 to organizations[1].

While the ISO 14020 are structured as follow:

- ISO 14021:2016: specifies requirements for self-declared environmental claims, including statements, symbols and graphics, regarding products (Type II Eco-Labels)[1].
- ISO 14024:2018: establishes the principles and procedures for developing Type I environmental labelling programmes as well as the certification procedures for awarding the label[1].
- ISO 14025:2010: establishes the principles and specifies the procedures for developing Type III environmental declaration programmes and Type III environmental declarations[1].
- ISO 14026:2017: provides principles, requirements and guidelines for footprint communications for products addressing areas of concern relating to the environment[1].
- ISO 14027:2017: provides principles, requirements and guidelines for developing, reviewing, registering and updating PCR within a Type III environmental declaration or footprint communication programme based on life cycle assessment (LCA) according to ISO 14040 and ISO 14044 as well as ISO 14025, ISO 14046 (Environmental management - Water footprint - Principles, requirements and guidelines) and ISO/TS 14067 (Greenhouse gases - Carbon footprint of products)[1].

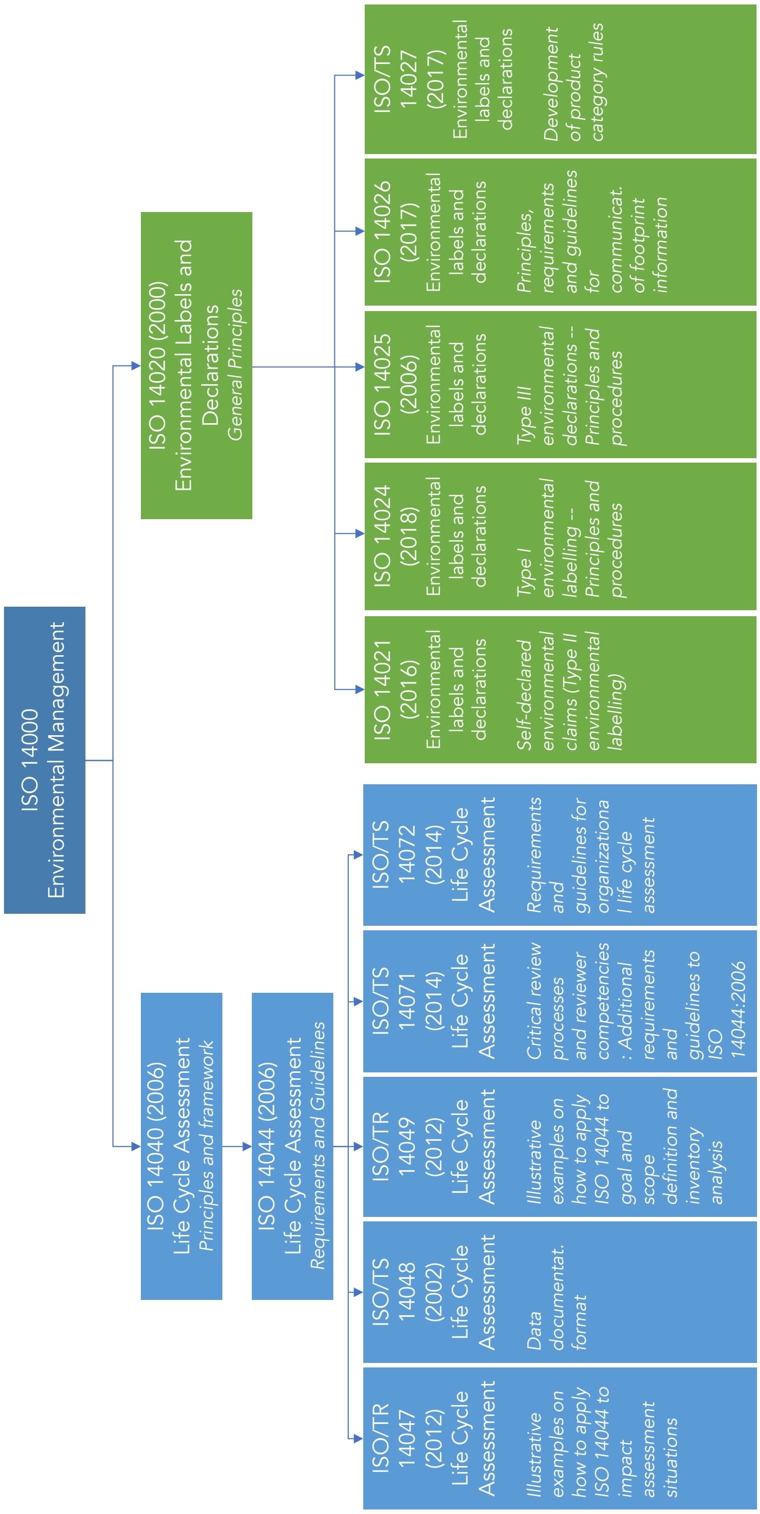

Fig. 2.6 – Environmental Management ISO Framework (Source: Bovea et al., 2014 - reworked by the Author)

When building sustainability is the object of the study, other important standards have to be considered, such as:

- ISO 15392:2008 (Sustainability in building construction - General principles): identifies and establishes general principles for sustainability in building construction. It is based on the concept of sustainable development as it applies to the life cycle of buildings and other construction works, from their inception to the end of life[22].
- ISO 21929-1:2011 (Sustainability in building construction - Sustainability indicators - Part 1: Framework for the development of indicators and a core set of indicators for buildings): establishes a core set of indicators to take into account in the use and development of sustainability indicators for assessing the sustainability performance of new or existing buildings, related to their design, construction, operation, maintenance, refurbishment and end of life[1].
- ISO 21931-1:2010 (Sustainability in building construction - Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings): provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of buildings and their related external works[1].
- ISO 21930:2017 (Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services): provides the principles, specifications and requirements to develop an environmental product declaration (EPD) for construction products and services, construction elements and integrated technical systems used in any type of construction works[1].

According to ISO, these standards regarding buildings sustainability are organized in conceptual levels from the general framework level to the specific building products level (Fig. 2.7).

[22] The standards descriptions have been taken directly from the ISO website: https://www.iso.org/home.html

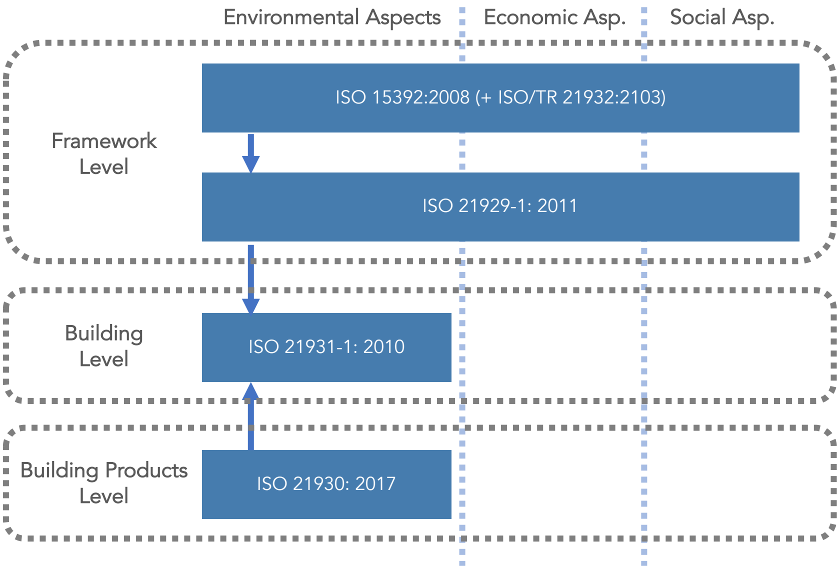

Fig. 2.7 – Conceptual framework of International Standards for sustainability in buildings (Source: ISO 15392:2008 - reworked by the Author)

In the European context, the standardization procedures are conducted by the European Committee for Standardization (CEN) which, through specific Technical Committees can adopt or modify the ISO standards or develop new ones. The committee in charge for regulating the assessment methods of buildings sustainability aspects, is the TC-350 which developed the following standards:

– EN 15643-1: 2010 (Sustainability of construction works - Sustainability assessment of buildings Part 1: General framework): provides the general principles and requirements, for the assessment of buildings in terms of environmental, social and economic performance taking into account technical characteristics and functionality of a building[23].

– EN 15643-2: 2011 (Sustainability of construction works - Assessment of buildings Part 2: Framework for the assessment of environmental performance): provides the specific principles and requirements for the assessment of environmental performance of buildings taking into account technical characteristics and functionality of a building[2].

[23] The standards descriptions have been taken directly from the CEN website: https://standards.cen.eu/index.html

– EN 15978:2011 (Sustainability of construction works - Assessment of environmental performance of buildings – Calculation method): specifies the calculation method, based on Life Cycle Assessment (LCA) and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment[2].

– EN 15804: 2012 (Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products): This European standard provides core product category rules (PCR) for Type III environmental declarations for any construction product and construction service[2].

Similarly to the organisation provided by ISO, also the TC-350 divide these standards on different conceptual levels as shown in Fig. 2.8.

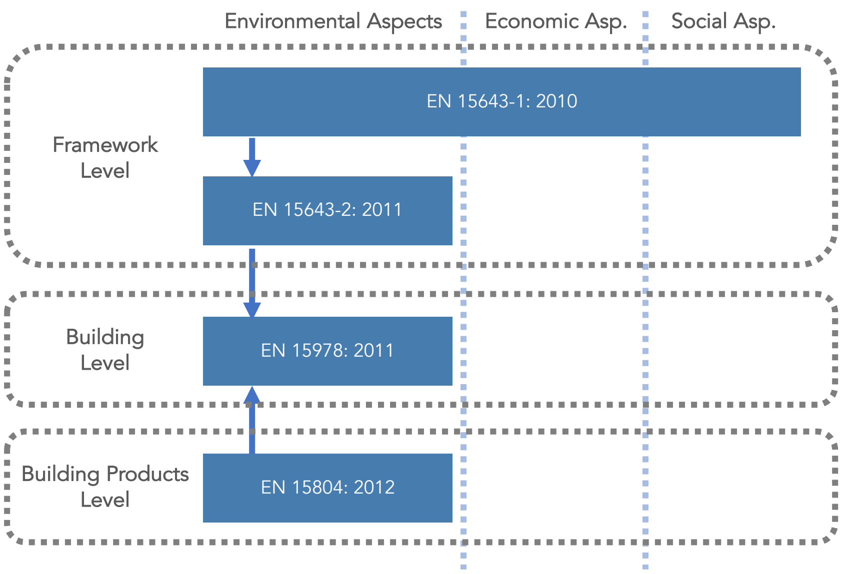

Fig. 2.8 – Conceptual framework of European Standards for sustainability in buildings (Source: CEN TC-350 - reworked by the Author)

2.2.1 European and Italian actions on buildings environmental impacts

In the European context, a number of actions have been taken in last years, aimed at strengthening the green economy across the member states. In particular on March 2011, the EU approved the Construction Products Regulation 305/2011(CPR), replacing the previous Directive 89/106/EEC (CPD), intending to overcome the technical barriers in construction products trading (Pacheco-Torgal, 2014).

To achieve the goal, the CPR focus on four main elements:

- a framework of harmonized technical specifications,
- a common conformity assessment system for each product category,
- a network of notified bodies for certifications,
- the products CE marking.

The CPR harmonizes the assessment and verification methods, the declaration of performance approaches and the conformity assessment system of construction products but it does not standardize the national regulations concerning the use of such products in construction works.

One of the main updates regards the introduction the Declaration of Performance (DoP) of construction products (Replacing the Declaration of Conformity) with different meaning and content: while the declaration of conformity certified the conformity of a product with the requirements of a technical standard (Article 13 CPD), the declaration of performance requires the manufacturer to certify the essential product performances according to the relevant technical specifications (Article 6 CPR).

The selection of the product required performance level is left to the Member States. However, these values must be expressed in coherence with the harmonized technical specifications.

The harmonized technical specifications of a product define the methods of verification and declaration of performance characteristics that influence the ability to satisfy the seven basic requirements (listed below) referred to the construction works (BRCW) which, in general, have to be accomplished. Members States, however, are autonomous in choosing how to apply them nationally.

1. Mechanical resistance and stability
2. Safety in case of fire
3. Hygiene, health and the environment
4. Safety and accessibility in use

5. Protection against noise
6. Energy economy and heat retention
7. Sustainable use of natural resources

With respect to environmental consequences, in particular three requirements have great relevance:

- Hygiene, health and the environment: "*The construction works must be designed and built in such a way that they will, throughout their life cycle, not be a threat to the hygiene or health and safety of workers, occupants or neighbors, nor have an exceedingly high impact, over their entire life cycle, on the environmental quality or on the climate during their construction, use and demolition, in particular as a result of any of the following:*

    a) *the giving-off of toxic gas;*

    b) *the emissions of dangerous substances, volatile organic compounds (VOC), greenhouse gases or dangerous particles into indoor or outdoor air;*

    c) *the emission of dangerous radiation;*

    d) *the release of dangerous substances into ground water, marine waters, surface waters or soil;*

    e) *the release of dangerous substances into drinking water or substances which have an otherwise negative impact on drinking water;*

    f) *faulty discharge of waste water, emission of flue gases or faulty disposal of solid or liquid waste;*

    g) *dampness in parts of the construction works or on surfaces within the construction works*"; (European Commission, *Regulation (EU) No 305/2011, Annex I*, p. L88/33)

- Energy economy and heat retention: "*The construction works and their heating, cooling, lighting and ventilation installations must be designed and built in such a way that the amount of energy they require in use shall be low, when account is taken of the occupants and of the climatic conditions of the location. Construction works must also be energy-efficient, using as little energy as possible during their construction and dismantling*"; (European Commission, *Regulation (EU) No 305/2011, Annex I*, p. L88/34)

- Sustainable use of natural resources: "*The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:*

  a) *reuse or recyclability of the construction works, their materials and parts after demolition;*

  b) *durability of the construction works;*

  c) *use of environmentally compatible raw and secondary materials in the construction works*" (European Commission, *Regulation (EU) No 305/2011, Annex I,* p. L88/34).

In recent years, other initiatives moved towards environmental goals for construction products, embodying older green economy precepts.

One of the first attempt to embrace sustainable approach within the European context, was the "Green Paper - public procurement in the European union: exploring the way forward" (European Commission, 1996), a document that provided the evidence of the growing attention towards the Green Public Procurement (GPP).

The GPP has been proposed as an approach to voluntary environmental policy aimed at supporting the development of products and services with reduced environmental impact through the public demand.

The "environmentally preferable" products were considered those with the less energy requirement, made of recycled material and/or free from harmful substances, easily recyclable and resulting from less impactful production processes (Tarantini et al., 2011).

Since European Commission estimates the member countries public spending for the purchase of goods and services to approximately reach 19% of the relative GDP (annually), GPP assumes significant weight in terms of the entire European economic system. Therefore, the GPP effectiveness in promoting the diffusion of a sustainable production and consumption model is evident (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, retrieved on March 2018)

For this reason, GPP has been recognized by the European Commission as a key tool of the Integrated Product Policy in 2003, within the related Communication COM 2003/302 ("Communication from the Commission to the Council and the European Parliament - Integrated Product Policy: Building on Environmental Life-Cycle Thinking").

The following year, the adoption of two European directives on public procurement: 2004/17/EC and 2004/18/EC, gave significant legal support to the GPP.

Recently, these directives have been replaced by the Directive 2014/24/EU on public procurement and Directive 2014/25/EU on the procurement procedures within the water, energy, transport and postal services sectors. Additionally, the Directive 2014/23/EU was also adopted with regards to the award of concession contracts.

At Italian national level, these directives have been implemented with the Legislative Decree 18 April 2016, n. 50 – "Code of public contracts" (amended by Legislative Decree 56/2017), making Italy the first country to establish the mandatory application of the GPP for the contracting authorities (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, retrieved on March 2018).

This decree, in particular, recalls the provisions contained in the inter-ministerial decree of 2008 ("Approval of the action plan for environmental sustainability of consumption in the public administration sector") with regards to the Minimum Environmental Criteria (Criteri Ambientali Minimi - CAM).

CAM are intended to be environmental requirements for the various stages of the purchasing process, aimed at identifying the project solution, the product or the service with the best environmental profile along the whole life cycle, considering the availability of the market.

With respect to construction products, CAM are regulated within the Ministerial Decree on Environment of 11 October 2017 ("Assignment of design services and works for the new construction, renovation and maintenance of public buildings") and they must be included in the contract documents.

In this context, the Environmental Product Declarations (EPD) –as based on LCA approach- are a useful tool for improving the information transparency and the environmental quality of projects, (see Section 2.4.1).

2.3 LCA Methodological Framework

Life Cycle Assessment is a systematic approach for the quantification and evaluation of environmental impacts related to specific activities that involve suppling resources, processing them and possibly transporting, assembling, using and eventually dismantling them (Dixit et al., 2012).

The ISO standards provide specification on how performing LCA analysis, defining a framework to use as a guidance.

The four main LCA stages are:

- The Goal and Scope,
- The Life Cycle Inventory Analysis (LCI),
- The Life Cycle Impact Assessment (LCIA), and
- The Interpretation.

An important concept to consider is that LCA is a relative approach (ISO 14040, 2006) being developed basing on a Functional Unit (FU) which describes the object of the study providing the reference to which all the data are referred.

The Functional Unit is arbitrary and has to be selected considering the function of the analysed object (quantification of performance characteristics) and the scale of the analysis. Selecting an appropriate F.U. is essential in order to compare the outputs from different analysis (Erlandsson & Borg, 2003).

Another element to determine before the assessment is the Reference Flow of the system, which is a quantified amount related to the object of the study, necessary to fulfil the intended function (the performance) described by the functional unit (Weidema et.al, 2004).

2.3.1 Goal and Scope

According to ISO 14040, the Goal of an LCA is intended to plot the context of the analysis answering the following questions:

- *What*: the intended application,
- *Why*: the reasons for carrying out the study,
- *For whom*: the intended audience, and

- *How*: whether the results are intended to be used.

The Scope is instead intended to provide specifications on the object of the study and the designated approach. Following the summary proposed by Simonen (2014), LCA Scope can be structured in:

- *Object of the study*: describing the system, the performance and the functional unit involved;
- *Boundary of the study*: which phases are included in the analysis;
- *Methodological approach* (see Section 3.1.3.3): indicating the allocation procedures, the impact category selected, the assessment and interpretation methodology;
- *Analysis details:* indicating the source of data, the data requirements, the assumptions and limitations of the study and the type of critical review (if any).

2.3.2 Inventory Analysis (LCI)

Life Cycle Inventory is a key phase composed by two fundamental steps: collection and calculation of data in order to quantify relevant inputs and outputs of a system (Simonen, 2014).

The collection procedure can be performed aggregating and classifying data in the following categories:

- Inputs such as energy, raw materials or other physical inputs,
- Products, co-products and waste,
- Output such as emissions to air, water and soil, and
- Other environmental aspects.

In order to determine the inputs quantities, it is necessary, firstly, to ascertain the amounts of materials and products constituting the object of the study (such as the building or a portion of it) through, for example, a bill of quantities or a BIM tool (see Section 3.3.1).

Then, for each material, data about manufacturing, construction, transportation, disposal activities etc. have to be collected following specific approaches.

Three methods are generally adopted depending on the sector for which the analysis is performed: Process-Based, Economic Input-Output (EIO) and Hybrid approaches (Yang, et al., 2017).

Process-based inventories aim at systematically investigating actual processes, itemizing inputs and outputs at each phase of the production as well as the other life cycle stages. Nevertheless, due to the scarcity of such a complete process information, this method is able to cover only a portion of the actual activities involved, likely leading to an underestimation (truncation error) up to 50%, of the real emissions, resource extractions, and impacts (Yang, et al., 2017).

On the other hand, inspired by economic principles, the Input-Output approach instead, traces the transactions (resources and pollutants) between industry sectors in mathematical form (matrix) as the annual outputs, in terms of emissions and waste, of a particular industry process, represent the inputs for another one, throughout the whole supply chain of a given product (Carnegie Mellon University, 2008). This method is, however, considered too aggregate as the risk of combining heterogeneous items, might hinder its application for detailed studies (Suh et al., 2004).

Hybrid inventory is the result of the combination of the previous methods, developed to correct their limitations while taking advantage of their strengths, aiming at achieving both specificity and system completeness (Suh et al., 2004). This approach is generally recognized as more accurate, but still raises some concerns about accuracy (Yang, et al., 2017).

Anyway, for practitioners willing to perform LCA analysis for the building sector, different formats of LCI data, such as literature or industry data, can be accessed from both open access and proprietary sources (Simonen, 2014).

Usually LCA databases are developed by enterprises from specific sectors (i.e. metals, plastic, cement, timber manufacturer) or organisations (academics and consultancy firms) which investigate and collect such data and, most likely, model the inventories on the basis of local manufacturing processes characteristics (Martínez-Rocamora et al., 2016).

In general, LCI data sources can be sorted in two main categories: generic LCA database, containing proxy (indirect) data suitable to local contexts, and product-specific LCA database (i.e. EPD, see Section 2.4) which are based on product and process-specific information and are representative of actual industrial practices of a certain location (Lasvaux et al., 2015).

Among the most common generic databases in Europe, are listed:

– *Ecoinvent*: developed by the Swiss Centre for Life Cycle Inventories, is considered consistent and transparent;

– *GaBi Database*: developed by PE INTERNATIONAL, is one of the most complete LCA databases currently available;

- *ELCD Database* (discontinued the 29th of June 2018): developed within the European Platform on Life Cycle Assessment (EPLCA) through the Joint Research Centre (JRC) of the European Commission, this database is open access and contains a great number of items, all compliant with UNE-EN ISO 14040 and 14044;
- *Ökobaudat*: a standardized database created for the German Federal Ministry for the Environment, Conservation of Nature, Construction and Nuclear Safety (Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit - BMUB).

While, popular American databases are:

- *Athena database*: includes data for construction materials, energy, transport, construction and demolition processes, maintenance, repairing, and waste disposal, reflecting the Canadian and the U.S.A contexts, since it considers different circumstances for transport, energy mix and recycled material (Martínez-Rocamora et al., 2016).
- *U.S. Life Cycle Inventory Database*: developed by the National Renewable Energy Laboratory of the U.S. Department of Energy. Data cover several Life Cycle modules including Cradle to Grave phases.
- *Quartz Project Database*: developed as an open data initiative for spreading knowledge about building products impacts. The database currently includes composition, environment, and health hazard information on 102 common building products.

The EeB Guide (Wittstock et al., 2012), a guidance drafted on the ILCD handbook[24] within the European Seventh Framework Programme for Research (FP7), specifies the importance of relying on consistent data from a single source.

Depending on the level of detail of the analysis ILCD handbook (Wolf et al., 2010) defines three kinds of applications: Screening LCA, Simplified LCA and Complete LCA) suggesting different approaches in data sourcing depending on the type of analysis. Generic databases are considered appropriate for elementary LCA, while product-

[24] ILCD handbook consists of a set of documents on LCA developed in compliance with the international standards (ISO 14040/44), by the Institute for Environment and Sustainability (IES) in the European Commission Joint Research Centre JRC), in co-operation with the Environment DG. The purpose of these documents is the endorsement of sustainable consumption and production approaches.

specific databases (EPD) should be preferred for more comprehensive assessments, resorting to generic data if specific data are missing for some products.

Using data that meet the requirements of EN 15978 and EN 15804 is an important aspect to consider when performing building LCA, especially within the European context.

After the collection, data have to be validated, related to each unit process and then related to the reference flow of the functional unit. If different input types are considered and they correspond to different elements within the system analysed, then an allocation step is needed in order to perform a right association between data and system elements.

The result of LCI is a detailed accounting of inputs (energy, materials etc.), products and outputs (emissions and waste).

Figure 2.9 shows the simplified inventory analysis procedure proposed by the ISO 14044:2006.

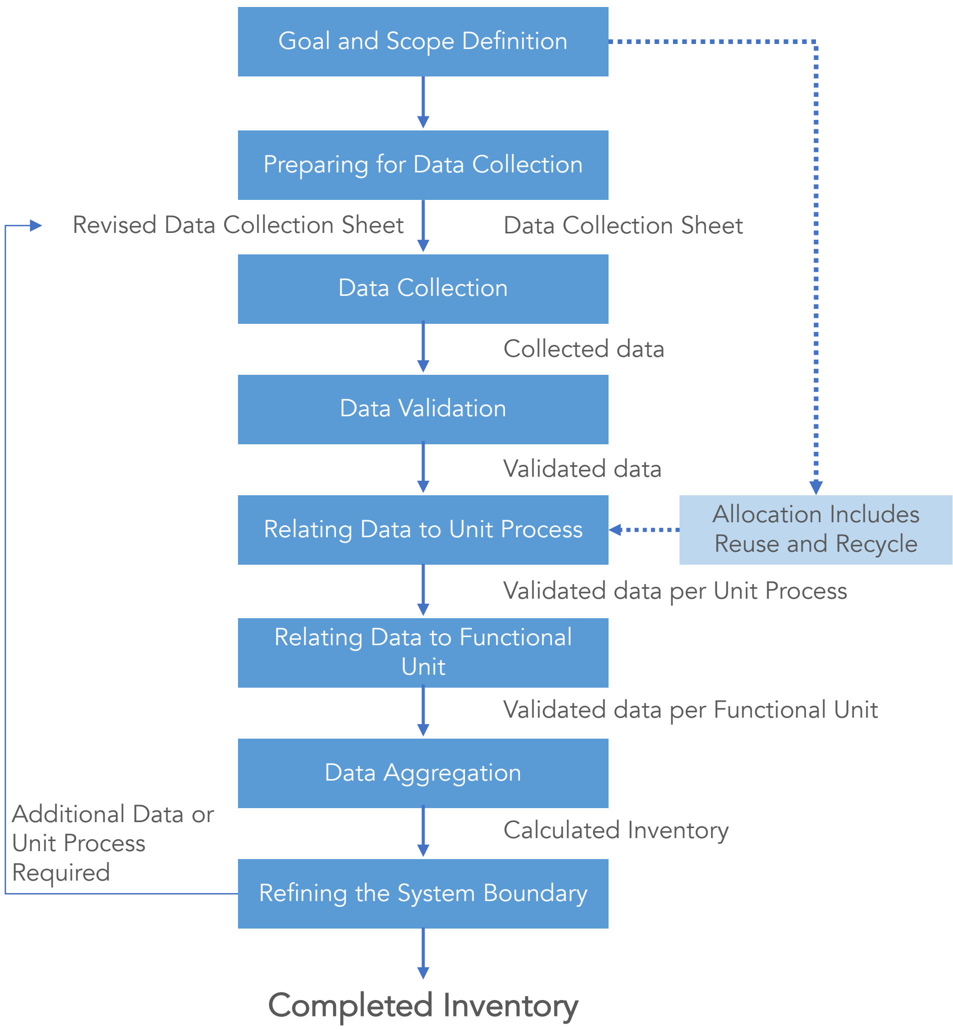

Fig. 2.9 – Simplified Inventory Analysis procedure (Source: ISO 14044, 2006 - reworked by the Author)

Due to the amount of data referring to complex systems such as those related to buildings, a further step is often needed in order to aggregate data into summary environmental impacts categories: the Life Cycle Impact Assessment (LCIA), which enables an easier interpretation of LCI outcomes.

2.3.3 Impact Assessment (LCIA)

As previously outlined, dealing with complex entities such as buildings, can lead to the draft of inventories containing hundreds or thousands of emission data types, relative to a great amount of chemicals or physical elements.It is, therefore, important to recognise which effects to the environment are caused by those emissions, thus understanding which impact categories and category indicators can be related to them.

The impact assessment phase is, therefore, intended to ascertain the significance of potential environmental impacts related to LCI in order to provide the basis for the interpretation (Wolf et al., 2010).

The first step consists in defining the LCIA Methodology to adopt, in compliance with the Goal and Scope of the study as well as with the geographical context of the analysis.

Firstly, the LCIA Methodologies available differ in the approach of assessment depending of the type of outcomes to achieve (Karim A. I. M., 2011). In particular, three approaches are identified:

- Mid-Point approach which focus on single environmental issues (problem-oriented), or
- End-Point approach which is more detailed and refers to specific damages (damages-oriented) (Fig. 2.10), or
- Combined approach.

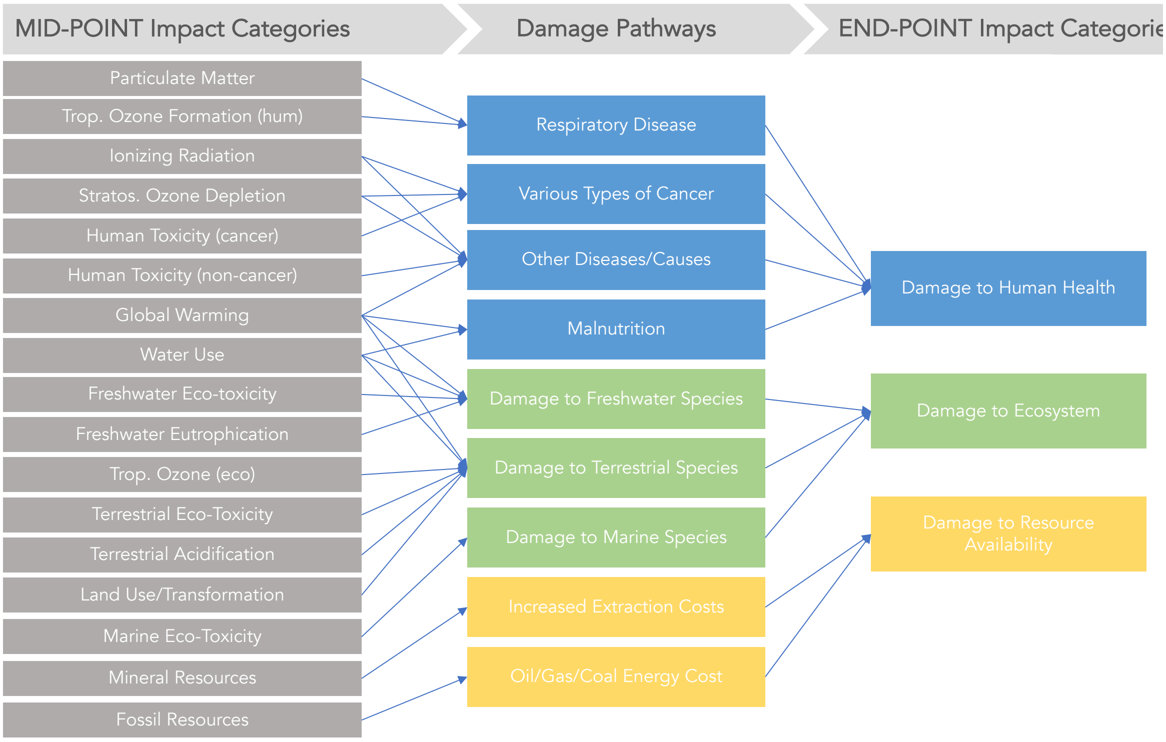

Fig. 2.10 – Mid-Point and End-Point impact categories according to ReCiPe method (Source: The Dutch National Institute for Public Health and the Environment (RIVM), 2016 - reworked by the Author)

According to ISO 14040:2006, the impact assessment stage includes two mandatory steps:

– *Classification* is the step in which the elementary flows resulting from LCI are assigned to specifically selected impact groups. For instance, Carbon Dioxide emissions are addressed to the Climate Change category while Methane emissions are addressed to Climate Change as well as to Photochemical Ozone Creation Potential since they effect both the phenomena. Nevertheless, emissions have different impact, hence different weights, in relation to specific impact indicators. For this reason, another relevant step has to be performed.

– *Characterisation* is the phase through which the LCI outputs, for each Impact Category they belong to, are multiplied with specific Impact Factors (or Characterisation Factors) according to the Characterisation Model defined in the selected LCIA Methodology. The Characterisation can be conducted through the following equation (2.1) (Karim A. I. M., 2011):

$$\text{(2.1) Category Indicator} = \sum_{s} \text{Characterization Factor}_s \cdot \text{Emission Inventory}_s$$

s:considered chemicals

Through this step, all the emissions considered in the study, assume different weights depending on the Impact Categories to which they are assigned (Fig. 2.11).

In order to assign different emissions to different Impact Categories, each category needs to be expressed with a specific unit, to which all the related emissions have to refer. Similarly, the characterization factors express the contribution of a unit mass (1 kg) of a specific emission to the environment.

For example, being the CO_2 the most abundant Greenhouse Gas (GHG), the Global Warming Potential indicator (GWP) is generally expressed in units of carbon dioxide equivalent (CO_2e). Anderson and Thornback (2012) explain that this unit provides "*the relative measure of the amount of CO_2 which would need to be released in the atmosphere in order to have the same radiative forcing effect*[25] *as a release of 1 kg of the GHG (considered) over a particular time period*".

GWP, therefore, is an indicator for measuring the impact on climate change of a particular gas, normalised to the GWP of CO_2. A list of the most common GHGs and their conversion to carbon dioxide potential is shown in Table 2.1 below, extracted from the Characterisation Model proposed by the Intergovernmental Panel on Climate Change (IPCC).

[25] According to IPCC Synthesis Report on Climate Change, Radiative Forcing "*is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism*" and it is expressed in W/m^2. (IPCC, 2007)

Industrial Designation or Common Name	Chemical Formula	Global Warming Potential for Given Time Horizon		
		20 yr	100 yr	500 yr
Carbon Dioxide	CO_2	1	1	1
Methane	CH_4	72	25	7.6
Nitrous oxide	N_2O	289	298	153
Sulphur hexafluoride	SF_6	16,300	22,800	32,600
HFC-134a (tetrafluoroethane)	CH_2FCF_3	3,830	1,430	435

Tab. 2.1 – Extract of the GWP Characterization by IPCC AR4 (2007) (Source: IPCC, 2007 – reworked by the Author)

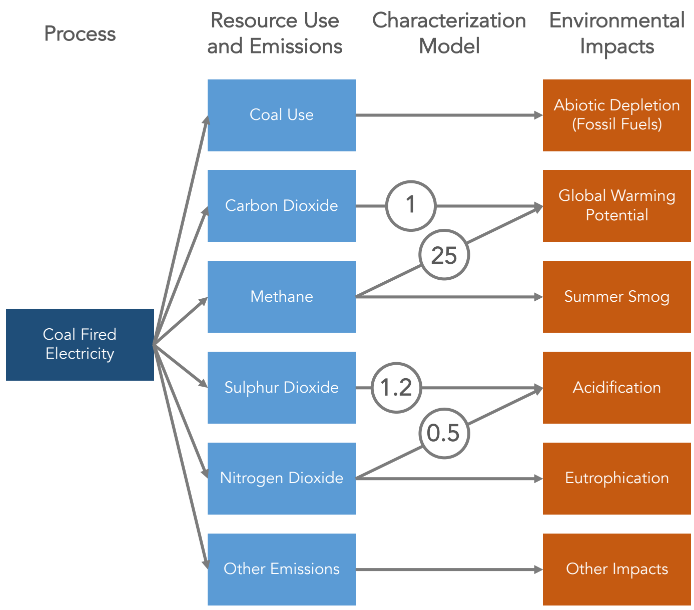

Fig. 2.11 – Example of Characterization Phase (Source: Anderson and Thornback, 2012 - reworked by the Author)

Two additional steps are indicated in the ISO standards which are optional:

– *Normalization*: some LCA applications might further explain also the relative significance of a product's impacts within specific geographic context over a certain time span with regard to specific topics (e.g. the impacts of a European Citizen, to illustrate the relative significance of a product's impacts to European activity as a whole). In this way, different impact indicators can be compared to each other. The equation expressing the Normalization is expressed below (2.2):

$$(2.2)\ \text{Normalized Indicator}_k = \frac{\text{Category Indicator}_k}{\text{Reference value}_k}$$

$$k\text{=impact category}$$

- *Weighting*: this stage is a subjective method of assessing different indicators by converting them into other values through specific weighting factors (See equation 2.3) (Karim A. I. M., 2011). It, therefore, enables to weight and compare different normalized impacts for the definition of their relative importance. The weighting factors are subjective and can differ depending on, for instance, socioeconomic aspects. A clear example of it, is the "water consumption" indicator, which can vary greatly depending on the country for which is calculated. It can assume relevant importance for those countries suffering from drought, while it will assume less importance for the countries in good water supply conditions.

$$(2.3)\ \text{Environmental Impact} = \sum \text{Weighting factor}_k \cdot \text{Category (or Normalized)Indicator}_K$$

$$k\text{:impact category}$$

Today several LCIA Methodologies are available, more than 50 in Europe (Invidiata et al., 2017), and have to be selected considering, for example, the local (national) differences in production processes or energy mixes (having an effect on the characterisation and normalisation factors) and the political, social and ethical issues (which effect the weighting factors) (Karim A. I. M., 2011).

A list of the major LCIA Methodologies[26] are listed below:

- CML 2011
- CML 1996
- Eco-Indicator 95
- Eco-Indicator 95 RF
- Eco-Indicator 99

[26] Most of the methodologies were taken from the list in the GaBi software website (Thinkstep): http://www.gabi-software.com/software/gabi-software/gabi/functionalities/impact-methodologies-lcia/ (retrieved on August 2018)

- EDIP 1997
- EDIP 2003
- EPS 2000
- Impact 2002+
- Method of Ecological Scarcity (UBP Method)
- MEEuP
- LIME
- ReCiPe
- TRACI 2.0
- USEtox

2.3.4 Analysis Interpretation

The Interpretation phase consists in a critical review of the assessment, in order to identify the relevant issues arising from the LCI and LCIA phases elaborating conclusions, limitations and recommendations (ISO 14044, 2006).

The ISO 14044:2006 addresses a number of evaluation procedures in order to validate the LCA outcomes reliability: completeness, sensitivity and consistency checks can be performed to verify whether some item or information is missing and needs to be implemented, it the assumptions and choices taken provide enough sensitivity to the analysis and if the goal and the scope of the study have been met (Fig. 2.12).

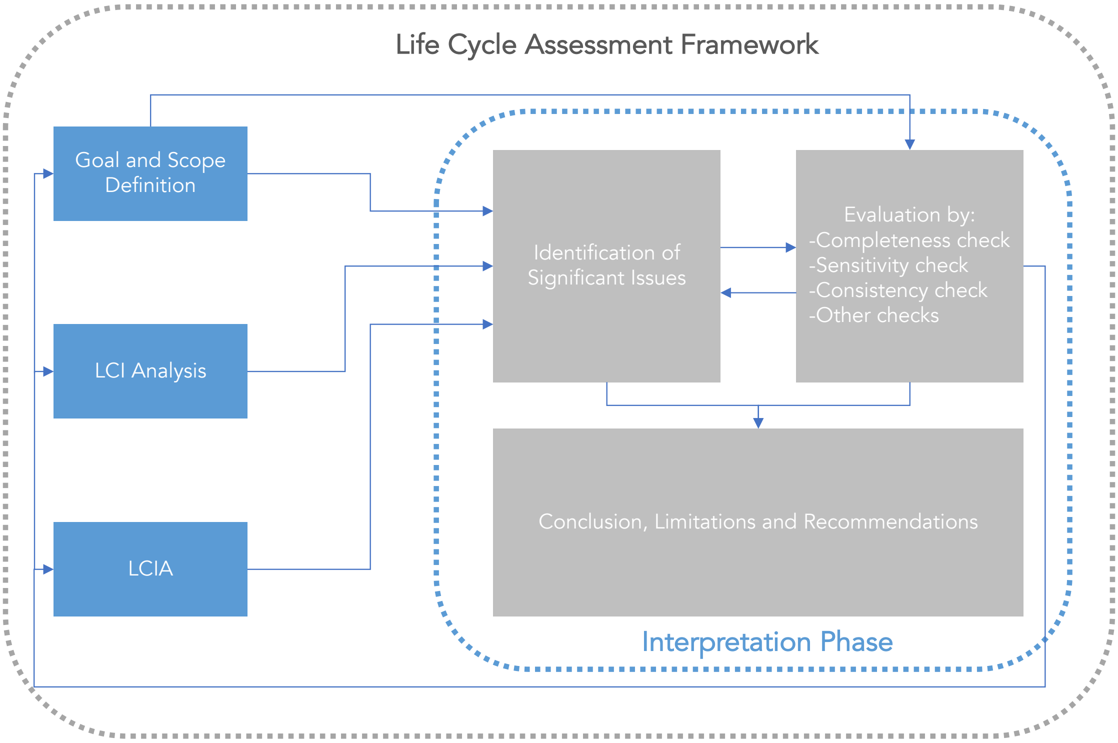

Fig. 2.12 – Relation between the Interpretation Phase and the other phases of the LCA Framework (Source: ISO 14044, 2006 - reworked by the Author)

2.4 Buildings Products and LCA

For buildings products, as well as for many other kinds of goods and services, LCA can be employed for certifying relevant environmental information in order to guide the market towards more aware choices (Gazulla Santos, 2014).

A common means broadly available in the market, used to identify products with better environmental performance in comparison with other (functionally equivalent) goods, are the Eco-labels, developed for different purposes and characterized by different attributes (Cobut et al., 2013). Eco-labelling programmes have been activated in almost every industrialized country and some initiatives have been undertaken also in developing countries. The most common voluntary types of ecolabels regarding environmental information were developed in accordance to ISO and are divided into three categories: Type I (certified eco-labels), Type II (product self-declarations) and Type III (environmental product declarations - EPD) (Gazulla Santos, 2014). Even though they all pursue the achievement of environmental goals, only type I and type III eco-labels are based on LCA approach although in different ways.

Type I eco-labels are regulated by ISO 14024 and are aimed at certifying, through a third party multi criteria evaluation, the environmental preference of products or services within their product category. The awarding criteria as well the quality threshold adopted by the label programs, are based on the most relevant environmental and market relative information, in order to obtain and promote a representation of the best performances within each category. In order to achieve this, an LCA approach has to be involved in the procedure (as established by the ISO 14024), but no specific indications are given about the extent of the LCA methodology that has to be followed, thus leading to several divergences between different schemes.

Some of the most common Type I eco-labels such as: the EU Eco-label, the northern Europe Nordic Swan, the German Blue Angel, the Australian GECA and the American Green Seal (Fig. 2.13), are administered by national or regional public organizations, and they are mostly customer addressed (Business to Customer or B2C).

Fig. 2.13 – Some of the most common (Source: EU Eco-label, Blauer Engel Nordic Swan, GECA, Green Seal)

Within this type of eco-labels, it is possible to identify another group, similar to Type I as they are subjected to a verification and certification process, but centred only on single issues such as energy consumption, sustainable forestry, etc. Belong to this category labels such as: FSC Trademark, PEFC for trees preservations, Energy Star for energy efficiency of appliances and others.

Type II eco-labels, or product self-declarations, conversely, are formulated directly by manufacturers or distributors in order to provide environmental information about the compliance of their products or services to specific environmental goals. The main differences with the other types of eco-labels are that: they do not provide a certification but only release a written statement or a symbol, they are not subjected to a third-party revision as they are developed internally by companies and, eventually, no LCA approach is explicitly required by ISO 14021:1999 that regulates their development (Gazulla Santos, 2014).

Likewise Type I, also Type II eco-labels have been developed primarily for customers usage.

2.4.1 Type III eco-labels: Environmental Product Declarations (EPD)

Environmental Product Declarations, the third type of eco-labelling, embody LCA approach in a more comprehensive way.

They "*present quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function*" […] "*using predetermined parameters and, where relevant, additional environmental information*" (ISO 14025, 2010, p. iv).

Within the building sector, EPD are aimed at providing environmental data for conducting reliable LCA analysis helping designers and decision makers in choosing more sustainable products and to orient the market towards less environmental harmful products. For this reason, they are addressed either to producers (Business to Business - B2B) and to final consumers (Business to Customers - B2C)

In particular, EPD:

- Are developed on a voluntary basis;
- Include the analysis of a series of impact categories with respect to LCI and LCIA indicators, relying on LCA methodologies compliant with the ISO 14040: 2006 series;
- Are validated by third party organizations which certify their reliability with respect to the functional unit and the scope of the analysis;

- Do not provide any kind of judgment criteria, hence not inducing explicit preferences: eventual considerations or data interpretations are left to users.
- Are managed by national or international programme operators which, for the development of EPD, should apply specific Product Category Rules (PCR) enforcing a "*set of specific rules, requirements and guidelines for one or more product categories*" (ISO 14025, 2010), in order to enable fair comparisons between different products.

PCR aims at ensuring the comparability of LCA-based data contained in the EPD developed by different operators, defining LCA attributes such as the functional unit, the scope, the boundaries, the life cycle inventory data and the impact categories (Bovea et al., 2014), in compliance with ISO 14040/44:2006, ISO 14027:2017, ISO 21930:2017 and EN 15804:2012.

As the products manufacturing process changes in time, also PCR need to be updated. For this reason, their validity covers only a programmed period, usually from 3 to 5 years.

The typical PCR and EPD contents are showed in figures 2.14 and 2.15.

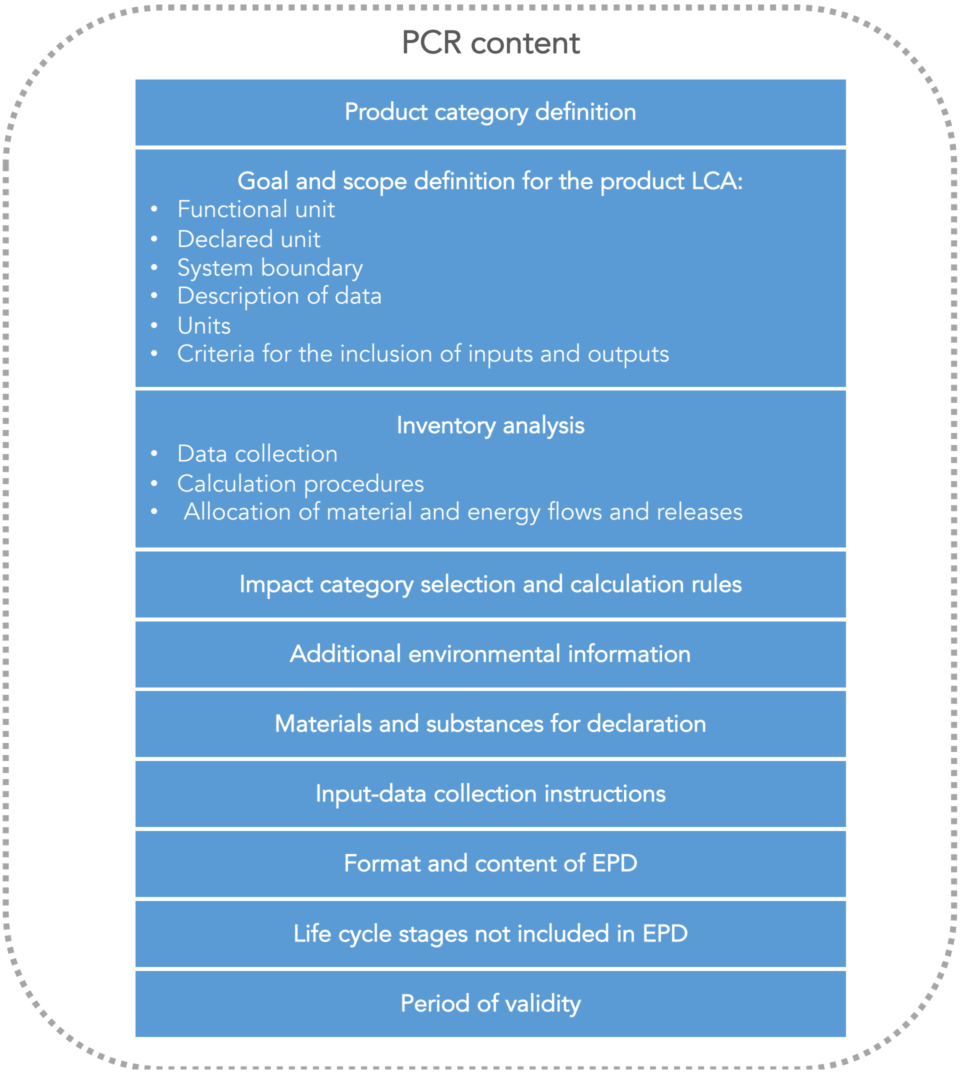

Fig. 2.14 – PCR content in compliance with ISO 14027:2017 and EN 15804:2012 (Source: Bovea et al., 2014 - reworked by the Author)

EPD content

Producer details

Product description and content declaration

EPD publication date and period of validity

The name of the EPD progamme and programme administrator/operator

References to the PCR, including PCR publication date and period of validity

Life cycle-based data (LCI and LCA data):

Life cycle inventory data (LCI):

- Inputs: raw material, energy, water, etc.
- Outputs: water, air and soil emissions

Impact categories data (LCIA):

- Global warming
- Ozone layer depletion
- Acidification Eutrophication
- Photochemical oxidation
- Abiotic depletion and other

Other: The omitted life cycle stages

Additional environmental information

Standard comments on comparability

Information about verification process and body:

- Information on the review of the PCR and the agency responsible for carrying it out.
- Name and organisation of the coordinator and contact information.
- Independent verification of the declaration and data, according to ISO 14025 (2006).
- Third party verifier (optional for business-business communication and compulsory for business-consumer communication).

References to further information

Fig. 2.15 – PCR content in compliance with ISO 14025:2010 (Source: Bovea et al., 2014 - reworked by the Author)

As in the case of Type I eco-labels, several national and international operators are committed to manage and promote EPDs but just a few include buildings products declarations, such as BRE Global (UK), EPD Norge (Norway), IBU (Germany), EPD Italy (Italy), Environdec or International EPD Programme (Sweden/Europe) and Australasian EPD programme (Australia and New Zealand).

Even though EPD have to be developed in compliance with international standards, they often can differ in content, calculation rules and format because each operator can customize rules and requirements, hindering the possibility of direct comparisons (Bovea et al., 2014). For this reason, relying on the same PCR for the development of products EPD, is the only way to assure fair comparisons. Likewise, the same functionality and use purpose have to be considered when comparing different products (e.g. EPD for 1 m^3 of concrete cannot be compared with an EPD for 1 kg of structural steel section).

Furthermore, if different products are compared at the building level, they must not be evaluated alone but as a part of a system, specifying the same functionality, for example the mass of product needed to fulfil the same structural function, as well as all the other materials composing the element (Anderson and Thornback, 2012).

Thanks to the certification procedures they are subjected to, which provide greater reliability and consistency, buildings products EPD can effectively represent a reliable source of data for LCA application to buildings, playing a crucial role also in the GPP initiatives requirements.

It is important, however, remarking the fact that EPD may not be always a comprehensive source of LCA data as, depending on the PCR adopted, LCI or LCIA indicators could be neglected and cut-off criteria may not be much detailed.

In order to reach higher level of accuracy (going beyond the scope of EN 15804) it may be necessary to rely on generic dataset (Wittstock et al., 2012).

2.5 LCA Strengths and Weaknesses

Elaborating a comprehensive overview of the opportunities and limitations of the LCA analysis is a key aspect for its correct application within the built environment.

Since their development, LCA applications have been regulated, updated, discussed, endorsed and criticized, but there is still no unanimous agreement on their actual employment within the building sector (Rønnin and Brekke, 2014; Ingrao et al., 2018).

Several authors have increased its effectiveness applied to construction, drafting a list of strengths and weaknesses.

Simonen (2014) recognised a series of positive features, arguing that an LCA is:

- Quantifiable, since it relies on measurable metrics able to describe several environmental impacts;
- Structured, as it benefits from a robust international standardization that makes it a systematic evaluation tool;
- Comprehensive, due to its coverage throughout the whole life cycle of a product, from the extraction of raw materials to the end of life phase;
- Comparable, when the frameworks of different applications rely on the same setting (for example, same goal and scope, same methodology, same data sources etc.), different options can be compared through an LCA;
- Indicative, when the conditions of the analysis are clear, and the outcomes are comprehensible and correctly displayed, an LCA can provide robust insights into the environmental profiles of different products and choices;

On the other hand, a number of limitations at each stage have been also acknowledged, which hinder LCA applicability, widespread utilization as well as the opportunity to enable fair and reliable comparisons between products and buildings environmental performance.

Simonen (2014) also identified a number of critical issues, as an LCA can be:

- Time consuming, as calculations can be extremely complicated, requiring time to ascertain the process involved, set the framework, detect correct data sources, collect the data, perform calculations and elaborate conclusions. Modelling environmental impacts can be even more complex for constructions due to the variety of building techniques and technical solutions.

– Incomplete, because specific local impact information is not easy to perceive. Moreover, the focus is mainly on material and energy flows, but not all types of impacts are equally well covered in a typical LCA and some issues are not adequately treated, such as biodiversity, land use or freshwater sources (Ding, 2014). At the same time, social and economic issues are not included but have to be evaluated separately through, for example, a Life Cycle Costing (LCC) or a Social LCA (S-LCA), although some evidence of the development of a Life Cycle Sustainability Assessment (LCSA) is evident (UNEP/SETAC Life Cycle Initiative, 2011).

– Data scarcity, since some data sets for specific locations or processes are not available or are incomplete.

– Subjective, despite being robustly standardized, several subjective decisions and assumptions about, for instance, the scope of the analysis and the life cycle scenarios are still required. Additionally, interpreting the outcomes requires expertise and judgement.

– Inconclusive, in comparative cases in which one option is not distinctly preferable with respect to others.

– Uncertain, as the life cycle approach requires a complex prevision of the service life of building materials involving many variables such as: user patterns, maintenance cycles, climatic conditions as well as detailing and workmanship during design and construction. Products' end-of-life is another delicate topic since providing reliable scenarios in advance about how products can be disassembled and recycled as well as acknowledging the recyclability level of materials is not easy.

– Inaccurate, LCA precision is deeply dependent on the availability and reliability of robust LCI data sources, as well as on the quality of manufacturing process data as it strictly depends on geography locations (e.g. there is a significant gap in the LCI data in developing countries) (Ding, 2014).

Rønnin and Brekke (2014), reviewed the strengths and the weaknesses of LCA within the building sector. They considered one of the main strengths of the method to be the cause of one of the weakest features, stating that "*despite (or maybe because of) the holistic approach LCA offers, inherent ambiguities in the methodology represent limitations as it is presently used*" (Rønnin and Brekke, *Life cycle assessment (LCA) of the building sector: strengths and weaknesses*, 2014, p.80).

In their review, they analysed this matter at two different levels of detail: a macro level and a micro level in order to deepen each LCA stage.

They believe that, at a macro level, the main issue corresponds to the match between the ambition of global standardisation and the complexities and ambiguities of the building sector, sustaining the need for a 'translation processes' between the two aspects.

This macro issue is an aggregate of a number of pragmatic barriers at micro level such as: the lack of time and the difficulty of collecting all the significant data, the complexity of comprehending all relevant environmental impacts, the lack of agreement (as well as too wide a selection of methodologies) on the designation of the relative weight of the environmental impacts and the poor harmonisation of compared outcomes.

The LCA interpretation step is fundamental in assisting the comprehension and identification of the most relevant issues at product scale or at whole building scale.

Through a review of previous studies, Rønnin and Brekke (2014) indicated that the results arising from LCA building applications are too reliant on the LCA tool adopted and comparison with those produced through different tools is impossible (or at least not recommended).

Bribián et al. (2009) listed a number of weaknesses of LCA underlining the gravity of the interpretation of the results, related to a number of issues such as: the arbitrariness of the results, poor cooperation between application manufacturers and potential customers, the variety of results displayed by different applications, the difficulties in understanding and applying LCA results, the lack of legal requirements and a low link with energy certification applications (Bribián et al., 2009).

Nevertheless, the Life-Cycle Assessment is still considered one of the most suitable methods for evaluating the environmental impact of buildings (Röck et al., 2018).

Rønnin and Brekke (2014), after their review of LCA limitations, listed a number of recommended actions to reduce the variations in the results obtained by the LCA method.

Regarding each stage of the LCA framework, they came up with the following recommendations:

- Clarify the goal(s) and define the scope in a detailed and unambiguous way, paying particular attention to the selection of functional units and the delimitation of system boundaries;
- Rely only on transparent, valid and reliable data sources;

- Make a strict and shared/common selection of relevant impact categories, in order to simplify the applications.
- Refer the LCA results to the goals and scope of the analysis during the interpretation phase, carefully considering the characteristics of the building, such as: its design, composition, position and relationship with the context, and its intended use. These features greatly affect the environmental performance of the building, thus its assessment outcomes with respect to the declared scope (Rønning and Brekke, 2014).

Soust-Verdaguer et al. (2016), through their research to find a simplified LCA approach for the single-family houses segment, produced several simplification strategies similar to those suggested by Rønning and Brekke (2014). They also recommended the optimization of the data collection process, the reduction of the functional unit, the restriction of the analysis only to significant stages and modules, the simplification of the scenario definition, and the limitation of environmental indicators.

With regard to the latter aspect, in their view, the life cycle inventory analysis can be restricted to the main components and processes, and the impact assessment phase can be reduced to a few impact categories.

Regarding communication of the outcomes, the EN 15978 standard provides more precise specifications than the ISO 14040 series, but it underlines the need for common and more effective communication rules to achieve better and easier comparisons between similar building typologies.

The solution proposed by Soust-Verdaguer et al. (2016) consists of presenting the outcomes in terms of the component or system composing the building, organized by life cycle stages (e.g. building envelope, windows, roof, and structure), enabling more reliable comparisons of similar case studies.

These actions should be able to heighten the credibility of the data and calculation methods, and to encourage the use of outcomes in actual construction processes among industries as well as among decision and policy makers Russell-Smith, et al., 2015; Østergård, et al., 2016).

2.6 Integration of the Life Cycle Approach with Sustainability Rating Systems

The LCA approach has strengthened our knowledge and awareness of environmental impacts, driving designers, producers, stakeholders and policy makers towards more responsible choices and behaviours (Russell-Smith, et al., 2015; Østergård, et al., 2016). Nevertheless, when it comes to buildings, different methods of use, as well as difficulties in data collection, calculations and the projection of service life scenarios, have led to different interpretations of the outcomes, increasing the challenge of accomplishing a comprehensive analysis Rønnin and Brekke, 2014). Due to this level of complexity, the building sector has not yet been able to exploit the potential of LCA as other sectors have, requiring the identified simplification and harmonisation (Soust-Verdaguer et al., 2016).

2.6.1 Aim and methodology

Starting from the comprehension of a number of weaknesses limiting LCA applications to the built environment, the second research question of the thesis, aimed at identifying the most representative characteristics of the LCA approach applied to buildings, was intended as a starting point to overcome some of the LCA related issues.

The approach adopted for this purpose is in line with the method implemented in the first part of the research: a comparative analysis of a series of GBRSs, investigating and tracing their shared features.

In this case, the objective was to compare the LCA attributes included in their protocols, identifying which elements of the LCA framework they have in common, and to what extent and how they are managed.

The methodology adopted within this study includes the following steps:

– the selection of a number of international GBRSs through a screening phase with regards to the LCA framework criteria;

– the collection of data from primary sources when available (GBRS technical manuals) and from secondary sources (such as journal articles and other kinds of publications) to integrate the missing information;

– an analysis of the collected data through draft tables to classify and quantify the extent of the shared elements. In particular, the analysis was conducted with respect to:

- the credit potentials of the LCA-related indicator and their relative weight in order to outline which Rating System gives more importance to the LCA approach;
- the LCA framework elements considered within the GBRSs criteria to outline the similarities and differences between them, with the eventual goal of identifying which features are the most shared and thus more representative for the building sector.

The selection of the GBRS sample started with the inclusion of a number of international systems particularly common in different areas of the world, thus presenting a significant number of certifications issued.

For the American area, the following were considered:

- LEED from the United States, with 62,433 certifications;[27]
- Green Globes from Canada, with 1,385 certifications;[28]

For the European area, the following were considered:

- BREEAM from the United Kingdom with 565,700 certifications;[29]
- DGNB from Germany, with 1,265 certifications;[30]
- Protocollo ITACA (which became UNI/PdR 13:2015 for residential buildings) from Italy, with 619 certifications (only in Italy);[31]
- Active House from Denmark, with 48 verified radars;[32]

For the Australasian area the following were considered:

- Green Star from Australia with 1,900 certifications;[33]

[27] Source: https://new.usgbc.org/leed retrieved in April 2017;

[28] Source: https://www.thegbi.org/green-globes-certification/ retrieved in April 2017;

[29] Source: https://www.breeam.com retrieved in April 2017;

[30] Source: https://www.dgnb-system.de/de/ retrieved in April 2017;

[31] It was not possible to find the number of certifications issued, but it was included in the screening as one of the main Rating Systems in Italy;

[32] Radar is the tool used to rate buildings. Even though the number of verified radars is not high, this rating system has been included as it is an emerging system considered particularly interesting for the goal of the analysis;

[33] Source: https://new.gbca.org.au/green-star/ retrieved in April 2017;

- CASBEE from Japan with 641 certifications.[34]

From this selection, only LEED, BREEAM, DGNB, Green Globes, Green Star and Active House were considered. Protocollo Itaca was excluded as it does not include LCA-related evaluation criteria, as was CASBEE which only considers the Global Warming Potential indicator, thus neglecting other aspects. The mere inclusion of a carbon indicator is considered insufficient to describe the environmental impacts of the buildings in the life cycle (Invidiata et al., 2017).

The data on LCA elements within the selected GBRSs was collected through a desktop study of the technical manuals of the systems, and classified in two tables (Tab. 2.2, 2.3).

The first table (Tab.2.2) outlines the importance, in terms of credit potential and relative weight, given to the LCA and EPD related criteria by GBRSs. In some cases, the weights listed do not come from the simple proportion of the credit potential criteria over the total credits achievable but result from a specific weight assigned by the systems.

The second table (Tab. 2.3) itemises a number of LCA framework elements with particular regard to the Goal and Scope definition and Interpretation, such as:

- Life Cycle Modules;
- Reference buildings service life;
- Functional unit adopted;
- Building elements assessed;
- Impact indicators included;
- Impacts thresholds and benchmarks.

Other LCA framework phases such as the Life Cycle Impact Analysis (LCI) and the Life Cycle Impact Assessment (LCIA) (as defined in ISO 14040:2006) were not included in the comparison as they specifically refer to raw data collections and interpretation. These aspects usually concern the methods for creating dataset and are not included in GBRS specifications.

[34] Source: http://www.ibec.or.jp/CASBEE/english/ retrieved in April 2017

2.6.2 Mapping the LCA framework and Rating Methods within GBRS protocols

The analysis intends to understand how LCA related aspects were considered within the GBRS protocols in order to outline similarities and differences, identifying which components are shared the most and are thus the best-fitting LCA building applications.

The first part of the analysis is summarized in table 2.2.

Rating Systems Information				LCA + EPD Categories Data				LCA Criteria Data				EPD Criteria Data				R.S. Data	
Name	Version	Year	Origin	LCA related Categories	N. of Criteria within the Category	Category Credits Potential	Category relative weight [%]	LCA related Criteria within the category	Criterion Credits Achievable	Relative Weight [%]	Total LCA Weight [%]	EPD related Criteria within the category	Criterion Credits Achievable	Relative Weight [%]	Total EPD Weight [%]	Total LCA + EPD Weight [%]	Total Credits Available
DGNB	Int. CORE14 Office	2014	DEU	Effects on the global and local environment (ENV 10)	3	110	12,4	Env.1.1 Life Cycle Impact Asessment	70	7,9	13,5	Env.1.1 Life Cycle Impact Asessment	***	/	/	13,5	850
				Resource consumption and waste generation (ENV 20)	3	90	10,2	Env.2.1 Life Cycle Assessment - Primary Energy	50	5,6		Env.2.1 Life Cycle Assessment - Primary Energy	***	/			
BREEAM	Int. New Constr. 2016	2016	GBR	Materials	6	14	12,5	Mat 01 Life cycle impacts	5	4,5*	4,5	Mat 01 Life cycle impacts	1+1	1,8	1,8	6,3	150
								Mat 02 Hard landscaping and boundary protection**	/	/		Mat 02 Hard landscaping and boundary protection**	/	/			
LEED	V.4 BD+C (New Constructions)	2017	USA	Materials and resources	5+2	13	11,8	Building life-cycle impact reduction	3	2,7	2,7	Building product disclosure and optimization - environmental product declaration	1/2	1	1	3,7	110
Green Globes	V.1.5 (New Constructions)	2018	CAN	Materials and resources	10	125	12,8	Building Core and Shell - Path A: Performance Path for Building Core and Shell	33	3,3	4,9	Building Core and Shell - Path B: Prescriptive Path for Building Core and Shell	20	2	3	7,9	1000
								Interior Fit-outs (including Finishes and Furnishings)- Path A: Performance Path for Interior Fit-outs	16	1,6		Interior Fit-outs (including Finishes and Furnishings)- Path B: Prescriptive Path for Interior Fit-outs	10	1			
Active House	v.2	2013	DNK	Environmental Loads	6	22,2	22,2	Buildings Primary Energy Consumption during Entire Life Cycle	3,7	3,7	22,2	Buildings Primary Energy Consumption during Entire Life Cycle	***	***	/	22,2	22,2
								Global Warming Potential(GWP) during Entire Life Cycle	3,7	3,7		Global Warming Potential(GWP) during Entire Life Cycle	***	***			
								Ozone Depletion Potential (ODP) during Entire Life Cycle	3,7	3,7		Ozone Depletion Potential (ODP) during Entire Life Cycle	***	***			
								Photochemical Ozone Creation Potential (POCP) during Entire Life Cycle	3,7	3,7		Photochemical Ozone Creation Potential (POCP) during Entire Life Cycle	***	***			
								Acidification Potential (AP) during Entire Life Cycle	3,7	3,7		Acidification Potential (AP) during Entire Life Cycle	***	***			
								Eutrophication Potential (EP) during Entire Life Cycle	3,7	3,7		Eutrophication Potential (EP) during Entire Life Cycle	***	***			
GREEN STAR	Design & As Built v.1.1	2015	AUS	Materials	4	14	14	19 Life cycle Impacts	7	7	7	20 Responsible Building Materials	1	1	4	11	100
												21 Sustainable Products	3	3			
						Average	**15,98**			Average	**9,13**			Average.	**2,45**	**10,77**	**372**

*: 14:12,5=5:X

**: Not evaluated as a standalone criterion, but included in Mat 01

***: included within the LCA criteria

Tab. 2.2 – GBRS LCA and EPD criteria comparison (Source: Author)

The second part of the analysis is summarized in table 2.3.

LCA Framework Analysed			Green Buildings Rating System: DGBN Core 14 Germany	BREEAM International New Construction 2016 UK	LEED V.4 (BD+C) New Constructions USA	Green Globes New Construction v.1.5 Canada	Active House v.2 Denmark	GREEN STAR Design & As Built v1.1 Australia	Sharing Extent
Goal and Scope – Modules	Raw Material Supply	A1	•	•	•	•	•	•	100%
	Transport	A2	•	•	•	•	•	•	100%
	Manufactoring	A3	•	•	•	•	•	•	100%
	Transport	A4	✕	•	•	•	✕	•	67%
	Construction Install. Process	A5	✕	•	✕	•	✕	•	50%
	Use	B1	•	✕	•	✕	•	•	67%
	Maintenance	B2	•	✕	•	Partial	•	•	83%
	Repair	B3	•	✕	•	✕	•	•	67%
	Replacement	B4	•	✕	•	•	•	•	83%
	Refurbishment	B5	•	✕	•	✕	•	•	67%
	Operational Energy Use	B6	•	✕	•	Option	•	•	67%
	Operational Water Use	B7	✕	✕	•	✕	•	✕	33%
	Deconstruction - Demolition	C1	✕	•	•	•	•	•	83%
	Transport	C2	✕	•	•	•	•	•	83%
	Water Processing	C3	•	•	•	✕	•	•	83%
	Disposal	C4	•	•	•	•	•	•	100%
	Recycling Potential	D	✕	✕	✕	Option	✕	✕	0%
Service Life			50 years (depends on the DGNB scheme adopted)	60 years	60 years	60-120 years	50 years	60 years (unless otherwise stated)	67 years
Functional Unit			m2 of Net Floor Area (NFT)	1 m2	N.S.	N.S.	N.S.	1 m2 project Gross Floor Area (GFA) basis (Additional FU allowed)	1 m2
Building Elements Assessed	Footing and foundations		•	✕	•	•	•	•	83%
	Ground slabs		•	•	•	•	•	•	100%
	Floor Slabs		•	•	•	•	•	•	100%
	Other structural elements		✕	✕	•	•	✕	•	50%
	Roof assemblies		•	•	•	✕	•	•	83%
	External Envelope		•	•	•	•	•	•	100%
	Inner walls		✕	•	✕	✕	•	•	50%
	Ceilings		✕	✕	✕	✕	•	•	33%
	Windows and doors		•	•	•	•	•	•	100%
	Technical installations		•	✕	✕	✕	•	•	50%
	Finishes		✕	✕	•	•	✕	•	50%
	Underground parking		✕	✕	•	•	✕	•	50%
Impact Indicators | Units	Climate Change	GWP	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq (100yr)	kg (CO2)eq/m2 x a	kg (CO2)eq (100yr)	100%
	Water Extraction	WD	✕	m3	✕	✕	✕	m3	33%
	Mineral Resource Extraction	TMR/ADP-e	✕	tonnes	✕	✕	✕	kg Sb eq	33%
	Stratospheric Ozone Depletion	ODP	kg (R11)eq/CFC-11 eq	CFC-11 eq	CFC-11 eq	CFC-11 eq	kg (R11)eq/m2 x a	CFC-11 eq	100%
	Human Toxicity	HTP	✕	kg (1.4 -DB)eq	✕	✕	✕	○ kg (1.4 -DB)eq	33%
	Ecotoxicity to Freshwater	WTP	✕	kg (1.4 -DB)eq	✕	✕	✕	✕	17%
	Ecotoxicity to Land	LTP	✕	kg (1.4 -DB)eq	✕	✕	✕	✕	17%
	Nuclear Waste		✕	mm3	✕	✕	✕	✕	17%
	Waste Disposal		✕	tonnes	✕	✕	✕	✕	17%
	Fossil Fuel Depletion	ADP-ff	✕	MJ (TOE?)	MJ	MJ	✕	MJ	67%
	Eutrophication	EP	kg(PO4) eq	kg(PO4) eq	kg N2 or kg PO4	kg N2	kg (PO4)eq./m2 x a	kg(PO4) eq	100%
	Photochemical Ozone Creation	POCP	kg(C2H4)eq	kg(C2H4)eq	kg NOx, kg (O3)eq, or kg (C2H4) eq	kg (O3)eq	kg (C3H4) eq./m2 x a	kg(C2H4)eq	100%
	Primary renewable energy consumtion	PERE	✕	✕	✕	✕	kWh/m2 x a	✕	17%
	Primary non-renewable energy consmption	PENRE	✕	✕	✕	✕	kWh/m2 x a	✕	17%
	Acidification	AP	kg(SO2)eq	kg(SO2)eq	moles H+ or kg (SO2)	kg(SO2)eq	kg (SO2)eq./m2 x a	kg(SO2)eq	100%
	Ionising Radiation		✕	✕	✕	✕	✕	○ kg(U-235) eq to air	17%
	Paticulate Matter	PMF	✕	✕	✕	✕	✕	○ kg(PM2.5) eq	17%
	Land Use		✕	✕	✕	✕	✕	○ m2	17%

Tab. 2.3 – GBRS LCA framework elements comparison (Source: Author)

The rating methods and benchmarks adopted by the GBRSs are listed in the following table (Tab. 2.4)

GBRS	Rating Method			Rating Method Criteria
	Reference Building	Direct Benchmark	Other	
DGNB	X	•	X	Different credits are assigned basing on the results achieved for each impact indicator, based on three different thresholds: Limit value = 1 point GWP = 13.16 $kgCO^2eq/m^2$ NFA*a ODP = 5.3*10^{-6} $kgR11eq/m^2$ NFA*a AP = 0.062 $kgSO_2eq/m^2$ NFA*a EP = 0.0033 $kgPO_4{}^{3-}$ eq/m^2 NFA*a POCP = 0.0029 kgC_2H_4eq/m^2 NFA*a PENRE = 172 kWh/m^2NFA*a PE tot = 211.4 kWh/m^2NFA*a Reference value = 5 points GWP = 9.4 $kgCO^2eq/m^2$ NFA*a ODP = 5.3*10^{-7} $kgR11eq/m^2$ NFA*a AP = 0.037 $kgSO_2eq/m^2$ NFA*a EP = 0.0047 $kgPO_4{}^{3-}$ eq/m^2 NFA*a POCP = 0.0042 kgC_2H_4eq/m^2 NFA*a PENRE = 123 kWh/m^2NFA*a PE tot = 151 211.4 kWh/m^2NFA*a Target value = 10 points GWP = 6.58 $kgCO^2eq/m^2$ NFA*a ODP = 3.7*10^{-7} $kgR11eq/m^2$ NFA*a AP = 0.026 $kgSO_2eq/m^2$ NFA*a EP = 0.0094 $kgPO_4{}^{3-}$ eq/m^2 NFA*a POCP = 0.0084 kgC_2H_4eq/m^2 NFA*a PENRE = 86.1 kWh/m^2NFA*a PE tot = 60.4 kWh/m^2NFA*a (NFA: Net Floor Area)
BREEAM	X	X	•	The spreadsheet “Mat.01 Calculator” has to be used. Users have to indicate a series of information related to the LCA methods adopted (some mandatory) achieving a result expressed as a percentage. Points are assigned based on the following criterion: 25.0% = 1 point 62.5% = 2 points 75.0% = 3 points 80.0% = 4 points 82.5% = 5 points 85.0% = 5 points + Ex

Tab. 2.4 – GBRSs rating methods for LCA criteria – Part 1 (Source: Author)

<table>
<tr><th rowspan="2">GBRS</th><th colspan="3">Rating Method</th><th rowspan="2">Rating Method Criteria</th></tr>
<tr><th>Reference Building</th><th>Direct Benchmark</th><th>Other</th></tr>
<tr><td>LEED</td><td>•</td><td>X</td><td>X</td><td>Users have to design a baseline building of comparable size, function, orientation and operating energy performance with respect to the proposed buildings.
A minimum of 10% reduction (compared to the b.l. building) has to be achieved with respect to, at least, three/six impact categories (GWP mandatory).
No impact category must increase by more than 5% (compared to the b.l. building).
If the criterion is satisfied 3 points are assigned.</td></tr>
<tr><td>Green Globes</td><td>•</td><td>X</td><td>X</td><td>Core and Shell
A. Performance Pathway: (33 points) Whole LCA analysis with Athena Impact Estimator for Buildings (or other LCA tool) evaluating a minimum of two different core and shell designs, resulting in the selection of the one with the minimum anticipated impact.

B. Prescriptive Pathway: (up to 20 points) Points are awarded based on the percentage of core and shell products that have: EPD (utilizing recognized Product Category Rules, conforming to ISO standards, and including at least the cradle-to-gate scope) and/or Third-party certifications and/or Third-party verified product life cycle assessments and/or Third-party sustainable forestry certifications.
≥ 40% = 20 points
25 - 39% = 15 points
10 - 24% = 10 point
1 - 9% = 0 points
No = 0 points

Interior Fit-outs (including Finishes and Furnishings)
A. Performance Path for Interior Fit-outs (16 points)
B. Prescriptive Path for Interior Fit-outs (10 points)</td></tr>
</table>

Tab. 2.4 – GBRSs rating methods for LCA criteria - Part 2 (Source: Author)

GBRS	Rating Method			Rating Method Criteria
	Reference Building	Direct Benchmark	Other	
Active House	X	•	X	Points are awarded from 1 to 4 (1 is the best, 4 the worst) based on specific benchmarks for the six impact categories evaluated: PE tot 1. < -150 kWh/m^2 x a 2. < 15 kWh/m^2 x a 3. < 150 kWh/m^2 x a 4. < 200 kWh/m^2 x a GWP 1. < -30 kg CO_2-eq./m^2 x a 2. < 10 kg CO_2-eq./m^2 x a 3. < kg CO_2-eq./m^2 x a 4. < 50 kg CO_2-eq./m^2 x a OPD 1. < 2.25E-07 kg R_{11}-eq/m^2 x a 2. < 5.3E-07 kg R_{11}-eq/m^2 x a 3. < 3.7E-06 kg kg R_{11}-eq/m^2 x a 4. < 6.7E-06 kg kg R_{11}-eq/m^2 x a POCP 1. < 0.0025 kg C3H4-eq./m^2 x a 2. < 0.0040 kg C3H4-eq./m^2 x a 3. < 0.0070 kg C3H4-eq./m^2 x a 4. < 0.0085 kg C3H4-eq./m^2 x a AP 1. < 0.010 kg SO_2-eq./m^2 x a 2. < 0.075 kg SO_2-eq./m^2 x a 3. < 0.100 kg SO_2-eq./m^2 x a 4. < 0.125 kg SO_2-eq./m^2 x a EP 1. < 0.0040 kg PO4-eq./m^2 x a 2. < 0.0055 kg PO4-eq./m^2 x a 3. < 0.0085 kg PO4-eq./m^2 x a 4. < 0.0105 kg PO4-eq./m^2 x a

Tab. 2.4 – GBRSs rating methods for LCA criteria - Part 3 (Source: Author)

GBRS	Rating Method			Rating Method Criteria
	Reference Building	Direct Benchmark	Other	
Green Star	•	X	X	A. Performance Pathway: (up to 7 points) The whole LCA has to be conducted on both the proposed and reference building. Points are awarded based on the extent of the reduction achieved against environmental impact categories when compared to a reference building: 1 point for the first 30% cumulative reduction and an additional point for every additional 20% cumulative reduction to a maximum of 6 points (i.e. a 130% cumulative reduction). 1 extra point if an additional five impact categories are included. B. Prescriptive Pathway: (up to 5 points) the proposed building has to reduce the amount of building materials used with respect to: Concrete, Steel and Building Reuse

Tab. 2.4 – GBRSs rating methods for LCA criteria – Part 4 (Source: Author)

2.6.3 Results and Observations

The comparison provided the following outcomes:

– A different sharing extent was reported for the LCA modules: 100% sharing for Raw Material Supply (A1), Transport (A2), Manufacturing (A3) and Disposal (C4). 83% for Maintenance (B2), Replacement (B4), Demolition (C1), Transport (C2) and Water processing (C3). Instead, greater discrepancy was reported for the remaining modules.

– With respect to impact categories: 100% sharing was reported for Climate Change (GWP), Stratospheric Ozone Depletion (ODP), Eutrophication (EP), Photochemical Ozone Creation (POCP) and Acidification (AP). 67% for Fossil Fuel Depletion (ADP), while minor agreement was reported for the other impact categories. This outcome seems to confirm the indications expressed in the EN 15804:2012 and EN 15978:2011, which define seven impact categories for buildings LCA: GWP, ODP, AP, EP, POCP, ADP-non-fossil, ADP-fossil.

- The building elements considered by the majority of GBRSs are: ground slabs, floor slabs, external envelope, windows and doors (100%), footings, foundation and roof assemblies (83%), while sharing to a lesser extent was reported for the other building elements.
- Four out of the six considered GBRSs include EPD-specific credits, generally rating the number or the percentage of building components with EPD. Other GBRSs include EPD within the LCA criteria as a possible source of data to perform the analysis.

Regarding the rating methods, the majority of the analyzed GBRSs rate the LCA impact reduction with respect to a reference building that must be specifically designed according to protocol requirements (usually according to national regulations). In particular:

- LEED (USA): The building to be used as a reference must reflect the project building with regard to: size, function, orientation and operating energy performance. The significative differences between the baseline and the project building are represented by the structural typology and the technological configurations such as the external envelope and technical installations which must, however, be compliant with the local minimum regulations for energy and thermal performance. LEED requires a (at least) 10% improvement for (at least) three indicators, of which GWP is mandatory. In addition, all other environmental indicators must not increase more than 5%. It is therefore not clear what can be considered a good result in absolute terms, as the improvement achieved depends on the initial conditions, which are conditioned by the designer's choices.
- Green Star (Australia) enables two pathways for the LCA analysis interpretation. The first one is similar to the one proposed by LEED, in which the performance of the project building has to be compared to a standard practice reference building which is a hypothetical standard contemporary construction with the same structural requirements, scale, function, location, tenant requirements, materials, aesthetics, site conditions (including underlying geology), planning constraints, orientation and construction season. The reference building, in addition, must be compliant with the national codes and regulations on materials and energy performance. The second pathway requires the project building to be compared with an actual reference building, constructed in the last five years that is similar to the usage, construction and operation of the project building. The building must match the project building at least in terms

of the structural requirements, scale, function, location and site conditions. Unlike LEED, which only permits one level of improvement (10%) with respect to the reference building, assigning only 3/110 points, Green Star awards up to 6/100 credits (+ 1extra point) based on increasing the cumulative impact reduction from 30% to 130%.

- Green Globes (Canada) does not require detailed specifications for a reference building but rather limits the selection, through an LCA tool compliant with ISO 14040:2006 and ISO 14044:2006, to the building with the least anticipated environmental impact between (at least) two different core and shell designs. Green Globes awards up to 33/1000 credits, identifying three different reduction levels (10%, 15%, 20%) with respect to three impact indicators, one of which must be global warming potential. Another requirement to obtain the credits is that only one impact indicator can exceed the reference building result.
- DGNB (Germany) is one of the few GBRSs setting predefined benchmarks for the lifecycle impacts of buildings. The threshold values were identified through research on the German building stock, promoted by the German Federal Ministry of Transport, Building and Urban Development (BMVBS) and they were updated to align with new national regulations (Ganassali et al, 2016). Similarly, Active House also defines specific benchmarks, but it is not clear how they are determined.
- BREEAM requires the use of a specifically developed tool ("Mat.01 Calculator") to rate a variety of LCA analysis aspects.

One of the first consequences emerging from this study is the impossibility of comparing the LCA outcomes from different GBRSs as the calculation and rating methods adopted differ greatly from one system to another. With respect to threshold values, two main approaches were identified: one is based on the comparison with a reference building, while the other one relies on predefined benchmarks. In the first case the thresholds vary from project to project and credits are awarded depending on the relative improvement achieved with respect to one or more design alternatives which, however, still depend on the designer's choices. This method, therefore, cannot provide an objective measure of the severity of the actual impacts deriving from the project. The approach specified by DGNB, conversely, aims to provide objective values to refer to in order to understand the relevance of the environmental impacts over the building's life cycle.

The DGNB methodology was used in the study conducted by Gervasio et al. (2018) as part of the research project "EFIResources: Resource Efficient Construction towards Sustainable Design" within the Horizon 2020 context.

Inspired by the European energy performance certification, Gervasio et al. (2018) aimed to set benchmark values for LCA outcomes at the building scale, based on the statistical evaluation of a sample of purposely selected buildings, discerning "conventional" practice from "best practice". In order to set reliable and representative threshold values, they considered three main factors such as: the building typology, the seismic area and the climatic area.

This kind of approach likely represents the proper way to determine objective reference benchmarks for the building stock.

2.7 Outcomes

In order to mitigate the negative effects on the environment arising from the production, transportation, assembly, maintenance and disposal of buildings elements (i.e. embodied impacts), tools such as the Life Cycle Assessment (LCA) have to be implemented in design processes to measure and, therefore, limit the impacts on the environment.

The growing interest in the life cycle approach to buildings within the EU context led this research to focus on the LCA methodology to further our knowledge of its framework, as well as the conditions and the methods of its application to buildings in an attempt to identify the most characteristic aspects for building applications.

In Part II, an extensive in-depth analysis on the LCA regulatory and methodological framework was presented, including an overview of the principal LCA-based items for buildings products such as: Environmental Product Declarations (EPD) and Products Category Rules (PCR).

In addition, a comprehensive comparison between the LCA framework included in six international GBRSs (LEED v4, DGNB Core 14, BREEAM NC v.2016, Green Star v.1.1, Green Globes v.1.5 and Active House v.2) was performed.

This comparison allowed us to draft a shared buildings LCA framework (with particular reference to Goal and Scope definition) indicating a number of common LCA modules, impact categories, building elements to include in the assessment, reference functional units and reference life for buildings.

This study also investigated the GBRS rating methods, identifying two main approaches: one based on environmental impact reduction with respect to a reference building, and one centred on predefined impact benchmarks.

The first approach, which was more subjective and less restrictive, allows more open management of environmental variables and greater discretion in defining the reference building but, on the other hand, it provides greater adaptability to different contexts. The second approach, on the contrary, more rigid and objective, limits the scope of actions but enhances the achievement of more sustainable goals.

This study, despite having confirmed some evidence found in literature on a simplified and standardized approach to building applications has, however, also underlined several discrepancies in the method's application within a broad context and in the interpretation of the results.

These considerations have motivated further investigations on these topics.

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Part III

A SIMPLIFIED LCA APPROACH FOR THE EARLY DESIGN PHASE

3.0 Research Question no. 3

The results produced by the study so far on the one hand reveal some shared features (in particular with respect to Goal and Scope requirements) that can be considered representative for LCA applications to buildings while, on the other hand, they indicate a lack of agreement on several other aspects, confirming some of the weaknesses highlighted by the literature findings.

At this point, the core issue of the research was identified: although LCA is recognized as an indispensable tool for assessing the embodied impacts of buildings, its implementation in practice is still affected by a series of limitations, hindering widespread diffusion (Bribián et al., 2009; Rønnin and Brekke, 2014; Simonen 2014).

The heterogeneity of the measurement methods, the entity and the nature of the data involved in the evaluation processes complicate its correct application, requiring time-consuming tasks and specific technical skills.

These critical issues primarily concern the early design stages in which the key variables that shape the environmental profiles of buildings are usually defined.

The lack of economical and effective tools to compare technological alternatives leads designers to only consider the environmental aspects at the end of the process when all the required information is accessible, but project variations result in significant additional costs and effort (Akomah, et al., 2018). In this way, the LCA cannot provide relevant feedback capable of guiding the design process and thereby improving the sustainable aspects (Basbagill et al, 2013).

Despite being more challenging, the implementation of sustainable design should occur in the early phases when the decisions that most influence the environmental aspects of the project are made, considering the entire building life cycle at the same time (Antón and Diaz, 2014).

These considerations inspired the third research question, as the core of the research advancement:

RQ3 ***How can LCA limitations be overcome, allowing simplified but representative applications on buildings during the initial design phases?***

The critical issues found in literature relating to the LCA methodology, explained in a diversified way, were aggregated into groups making it easier to outline the following activities.

The research outcomes up to this point, as well as further studies of the technical literature, suggested a series of opportunities to address the highlighted LCA weaknesses identified. In addition to the GBRS analysis outcomes described in Part II, two tools in particular turned out to be suitable for approaching the identified LCA issues:

- the common EU framework: Level(s), which developed a framework of "*core indicators for the sustainability of office and residential buildings*" providing *"a set of indicators and common metrics for measuring the environmental performance of buildings along their life cycle"* (Dodd et al. *Level(s) – A common EU framework of core sustainability indicators for office and residential buildings,* Parts 1 and 2, 2017, p.6), for the methodological issues;
- Building Information Modelling (BIM) tools for the measurement issue.

Part III of the thesis, therefore, deals with the development of a simplified framework for LCA applications to buildings suitable for implementation during the initial design phases. In order to meet the requirement of the easier application of the tool, thereby attaining a convenient decision-making method suitable for day-to-day use by designers with no LCA expertise (Antón and Diaz, 2014), the framework was applied to a workflow specifically designed to integrate the LCA analysis with BIM models.

Finally, in order to test the proposed workflow, an illustrative application was performed on a case study in Part IV.

3.1 Managing LCA Weaknesses

Through the study of literature on LCAs, a series of considerations from several authors (Bribián et al., 2009; Simonen. 2014; Rønnin and Brekke, 2014; Bribián et al., 2009) on what, today, appear to be adverse conditions for the implementation of LCA within the building sector was archived. The main limitation identified by most of authors regards aspects such as: subjectivity (as many LCA aspects are optional and discretionary), inaccuracy (as LCA outcomes depend on the quality of data), incompleteness (since not all types of impacts are equally covered and available), data scarcity (since specific data may not be available or missing) and time-consuming (as a consequence of data collection and calculation complexity).

For this reason, in order to deal with these weaknesses, the literature findings are organized into four major groups, containing various sub-issues:

- *Methodological inhomogeneity*: regarding all the issues related to LCA framework aspects, such as: Goal and Scope definition, LCI and LCIA drafting etc.;
- *Operative complexity*: regarding the difficulties in collecting/managing data and computing environmental impacts for building elements;
- *Promiscuity of methods effectiveness boundaries*: regarding data availability and validity within specific geographic contexts (such as the EU context);
- *Ambiguity of outcomes interpretation*: regarding the subjectivity of interpreting the significance of the impacts.

All the above-mentioned issues occur in particular at the beginning of the design process, when the level of detail of the project does not provide in-depth knowledge of the building's characteristics (Meex et al., 2018). Nevertheless, these phases (such as pre-design and concept design) are considered crucial for shaping the future environmental profile of buildings, since many of the key design choices are made under these conditions (Meex et al., 2018).

Environmental impact assessment tools appear to represent a robust means of supporting process decisions, providing positive effects over the entire life cycle of buildings and, despite being more challenging, the implementation of sustainable design must occur in the early phases (Antón and Diaz, 2014).

In order to overcome some of the LCA weaknesses identified, this research detected a key document considered as guidance to approach the development of a common and simplified LCA framework. This reference is the recent voluntary communication framework developed by the European Commission, which defines a "sustainable" workflow for the construction sector, called “Level(s)” Dodd et al., 2017).

This document, which proposes a set of common indicators and metrics for measuring the environmental performance of buildings over the life cycle, defines the methods for carrying out a common, and therefore comparable, sustainability analysis within the European Union context Dodd et al., 2017).

The integration of Level(s) indications with the outcomes resulting from the GBRS comparison conducted in Part II led to the development of a simplified LCA framework suitable for implementation in the early stages of the project and, at the same time, capable of adapting as the project advances.

This aimed to respond in particular to three out of the four weaknesses identified: methodological inhomogeneity, contexts of effective promiscuity and interpretation ambiguity outcomes.

The remaining issues regard the operative challenges for which the framework alone is not sufficient because, besides providing a simplified procedure, it cannot directly facilitate the computational operations.

In the literature (Meex et al., 2018) it is argued that the assessment needs to be integrated directly into the design process so that effort and time-consuming activities would be drastically reduced.

Since the LCA analysis involves managing a large amount of data, the tool that potentially best suits this type of operation is a BIM platform as it can reduce and optimize LCA applications (Soust-Verdaguer et al., 2017).

To better comprehend how to interrelate an LCA analysis within a BIM platform, a thorough examination of this technology has been performed through a desktop study of literature, international standards and technical manuals.

Figure 3.1 shows a schematic approach for overcoming the identified critical issues.

The following sections, therefore, focus on the Level(s) structure for the development (together with the outcomes of a GBRS comparison) of a simplified LCA framework and on BIM technology to implement the framework during the design process.

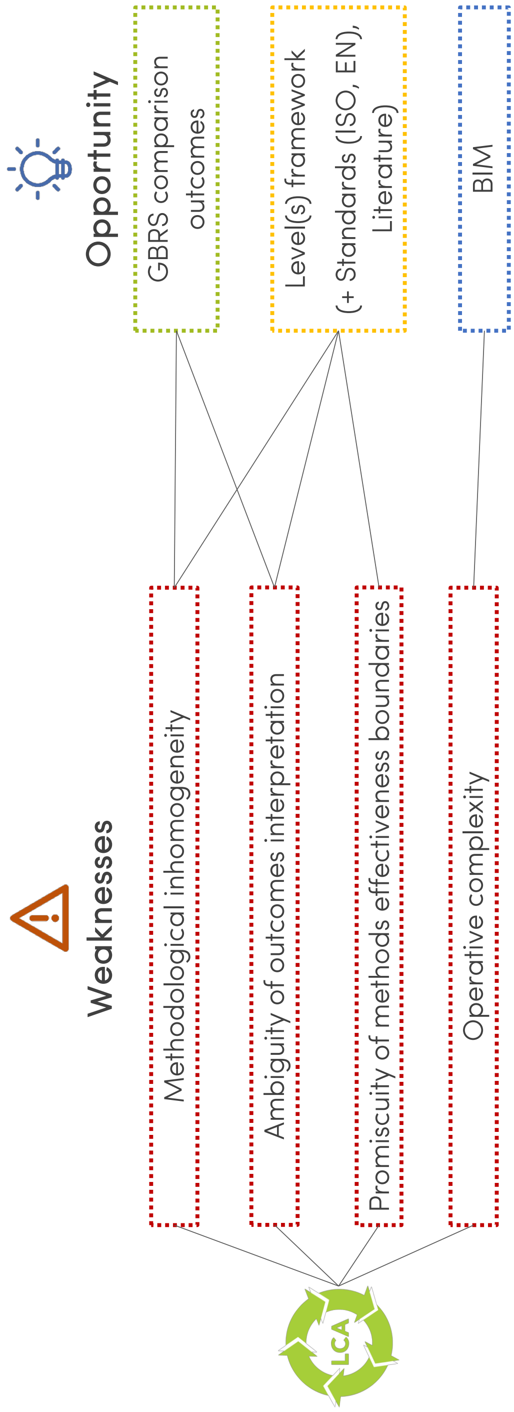

Fig. 3.1 – Scheme of the proposed approach to overcome the identified set of weaknesses (Source: Author)

3.2 Developing an EU Common and Simplified LCA Framework for the Early Design Phase

Within the European context, many initiatives have been undertaken to define sustainable goals for the built environment. It emerged in Part II that great effort has been made to provide standards, guidelines and regulations, especially to encourage and pilot the environmental assessment over the entire building life cycle.

Green building rating systems represent a further demonstration of the direction that building processes must take, both for new construction and for existing ones too. Although the available tools do not fully cover each aspect of sustainable development and assessment, new frameworks are being developed with the aim of overcoming the existing drawbacks and providing further support to practitioners.

The main goal is to boost wider diffusion of sustainability tools and the adoption of sustainable development strategies, at the same time allowing extended contexts to be homogenized through the use of common languages and metrics, making different situations comprehensible and comparable.

Recently, the European Commission through the Joint Research Centre (JRC) (Unit 5, Circular Economy and Industrial Leadership, 2017) drafted a document which moves in this direction, providing a European common framework on the sustainability of buildings: Level(s).

3.2.1 Level(s) overview

"*Developed as a common EU framework of core indicators for the sustainability of office and residential buildings, Level(s) provides a set of indicators and common metrics for measuring the environmental performance of buildings along their life cycle*" (Dodd et al., *Level(s) – A common EU framework of core sustainability indicators for office and residential buildings,* Parts 1 and 2, 2017, p. 6).

"*Level(s) aims to provide a general language of sustainability for buildings. This common language should enable actions to be taken at building level that can make a clear contribution to broader European environmental policy objectives*" (Dodd et al., *Level(s) – A common EU framework of core sustainability indicators for office and residential buildings,* Parts 1 and 2, 2017, p. 6).

The document, which is not intended to be a standalone building certification scheme, but rather a voluntary reporting framework for guiding buildings sustainable development and assessment, is composed of four components that enable the adoption and the comparison across EU members. The components are:

- *Macro-objectives*: a key set of six macro-objectives (Tab. 3.1) covering thematic areas such as: life cycle environmental performance, health and comfort and cost, value and risk;
- *Core Indicators*: a set of 9 indicators (Tab. 3.2) to shape the performance of buildings in order to achieve each macro-objective;
- *Life cycle tools*: a set of 4 scenario tools and 1 data collection tool, together with a simplified Life Cycle Assessment (LCA) methodology, which consider the whole life cycle thinking approach to conduct comprehensive analysis;
- *Value and risk rating*: a checklist and rating procedure to ascertain the level of reliability related to the Level(s) performance assessments.

In particular, Level(s) framework aims at promoting a wider diffusion of Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) across Europe (Dodd et al., 2017).

Thematic Area	Macro-objectives	Description
Life cycle environmental performance	**1. Greenhouse gas emissions along a building's life cycle**	Minimize the total greenhouse gas emissions along a building's life cycle, from cradle to cradle, with a focus on emissions from building operational energy use and embodied energy
	2. Resource efficient and circular material life cycles	Optimize the building design, engineering and form in order to support lean and circular flows, extend long-term material utility and reduce significant environmental impacts
	3. Efficient use of water resources	Make efficient use of water resources, particularly in areas of identified long-term or projected water stress
Health and comfort	**4.Healthy and comfortable spaces**	Create buildings that are comfortable, attractive and productive to live and work in and which protect human health
Cost, value and risk	**5. Adaptation and resilience to climate change**	Futureproof building performance against projected future changes in the climate, in order to protect occupier health and comfort and to sustain and minimize risks to property values
	6. Optimized life cycle cost and value	Optimize the life cycle cost and value of buildings to reflect the potential for long term performance improvement, inclusive of acquisition, operation, maintenance, refurbishment, disposal and end of life

Tab. 3.1 – Level(s) framework Macro-objectives (Source: Dodd et al., 2017 - reworked by the Author)

Macro Objectives	Indicator or life cycle tool	Unit or performance measurement
1. Greenhouse gas emissions along a building's life cycle	1.1 Use stage energy performance 1.1.1 Primary energy demand 1 1.1.2 Delivered energy demand (supporting indicator)	kilowatt hours per square meter per year ($kWh/m^2/yr$)
	1.2 Life cycle Global Warming Potential	kg CO_2 equivalents per square meter per year (kg CO2 eq./m^2/yr)
2. Resource efficient and circular material life cycles	2.1 Life cycle tools: Building bill of materials	Reporting on the Bill of Materials for the building, as well as for the four main types of materials used
	2.2 Life cycle tools: scenarios for building lifespan, adaptability and deconstruction	According to the performance assessment level: 1. Design aspects 2. Semi-qualitative assessment 3. LCA-based assessment.
	2.3 Construction and demolition waste and materials	kg waste and materials per m^2 of total useful floor area (per life cycle and project stage reported on).
	2.4 Cradle to grave Life Cycle Assessment	Seven environmental impact category indicators.
3. Efficient use of water resources	3.1 Total water consumption	m^3 of water per occupant per year
4. Healthy and comfortable spaces	4.1 Indoor air quality	4.1.1 Good quality indoor air: Parameters for ventilation, CO_2 and humidity. 4.1.2 Target list of pollutants: Emissions from construction products and external air intake.
	4.2 Time outside of thermal comfort range	% of the time out of range of defined maximum and minimum temperatures during the heating and cooling seasons.
5. Adaptation and resilience to climate change	5.1 Life cycle tools: scenarios for projected future climatic conditions	Scenario 1: Protection of occupier health and thermal comfort. Simulation of the building's projected time out of thermal comfort range for the years 2030 and 2050.

Tab. 3.2 – Level(s) framework indicators and tools - Part 1 (Source: Dodd et al., 2017 - reworked by the Author)

6. Optimized life cycle cost and value	6.1 Life cycle costs	Euros per square metre of useable floor area per year (€/m^2/yr).
	6.2 Value creation and risk factors	Reliability ratings of the data and calculation methods for the reported performance of each indicator and life cycle scenario tool.

Tab. 3.2 – Level(s) framework indicators and tools – Part 2 (Source: Dodd et al., 2017 - reworked by the Author)

Although Level(s)' aim is to encourage a full life cycle thinking in approaching sustainable goals for the built environment, the framework concentrates on those aspects considered the most relevant for sustainable buildings, in order to calibrate the complexity and the comprehensiveness of the evaluations, to users' specific needs and level of expertise.

Consequently, the European Commission aims, through Level(s) implementation, at:

– providing "*an easy starting point to introduce sustainability and life cycle thinking into projects*";

– focusing "*on a manageable number of essential concepts and indicators that contribute to achieving environmental policy goals*";

– supporting "*efforts to optimise building designs and their operation, with a focus on the precision of data, calculation methods and simulations*";

– supporting "*efforts to minimise gaps between design and actual performance, in terms of both measured performance and occupant satisfaction*";

– supporting "*commitments to track performance all the way from design stage through to operation and occupation of a building*";

– enabling "*comparisons to be made between buildings in a geographical area or in a portfolio, or between design options at an early stage*";

– allowing "*users to select between three different levels of comprehensiveness in how performance can be calculated and reported on, chosen according to the different priorities and goals of users*";

– ensuring "*that when using these indicators, users will be working to common performance assessment methods and standards used in the EU, so as to complement and reinforce existing initiatives*"; (Dodd et al., 2017)

These goals are in line with the purpose of the thesis and, especially for this reason, Level(s) has been taken as a reference, since it can provide valuable guidance in formulating a simplified common LCA framework for buildings, capable of being implemented from early design stages and suitable for the adoption in a wide context (such as the EU).

Among the declared Level(s) aims, is revealed the characteristic that gives the name to the framework: the capability, for users, to "*select between three different levels of comprehensiveness in how performance can be calculated and reported on*".

In fact, the framework provides users with three levels of performance assessment (Tab 3.3) that can be implemented through the indicators, which represent the increasing level of accuracy and reliability of the assessment, together with the increasing level of professional expertise required. The three progressive levels are described as follow:

- *Common performance assessment*: is the first level of assessment as it "*provides the simplest and most accessible type of use for each indicator*";
- *Comparative performance assessment*: is aimed at enabling "*meaningful comparisons between functionally equivalent buildings*". The comparability of results is supported by the framework at a national level or building portfolio level;
- *Optimized performance assessments*: supports a more detailed use of each indicator, enabling more accurate calculations, optimized design and as-built performance as well as a more precise estimates of future costs, risks and opportunities along the building's life cycle.

Methodological Aspects	Level 1: Common performance	Level 2: Comparative Performance	Level 3: Optimized Performance
General description	Use of the same common unit of measurement, calculated according to defined reference standards.	Calculation according to more specific rules in order to make results more comparable.	Calculation using more representative and precise data, as well as more advanced simulation models and calculation methods.
The metric	Use of the common unit of measurement.	Use of the common unit of measurement.	Use of a common metric, with the potential for reporting on more detailed performance aspects.
Reference unit	m^2 useful floor space/yr	m^2 useful floor space/yr	Possibility to use other units such as per bed space or workspace.
Calculation method	Common reference are standards specified. Some flexibility to reflect variations in methods between Member States is allowed.	Common reference are standards specified.	Common reference standards are specified. The possibility is given to use more complex methods.
Input data	Simplified guidance on quality and sources of input data.	Certain input data items and assumptions needed for calculations are pre-defined or based on default values in reference standards.	Detailed guidance on which aspects of input data selection can be improved in order to achieve greater representativeness and precision from calculations
Use of life cycle tools	Simplified method to calculate Global Warming Potential (as an individual indicator) and LCA as an overarching assessment tool.	Simplified method to calculate Global Warming Potential (as an individual indicator) and LCA as an overarching assessment tool.	Advanced method to calculate Global Warming Potential (as an individual indicator) and LCA as an overarching assessment tool for different life cycle scenarios.
Inspections and sampling methods (where relevant)	Common methods specified.	Common methods specified.	More complex methods be more may appropriate for use in order to improve the analysis.

Tab. 3.3 – Three levels of performance assessment supported by Level(s) (Source: Dodd et al., 2017 - reworked by the Author)

In order to consider the building performance over the entire life cycle, indicators are employable at each stage of the project, thus allowing to track the relations between them. In particular, Level(s) enables the report on building performance during:

– Design stage, based on calculations, simulations and scenarios;

– Implementation stage, based on as-built drawings, specifications and tracking;

– Completion stage, based on commissioning and testing;

– Operation stage, based on measured performance and occupant satisfaction).

In addition, Level(s) supports two way of performing the assessments, allowing the framework to better suit users' needs. The two paths are:

– *Direct route*: implies a full implementation of the guidance and the reporting formats;

– *Indirect route*: allows the use of an external building assessment scheme, investor reporting tool or indicator set, if specifically aligned with the Level(s) framework.

Level(s), besides specifying a life cycle assessment framework, provides also a reporting format for each indicator, indicating a "Minimum Reporting Requirements" and a "Optional Additional Reporting".

The minimum reporting format includes:

– the goal and scope definition, describing the fundamentals of the building, the location and the intended use;

– the calculated or actual performance for the core indicators, as a minimum according to the common performance assessment and its reference methodology.

While the optional reporting includes:

– the bill of materials, describing the materials constituting each building element and component;

– the outcomes of the life cycle scenarios, providing an insight into the potential future performance of the building;

– the reliability rating, providing an outlook on the primary data, on the calculation method and simulation tools adopted for the performance assessment.

- The results from a Life Cycle Assessment.

3.2.2 Recommendations for the development of a common and simplified LCA framework

This research intends to propose a simplified LCA framework, suitable for the adoption of the building process during the early stages and capable of adapting to the European context.

In order to provide such a framework, the first intention is to comply with a series of recommendations on the LCA simplification of buildings that emerged from the literature analysis presented in section 2.5 (Part II) and reported below:

- Clarify the goal(s) and define the scope;
- Rely only on transparent, valid and reliable data sources;
- Optimize the data collection process;
- Reduce the functional unit;
- Restrict the analysis to significant stages and modules only;
- Simplify the scenario definition;
- Restrict the life cycle inventory analysis to the main components and processes and reduce the impact assessment phase to a few impact categories.

The goal is to intersect the outcomes of the GBRS comparison conducted in Part II with appropriate hints and guidance on developing a common LCA approach obtained from the Level(s) framework.

The aspects of the framework through which the Level(s) contributes to the life cycle approach and that constitute a solid reference for the proposed simplified LCA path are shown in Table 3.4.

Part of the Level(s) framework	How it contributes to a life cycle approach
Goal and scope definition	A functional description of the building and how it will be used
Inventory data flow	Data on the building's construction (bill of materials) and flows of energy and water over its life cycle
Indicators that measure the environmental impacts of a building	These allow specific environmental impacts to be measured either using simple common indicators or indicators based on Life Cycle Impact Assessment methods
Scenarios that describe a life cycle aspect of a building	Guidelines to support building professionals to analyze how building designs may perform in the future and over the life cycle
A cradle to cradle LCA of a building	This is the most advanced option within the framework. Users of the framework may choose to go directly to an LCA, or to use other separate LCA steps from the framework first
The quality and reliability of life cycle inventory data	The quality and reliability of data is a key challenge in seeking to ensure that the results are as representative as possible of the building being assessed

Tab. 3.4 – Contribution of Level(s) framework to life cycle approach (Source: Dodd et al., 2017 - reworked by the Author)

3.2.2.1 Recommendation no.1: Goal and Scope

The first recommendation on conducting simplified but reliable LCA emerged from the literature and reported in section 2.5 (Part II), concerns the description of the building to analyze and the specifications about the analysis methods to adopt: "*clarifying the goal(s) and defining the scope in a detailed and unambiguous way, paying particular attention to the selection of functional units and to the delimitation of system boundaries*" (Rønnin and Brekke, 2014).

Level(s) provides a detailed "Goal and Scope definition" that is taken as reference and described in Table 3.5.

Goal and Scope elements	Description	Content
1. The building and its elements	The building type (or use class) and the pre-defined minimum scope of building parts and elements.	Building type and site, minimum scope of buildings parts and elements,
2. The building type, ownership and market segment	A description of the building's market segment, ownership structure and intended service life.	Location, climate zone, project type, year of construction, physical form of the building, market segment, ownership structure, service life, building form, property schedule
3. The unit to be used for comparative proposes	The common methods to be used for measurement of the total useful floor area within a building.	Reference floor area measurement (1 m^2 of useful internal floor area according to IPMS standard) and additional comparative reference units
4. How the building will be used and the lifespan of its elements	A description of the outdoor environment to which the building is exposed, the intended conditions of use, occupant related usage patterns. Default service lifespans for building parts and components are also provided.	Building level in-use conditions according to seven factors of relevance from A to G (ISO 15686-8:2008), building occupation and conditions of use, building elements service life estimations
5. The time scale for the performance assessment	The intended or default service life of the building being studied.	The timescale for the performance assessment = 60 years
6. Which stages in the life cycle	The life cycle stages that shall be considered when making the performance assessment.	The system boundary of the LCA assessment in terms of life cycle stages according to EN 15978:2011

Tab. 3.5 – Goal and Scope definition according to Level(s) (Source: Dodd et al., 2017 - reworked by the Author)

The reporting format for the building description is reported in Table 3.6.

Parameter	Office Building	Residential building
Location	Country and Region	
Climate Zone	Zone (according to Ecofys (2012) and Keepcool II (2010)) Heating and cooling degree days	
Project type	New build or major renovation	
Year of construction	For both new build and renovations	
Original year or construction	For major renovations only	
Service life or holding period	Clients intended service life or investment holding period in years (to be specified which)	Clients intended service life or investment holding period. Warrantied service life of property for sale
Building form	- Low rise office park - In-fill urban block - Perimeter urban block - Urban city block - Tower/skyscraper - Other (to be described)	Please select from: - Free standing, detached house - Semi-detached house - Row or terraced house - Multi-family house or apartment block (up to 4 floors/5-9 floors/more than 9 floors)
Property schedule	Total useful floor area	Schedule of accommodation for the development or renovated stock - Number of units per bed space/form type - Net useful floor area of each form type in the schedule
Floor Area measurement	IPMS Office 3 (or another standard that should be specified)	IPMS Residential 3c (or another standard that should be specified)
Market segment	Owner occupation or for rent, with reference to a combination of the following BOMA* building class definitions: International base definitions: - Investment - Institutional - Speculative Metropolitan base definitions A: Premium rental B: Average rental C: Below average rental	By tenure - Owner occupation - Leasehold, social - Leasehold, market rental - Leasehold, student - Leasehold, seniors - Other (to be described)
Servicing	With/without centralised ventilation and/or air conditioning	With/without centralised heating, ventilation and/or air conditioning

Tab. 3.6 – Goal and Scope reporting format according to Level(s) – Part 1 (Source: Dodd et al., 2017 - reworked by the Author)

Condition of use	National calculation method for energy performance that defines the building's conditions of use	
Projected occupancy density	Area of workspace in m^2 per full time person equivalents	n/a
Projected pattern of occupation	Number of hours and days per year	n/a
Assumed void rate	Applicable to leasehold property/space. Proportion of lettable floor space projected, on average, to be vacant/unoccupied.	

*BOMA (Building Owners and Managers Association), Building class definitions, http://www.boma.org/research/Pages/building-class-definitions.aspx

Tab. 3.6 – Goal and Scope reporting format according to Level(s) – Part 2 (Source: Dodd et al., 2017 - reworked by the Author)

3.2.2.2 Recommendation no. 2: Source of environmental data

Another recommendation that emerged in Part II on LCA application in buildings concerns the source of environmental data. The literature prompts us to rely only on transparent, valid and reliable data sources.

For this reason, intending to comply with the recent regulatory initiatives on the environmental profiles of products (CPR 305/201, Italian Legislative Decree no. 50 - 18 April 2016, implementation of the European directives 2014/23/EU, 2014/24/EU and 2014/25/EU), this research endorses the use of the Environmental Product Declarations (EPDs) as a primary source of environmental data.

Level(s) consider EPD as a reliable data source as well, stating that "*data must be relevant and accurate, irrespective of the selected type (e.g. specific LCI data, average LCI data). In general, specific and verified LCA data (i.e. from Environmental Product Declarations) is more precise than generic LCA data" (Dodd et al., 2017).*

In particular, the EPDs considered suitable for the European context are those compliant with EN 15804, which provides specifications on EPD and PCR development.

In this way, a series of issues related to LCA application are overcome, such as the selection of the LCIA characterization model which is already included within the EN standards. The specified characterization factors for GWP, ODP, EP, AP, POCP and ADP are taken from CML–IA (Institute of Environmental Sciences Faculty of Science University of Leiden, the Netherlands).

Currently, the development of product specific EPDs is encouraged by national and international initiatives, aimed at simplifying the assessment procedures and providing more consistent, accessible and comparable environmental data.

As reported by Lavagna and Palumbo (2017), however, employing the EPDs to conduct comprehensive LCA assessments would only be methodologically feasible if they include all the necessary information for a holistic evaluation of the building.

Currently, when developing an EPD for construction products, the only life cycle stages that must be considered are those relating to the manufacturing process, i.e the A1 to A3 phases (from cradle to gate).

Lavagna and Palumbo (2017) therefore advise that further work must be done to empower accessibility to data, thus avoiding limiting the analysis scope to specific processes or phases only.

As they are based on reliable and constantly updated datasets, generic databases such as Ecoinvent or GaBi represent a valuable alternative to EPDs as a source of environmental data. However, these databases are usually only adopted by LCA professionals, since they require costly licenses or subscriptions to access them.

Generic sources such as Oköbaudat (Germany), which are free or not as costly, might represent a complementary source if specific EPDs are not available.

3.2.2.3 Recommendation no.3: Data collection process

This issue concerns the optimization of environmental data collection, which is usually one of the most relevant phases within the LCA assessment. As previously stated, this research intends to rely particularly on EPDs which can be accessed from several Program Operators web platforms. The proposed data collection approach relies on the draft of a spreadsheet which must fulfill specific requirements. Refer to Section 3.3.5. for a detailed explanation.

3.2.2.4 Recommendation no.4: Functional unit

An important aspect that must be addressed in order to perform fair comparisons of buildings performance, is the reference unit (or 'reference flow') to which results should be reported following the principle of functional equivalence.

Reference units permit to normalize the outcomes of the analysis to a common measurement or parameter representative of the building.

From the comparative analysis on GBRSs conducted in Part II, the most recurrent reference unit resulted to be: "one square metre", either referred to net floor area or gross floor area of the building.

Since the Level(s) framework adopts "one square metre of useful internal floor area" (net internal area) i.e the usable area measured to the internal finish of the perimeter or party walls, this is the reference unit adopted within the proposed framework as well.

3.2.2.5 Recommendation no. 5: Stages and modules

This is one of the most critical aspects concerning the proposal of a simplified LCA framework. Although, as reported in literature (Rønning and Brekke, 2014; Soust-Verdaguer et al., 2016; etc.), simplifying an LCA application means making a strict selection of the most significant life cycle stages, reducing the scope of the assessment hinders a complete and reliable determination of the actual environmental profile of a building.

At the same time, several life cycle stages, according to EN 15978, rely on building-specific scenarios which may not represent the actual conditions of the building process.

As the proposed framework aims to fit the application especially during the initial stages of the process in order to guide practitioners towards more informed decisions about the building development, particular attention has been paid to product environmental profiles.

The GBRS comparison showed that the life cycle modules shared by all the considered protocols concern the upstream process, or product stage (A1, A2, A3), and the disposal phase (C4) as part of the end of life stage.

Level(s) suggests conducting complete assessments of the whole life cycle of the buildings, however, it also includes the possibility of carrying out simplified options, reporting that simplified LCAs "*may be adopted by focusing first on those life cycle stages in which material use and environmental impacts will have taken place upon completion of the building, and will be directly influenced by design decisions*" (Dodd et al., 2017).

For these reasons, additional life cycle stages are included within the proposed framework.

The core process of the life cycle (construction process stage, A4 and A5 phases) is shared by less than 70% of the analyzed GBRSs and neglected by Level(s) suggested simplified options, consequently it has been omitted from the framework.

The A4 phase (product transport from the factory to the building site) is also considered optional by the EeB Guide (part B: Buildings) "*because of both potentially missing data and minor relevance at the scale of full building LCAs*" (Wittstock et al.,

2012) while module A5 (construction installation process) is not easy to determine during the design phase as "*it may be difficult to assess the information for land preparation, water and energy consumption, owing to the lack of data*" (Wittstock et al., 2012).

The EeB Guide also provides an example of the breakdown of impacts related to the construction site, as reported in figure 3.2, showing the minor impacts on worksite aspects such as, water, energy, the transport of workers and capital goods with respect to building products.

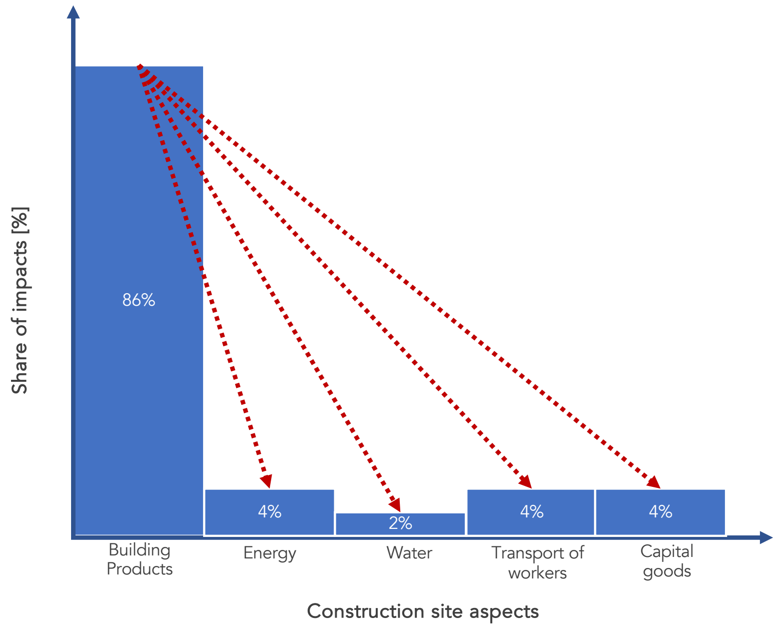

Fig. 3.2 – Example of an impact breakdown related to the construction site (Source: Wittstock et al., 2012 - reworked by the Author)

With respect to the use stage (phases B1-B7), a strict selection has been made, supported by the provisions contained in the EeBGuide-part B: Buildings (Wittstock et al., 2012).

Only the B2 (maintenance) and B4 (replacement) phases have been included in the framework since they are shared by 83% of the GBRSs analyzed in Part II.

Moreover, these two phases are related to building product manufacturing as they concern aspects which can be directly declared by manufacturers in EPDs.

They depend on predetermined scenarios, however, their impact on a building's life cycle is easier to determine compared to other features related to building operation.

Replacement (A4), for instance, can be evaluated by normalizing the life span of the products (thus the related impacts) in relation to the building's expected life span (Fig. 3.3).

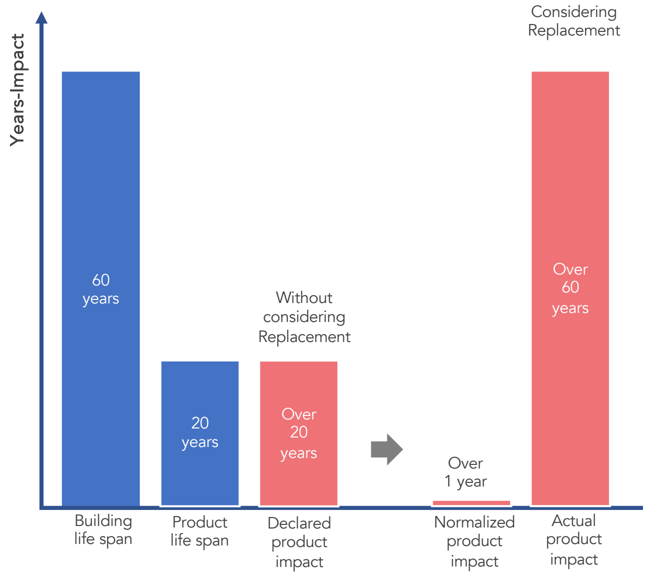

Fig. 3.3 – Example of product replacement impact (A4) within the proposed framework (Source: Author)

Other phases related to the use stage, such as B6 (operational energy use) and B7 (operational water use), have not been included because they are not directly connected to the products themselves but to the construction systems they are part of, as they are influenced by the quality of the installation and the behaviour of the building's users.

The B1 phase (use), concerning the emissions of dangerous substances into indoor air during the use stage, *"should be assessed in the context of a complete LCA, according to the European standards from CEN/TC 351"* (Wittstock et al., 2012), which provides information on how to determine health-related emissions from product use. As a consequence, the impact resulting from this phase is not part of the LCIA (Wittstock et al., 2012) but is related to LCI in terms of mg/m^2 or kg per time unit or service life.

For these reasons and the complexity in determining such impacts, considering the proposed framework based on a simplified approach, this aspect has been omitted.

As regards the end of life phases, along with the C4 phase, the C1 (deconstruction-demolition), C2 (transport) and C3 (water processing) phases have also been included as they are shared by 83% of the GBRSs analysed, and such end of life phases are often included in product EPDs.

3.2.2.6 Recommendation no.6: Scenarios definition

Scenarios for the product-related life cycle phases are generally included within the product specific EPDs according to the provisions of EN 15978 standards. In addition, guidance on how to formulate consistent scenarios are provided in section 2.2 (Part 3) of Level(s) framework with regard to:

- Building and elemental service life planning (scenario 1);
- Design for adaptability and refurbishment (scenario 2);
- Design for deconstruction, reuse and recycling (scenario 3).

3.2.2.7 Recommendation no. 7: Life cycle inventory and impact categories

Another important issue that greatly affects the computation of buildings' environmental profiles is the selection of the Life Cycle Inventory (LCI) indicators and the Life Cycle Impact Assessment (LCIA) categories.

According to Level(s), thus the provisions of EN 15978 and EN 15804, the impact indicators considered within the proposed framework are the "midpoint indicators" which "*are considered to be a point in the cause-effect chain (or environmental mechanism) at which an impact on the environment can be quantified. An impact can be calculated by applying characterization factors that reflect the relative importance of an emission or extraction in a Life Cycle Inventory (LCI)*" (Dodd et al., 2017).

The characterization factors adopted, as stated in Section 3.2.2.2, are those proposed by the CML-IA methodology.

From the GBRS comparison conducted in Part II, the results that those impact categories considered (shared by 100% of the analyzed protocols) are also midpoint indicators, such as:

- Global Warming Potential (GWP);

- Ozone Depletion Potential (ODP);
- Acidification Potential (AP);
- Eutrophication Potential (EP);
- Photochemical Ozone Creation Potential (POCP).

According to the provision contained in standards EN 15978 and EN 15804, besides the aforementioned impact categories, the Level(s) framework also considers the Abiotic Resource Depletion Potential (ADP) in terms of elements and fossil fuels. The latter were the second most shared impact category by the GBRSs analyzed.

Among other possible aspects that could be considered within an LCA assessment, energy-related indicators such as Primary Energy Consumption both from renewable (PERE) and non-renewable (PENRE) sources are particularly relevant.

Although these indicators are not considered by the majority of GBRSs with respect to materials and resources criteria (only Active House incudes them within the "Environmental Loads" category), they are separately assessed by all of them. Moreover, it is possible to find PERE and PENRE information in the majority of the EN15804-compliant EPDs.

For these reasons, they are also considered within the proposed framework, in order to enrich the range of buildings with representative environmental features.

3.2.3 Proposal of a common and simplified LCA framework for the early design phase

In order to summarize the content of the proposed LCA framework, a synthetic table (Tab. 3.7) is presented below:

Proposed Common and Simplified LCA framework	
LCA framework parts	Description
Goal and scope definition	According to Level(s) reporting format (Part 3, section 1)
Environmental data source	Primary data source: product specific EPDs (EN15804 compliant) Secondary data source: generic LCA databases (EN 15804 compliant)
Reference Functional Unit	$1m^2$ of building useful floor area (net floor area)
LCA stages and modules	Product stage: A1, A2, A3 Use stage: B2, B4 End of Life stage: C1, C2, C3, C4
Scenarios definition	According to specific EPDs content and Level(s) scenarios guidance (Part 3, section 2.2)
LCI categories	Use of renewable primary energy excluding energy resources used as raw material*, Use of non-renewable primary energy excluding primary energy resources used as raw material**
LCIA categories	GWP, ODP, AP, EP, POCP, ADP (elements), ADP (fossil fuels)
LCIA characterization factors	CML-IA, according to EN 15804

*This LCI category is later indicated as:"PERE"(Primary Energy REnewable);
** This LCI category is later indicated as:"PENRE"(Primary Energy Non-REnewable)

Tab. 3.7 – Summary of the proposed LCA framework content (Source: Author)

The presented simplified LCA framework (referred, in particular, to the scope of the analysis), similarly to the simplified approaches presented by other authors (Kellenberger and Althaus, 2009; Malmqvist et al., 2011; Soust-Verdaguer et al., 2016), can help on the optimization of the evaluation process with regards to different aspects such as: optimization of data collection process, reduction of the functional unit, limitation of the study to relevant stages and modules, simplification of the scenario definition, use of databases or other generic data sources, use of calculation methods, and reduction of environmental indicators (Soust-Verdaguer et al., 2016).

A simplified approach can be particularly suitable, for example, to compare different materials or different building components (Kellenberger and Althaus, 2009) as long as the same framework is implemented for each material/component assessed, otherwise it is not possible to ensure the comparability of the results (Soust-Verdaguer et al., 2016).

Such simplifications can therefore encourage users to perform LCA assessments (Anand and Amor, 2017) and, in some cases, they are necessary during LCA application (Soust-Verdaguer et al., 2016). However, it should be specified that the accuracy of the outcomes reflects the level of simplification adopted (Anand and Amor, 2017), as it can affect the reliability, transparency and comparability of the results (Soust-Verdaguer et al., 2016). Users must be aware that calculated impact is exclusively associated with the input data (Malmqvist et al., 2011). Anyhow, simplifications must be based on relevant, appropriate and justified assumptions (Malmqvist et al., 2011).

As suggested by Soust-Verdaguer et al. (2016), it is necessary to further develop simplification approaches capable of limiting (or not altering) the representativeness and the comparability of outcomes.

3.3 The Operative Issue: LCA-BIM Integration

Some recent initiatives for the regulation of public procurements, such as the Italian Legislative Decree 18 April 2016, No. 50, which implements the contents of the European Directive 2014/24/EU on public procurement (see section 3.3.2), are leading to a progressive intensification in the use of digital systems for the projects information management, known as Building Information Modeling (BIM). As specified in the regulations mentioned above (such as the Italian Legislative Decree 18 April 2016, No. 50), BIM procedures will become part of the common practice in the near future.

The use of BIM is increasingly requested, even in the preliminary stages of the tendering procedures for public works (Russo Ermolli and Pasquale De Toro,2017; Manderson et al., 2017). In fact, in addition to the presentation of technical and economic offers, also the "information management offer" (pre-contract BIM Execution Plan) can be required, for which it is necessary to provide the "BIM information specification" (Employers Information Requirements or -in Italian- Capitolato Informativo BIM) i.e. an introductory document encompassing the minimum contents for the production, management and transmission of data and information.

Once the procurement is assigned, it is required to draft and submit to the contracting authority the final BIM Execution Plan (BEP) (ISO 19650-2:2018).

In Italy, for example, most of the calls for tenders proposed by the state property agency[35] require the implementation of these documents starting from the feasibility study.

3.3.1 Introduction to Building Information Modelling (BIM)

"Building information modelling provides a digital technology for describing and displaying information required in the planning, design, construction and operation of constructed facilities. Increasingly, this modelling approach is expanding to encompass all aspects of the built environment, including civil infrastructure, utilities and public space. These are collectively referred to as construction processes. This approach to managing information brings together the diverse sets of information used during the life cycle of the built environment into a common information environment, reducing, and often eliminating the need for the many types of paper documentation currently in use" (ISO EN 29481-1:2017, p. V).

[35] Source: http://www.agenziademanio.it/opencms/it/gare-aste/lavori/. Retrieved in September 2018.

In other words, Building Information Modelling (BIM) is considered a set of interacting policies, processes and technologies generating a "*methodology to manage the essential building design and project data in digital format throughout the building's life-cycle*" (Penttilä, H. ,2006).

It is a modeling approach which, through the interrelation of a set of processes, enables the production, the communication and the analysis of a building digital model, characterized by a number of key aspects (Dalla Mora et al., 2014) such as:

- building components are represented through parametric digital objects containing graphic representation and data attributes, governed by parametric rules that enable objects manipulation within certain boundaries, making them "smart objects" (Ibrahim & Krawczyk, 2003);
- the components include data describing their behaviour during analysis or work processes considering physical and functional attributes;
- the data are consistent and not redundant in such a way that changes affect the whole model;
- the data and the components refer to the central common database, so that the information is always up to date and errors are minimized.

The National Building Information Model Standard Project Committee provides one of the most frequently adopted definition of BIM as "*a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition*"[36].

This definition highlights a key concept: BIM represents the connection between digital models (made of objects, data, analysis and graphic representations) and all the people involved in the process (designers, builders, policy makers, facility managers etc.). The building model assumes, therefore, the role of a common language between all the stakeholders who, through a BIM process, are able to interoperate.

BIM must be interpreted as an integration of product and process modelling and not just as an unrelated set of technologies and procedures (Succar, 2009). Succar (2009), was one the first authors performing a systematic investigation of the BIM domain, providing a comprehensive framework. The proposed framework is based on

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[36] "Frequently Asked Questions About the National BIM Standard-United States - National BIM Standard - United States". available at: https://web.archive.org/web/20141016190503/http:/www.nationalbimstandard.org/faq.php#faq1. Retrieved on March 2018.

three main dimensions and can be represented by a tri-axial knowledge graph (Fig. 3.4) made of:

- *BIM Fields*: this dimension contains all the phases of a BIM process related to the operators involved (players) and their activities (deliverables) (x-axis);
- *BIM Stages*: this dimension regards the implementation maturity levels (y-axis);
- *BIM Lenses*: this dimension provides focuses on specific BIM Fields and BIM Stages, enabling detailed analysis and deepening on any aspect of the AECO industry (z-axis).

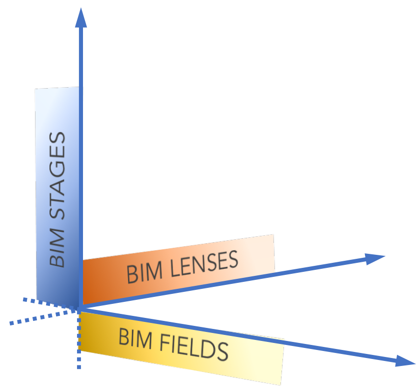

Fig. 3.4 – BIM conceptual tri-axial dimensions (Source: Succar, 2009 - reworked by the Author)

The BIM Fields can be presented as interconnected activities belonging to three principal groups: Technology, Process and Policy (TPP) populated by two sub-fields each: players and deliverables (Fig.3.5).

- *Technology Field* contains all the players involved in developing software, hardware, equipment and networking systems for the construction industry;
- *Process Field* clusters all the operators involved in construction process, such as facility owners, designers, builders and contractors, facility managers etc;
- *Policy Field* groups all the players involved in the preparatory, regulatory and contractual activities such as insurance companies, research and educational institutions and regulatory bodies.

From the Fields overlapping, many of the outputs produced (deliverables) by the players are intended to be connected and interact trough knowledge transfers (data, team dynamics and contractual relationships) in order to proceed with the process.

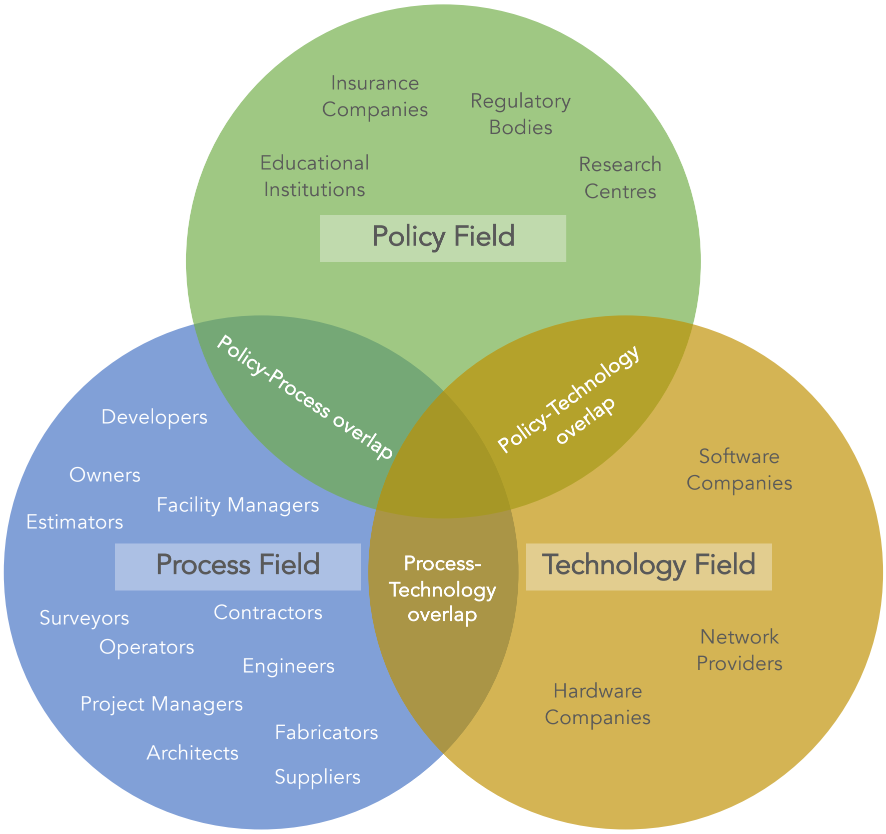

Fig. 3.5 – BIM Fields connections (Source: Succar, 2009 - reworked by the Author)

Succar (2009) defines the BIM Stages (the second dimension) as the gradual maturity of the BIM process from a starting point ("Pre-BIM") throughout three progressive stages ("Object-based Modelling"," Model-based Collaboration", "Network-based Integration") up to the end of the process, identified with the final implementation of BIM ("Integrated Project Delivery – IPD") (Fig.3.6).

In order to better comprehend the meaning of the BIM Stages, two key aspect are explained by the author: BIM Data Flows and Project Lifecycle Phases.

– *BIM Data Flows* occurs when "semantically rich" objects (smart objects) and/or document-based information are exchanged between BIM players in different ways, depending on the types of data and the BIM stage to which they are related. "Semantically reach" object refers to physical elements (buildings components) which contains different type of meta-data (about their geometry, appearance, functions and physical attributes) (Fig. 3.7) and are subjected to semantic rules that enable specific interrelations between different entities and allow the management of the objects through predetermined hierarchies.

– *Project Lifecycle Phases* is the subdivision of the framework in three sequential phases that cover the entire lifecycle of the process: Design, Construction and Operations composed by sub-phases which are, in turn, further subdivided into multiple activities, sub-activities and tasks.

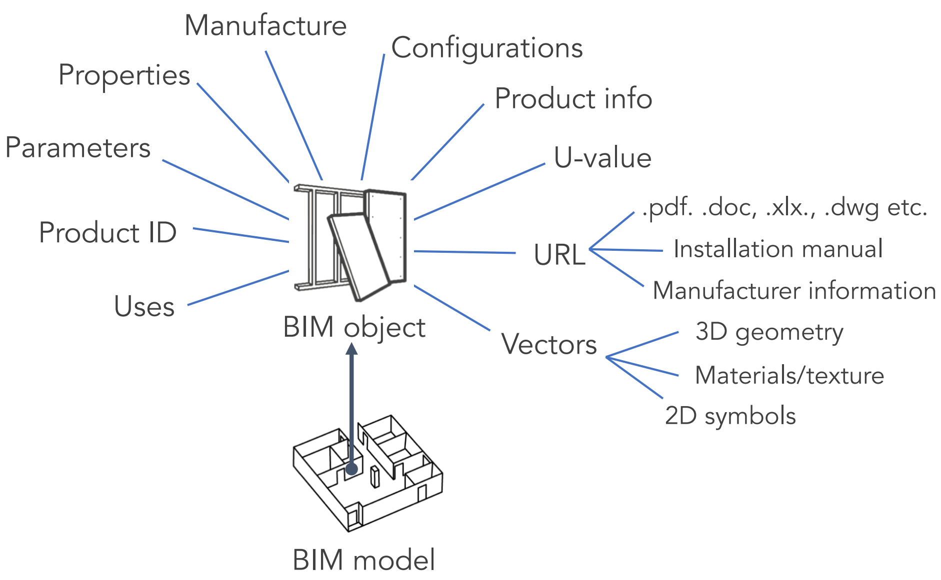

Fig. 3.7 – BIM object attributes, example of a wall (Source: Dalla Mora et al., 2014 - reworked by the Author)

After the "Pre-BIM" phase, in which the BIM implementation is not yet started, and before the "IPD" phase, in which the implementation is completed, three main stages have been identified by Succar (2009):

– *Object-Based modelling*: this stage involves the realization of a (smart) object-based building model through a 3D parametric software tool such as Revit©[37], ArchiCAD©[38] or Allplan© with respect to single-disciplinary models (architecture, structure, MEP, facility management etc.) within either design,

[37] © 2018 Autodesk, Inc

[38] © 2018 NEMETSCHEK SE

construction or operation phases, but without any significant model-based exchanges between disciplines.

- *Model-based collaboration*: this stage involves active information interchanges between different players. It can occur between players belonging to the same discipline within the same lifecycle phase or players belonging to different disciplines of different phases. A crucial aspect is that the interchanges between two disciplines need to be based on the same collaborating 3D model. In this way it is possible to go forward the 3D concept and reaching other dimensions such 4D (time analysis), 5D (cost estimating).
- *Network*-Based Integration: this stage involves the sharing and the collaboratively maintenance of the model, reaching a fully interdisciplinary level, throughout the whole Project Lifecycle. In this way, other dimensions beyond the 5D can be achieved, allowing complex multi-disciplinary analyses, including business intelligence, lean construction principles, green policies towards the 6D (performance analysis/sustainability) and the 7D (facility management) (Fig. 3.8) (Czmoch and Pękala, 2014).

The "Integrated Project Delivery" (IPD) can be considered a conclusive stage of the BIM process, in which people, systems, business structures and practices are efficiently connected. IPD is intended to be an innovative project delivery system that integrates all resources used in the project life cycle (Chong et al., 2017).

Unlike the maturity progression stages, which are accurately defined, IPD can vary depending on the process scope.

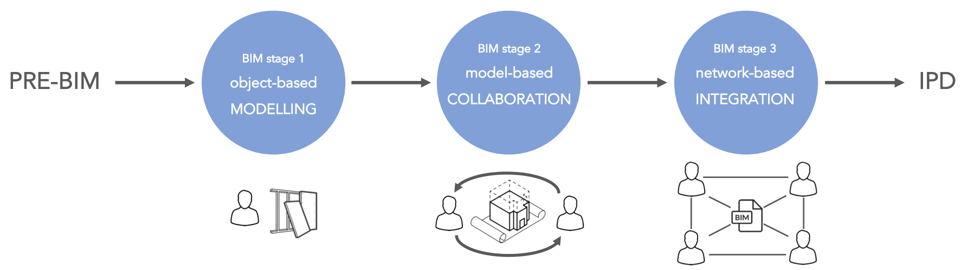

Fig. 3.6 – BIM Stages (Source: Succar, 2009 - reworked by the Author)

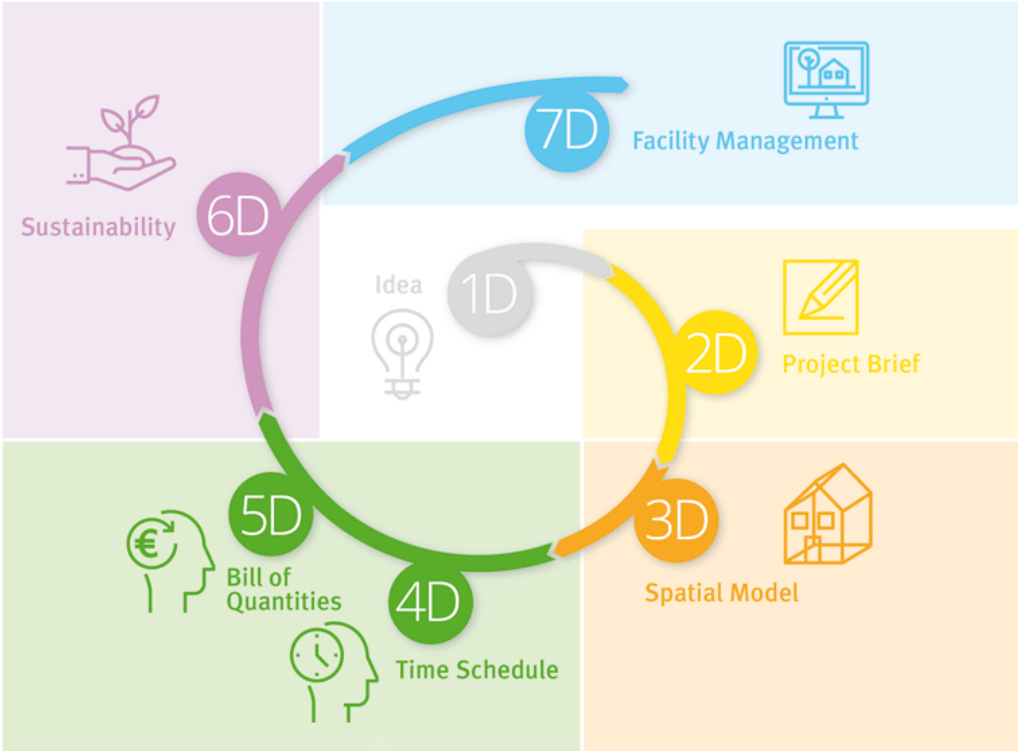

Fig. 3.8 – BIM operative dimensions, from the idea to facility management (source: Ržišnik Perc Group. Available at: https://www.protim.si/en/bim)

The third dimension of the BIM framework (Fig. 3.9) proposed by Succar (2009), concerns the BIM Lenses, which represent a means for in depth analysis on BIM Fields and Stages with respect of any aspect of the AECO industry. Lenses can be applied on different disciplines, scopes and concepts.

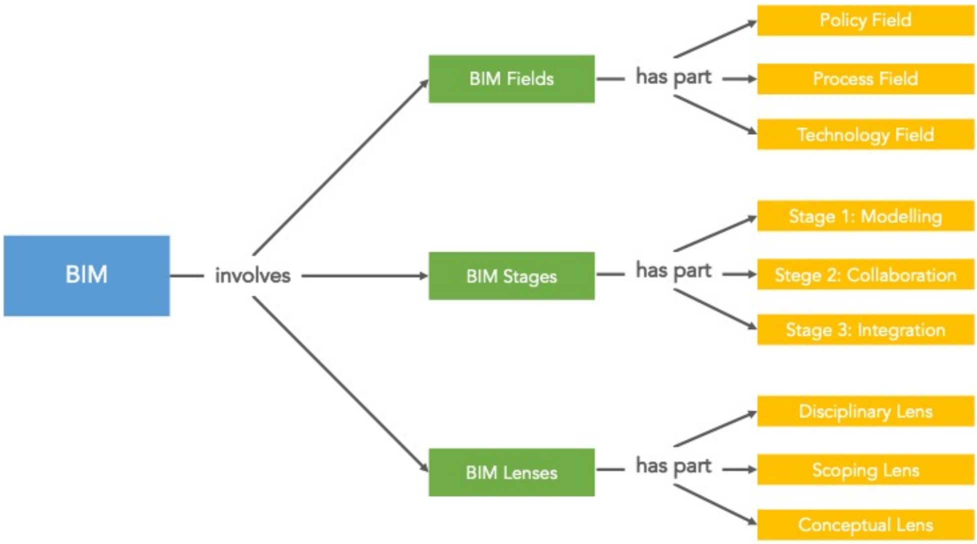

Fig. 3.9 – BIM Framework (Source: Succar, 2009 - reworked by the Author)

The transition from a zero level (Pre-BIM) to a final level, in which the BIM implementation is complete, and process can be considered integrated, occurs through gradual steps to which correspond a number of maturity achievements.

Several authors and organizations have addressed the issue of maturity levels, using different approaches that require different interpretations.

The first attempt to theorize the concept of BIM maturity was proposed by Mark Bew and Mervyn Richards in 2008, which identified four progressive levels through a diagram known as "the wedge" (Fig. 3.10), in order to group and classify the technical and collaborative working procedures and approaches, linked with certain tools and techniques with respect to various level of expertise (BIM Industry Working Group, 2011).

– *Level 0*: Unmanaged CAD through 2D representation, using paper (or electronic paper) as a means of information exchange;

– *Level 1*: Managed CAD in 2 or 3D. Data are supposed to be structured and formatted through standard protocols and the collaboration is supposed to be enhanced by specific tools.

– *Level 2*: Managed 3D environment through the introduction of BIM models for different disciplines. Data are shared between the parties involved and 4D and 5D models are supposed to be implemented in the process.

– *Level 3*: Fully open process and data integration over the whole process lifecycle is implemented. A collaborative model server is used to exchange interoperable data (IFC / IFD standards) through specific web services. This level matches the definition of iBIM or integrated BIM (BIM Industry Working Group, 2011).

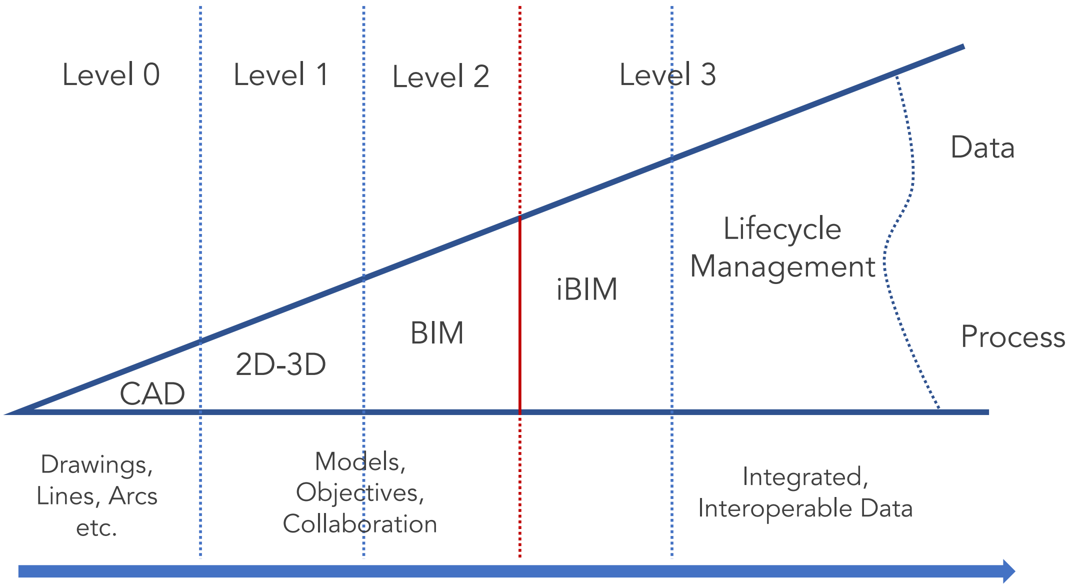

Fig. 3.10 – BIM maturity levels (Source: Bew and Richards, 2008 - reworked by the Author)

Succar (2010) introduced a complementary definition of BIM maturity, denoting "the wedge" as a strategic roadmap to BIM implementation rather than a maturity indication. His interpretation comprises five distinct levels which "*signify the evolutionary improvement of processes, technologies and policies within each BIM Stage*", and are expressed by maturity indexes (BIMMI).

The five maturity levels identified ("Initial/Ad-hoc", "Defined", "Managed", "Integrated" and "Optimized") describe the progression in terms of improvement with respect to process control, predictability/forecasting of events and effectiveness in reaching goals by minimizing variations between targets and variability in competency, performance and costs (Succar, 2010).

3.3.2 BIM regulatory framework

A substantial and effective BIM implementation within the current practice, can occur only through the collaboration of all the players identified by Succar (2009) and relying on comprehensive technical and regulatory tools.

The construction industry has been experiencing a tradeoff between technological and regulatory advancement. BIM-based technologies, in fact, have been progressively developed over the last ten years. BIM implementation and adoption within the building sector has been relatively slow compared to other innovation completion within other sectors (Smith, 2014).

The country considered the pioneer and, probably, still the global leader in BIM development and implementation in construction industry is the United States of America (Wong et al, 2009).

The United States, holder of the largest portion of the BIM market, has for many years defined guidelines and operating manuals, such as the "National BIM Standard" (internationally adopted), that are managed by the General Services Administration (GSA), the US Federal State Property Agency, not only for new construction works but, also for facility management of existing buildings (Smith, 2014). The US firstly established, in 2003, the "National 3D-4D BIM Program" as well as BIM implementation initiatives such as CIBER in 2012 (Smith, 2014). In addition, they hold a real estate registry: the Central Facility Repository, which is employed to provide an efficient asset management (GSA - The National 3D-4D-BIM Program, retrieved in June 2018).

Among the documents considered important guides in the American context, there are those provided by the American Institute of Architects (AIA) such as: the AIA Document E201-2013 (Project Digital Data Protocol Form) and the AIA Document E203-2013 (Building Information Modelling and Digital Data Exhibit).

Among the European countries, the United Kingdom and Germany were the first in digitization of the construction sector, having developed many regulations and guidelines for years, with particular regard to the public sector and the related contractual and procedural frameworks (Smith, 2014).

The UK, in particular, established a number of PAS (Publicly Available Specification) consisting in standards published by the BSI, submitted to a public assessment stage and then issued to provide a rapid response to specific needs of defined production sectors. With respect to BIM implementation, the UK has issued the 1192 series PAS (part 2, 3, 4, 5, 6, 7), conceived as the development and evolution of BS 1192: 2007 + A3: 2016.

- PAS 1192-2:2013 - Specification for information management for the capital/delivery phase of construction projects using building information modelling;
- PAS 1192-3:2013 - Specification for information management for the operational phase of assets using building information modelling (BIM);
- BS 1192-4:2014 - Collaborative production of information. Fulfilling employer's information exchange requirements using COBie. Code of practice;
- PAS 1192-5:2015 - Specification for security-minded building information modelling, digital built environments and smart asset management;
- PAS 1192-6:2018 - Specification for collaborative sharing and use of structured Health and Safety information using BIM;
- PAS 1192-7:2018 - Defining and sharing structured digital construction product information – specification (Still under development).

The PAS standards part 1 (principles) and part 2, will be replaced in 2019 by the first two international BIM standards, currently under development:

- BS EN ISO 19650-1 - Organization of information on construction work - Information management using building information modelling, Part 1: Concepts and principles (adaptation of the ISO 19650-1:2018);
- BS EN ISO 19650-2 - Organization of information about construction works - Information management using building information modelling, Part 2: Delivery phase of the assets (adaptation of the ISO 19650-2:2018).

In early 2020, further international BIM standards are expected to be published, which will replace PAS 1192 part 3, including:

- BS EN ISO 19650-3 - Organization of information on construction work - Information management using building information modelling, Part 3: Operational phase of assets;
- BS EN ISO 19650-5 - Organization of information on construction work - Information management using building information modelling, Part 5: Specification for security-minded building information modelling, digital built environments and smart asset management.

The United Kingdom is recognized as the country with "*the most ambitious and advanced centrally driven BIM implementation program*" (Smith, 2014) since in 2011 it introduced the use of BIM Level 2 for all public projects by 2016, through the launch of the “UK Government Construction Strategy" with the aim of reducing by 20% the procurement costs. In the last years, UK has undertaken a new round of investments for the development of common standards and protocols, providing free of charge access in order to promote the dissemination of BIM especially among SMEs.

Meanwhile, a new strategy, still under development, called "Digital Built Britain" Level 3, was launched in 2015, with the aim of outlining the roadmap towards the definition of advanced standards for the development of new business models and for the implementation of new technologies dedicated to the construction of public infrastructures (HM Government, 2015).

Germany has also been working for several years on the transition to the full BIM within the public sector. In 2013, Germany’s Federal Ministry of Transport and Digital Infrastructure (BMVI) founded the “Construction of Major Projects Reform Commission” an initiative aimed at ensuring that: *“the public develop greater confidence in major projects, that public funds are spent efficiently and that the good international reputation of the German planning and construction industries is preserved*”[39]

In 2015, Germany has introduced the "Road Map for Digital Design and Construction", a strategy developed by the “planen-bauen 4.0 Gesellschaft zur Digitalisierung des Planens, Bauens und Betreibens mbH” (Planen-Bauen 4.0) on behalf of the BMVI, defining a plan for the gradual introduction of BIM approaches in public projects (Federal Ministry of Transport and Digital Infrastructure, 2015). The program defined “Performance Level 1” aims at the BIM implementation for all infrastructure projects by 2020 through a preparation phase (which took place in 2015-2017) and an extended phase of pilot projects for the period 2017-2020, from which gathering the essential experiences for the definition of future standards, guidelines, executive plans and codifications. In addition, Germany has been approaching standardization initiatives through the Association of German Engineers (VDI) which, on behalf of the government, is drafting standards such as the VDI2552 series which is intended to become the German national BIM standard in cooperation with the German Institute for Standardization – DIN.

Other member states of the European Union, such as France, the Netherlands and the Scandinavian countries have autonomously initiated experimentation and standardization actions, such as “COBIM- Common BIM Requirements” (Finland, 2012) or Statsbygg BIM Manual 1.2.1 (Norway), while the European Commission is finalizing

[39] German Federal Ministry of Transport and Digital Infrastructure, “Construction of Major Projects Reform Commission”, available at: https://www.bmvi.de/SharedDocs/EN/Articles/G/construction-of-major-projects-reform-commission.html, retrieved on May 2018

a strategy to spread common and shared practices in order to institute a coordinated European network in the use of BIM for public sector[40]. An example of the EU work on the BIM implementation comes from the EU BIM Task Group, which has drafted the manual; "Handbook for the introduction of Building Information Modeling by the European Public Sector", dedicated to public administrations and public bodies, procurement measures, technical considerations, cultural and skills development for the use of BIM in the realization of public construction works (EU BIM Task Group, 2016).

Other relevant international provisions have been developed on BIM issues by the ISO/TC59/SC13/WG13: "Information Management" committee, promoted and coordinated by the UK. The ISO working group has published so far:

- PD ISO/TS 12911:2012 - Framework for building information modelling (BIM) guidance;
- ISO 10303 - Automation systems and integration - Product data representation and exchange (informally known as STEP: STandard for the Exchange of Product model data);
- ISO 16354:2013 - Guidelines for knowledge libraries and object libraries;
- ISO 12006-2:2015 - Building construction. Organization of information about construction works. Framework for classification;
- ISO 12006-3:2016 - Building construction. Organization of information about construction works. Framework for object-oriented information;
- ISO 16739:2016 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries;
- ISO 16757-1:2015 - Data structures for electronic product catalogues for building services. Concepts, architecture and model;
- ISO 16757-2:2016 - Data structures for electronic product catalogues for building services. Geometry;
- ISO 29481-1: 2017 - Building information models - Information delivery manual Part 1: Methodology and format;
- ISO 29481-2: 2016 - Building information models - Information delivery manual Part 2: Interaction framework.

[40] EUBIM Task group, available at: http://www.eubim.eu/about-the-eu-bim-task-group/, retrieved on May 2018.

The European Committee of Standardization (CEN), through the committee CEN/BT/WG215 "Building Information Modeling", promoted and coordinated by Norway, has worked to implement some of these standards, publishing: the EN ISO 16739:2016, EN ISO 12006-3:2016, EN ISO 29481-1: 2017 and the EN ISO 29481-2: 2016.

Italy, like other countries of the European Union, refers to the contents of European Directive 2014/24/EU on public procurement in which, for the first time, BIM is mentioned; "*specific electronic tools such as building information electronic modeling or similar*" (European Union, *Directive 2014/24/EU*, Art.22 c.4, p. L94/107). Although in the Directive the reference to the BIM is unequivocal, the Italian translation contained in the new Procurement Code (Legislative Decree 18 April 2016, No. 50), is similar but more generic, indicating that "*Member States may require the use of specific electronic tools, such as electronic simulation tools for building information or similar*" (original Italian version: "*gli Stati membri possono richiedere l'uso di strumenti elettronici specifici, quali gli strumenti di simulazione elettronica per le informazioni edilizie o strumenti analoghi*" (European Union, *Directive 2014/24/EU*, Art.22 c.4, p. L94/107).

In order to implement the content of the 2014/23/EU directive (Art.181) and in particular those contained in the 2014/24/EU (Art.23 directive), the Italian Minister of Infrastructures and Transport issued Decree no. 560 of December 1st 2017 ("BIM decree") which defines "*the methods and timing for the progressive introduction for the contracting authorities, public administrations and economic operators, of the mandatory adoption of methods and specific electronic tools, such as those for buildings and infrastructures modeling, in the design, construction and management phases and related monitoring*"(Italian Minister of Infrastructure and Transports, *Decree no. 560 of December 1st 2017*, p. 1).

The mandatory calendar presented in the decree is divided into the following deadlines;

- for complex works of 100 million Euro value, starting from 1 January 2019;
- for complex work with contract starting price of 50 million Euro or more, starting from 1 January 2020;
- for complex works with contract starting price of 15 million Euro or more, from 1 January 2021,
- for works with an amount based on contract starting price equal to or higher than the threshold referred to in Article 35 of the Public Procurement Code, with effect from 1 January 2022;

- for works with an amount equal to or higher than 1 million Euro, starting from 1 January 2023;
- for new works with contract starting price of less than 1 million Euro, starting from 1 January 2025.

The provision, besides defining the procedures and timing for the gradual BIM introduction for procurement and concessions, regulates the fulfillment of the contractors, which must have plans dedicated to implementing BIM and tools for the control and management process. Although there is no clear reference to technical regulations in the decree, Italy is working on this aspect.

Following the UK experience, Italy is involved in the development of European BIM technical standards which, so far, have produced the UNI 11337:2017 ("Digital management of construction information processes").

Among the parties involved in the standardization panel there are: regulatory bodies such as ISO, UNI and CEN (with the CEN/TC 442 working group), professional firms, companies, industrial associations, public (such as MIT and ANAC) and private bodies, software and hardware developer and academic institutions.

The standard, which replaces the previous UNI 11337:2009 (Code for the codification of works and construction products, activities and resources), is composed of 10 parts. The parts already available, which represent the framework of the system, are parts 1, 4, 5 and 6, while the publication of parts 2 and 3 is planned by the end of the year, (part 3 is currently available in the version 2015).

The 10 parts deal with the following topics:

- Part 1: models, drawings and informative objects for products and processes;
- Part 2 and 3 (update): coding and classification using IT tools, information sheets, LOI and LOG;
- Part 4: evolution and informative development of models, designs and objects;
- Part 5: information flows in the digitized processes;
- Part 6: guidelines for the preparation of the information documents;
- Part 7: qualification of the figures involved: BIM Manager, BIM Coordinator, BIM Modeler / Specialist;
- Part 8: guidelines for applying BIM to the sector processes;
- Part 9: "Due Diligence" and the digital survey, rules for the construction of the company "Platforms of Collaboration" and the "Digital Booklet";

– Part 10: Administrative management.

3.3.3 BIM Interoperability

BIM represents a further step in the development of computer-aided design, that involves the entire construction industry, thus not limiting to design procedures but innovating the whole building process concept.

"*Disruptive technology*", "*process change*" and "u*nbounded and systemic innovation*" are just few examples, collected by Succar and Kassem (2016), of how BIM spreading has been interpreted as a consequence of its impact on industry's outputs, relationships and roles (Succar and Kassem, 2016).

From the practice point of view, through the development of a comprehensive and intelligent 3D model, it is possible to include documentations related to each AECO discipline with respect to architecture, landscaping, construction and installation designs as well as bills of quantities, cost estimates, performance analysis and facility management plans (Czmoch and Pękala, 2014), achieving new forms of relationship and collaboration.

The British standard PAS 1192-2:2013, characterizes the BIM model as the union of Project Information Model (PIM), which covers all the process phases up to the building handover, and Asset Information Model (AIM) covering the following phases (Fig. 3.11).

The collection and the exchange of information occurs within the Common Data Environment (CDE), which is defined by the PAS 1192-2:2013 as the "*single source of information for any given project, used to collect, manage and disseminate all relevant approved project documents for multi-disciplinary teams in a managed process*" (BSI, *PAS 1192-2: 2013*, p.46).

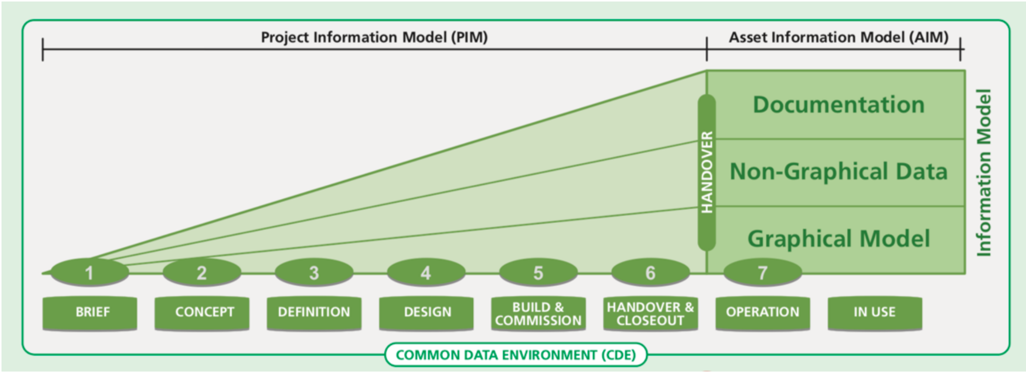

Fig. 3.11– BIM model scheme (Source: PAS 1192-2:2013)

With reference to the BIM model, the level of maturity is identified by the quantity and the quality of information provided. In order to characterize information types (graphical and non-graphical), the American Institution of Architects (AIA) have developed a specific metric for BIM models; the Level of Development (LOD) (Tab. 3.8) which "*describes the minimum dimensional, spatial, quantitative, qualitative, and other data included in a Model Element*" (AIA, *Guide, Instructions and Commentary*

to the 2013 AIA Digital Practice Documents, p. 11). The AIA recognizes five levels (from 100 to 500) specified in the AIA G202-2013 guidelines.

The BIMForum[41], using the definition proposed by AIA, developed the; "LOD Specification", a document (periodically updated) that provides an handbook in order to "*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*"[40], defining and explaining the "*characteristics of model elements of different building systems at different Levels of Development*"[42].

[41] BIMForum is the US chapter of buildingSMART International, an international body involved in the development of open, international standards for driving the transformation of the built asset economy (https://www.buildingsmart.org/about/).

[42] BIMForum, Level of Development Specifications, available at: https://bimforum.org/lod/, retrieved in July 2018.

LOD	Definition	Data available
100	The element is represented with a generic representation	Building approximate size and volume
200	The element is represented with a generic object	Approximate size and shape
300	The element is represented as a specific object without a specific assembly	Size, shape and assembly detail
400	The element is represented as a specific object with a specific assembly	Size, shape, assembly detail and installation detail
500	The element is represented as a specific object with a specific assembly and with the installation detail	Size, shape, assembly detail and installation detail

Tab. 3.8 – LOD definition and data availability according to BIMForum (Source: BIMForum[6], 2018)

A key concept that emerges as one of the major innovation drivers in the building process transformation is: "interoperability", defined, from a technical point of view, as "*the ability of two or more systems or components to exchange information and to use the information that has been exchanged*" (Geraci et al., 1991).

This concept, applied to a progressive process such as the building one, leads to new collaborative working environments, empowering accuracy in the definition of building purpose and needs, supporting project design, development, analysis and construction, and improving building management during operation and decommissioning (Grilo and Jardim-Goncalves, 2010).

Interoperability means interactions between players through the exchange of different sources of information, expressed in different formats such as: 3D models (or part of it), text documents, database, spreadsheet or schedules.

Grilo and Jardim-Goncalves (2010) have identified five types of interoperability interactions that can be applied in the BIM context.

- *Communication*: the digital innovation, especially within the AECO sector, have also changed the way of communicating. Web pages are no longer merely informative spaces, but become exchange spaces; now it is possible, for instance, to download information, or digital objects (CAD blocks or BIM objects), directly from producers' web sites. 3D CAD or BIM models have the ability to communicate design intents in new efficient ways by, for example, showing different design alternatives with different focus and levels of detail. In the "value level" diagram proposed by Grilo and Jardim-Goncalves (2010) (Fig. 3.12), communication in the BIM context, reaches the "Efficiency Level".

- *Coordination*: "*aligning activities for mutual benefit, avoiding gaps and overlaps, and thus achieve results efficiently*". One of the core aspects, with respect to BIM processes, is the possibility to coordinate complex project systems between different players from different disciplines, allowing a mutual control on the project advancement. The "Clash Detection" is a significant example of the coordinated way to find and resolve model conflicts. The value level in this case is located between efficiency and low differentiation.
- *Cooperation*: is a higher level of interaction which involves work partitioning and sharing. Some types of project management information system (PMISs) can be employed and, in the case of BIM, it can be embodied in the BIM platform. The access to building process information, enables the connection between the 3D model quantitative data and other kinds of information allowing, for example, cost estimates or energy performance simulations, thus enhancing the cooperation between project team of external players. The value level obtained, is close to differentiation.
- *Collaboration*: is the real shifting from singular detached work to collective work with shared goals and shared responsibilities. The approach needs to be innovative and immersed in an actual collaborative environment through, for example, on-line platforms and services. Comprehensive and participated BIM models are a valuable base for innovative collaboration.
- *Channel*: Even though the EACO products are physical objects, many sub-products and services can be delivered in a digital format through the internet channel. Service-Oriented Architecture (SOA) applied to the BIM process can lead to a highly distributed and fully digital ecosystem of players where any project information and service can be exchanged on-line in a digital form. This type of interoperability represents the disruption of the traditional process.

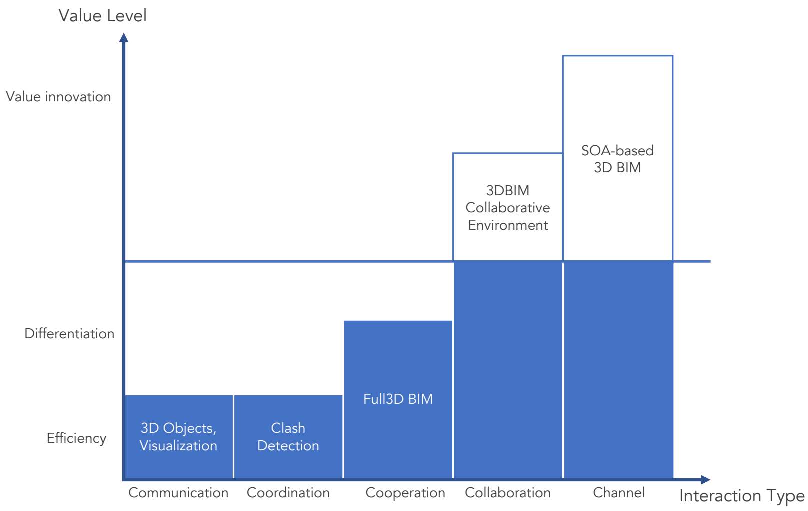

Fig. 3.12 – BIM Interoperability value level diagram (Source: Grilo and Jardim-Goncalves, 2010 – reworked by the Author)

The BIM inclination to represent an extremely collaborative and multidisciplinary working environment, embodies some information management issues, in particular the one related to data format which enable data interchange between different tools and technologies, thus empowering full interoperability (Cormier et al., 2011).

Two formats in particular have been developed in recent years, aiming at promoting universal open standards and workflows for BIM environment: GbXML (Green Building Open XML Schema) or IFC (Industry Foundation Classes).

While GbXML is essentially employed for energy simulation, IFC is intended to be a common language for information exchanges between all the AECO players, providing semantics and syntax of construction elements data, covering tangibles and abstract entities (Cormier et al., 2011). IFC can enable the exchange and the use of BIM model information developed through different tools based on different proprietary file formats.

Interoperability represents the condition of having the right data in the right format at the right time, minimizing time-consuming tasks for recreating, editing and converting data (Dalla Mora et al., 2014).

The effects of a comprehensive integration and collaboration between different actors of the building process is also expressed through the "MacLeamy Curve" (Zanchetta et al., 2014) (Fig. 3.13). The curve displays the typical bell shape of the traditional design process presenting the peak of effort and resources at the center of the construction and documentation phase, in contrast with the BIM curve, which presents a shift of the peak at the end of the preliminary design phase. It also shows that effective design changes are easier and less expensive in the early stages of the process and less effective and more expensive close to the conclusion (Zanchetta et al., 2014).

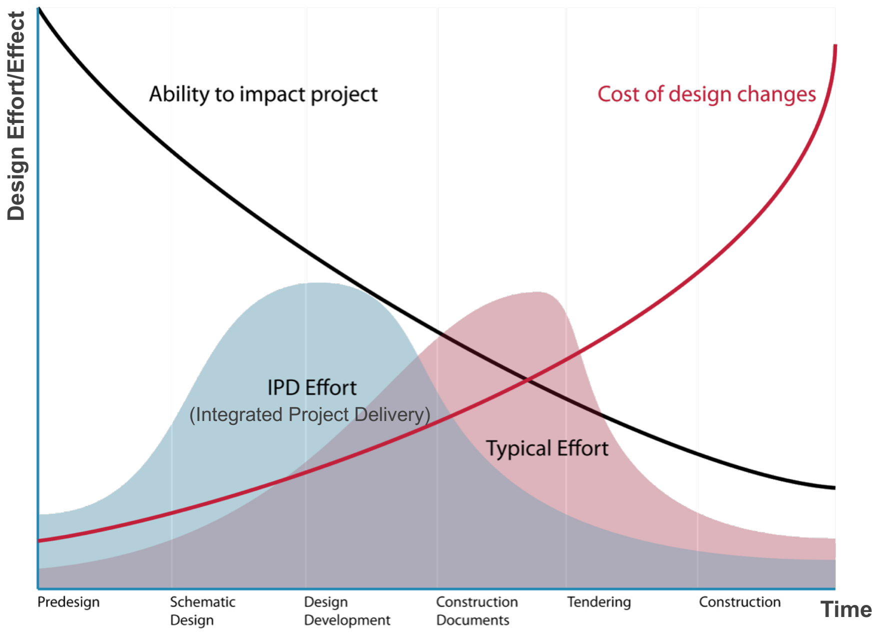

Fig. 3.13 – The MacLeamy Curve (Source: American Institute of Architects, 2007 – reworked by the author)

An illustrative evidence of the convenience resulting from the BIM employment in the design process, comes from the University of Stanford's Centre for Integrated Facilities Engineering (CIFE) (Azhar et al ,2008) which, in 2007, surveyed 32 major projects using BIM, recognizing a number of benefits, such as:

- the reduction of unbudgeted changes up to 40%;
- the improvement of accuracy in costs estimation close to 3%;
- reduction of up to 80% of the time required to generate a cost estimation;
- savings of up to 10% of the contract value through clash-detections;

- time saving related to project activities up to 7%.

3.3.4 Green BIM and LCA integration

Sustainability in its wider meaning or more simply referred to one of its dimensions (such as environment), is a concept that inevitably embodies all the phases of the design process. Sustainability is the result of the overlap of many disciplines, which relies on different approaches, methods and tools. When BIM is employed to achieve sustainability and/or improved building performance objectives on a project, it meets the definition of Green BIM (MacGrawhill, 2010) and concepts, such as "Interoperability" and "Integrated Project Delivery" are closely related to it. A Green BIM approach can be used both for new projects and existing buildings in case of renovations, refurbishment or energy retrofitting (Wong and Zhou, 2015).

BIM applications in new buildings can be implemented in the whole lifecycle, from the first concept to decommissioning, helping in the creation of prototypes, design options comparisons and facility management scenarios (MacGrawhill, 2010). If green goals are considered during the design stages for new constructions, BIM can enable the execution of effective analysis of the impact related to buildings, with particular respect to operational performance, selection of materials and energy efficiency (Chong et al., 2017). BIM tools can empower comfort and weather analysis, sensitivity analysis, thermal comfort analysis, acoustic, daylight and visual performance simulation, and energy efficiency modelling (Wong and Zhou, 2015).

With respect to the environmental dimension, BIM represents a convenient option in providing fundamental adaptation strategies for climate change and sustainable operations (Habibi, 2017). BIM is considered a fundamental strategy in supporting the improvement of sustainability improvement in refurbishment projects (Chong et al., 2017) helping the achievement of better and optimal comfort conditions. It plays a significant role in analysing and computing energy consumption in existing buildings, as well as predicting energy performance of retrofit measures, empowering the implementation of optimization strategies and assisting the resolution of complex challenges in refurbishment and renovation projects (Habibi, 2017).

According to several authors (Basbagill et al., 2013; Antón and Díaz, 2014; Wong and Zhou, 2015; Soust-Verdaguer et al., 2017; Najjar et al, 2017; Dupuis et al., 2017; Meex et al., 2018; Bueno and Fabricio, 2018; Röck et al, 2018) the implementation of sustainable approaches to the building process, has to occur at the beginning of the design phase.

Design is the core element addressed by the majority of BIM standards or guidelines. Aspects related to social, economic, and environmental sustainability are considered strictly related to the design progression especially with regard to the early or pre-design stages which, generally, imply influential choices such as: site selection, materials and products selection and energy efficiency strategies definition, considered crucial for the achievement of sustainable goals (Chong et al., 2017).

As a consequence, BIM tools are required to enable the evaluation of sustainability criteria throughout the project's life cycle. In particular, according to Chong et al, (2017), the assessment should rely on transparent specifications of building materials (including materials attributes, carbon footprint and hazardous on environment indications) as well as on energy modelling used in the project (including thermal performance of components, shade control systems, natural and mechanical ventilation, daylight and artificial lighting and other energy simulations).

Employing such an approach on the construction industry should have the potential to enhance the social and economic development while minimizing the environmental impacts but, a number of circumstances such as the lack of cooperation, make the sector still inefficient (Antón and Díaz, 2014).

The BIM tools available, if properly integrated, make it possible to perform a wide range of simulations on buildings performance, providing valuable information capable of influencing the design (Zhai and McNeill, 2014).

Among the operations that can be performed through BIM tools, the most common are: dimensional modeling, management of materials and component functionalities and performance attributes, topological integration of networks and installations, Bills of Quantities and cost estimates drafting and, depending on the tool, also energy, thermal, visual and acoustic simulations, MEP configurations, structural validation and maintenance activities planning (Chong et al., 2017).

In contrast, lower coverage of BIM tools is found in the literature, with respect to those issues related to embodied energy, embodied carbon or other pollutants emissions, resource depletion and global sustainability of buildings over their life cycle (Shadram and Mukkavaara, 2018).

As the regulatory context becomes more stringent about building energy efficiency, an accurate control of the impacts produced over the building’s life cycle, such as the emissions embodied in materials and components, is more necessary and significant (Eleftheriadis et al., 2017).

BIM and LCA are two suitable tools for such an integration, although the potential benefits, currently, are not properly expressed (Antón and Díaz, 2014), both because of the critical issues summarized at the beginning of Part III involving LCA applications, and because of the lack of optimized interoperability between BIM and LCA tools (Antón and Díaz, 2014).

Buildings are a complex combination of multiple elements, composed in turn by different materials resulting from heterogeneous manufacturing processes, therefore producing environmental evaluations over their life cycle is a challenging task (Rønnin and Brekke (2014). The assessments are further conditioned by the uncertainty of their operational performance and service life, by transport, installation, maintenance and disposal operations, requiring the formulation of hypothetical scenarios which hinder the level of accuracy in the definition of the embodied impacts (Buyle et al., 2013).

As previously stated, LCA is considered among the most reliable tool for the evaluation of the environmental impacts related to buildings due to its multidisciplinary, analytical and systemic approach, despite it is often subjected to methodological updating (Lavagna and Palumbo, 2017). Contrasting opinions, however, are expressed regarding the most correct moment of performing LCA within the design process (Bueno and Fabricio, 2016).

Traditionally, LCA are performed at the end of the design process when, therefore, the information about materials and products employed, transports and assembly procedures are available and hypothetical scenarios on the following life cycle phases are reduced (Meex et al., 2018). At the end of the process, however, all the relevant design choices, able of conditioning the environmental impact, are already taken.

Although reporting the impacts related to technical components during the preliminary design phase can offer greater flexibility and control over the environmental variables involved in the process, the accuracy of the LCA outcomes is reduced because the project information available at this stage is preliminary and incomplete (Röck et al., 2018).

The concept of BIM implementation itself, as showed in the "MacLeamy curve" (Fig. 3.13), is intended to concentrate the efforts and the resources at the beginning of the process (pre-design and concept design phase), thus providing benefits to the decision-making process, harmonizing both the information flow of the materials and the assessment of the related impacts (Najjar et al., 2017).

Consequently, implementing LCA approach within the early stages of BIM model development is considered equally valuable (Meex et al., 2018) as it can empower data management optimization with respect to time and effort, reducing manual data processing and minimizing, therefore, error-ridden activities (Antón and Diaz, 2014).

In this way, the benefit of LCA application are maximized at the beginning of the project development (Fig. 3.14).

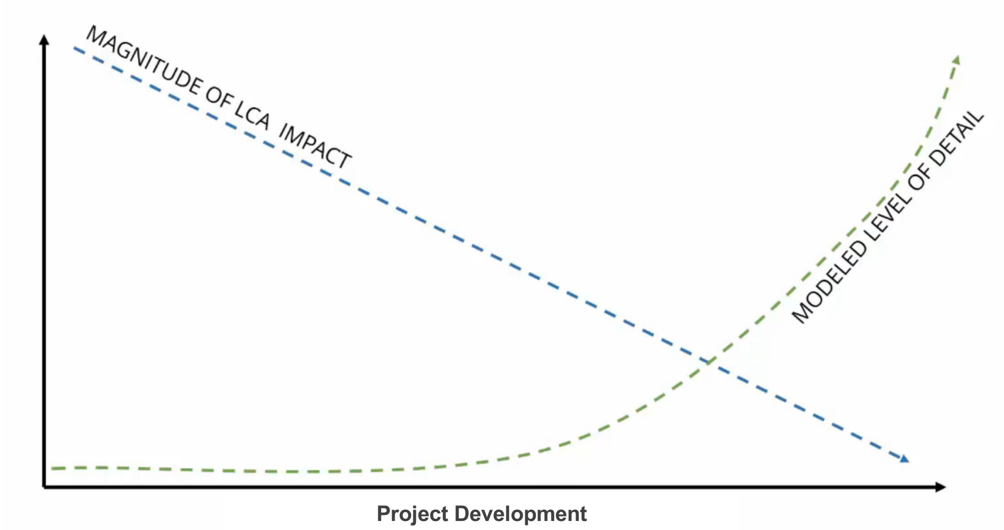

Fig. 3.14 – Relation between LCA implementation and BIM model level of detail over the project development (Source: Tally®[43])

The integration of LCA with BIM tools, emerges also as a possible solution for optimizing the LCA assessment process (Soust-Verdaguer et al., 2017), as it is recognized by several authors (Kellenberger and Althaus, 2009; Bribián et al., 2009; Malmqvist et al., 2011; Soust-Verdaguer et al., 2016) the need for simplified computational operations.

The simplification provided by the integration between LCA and BIM tools would result from an easier access to the information contained in the model such as quantity and functional characteristics, and from the consequent capability of drafting detailed Life Cycle Inventory, necessary for LCA analysis (Antón and Diaz, 2014).

3.3.5 Different approaches of LCA-BIM integration

With respect to possible LCA-BIM integration approaches, different experiences were identified from the literature, as the practitioner's intention is still to include an LCA analysis in the building design and construction processes as seamlessly and straightforwardly as possible (Bueno and Fabricio, 2018).

However, a current lack of comprehensive green BIM tools providing a full LCA analysis, thus including the embodied impacts of materials, water and waste

[43] ® KT Innovations

management and life cycle energy coverage, has been highlighted (Wong and Zhou, 2015).

A consistent distinction among integration approaches comes from Antón and Díaz (2014), who essentially identified two main types of integration (Fig. 3.15). The first approach has been defined: "*Direct access to BIM model information to calculate LCA performance*" as it relies on the simplicity of accessing the model information (quantities) through the BIM platform in order to export the data (in IFC format) and importing it into external LCA tools based on comprehensive databases such as Ecoinvent, Oköbaudat or ELCD, for a full assessment over the entire life cycle (Fig. 3.16).

The main advantages of this approach are essentially: the possibility of avoiding manual data-entry, performing complete LCAs and conducting real-time assessments as the project advances (Antón and Díaz, 2014). Several disadvantages have been identified, such as the impossibility of performing the analysis within the BIM platform itself, thus requiring iterative data importing into external tools and possible interoperability issues resulting from data format incompatibilities (Antón and Díaz, 2014). However, some issues resulting from this kind of approach presented in the paper (dated 2014), have been already overcome, as certain LCA plug-in software, such as Tally® and OneClick LCA©[44] which rely on Gabi 8.5 and Ecoinvent LCA databases respectively (Mazzucchelli and Calandri, 2018), have been developed to perform the assessment within the BIM platform, thus eradicating possible interoperability issues and enabling actual real-time analysis (Fig. 3.17).

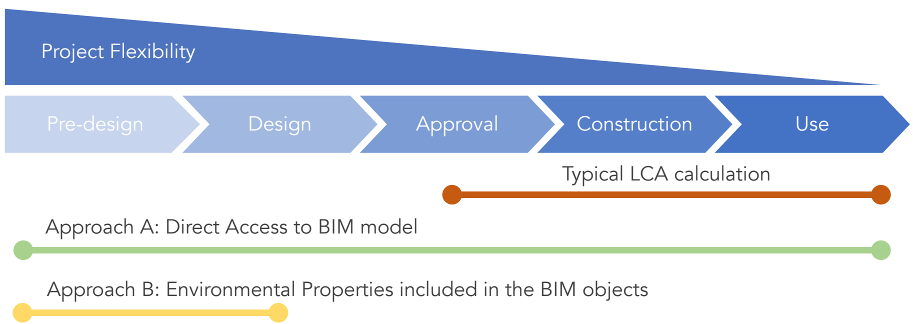

Fig. 3.15 – Different LCA-BIM integration approaches compared to the typical LCA calculation (Source: Antón and Díaz, 2014 - reworked by the Author)

[44] ©Bionova Ltd.

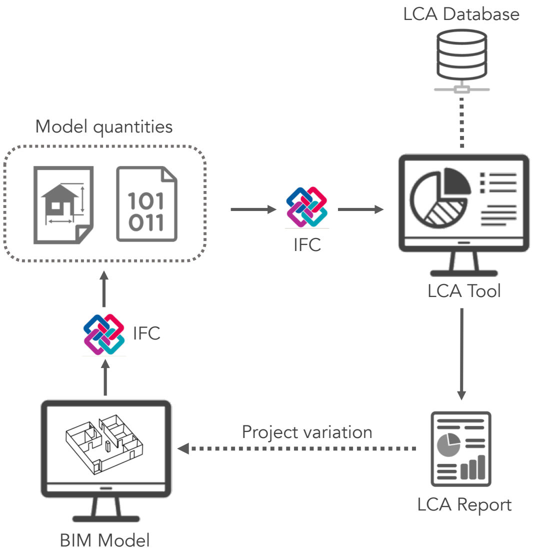

Fig. 3.16 – LCA-BIM integration approach A, according to Antón and Díaz (2014) (Source: Author)

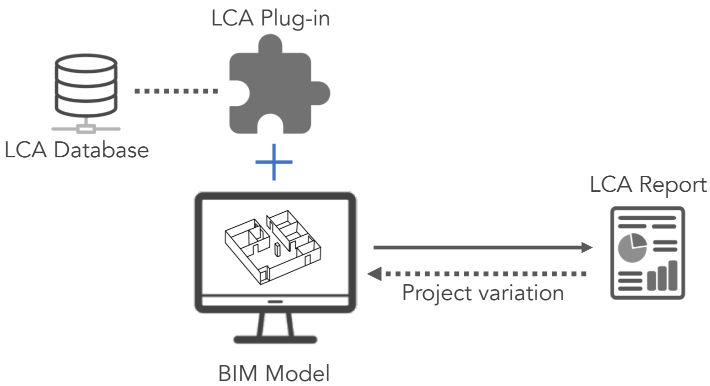

Fig. 3.17 – LCA-BIM integration approach through an LCA plug-in for the BIM platform (Source: Author)

The second approach described by Antón and Díaz (2014) has been defined as: "*Environmental properties included in the BIM objects*". This method consists of incorporating product LCA information (previously determined) into the BIM objects, which, by their nature, can incorporate different kinds of information, resulting in a material-oriented assessment (Fig. 3.18).

The main advantage of this approach resides in the possibility of exploiting the "smart aptitude" of the BIM object to incorporate environmental information, to be used as a decision-making tool, particularly suitable for the early design phases (Antón and Díaz, 2014).

This second path, although representing a further simplification of the evaluation procedures, is still considered immature and less accurate than a global evaluation of the entire life cycle of the product, since it should incorporate a range of data concerning all the phases of the process, such as transport, installation, operation and maintenance activities. Moreover, environmental data to be incorporated in the objects needs to be accurately defined according to specific framework and methodologies in order to avoid heterogenous and incomparable information.

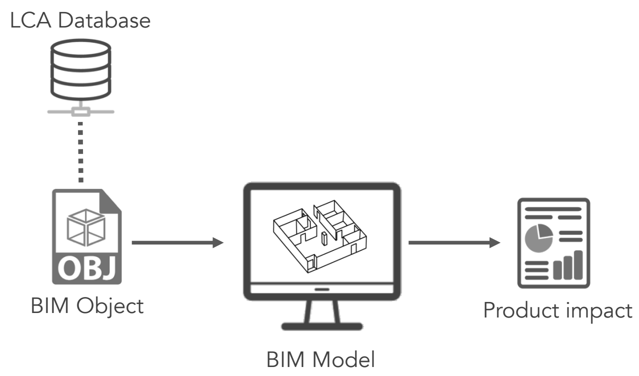

Fig. 3.18 – LCA-BIM integration approach B, according to Antón and Díaz (2014) (Source: Author)

A further study on the integration between LCA and BIM was conducted by Soust-Verdaguer et al. (2017) through the revision of a series of scientific papers dealing with LCA-BIM integration. They found that, in the majority of cases, the methodology implemented to perform an LCA analysis starting with a BIM model required the combination of a number of external software and tools such as:

- Autodesk Revit, Archicad and DProfiler as BIM authoring software;
- Green Building Studios (GBS), eQUEST, SIMIEN, Autodesk Ecotect, Integrated Environmental Solutions (IES), EcoDesigner for energy consumption calculation;
- Microsoft Excel or other databases for data exchange procedures;
- Athena Impact Estimator or EcoCalculator and SimaPro as LCA tool.

The methods that Soust-Verdaguer et al. (2017) were able to collect consisted of:

- the development of a green template including the environmental impacts of building materials;
- the development of a plug-in for the BIM software, connected to an external LCA tool;
- the integration of environmental data in Energy performance simulation software connected to the BIM software.

The paper also dealt with the aspect related to the level of detail that the BIM model should reach in order to perform a reliable LCA, concluding that, as stated by Lee et al. (2015), the preferred LOD is LOD 300 (Fig. 3.19).

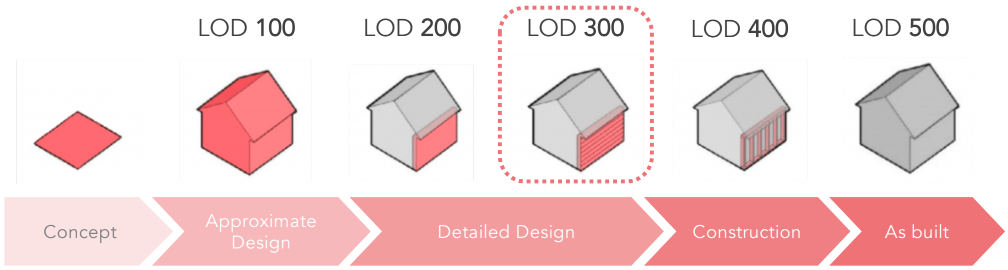

Fig. 3.19 – Preferred LOD for performing reliable LCA through the BIM platform according to Lee et al. (Source: Lee et al., 2015 - reworked by the Author)

Lee et al. (2015) concluded by arguing that the development of a BIM-based complete "cradle to-grave" environmental impact simulation is still scarce due to a number of challenges that are not completely solved yet, such as the BIM-LCA data exchange issue which requires improved automation. A consequent issue is the complexity of associating building products with the impact indicators related to each life cycle stage. This step would require automatic adaptation of BIM material attributes and bills of quantity to LCA method data structure. The importance of the local representation of data and building characteristics is emphasized as a major issue as well.

Similarly, Najjar et al. (2017), after a review of previous papers, proposed their LCA-BIM framework, basing it on the conceptual definition of BIM given by Succar (2009) as well as on the LCA framework described in ISO 14040:2006, aiming at providing a simplified but comprehensive decision-making tool, suitable for the early design phases.

The development of the proposed framework was motivated by recognition of a gap in the BIM and LCA integration literature due to insufficient methodological details provided in the papers reviewed. Najjar et al. (2017) suggested, therefore, the implementation of Autodesk Green Building Studio and Tally to estimate the building environmental impacts.

Nevertheless, Najjar et al. concluded that certain challenges are still hindering optimal LCA-BIM integration as Tally requires users to appropriately define materials in the software, and its regional coverage by geographical data source is still scarce.

Shadram and Mukkavaara (2018) and Röck et al. (2018), introduced a method of achieving integration between the BIM platform and external programs, employing visual programming (or visual scripting or computational design) applications, which, through the development of graphic algorithms, are able to extend the functionality of the BIM platforms, such as exporting/importing data from/into the model, thus reducing the need to engage other external tools and limiting the occurring of interoperability issues. Among those currently used in architecture, the most common are Dynamo© and Grasshopper© (Monteiro, 2016).

In particular, Röck et al. (2018) showed that, by limiting the scope of LCA analysis to materials only – thus excluding operating energy and water consumption – and structuring both the model data and environmental data in an aggregate and shared way, it is possible to obtain effective integration between LCA and BIM, starting from the initial design phases and enhancing the accuracy of the analysis as the level of detail of the model increases.

Bueno and Fabricio (2018) agreed with the aforementioned authors (Lee et al., 2015; Najjar et al., 2017; Shadram and Mukkavaara, 2018; Röck et al.,2018), as they also pointed out the difficulty of developing a comprehensive LCA tool suitable for the early design phases and capable of achieving consistent outcomes, outlining some significant knowledge gaps, inadequate interoperability between BIM-based sustainable tools, the absence of industry standards for green BIM applications and inaccurate BIM-based prediction models.

Bueno and Fabricio (2018) performed an interesting comparison between the simulations on a wall system using Tally, a simplified BIM plug-in for non-LCA specialists, and Gabi 6, an ad-hoc LCA software developed for LCA experts capable of performing detailed analysis and output interpretation.

Bueno and Fabricio (2018) concluded that, despite their attempt to equalize the scope of the studies aiming at providing a fair comparison, the results they achieved were not consistent, as Tally tends to underestimate the environmental impacts, probably due to the simplifications and assumptions required to allow non-expert users to perform LCA analysis.

Bueno and Fabricio also conducted an investigation in 2016 on a number of LCA tools capable of interacting with a BIM platform in order to evaluate their applicability from the BIM user's perspective (Bueno and Fabricio, 2016).

The outcomes of Bueno and Fabricio (2016) investigation are presented in Table 3.9:

BIM-LCA Tool Institution, Country	Features	Limitations
Elodie Centre Scientifique et Technique du Bâtiment (France)	– Simplified LCA compliant with European standards; – Design alternatives can be compared; – Energy performance in the design and construction solutions; – Environmental impacts assessment at the construction site; – Computation of transport of users and of major environmental contributions;	– Separate software needs to import data from BIM File; – Software –most of the information is only available in French;
eTool LCA International Team Effort (Australia, UK, Brazil, Germany)	– Detailed reports with comparable information on environmental data; – Multiple Impact Reporting, including CO2, Cost, Energy, Water, Land Use, Ozone Depletion, Human Toxicity; – Web-based software, with a pay-as-you-go certification, reviewed by third parties; – Compliant with ISO 14044 and European Standards;	– Separate software, needs to import data from BIM File; – Free version does not allow the user to print the assessment reports;

Tab. 3.9 – LCA-BIM integration tools comparison – Part 1 (Source: Bueno and Fabricio, 2016)

Green building assessment tool (GBAT) Istanbul Technical University, (Turkey)	– The framework builds a relationship between the BIM and the green building rating processes; – The framework builds a relationship between the BIM and the green building rating processes; – IMPACT Compliant assessments, including BREEAM credits;	– Separate software, needs to import data from BIM File; – Presents the available credits limited to only a subset of the available BREEAM materials; – The material database cannot be automatically updated from the BREEAM database and there is manual effort to convert it to the materials library;
Green Building Studio® Autodesk (USA)	– Carbon emissions report; – Energy analysis of complete buildings; – Daylighting, Water use and related costs and natural ventilation analysis; – Cloud-based software; – It can be used as a support tool for impact assessment of the building operation phase; – Support for LEED and Energy Star certifications;	– Very broad thermal and energy balance software, not only dedicated to LCA studies; – Does not perform full LCA studies, – Separate software, needs to import data from BIM File;
Impact Compliant Suite IESVE (United Kingdom)	– LCA compliant with British standards; – Integrated LCA, Life-Cycle Costing (LCC) and Capital Costing (CC); – IMPACT Compliant assessments, including BREEAM credits; – BRE ecopoint output;	– Separate software, needs to import data from BIM File;

Tab. 3.9 – LCA-BIM integration tools comparison – Part 2 (Source: Bueno and Fabricio, 2016)

LCA Design™ (Ecospecifier) National Research Center on Sustainable Built Environment (Australia)	– A single ecopoint score; – Choice of environmental inventory impacts and point-score measures; – Comparative ecoprofiling at all levels of design; – Detailed graphical and tabular outputs; – Cost variations; – Compliant with ISO Standards;	– Difficulty in finding detailed information about the software and the data and methods applied on it; – No trial version available for testing so far;
Lesosai Several institutions, notably the Solar Energy and Building Physics Laboratory of Ecolepolytechnique fédérale de Lausanne (Switzerland)	– Basic version of building LCA, directed mainly to Switzerland, France, Luxembourg, Italy, Germany and Romania; – Calculation of environmental impacts from energy consumption from building operation; – LCIA methodology according to the Swiss standards; – Database updated by the materials producers; – Unlimited time use for free Demo version;	– Separate software needs to import data from BIM File; – Very broad thermal and energy balance software not only dedicated to LCA studies; – LCA studies are regionally specific; – Demo version does not allow to print the assessment reports;

Tab. 3.9 – LCA-BIM integration tools comparison – Part 3 (Source: Bueno and Fabricio, 2016)

One Click LCA Bionova (USA)	– Simplified LCA; – Compliant with BREEAM, LEED, HQE, DGNB and other certification schemes; – Integrated building site impacts and life-cycle cost (LCC); – Environmental Product Declarations (EPD) database; – Verified by third parties;	– Difficult to find information;
Tally™ Kieran Timberlake Innovations in partnership with Autodesk and PE International (USA)	– LCA for the whole building or a comparative analysis of building design options; – Identification of the largest environmental impacts and their comparison between the different materials and design options; – As a Revit plug-in, it allows the user to perform LCA within BIM environment, with no special modelling practices; – Available information on applied data and methods, and complete tutorials; – Flexible non-commercial licenses; – Intuitive and user friendly interface;	– It is specific for Autodesk Revit software; – The inventory data as the LCIA methods cannot be changed or updated by the user;

Tab. 3.9 – LCA-BIM integration tools comparison – Part 4 (Source: Bueno and Fabricio, 2016)

3.3.6 A customizable LCA-BIM integration approach: development of a workflow

As a result of this investigation on LCA-BIM integration approaches, a series of conclusion can be formulated. It is highlighted that, despite many authors agreeing on the opportunity and priority of incorporating life cycle analyses within BIM platforms, the integration methods are not without critical elements.

Each of the alternatives presented has strengths and weaknesses which, respectively, promote their use but, at the same time, highlight the need for further developments.

The various advantages of implementing the LCA in the BIM environment include:

- easy access to data on the LCA environmental indicators of the materials with the assistance of the BIM model, consequently limiting computational errors and the complexity of manual data-entry;
- the possibility of easily comparing different scenarios and design and technological configurations from both a performance and environmental perspective;
- the opportunity of performing real-time assessments starting with the initial project phases and increasing the accuracy of the analysis as the model's level of detail increases.

At the same time, all the authors cited in Part III above agreed on the need for further developments in this area, again recognizing a variety of shortcomings and complex aspects that reduce its reliability and completeness.

Problems involving the accuracy of the analysis in determining scenarios relating to some life cycle phases, such as transport, assembly and the end of life, still give rise to doubts (Peng, 2016). Even the difficulties in obtaining the optimal and automatic interoperability of BIM platforms with external tools generate scepticism about the actual simplicity of the actions and remain an important and ongoing challenge (Soust-Verdaguer et al., 2017).

As stated at the beginning of Part III, the core aim of the research is to delineate possible approaches to overcome the identified LCA issues related to buildings, thus the operative complexity as well.

After having proposed an essential common LCA framework, this research identifies a robust approach for implementing such a framework, promoting suitable adoption early on in the design process.

BIM has been recognized as the correct means for this purpose, having become a common technology among practitioners, and especially among designers due to its flexibility and capability of enabling a great number of applications, especially with respect to sustainability aspects (Röck et al., 2018). Subsequently, a review of different LCA-BIM integration approaches has been carried out, identifying the various advantages and disadvantages resulting from each approach. From the documented experiences found in the literature, a series of features that LCA-BIM integration should satisfy and that should characterize a proposed integration approach, have been identified and listed as follows:

- Easy and fast: the implementation of LCA analysis within a BIM platform must be easy and fast to perform, as it needs to be executed also by non-expert LCA users, minimizing complex and repetitive setups. Therefore, few operations should be required to compute and visualize the embodied impacts of buildings.
- Minimize interoperability issues: the integration approach must reduce interoperability incompatibilities, thus avoiding, as far as possible, time-consuming and error-ridden activities such as those related to format conversions. The analysis should be performed within the BIM platform itself, avoiding building-related data being exported to external tools;
- Real-time evaluation: the environmental data of the designed building should be automatically updated and accessible at any time during the modeling. This would prevent designers from conducting specific analyzes each time a change is made in the model and it would enable a continuous control over the environmental variables as the project evolves and the level of detail increases;
- Allow easy comparison between design choices (materials and components selection): the visualization of the environmental profile of different design choices should be always accessible and displayable;
- Customizable and improvable: the integration method should be open to modification and upgrades by users, thus capable of adapting to different needs and scopes.
- Convenient: the integration method should be open source, thus free to be implemented by users and it should not require combination with other expensive tools. The costly aspect related to several tools often discourages their purchase by architectural or engineering firms, which have to incur high costs for other essential tools and technologies.

In order to consider these properties in the development of an LCA-BIM approach proposal, a series of considerations have been formulated. The proposed approach:

- should avoid employing external tools, for both economic reasons and possible interoperability issues;
- should allow users to perform the analysis and display the outcomes within the BIM platform itself;
- should be customizable depending on users' goals and level of expertise.

According to these intentions, among the approaches found in the literature, the most convenient appears to rely on the "smart" attitude of BIM objects i.e. the approach identified by Antón and Díaz (2014) as "*Environmental properties included in the BIM objects*" (see Section 3.3.4). This approach consists, as previously described, of incorporating embodied impact information into the BIM objects through a customized set of parameters linked to building materials.

Reflecting the approach proposed by Shadram and Mukkavaara (2018) and Röck et al. (2018), in order to facilitate and automate the management of environmental data related to building materials, this research relies on the employment of a visual scripting tool capable of associating the environmental impacts contained in the LCA database with the related materials and products of the BIM model. Visual scripting tools, through a graphical programming interface, empower the extension of the BIM platform capabilities.

Users, by drafting graphical algorithms, thus avoiding manual coding, can articulate and connect specific functionality blocks (Fig. 3.20) into an entire system or procedure, establishing a connection with the BIM platform and executing particular commands not available in the software (Natephra et al, 2017).

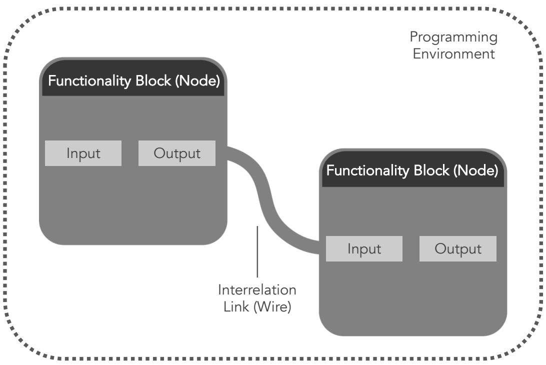

Fig. 3.20 – Visual scripting tool logic (Source: Author)

The main advantages of employing visual scripting interfaces are the capability of accessing and customizing the building model parameters efficiently and interrelating them with external data, providing custom workflows that improve building behavior and performances (Natephra et al, 2017). Considering the characteristics of the essential LCA framework proposed in Section 3.2.3, the LCA-BIM integration approach has to manage the environmental information collected from the LCA data source, such as the product EPDs which, in the majority of cases, are provided in the form of PDF documents, making direct data import impossible.

To manage such information more effectively, data should be handled by a spreadsheet and consequently linked to the BIM model objects through the visual scripting tool, accordingly to the adopted LCA framework (Fig. 3.21).

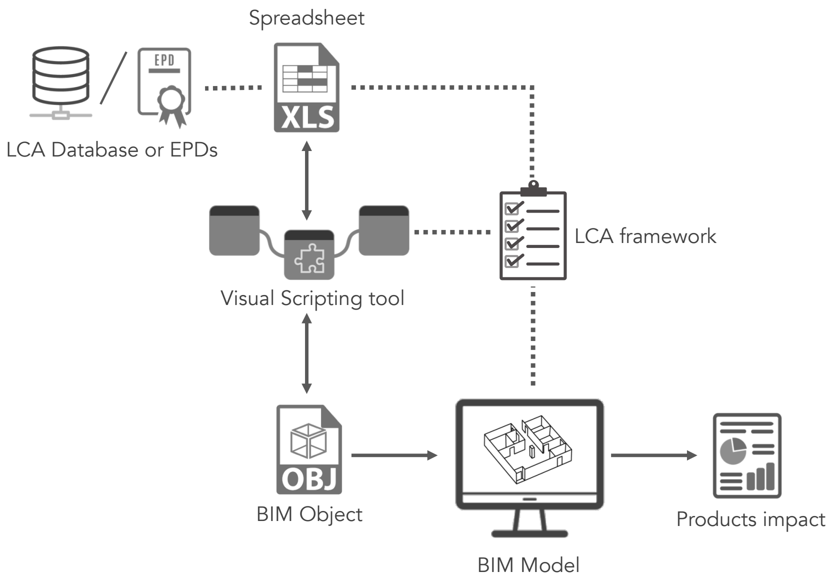

Fig. 3.21 – LCA-BIM integration proposed approach (Source: Author)

3.4 Outcomes

Starting with the recognition, from an in-depth analysis of the literature, of several limitations that currently hinder the wide diffusion of LCA application at a building level, this third part of the thesis dealt with the development of a simplified approach capable of overcoming the drawbacks that emerged with the intent of facilitating the environmental evaluation in the early phases of the process, considered particularly significant for the delineation of building environmental profiles (Meex et al., 2018).

The approach has been addressed both from a methodological and operational point of view.

With respect to the methodological aspects, the outcomes of the GBRS comparison performed in Part II has been considered and intersected with the indications contained in the recent voluntary communication framework developed by the European Commission, which defines a "sustainable" workflow for the construction sector, called Level(s) (Dodd et al., 2017).

The results of the GBRS comparison provide consistent evidence of the LCA features that could be considered particularly representative for building applications.

At the same time, the indications offered by the Level(s) framework, in compliance with the most recent European standards concerning the evaluation of a building's environmental performance (such as the EN 15978 and EN 15804), guarantee that the approach can be adapted to the European context.

As a consequence, a common and simplified building LCA framework, suitable for early design applications, has been developed and proposed.

With respect to the operational aspects, as the complexity of the LCA assessment is an acknowledged restraint for non-expert practitioners, implementation of the proposed framework within the Building Information Modelling (BIM) environment has been investigated, recognizing integration between the two approaches as a valuable opportunity (Habibi, 2017).

Furthermore, according to several authors (Basbagill et al., 2013; Antón and Díaz, 2014; Wong and Zhou, 2015; Soust-Verdaguer et al., 2017; Najjar et al, 2017; Dupuis et al., 2017; Meex et al., 2018; Bueno and Fabricio, 2018; Röck et al, 2018), LCA-BIM integration is considered a convenient and effective way to carry out environmental evaluations starting from the initial design phase, representing a beneficial means of fulfilling more aware choices and achieving more sustainable goals.

After an in-depth study of the existing LCA-BIM integration approaches, the research addressed the development of a customizable and convenient approach, presenting a workflow based on interaction between a BIM platform and an LCA database (managed through a spreadsheet) with the support of a visual scripting tool.

Such a workflow has been designed, in particular, to meet the needs of practitioners who are familiar with a BIM environment but are neither LCA experts nor inclined to make expensive economic investments in specific LCA tools or LCA commercial databases. Moreover, the workflow aimed to avoid combinations between the BIM platform and other external tools (such as those for LCA assessment) in order to perform the environmental evaluation within the BIM platform itself, thus eluding possible interoperability issues.

The outcomes resulting from the proposed framework, implemented through the proposed LCA-BIM workflow, might be used to revise design strategies and choices or to satisfy specific GBRS product environmental requirements, completing the integrated project process, which represents a key factor for achieving sustainable objectives (Antón and Diaz, 2014) and achieving greater building environmental quality.

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Part IV

LCA-BIM INTEGRATION:
WORKFLOW ON A CASE STUDY

4.0 Introduction to the Implementation Testing

At the end of Part II, a number of building LCA weaknesses emerged from an in-depth analysis of the literature, concerning both methodological and operational obstacles.

In Part III, a specific scenario was developed and proposed in order to overcome such drawbacks.

The methodological issues were addressed through the development of a common and essential evaluation framework, resulting from the intersection of the international GBRS comparison performed in Part II, which delivered a number of shared LCA characteristics (considered key for buildings applications), with the indications contained in Level(s), a recent voluntary communication framework developed by the European Commission, which defines a common "sustainable" workflow for the construction sector (Dodd et al., 2017).

With respect to the operational issues, the implementation of the proposed framework within the Building Information Modelling (BIM) environment was considered.

Currently, several assessment tools for construction process are available and can be considered a reliable opportunity, especially for the easy access provided to several environmental impact databases but, when data incompatibility between different tools occurs, they might not allow universal evaluations (Antón and Diaz, 2014), resulting in a time-consuming format conversion (Lee et al., 2015) with the risk of hindering the possibility of fair comparisons between building materials and products as well as between different design options.

In the literature, we are likely to find a number of possible solutions to conduct reliable and, in certain circumstances, comparable assessments. In the majority of cases, these solutions imply simplified methods that facilitate data collection and analysis completion.

The use of BIM is spreading rapidly, and, for designers and decision-makers, this technology can represent a valid means to facilitate LCA analysis at different scales.

Moreover, the capacity of BIM tools to easily produce (and provide access to) the bill of materials quantities delivers a continuous real-time update of the LCA evaluation as the project acquires a greater level of detail, hence a higher LOD.

In line with other experiences found in literature (Rock et al., 2018; Shadram and Mukkavaara, 2018; etc.) endorsing the use of visual scripting tools, a customizable and convenient approach has been proposed involving the employment of Autodesk Dynamo.

A specific workflow was therefore developed, relying on interaction between Revit and Dynamo in order to connect the BIM model with the building products environmental data managed through a spreadsheet.

Finally, in Part IV, the research tests the proposed LCA-BIM integration through an illustrative application on a case study in order to demonstrate the process, identifying the potential advantages and disadvantages of such an approach.

According to Antón and Diaz (2014), the aim is to achieve a convenient decision-making method, suitable for day-to-day use by designers with no particular LCA expertise.

4.1 Methodology

According to the approach proposed in Part III (Fig. 3.21), LCA-BIM integration intends to rely on the "smart" attitude of BIM objects, capable of hosting several types of information and supported by a visual scripting tool in order to interrelate the object's property fields with the environmental information managed externally through a spreadsheet.

A specific workflow was therefore developed to empower the implementation of the proposed LCA framework within the BIM environment, identifying a number of key steps. However, since the workflow was designed to be customizable, users may use it to implement alternative LCA frameworks depending on specific needs.

The development of the workflow, inspired by the LCA Design information flow illustrated by Seo et al. (2007), started with the identification of three essential phases: Input, Analysis and Output, within which the workflow steps are organized.

The Input phase is the preliminary setting of LCA-BIM integration, through which the environmental data is collected, and the BIM model is customized in order to host such data. It consists of:

1.1 Defining an initial design project, characterizing the principal dimensions and the main technical solutions.

1.2 Adopting a reference LCA framework (such as the proposed one) or defining a new framework depending on the practitioners' goal and scope (it might be defined based on the environmental requirements of a particular GBRS).

1.3 Selecting the materials and components constituting the project's technical solutions.

1.4 Collecting the environmental data from LCA databases or specific product EPDs, according to the scope of the adopted LCA framework. In this case data was collected from product specific EPDs.

1.5 Developing a structured and classified environmental database for the project using a spreadsheet (e.g. MS Excel) listing all the project's materials sorted by typology and/or function (rows) and indicating the related LCA impact categories unit values, organized by life cycle stages and modules, as well as the related functional units, service life and other relevant information (columns) (Fig. 4.1).

1.6 Processing, through the spreadsheet, the environmental unit values collected, referring them to the functional unit and the project building service life, according to the adopted LCA framework.

1.7 Modelling the building through BIM authoring software (e.g. Autodesk Revit), adopting for the BIM model's materials the same nomenclature used in the spreadsheet (the nomenclature within the BIM model can be automated through a visual scripting tool).

1.8 Adding to the BIM model's materials a set of customized parameters capable of hosting the environmental data contained in the spreadsheet, adopting the same nomenclature used in the spreadsheet (the nomenclature of the materials' parameters can be automated through a visual scripting tool).

Materials Environmental Data.xls

Material Name	Material Type	Other Info	LCA Modules (e.g. A1-A3)			Functional Unit	Service Life	Source
			LCA Indicator (e.g GWP)	LCA Indicator (e.g. ODP)	LCA Indicator (e.g AP)			
ID_Name	ID_Type	Info	Value/Unit	Value/Unit	Value/Unit	Value	Value	Reference
ID_Name	ID_Type	Info	Value/Unit	Value/Unit	Value/Unit	Value	Value	Reference
ID_Name	ID_Type	Info	Value/Unit	Value/Unit	Value/Unit	Value	Value	Reference
ID_Name	ID_Type	Info	Value/Unit	Value/Unit	Value/Unit	Value	Value	Reference

Fig. 4.1 – Sample of the Materials Environmental Data spreadsheet (Source: Author)

The Analysis phase is the sum of the actions to interrelate the external database with the BIM model, displaying the actual environmental impacts of the project. It involves:

2.1 Implementing a visual scripting tool (e.g. Autodesk Dynamo) in order to develop a series of algorithms capable of reading the information contained in the spreadsheet and exporting it into the BIM model. The script can be customized in order to execute a series of actions according to users' needs and level of expertise, however, the script must refer to the nomenclature used both in the spreadsheet and in the BIM model (for a more detailed explanation of the script development, see Section 4.2.3;

2.2 Running the script in order to populate the BIM model with the material parameters, previously defined with the environmental information included in the spreadsheet.

2.3 Drafting specific schedules within the BIM platform, in order to calculate the actual environmental impacts related to the BIM model's, based on the Bill of Quantities provided by the BIM platform itself. The schedules can be structured by single materials or building components. In addition, the schedules can display cumulative environmental impacts categorized per LCA module or LCA indicator as well as the totals.

The Output phase occurs when the outcomes resulting from the Analysis phase are used to validate/revise the project design or employed to fulfil GBRS environmental requirements, thus supporting the certification procedure. It comprises:

3.1 Drafting specific LCA reports according to the analysis scope (users may employ the visual scripting tool in order to import the analysis outcomes into a custom spreadsheet and manage the data in different ways for specific purposes).

3.2 Using the environmental analysis outcomes in order to revise and modify the project strategy (if necessary) or, possibly, performing an assessment according to the environmental requirements of a GBRS protocol. In the latter case, the reference LCA framework should be compliant with the GBRS criteria.

The proposed workflow is graphically described in the scheme below (Fig. 4.2).

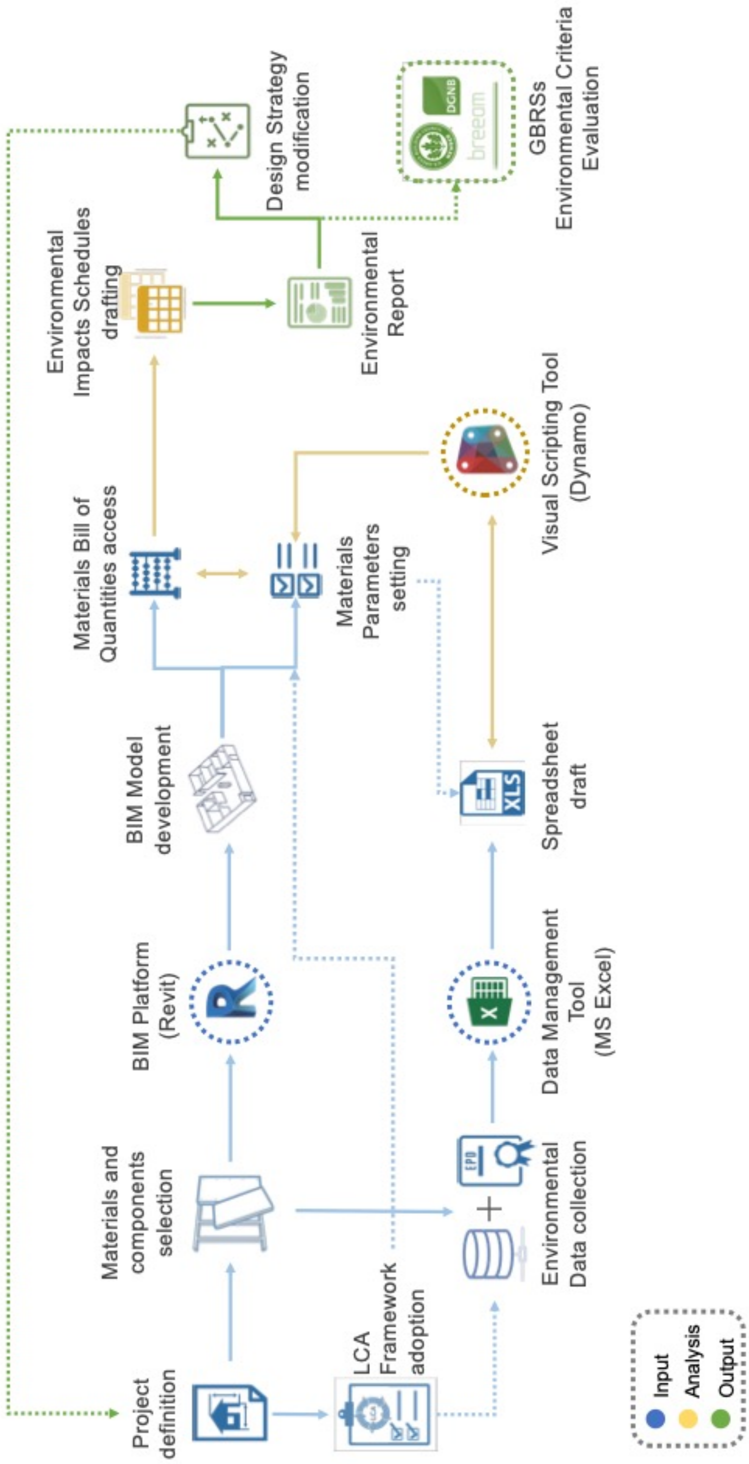

Fig. 4.2 – LCA-BIM integration proposed workflow (Source: Author)

4.2 Implementation of the LCA-BIM Integration Workflow

In this section, following the hierarchy presented in Section 4.1 (Fig. 4.3), the steps involved in the LCA-BIM integration workflow (excluding the Output phase), are described in detail, presented through an illustrative application on a case study. With respect to the Output phase, possible alternative uses of the workflow outcomes are discussed at the end of Part IV.

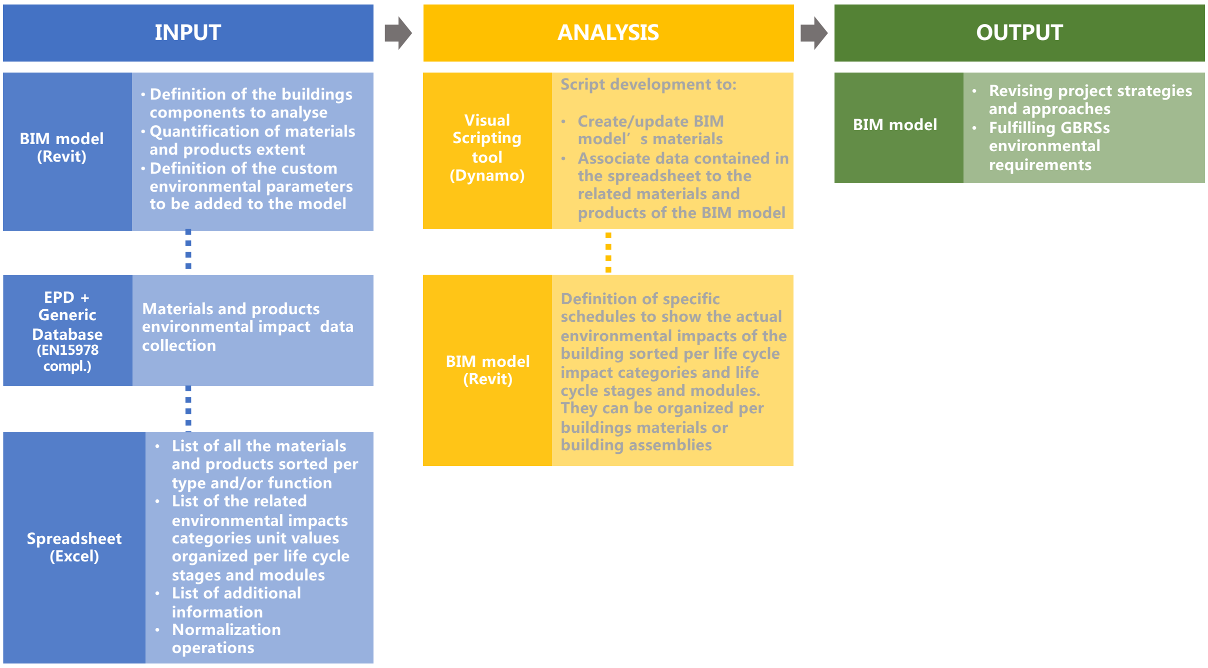

Fig. 4.3 – Workflow essential phases: Input, Analysis and Output (Source: Author)

4.2.1 The case study

The case study selected for the workflow testing is the model floorplan of a multi-storey student residence that will be located in Bologna, Italy. At the time of the writing (2018) the detailed design of the building is under development.

The BIM model of the case study[45] (Fig.4.4, 4.5) has been developed with the BIM authoring software Autodesk Revit, reaching a LOD 300 with which the elements are usually detailed with specific assemblies, and attributes such as quantity, size, shape, location and orientation are precisely identified.

[45] Courtesy of Open Project srl, architectural and engineering firm in Bologna, Italy

According to Lee et al. (2015) this is the most suitable LOD for the correct management of the environmental implications, since it can deliver more precise information about the actual environmental impacts related to building materials and products.

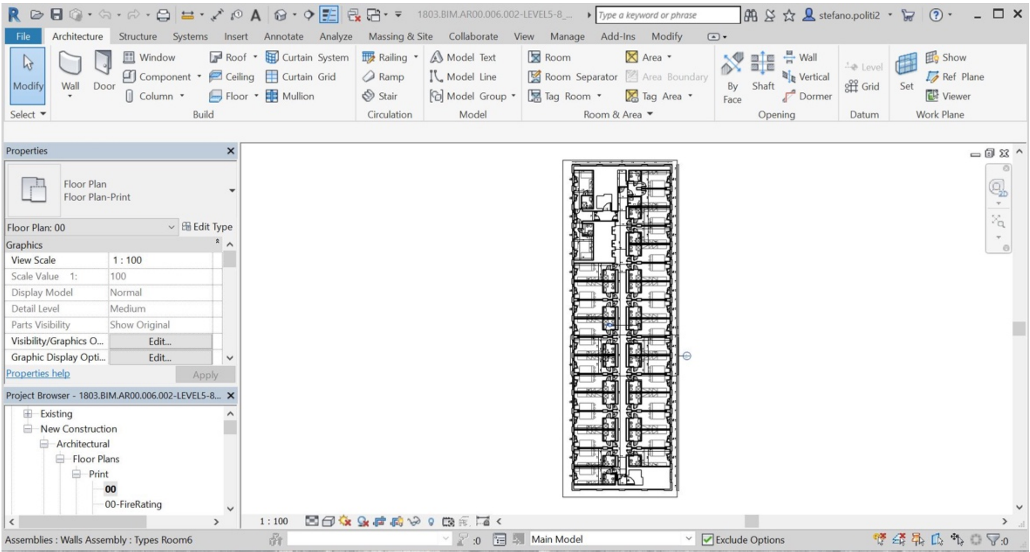

Fig. 4.4 – Case study model floor plan with Autodesk Revit (Source: Author)

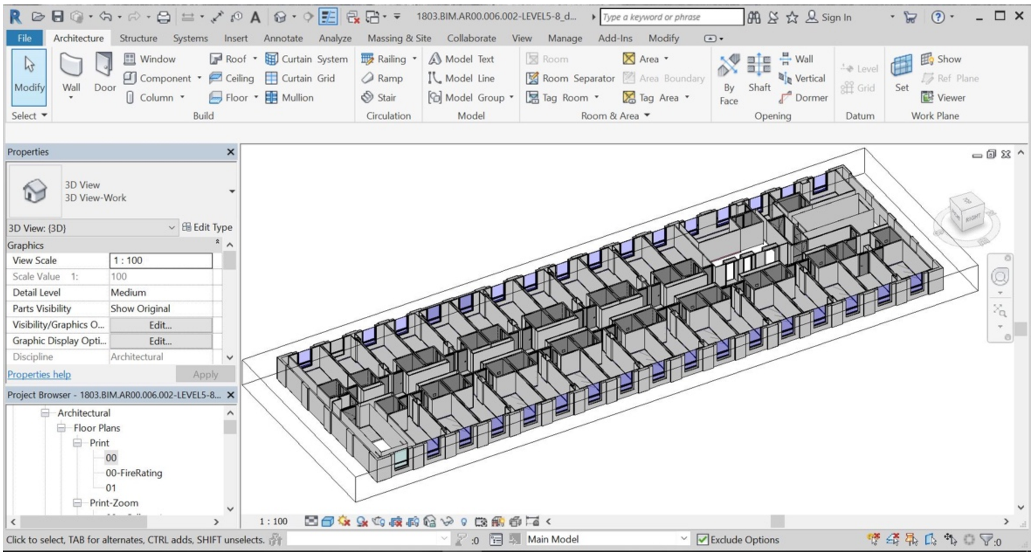

Fig. 4.5 – Case study 3D section view with Autodesk Revit (Source: Author)

The building's bearing structure is a reinforced concrete frame, and the external walls are mostly composed of aluminium frames insulated with different types of

Rockwool and mineral wool panels, enclosed in calcium-silicate sheets (plasterboards) and finished with skim-coat layers. The transparent envelope is made up of double-glazed windows with an aluminium frame (Fig. 4.6). The external envelope has been designed in compliance with the Italian regulations on the thermal performance of buildings; D.M. 26.06.2015.

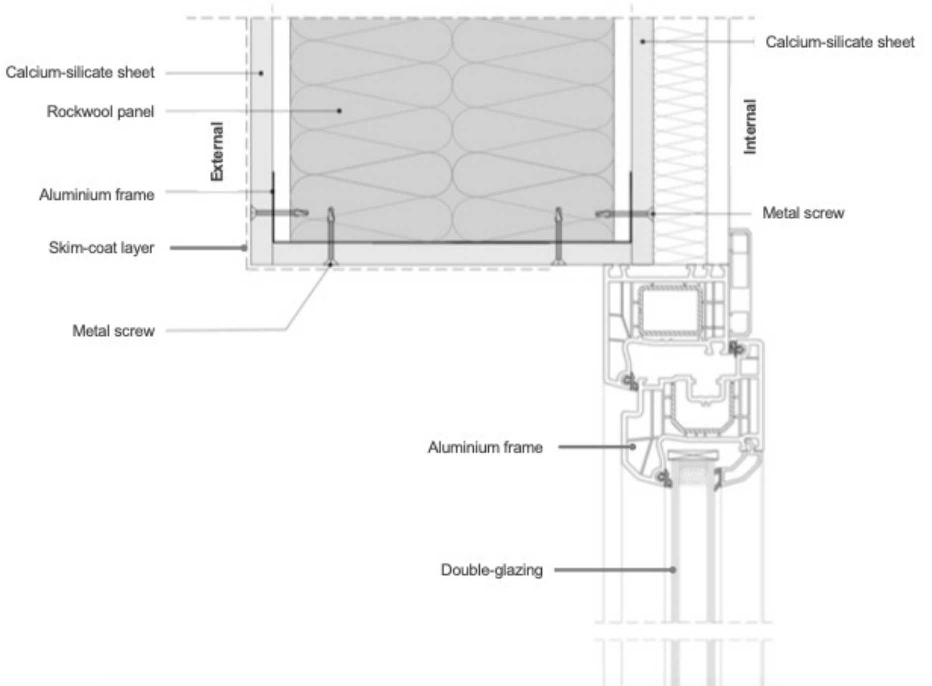

Fig. 4.6 – Stratigraphic layout of the external envelope of the case study (Source: Author)

For the application of the proposed workflow, only the external opaque envelope (thus excluding windows) was considered in the analysis, for two main reasons:

- it is intended to be an illustrative application only, therefore it is not necessary to consider all the building components for the scope of the study;
- the external walls represent key elements in shaping thermal and energy performance and cover a considerable portion of the total building surface, thus they have great environmental impact with respect to the building's overall impact (Azari, 2014).

4.2.2 Phase 1: Input

According to the eight steps identified in Section 4.1 for the Input phase, the following operations were performed:

1.1 Preliminary definition of the project: the architecture of the building adopted as case study for the application had already been designed at a detailed level, thus the bearing structures, the external envelope and the internal walls were already defined and the project materials had already been identified.

1.2 LCA framework adoption: the framework adopted for the illustrative application was defined according to the designer's needs, with the intention of evaluating in particular the product stage (A1-A3), the construction process stage (A4-A5) and the disposal of building's products (C4). In addition, the replacement module (B4) was also considered by normalizing the products' impacts on the building's service life, fixed at 60 years. The impact categories selected are compliant with EN15804 standard (except for the ADP impact category which has been excluded). Primary Energy, from both renewable and non-renewable sources, was also included within the analysis boundaries. The building reference unit was selected according to Leve(s) ($1m^2$ of useful floor surface) while for the building's materials $1m^3$ was selected as reference unit for practical reasons. The adopted framework is summarized in Table 4.1.

LCA framework parts	Content
Building Components	External Opaque Envelope (external walls and finishes).
Life Cycle Stages	Production Phase (A1-A2-A3), Construction Process Phase (A4-A5), Use phase (B4)[1], End of Life (C4).
Building Reference Unit	$1m^2$ of useful floor area
Materials Reference Unit	$1m^3$ of Building Materials[2]
Building Service Life	60 Years[3]
LCIA Indicators	GWP, EP, AP, ODP, POCP[4]
LCI Indicators	PERE, PENRE[4]
Primary Data Source	EPD (EN 15804 compliant)
Secondary Data Source	Generic Database (EN 15804 compliant)
Reference Standards	ISO 14040/14044; EN 15978; EN 15804

[1] Module B4 was considered by normalizing the products' impacts on the building's service life.

[2] The Functional Units provided by EPD developers not referring to a Volume unit were converted to $1m^3$ of building materials, based on Mass and Density information, and the Environmental Impacts were consequently adapted.

[3] For the materials whose Service Life differed from 60 years, related Environmental Impacts were considered (and modified) proportionally to the Service Life of the Building.

[4] According to EN 15978 and EN 15804 (Characterization Factor from CML-IA): GWP: Global Warming Potential [$kgCO_2eq$]; EP: Eutrophication Potential [kg $(PO_4)^3$-eq]; AP: Acidification Potential [kg SO_2-eq]; ODP: Ozone Depletion Potential [kg CFC 11eq]; POCP: Photochemical Ozone Creation Potential [kg Ethene eq]; PERE: Primary Energy Renewable [MJ]; PENRE: Primary Energy Non-Renewable [MJ].

Tab. 4.1 – Adopted framework for the illustrative application on the case study (Source: Author)

1.3 Technical solutions definition: the technical solutions for the project had already been defined at the time of the analysis.

1.4 Environmental data collection: environmental data was collected for the opaque envelope materials from entirely product specific EPDs. When an EPD was not available for a certain product, another EPD for a functionally equivalent product was chosen. In general, all the EPDs were downloaded from The International EPD® System[46] platform (Environdec).

1.5 Spreadsheet configuration: in order to manage the data in an optimized and replicable manner, a "common language" based on data structure and classification convention is one of the first tasks of the workflow development. This convention is necessary to interrelate LCA database with the BIM model (Röck et al., 2018). Therefore, a structured spreadsheet (Fig. 4.7) containing all the classified materials and product environmental impact information was produced following robust classification rules such as:

- organizing all the buildings materials by category/function and by type;
- codifying and indexing each material with specific type marks considering the previous organization;
- defining a number of columns equal to the number of environmental impact categories included in the analysis for each Life Cycle phase. In this case, seven impact categories are considered, while there are three life cycle modules[47] for a total of twenty-one (21) variables (columns). Further columns were added for other kinds of product-related information such as: type marks, manufacturer, and so on;
- assigning unique tags to each column in order not to create ambiguities with the Revit model codification;

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[46] The International EPD® System (Environdec) is a global programme for type III environmental declarations operating in accordance with ISO 14025. For construction products in Europe, the programme additionally aligns with the European standard EN 15804. Available at: https://www.environdec.com

[47] Impacts related to the modules A1, A2 and A3 were aggregated into the same stage. The same was done for modules A4 and A5.

Plastboard (cartongesso) "PB"								
	Parametro "**Description**" (valido anche per **Keynote**)	Parametro **"Life Cycle Assessment"**						
		Product Stage						
		GWP (A1-A2-A3)	ODP (A1-A2-A3)	EP (A1-A2-A3)	AP (A1-A2-A3)	POCP (A1-A2-A3)	PERE (A1-A2-A3)	PENRE (A1-A2-A3)
PB-Plastboard-Sheet-Standard	Lastra in gesso rivestito	364,8	0,000192	0,1632	5,184	0,2208	63,36	4704
PB-Plastboard-Sheet-Waterproof	Lastra in gesso rivestito resistente all'umidità	0	0	0	0	0	0	0
PB-Plastboard-Sheet-Fireproof	Lastra in gesso rivestito resistente al fuoco	0	0	0	0	0	0	0
PB-Plastboard-Sheet-Fireboard	Lastra in gesso rinforzato resistente al fuoco	0	0	0	0	0	0	0
PB-Plastboard-Sheet-Vidiwall	Lastra in gesso-fibra ad alta resistenza	0	0	0	0	0	0	0
PB-Plastboard-Sheet-Aquapanel	Lastra in cemento-fibra resistente all'umidità	0	0	0	0	0	0	0
PB-CalciumSilicate-Sheet	Lastra in calcio silicato	1895,04	1,03776E-05	0,492936	2,69592	0,165816	3113,28	27297,6
PB-Plastboard-Sheet-AluminiumVaporBarrier	Lastra in gesso rivestito con lamina di alluminio come barriera al vapore	30,69767442	5,5814E-06	0,014511628	0,19255814	0,016465116	189,7674419	530,2325581
PB-Plastboard-Sheet-StandardAzero	Lastra in gesso rivestito in classe A1 di reazione al fuoco	0	0	0	0	0	0	0
PB-Plastboard-Sheet-FireproofFzero	Lastra in gesso rivestito per l'antincendio in classe A1 di reazione al fuo	0	0	0	0	0	0	0

Fig. 4.7 – Portion of the project materials spreadsheet developed with Microsoft Excel (Source: Author)

1.6 Unit values processing: the environmental impacts unit values collected from the EPDs were processed through the spreadsheet, converting the declared functional unit (kg, m^2, etc. of product) to the same functional unit, i.e. $1m^3$ of material[48]. The products' service life was normalized and adapted to the building's expected life, thus considering replacement (B4) if the products' life is expected to be shorter than the building's life.

1.7 BIM model development: the BIM model was developed through the BIM authoring software Autodesk Revit, achieving a LOD 300. In particular, the external walls were modelled, defining a number of wall types with various stratigraphic layout configurations thus different combinations of materials and different dimensions (Fig. 4.8). The finishing layers were modelled as a separate object and not as part of the walls' stratigraphy. It is fundamental to adopt the same nomenclature used in the spreadsheet for the BIM model materials. Alternatively, nomenclature within the BIM model could be automated through a visual scripting tool (see Section 4.2.3, step 2.1).

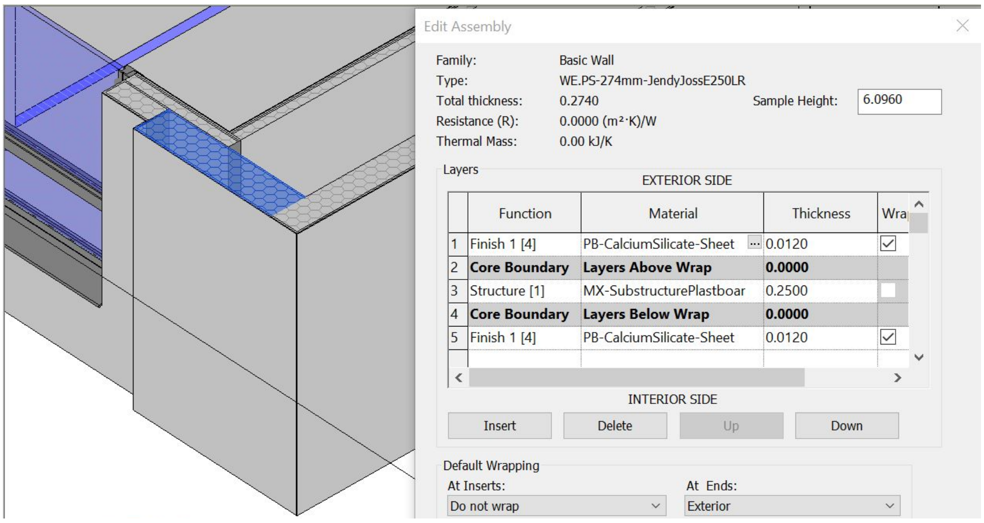


Fig. 4.8 – BIM model wall stratigraphy definition with Autodesk Revit (Source: Author)

48 Conversions were performed using other physical attributes indicated in the EPD such as: mass, volume and density of the product.

1.8 Customized parameters setting: at this point, several customized parameters ("shared parameters" in Revit) must be created in order to host the environmental data contained in the spreadsheet (Fig. 4.9). As many parameters as the environmental variables were created: one for each impact category and for each life cycle module (gathered into parameters groups), for a total of twenty-one parameters in this case (considering the aggregate modules). Particular care was taken to name the parameters, which must have the same nomenclature as the spreadsheet columns. Once the parameters were created, they were added to the project materials. The result, at this point, is that all the project materials have new empty parameters (Fig. 4.10).

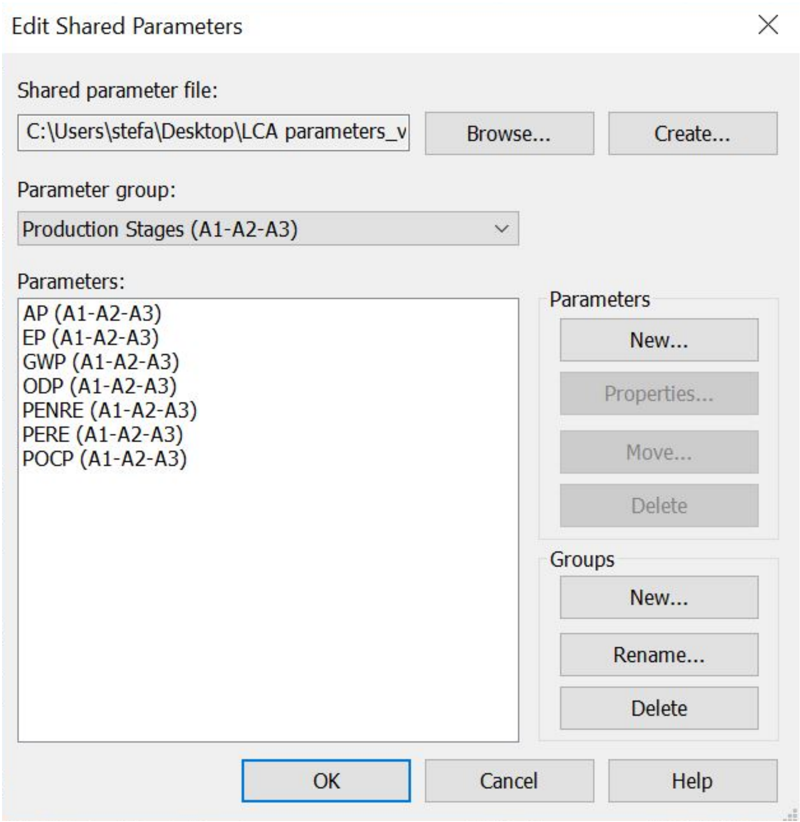


Fig. 4.9 – Creation of customized parameters (shared parameters) in Revit (Source: Author)

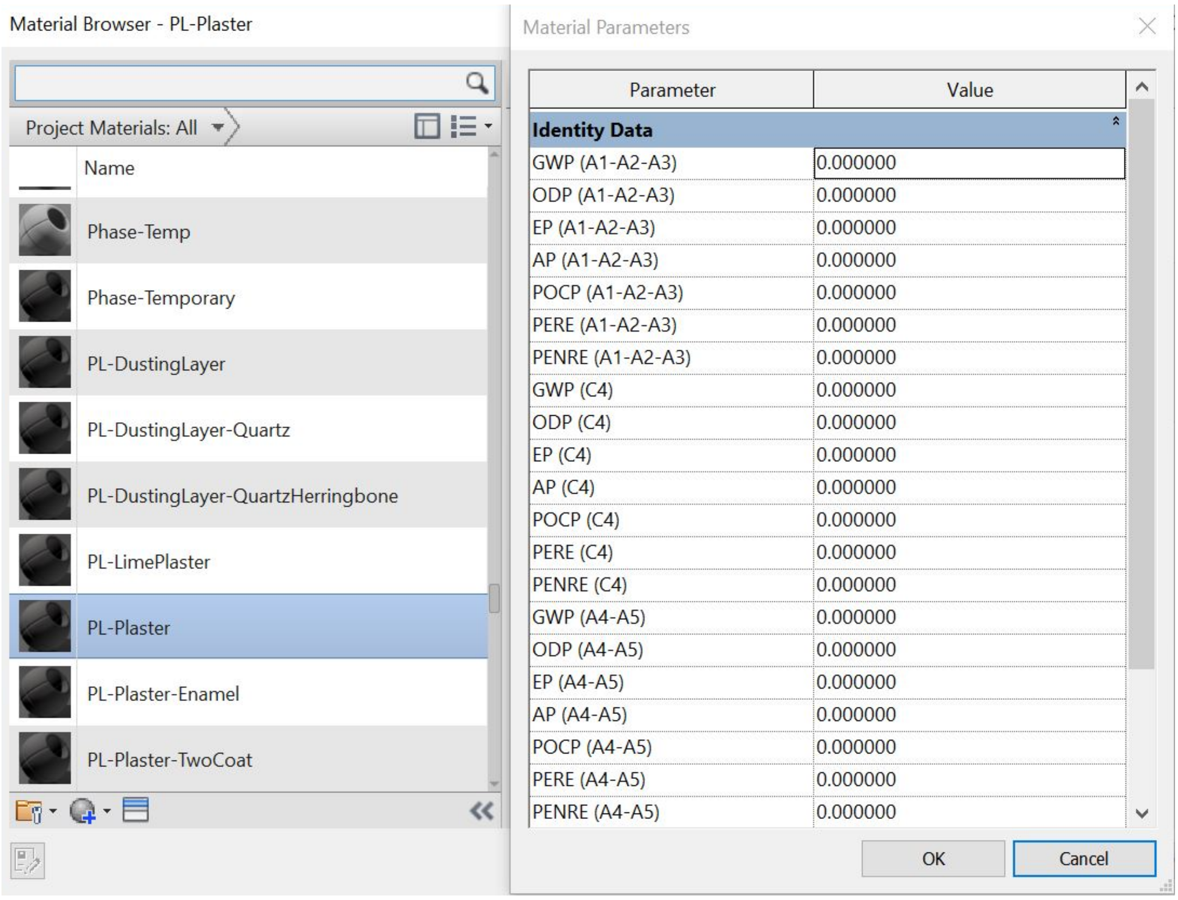


Fig. 4.10 – Customized parameters (values still unfilled) added to the project materials with Autodesk Revit (Source: Author)

4.2.3 Phase 2: Analysis

The second part of the workflow basically consists of the development of the script through the visual programming tool, capable of connecting the data contained in the spreadsheet with the new customized parameters in the BIM model. Consequently, specific schedules containing the actual environmental impacts related to the building's components can be drafted within the BIM platform.

2.1 Visual script development: Autodesk Dynamo, an open source visual programming tool, available for free as standalone software or as a Revit plug-in, was used to develop the script. Users of the Dynamo community can collaborate by providing predetermined blocks of commands or entire algorithms specifically developed in order to perform certain operations which would not be possible to perform by using only the BIM authoring software. Among the available blocks of command, it is possible to select those capable of communicating with external spreadsheets, importing/exporting data. The script (Fig. 4.11) has been designed in order to:

- Access an external spreadsheet (Excel file);
- Mine data contained in the spreadsheet, located in certain positions (indexes) such as specific columns/cells;
- Create as many lists as the number of spreadsheet columns from which data has been mined, populating these lists with the values (strings or numbers) contained in the columns;
- Create within the BIM model as many materials as the number of the spreadsheet rows (each row corresponds to the materials in the spreadsheet, except for rows containing headings) and name these materials with the names contained in the spreadsheet (first column).
- Select from the list of materials (containing all the materials included in the spreadsheet) only those to be allocated environmental data;
- Select from the list of environmental indicators only the (non-null) values which have to be allocated to the BIM model's materials;
- Identify, within the selected BIM model's materials, the customized parameters (see Section 4.2.2, step 1.8) to which to allocate the environmental data and populate these parameters with the selected values.

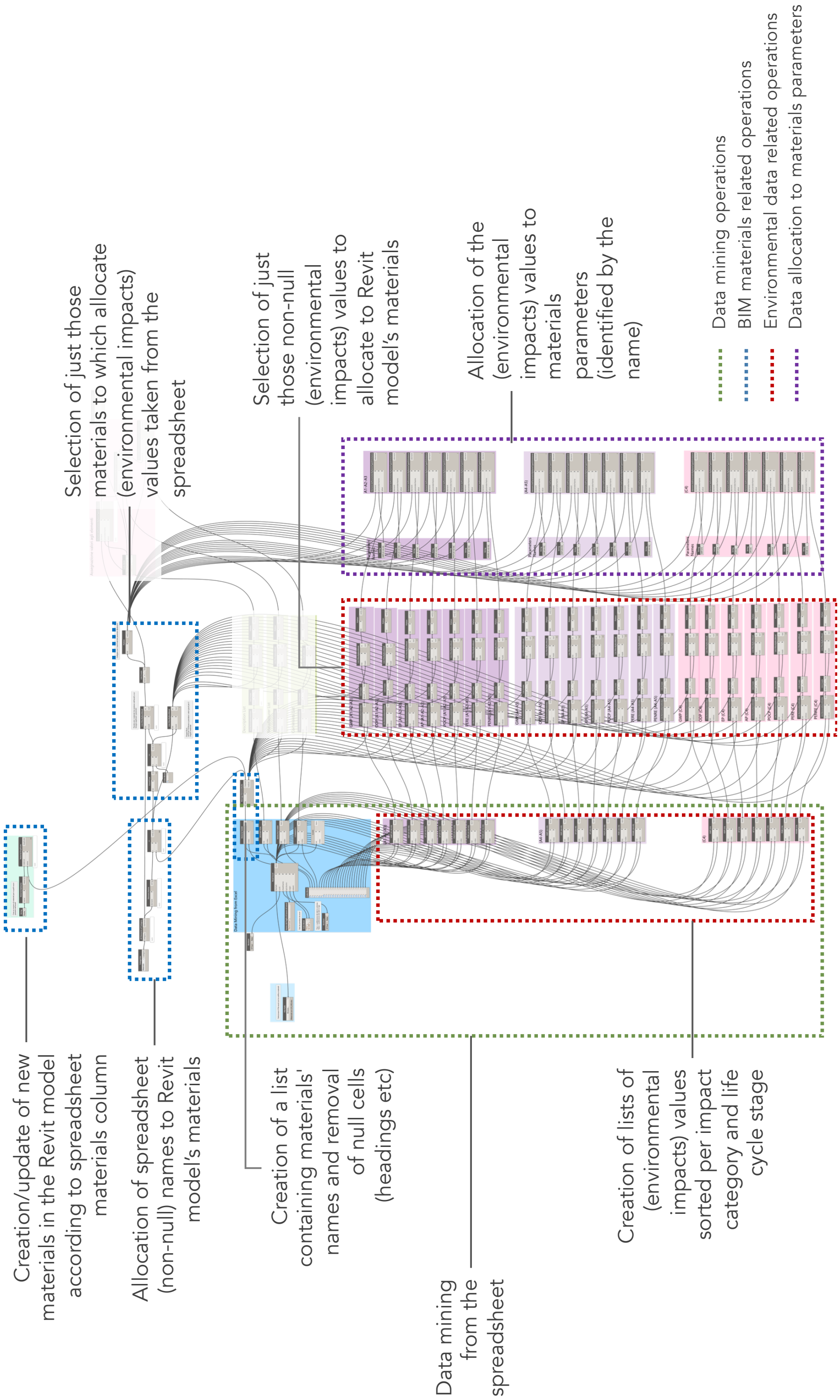


Fig. 4.11 – Description of the Autodesk Dynamo custom script (Source: Author)

2.2 Visual script run: the script was run in order to populate the BIM model's set of material parameters (Fig. 4.12) previously defined with the environmental information included in the spreadsheet;

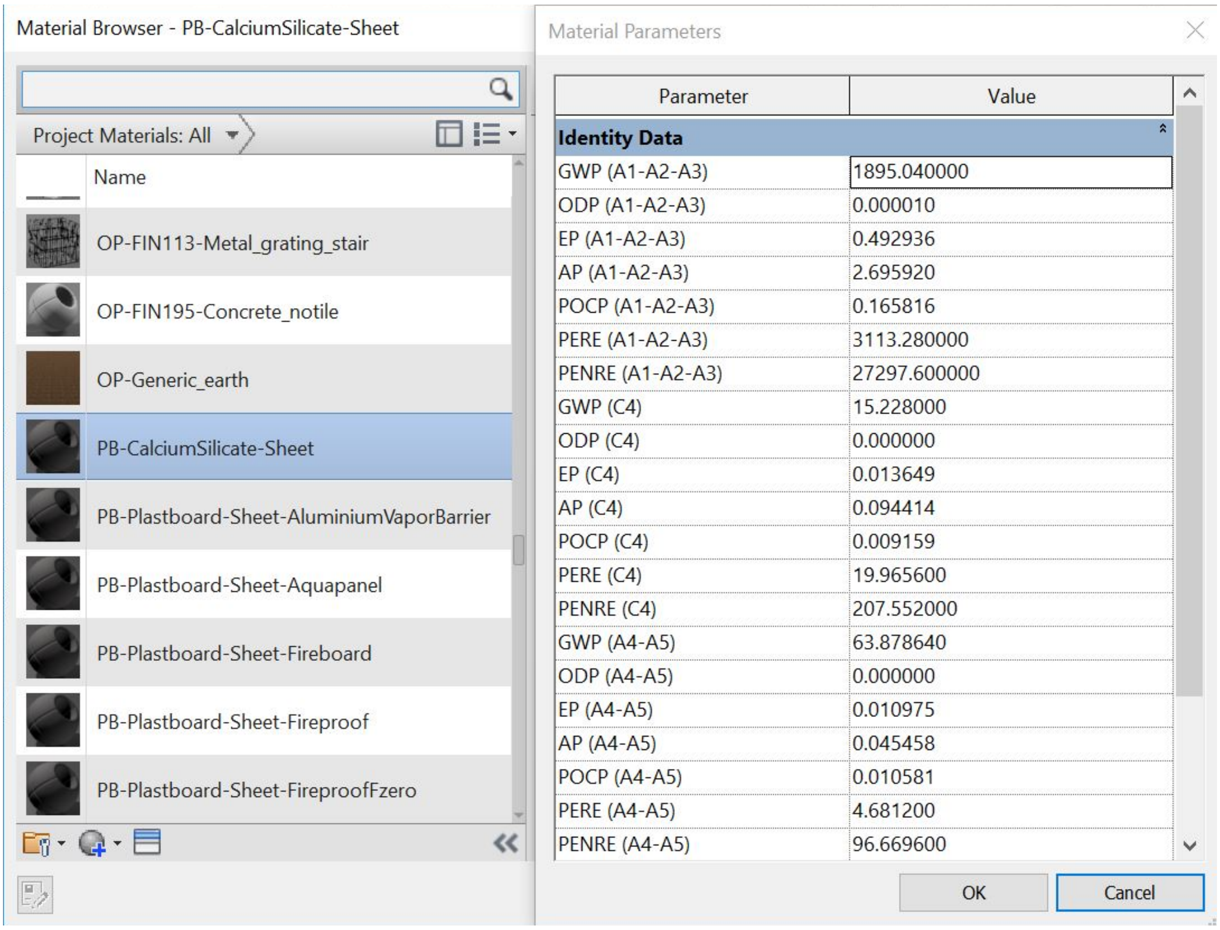


Fig. 4.12 – Allocation of environmental data to the material parameters of the Revit model (Source: Author)

2.3 Environmental data schedule drafting: Revit allows the creation of customized schedules capable of containing several types of information. In order to display the actual environmental impacts related to the materials employed in the project, two schedules were drafted: one showing the information related to single materials (Fig. 4.13 a, 4.13 b) and the other showing the impacts related to the building assemblies (external walls configurations in this case) (Fig. 4.14 a, 4.14 b). Impacts are calculated based on the materials bill of quantities multiplied by the environmental impacts' unit values. The schedules have been structured in order to display cumulative impacts categorized by LCA stage and LCA indicator as well as the grand totals;

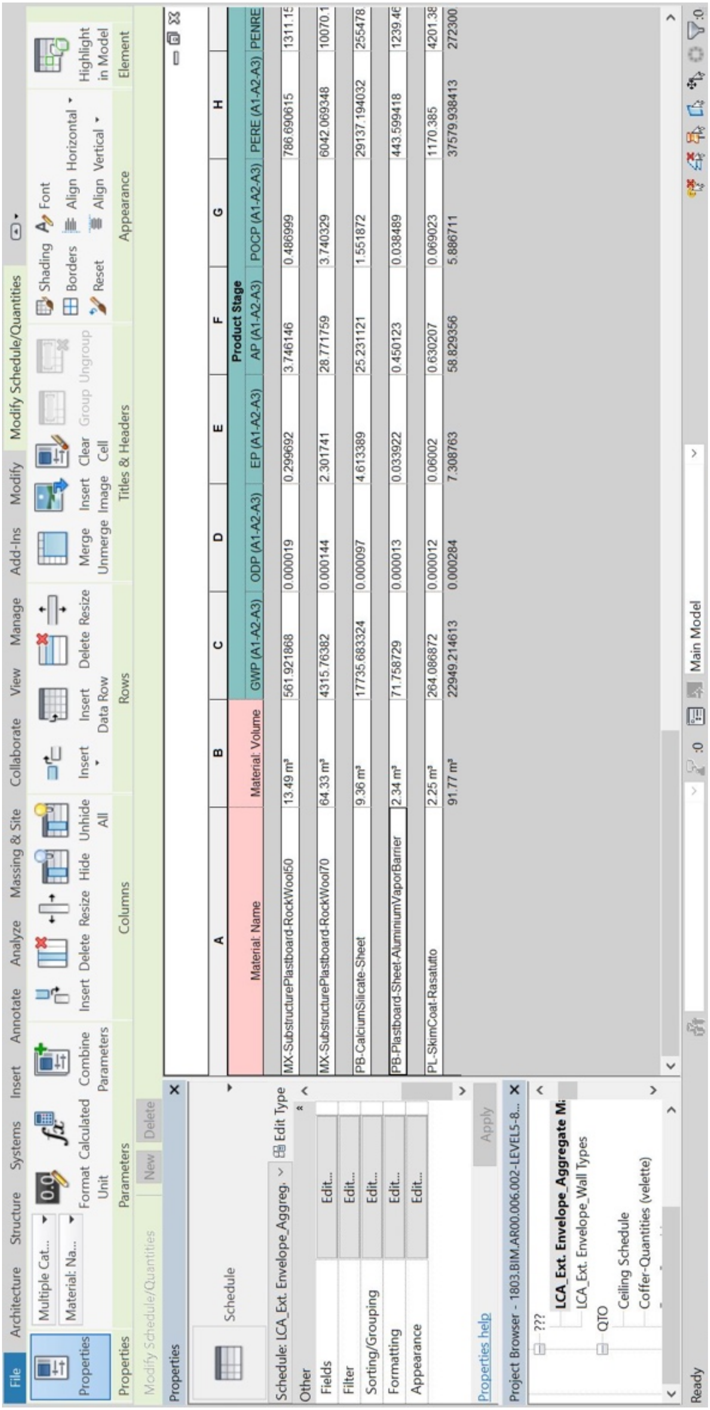


Fig. 4.13 a – Revit schedule of the opaque envelope sorted by materials - first part (Source: Author)

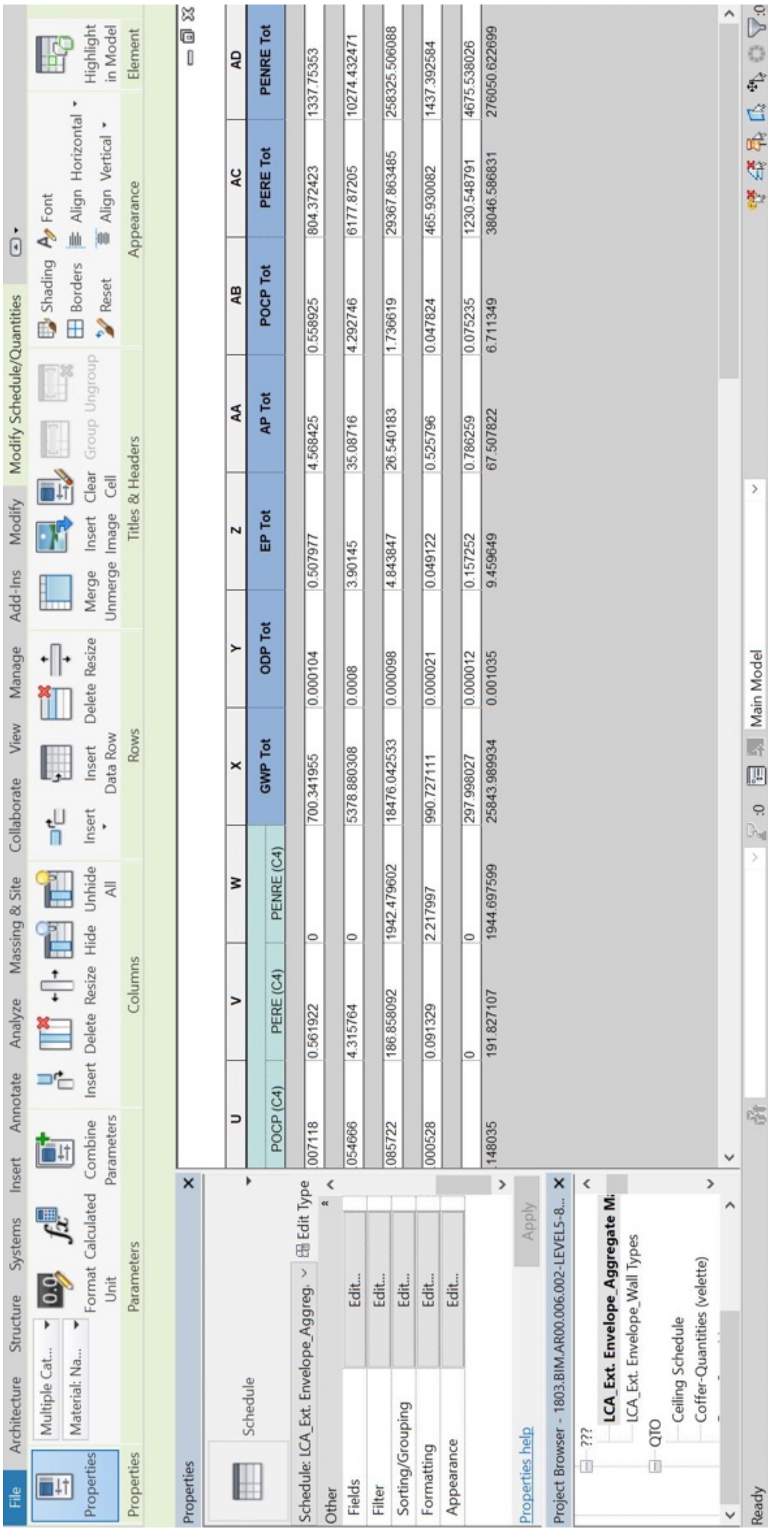


Fig. 4.13 b – Revit schedule of the opaque envelope sorted by materials - second part (Source: Author)

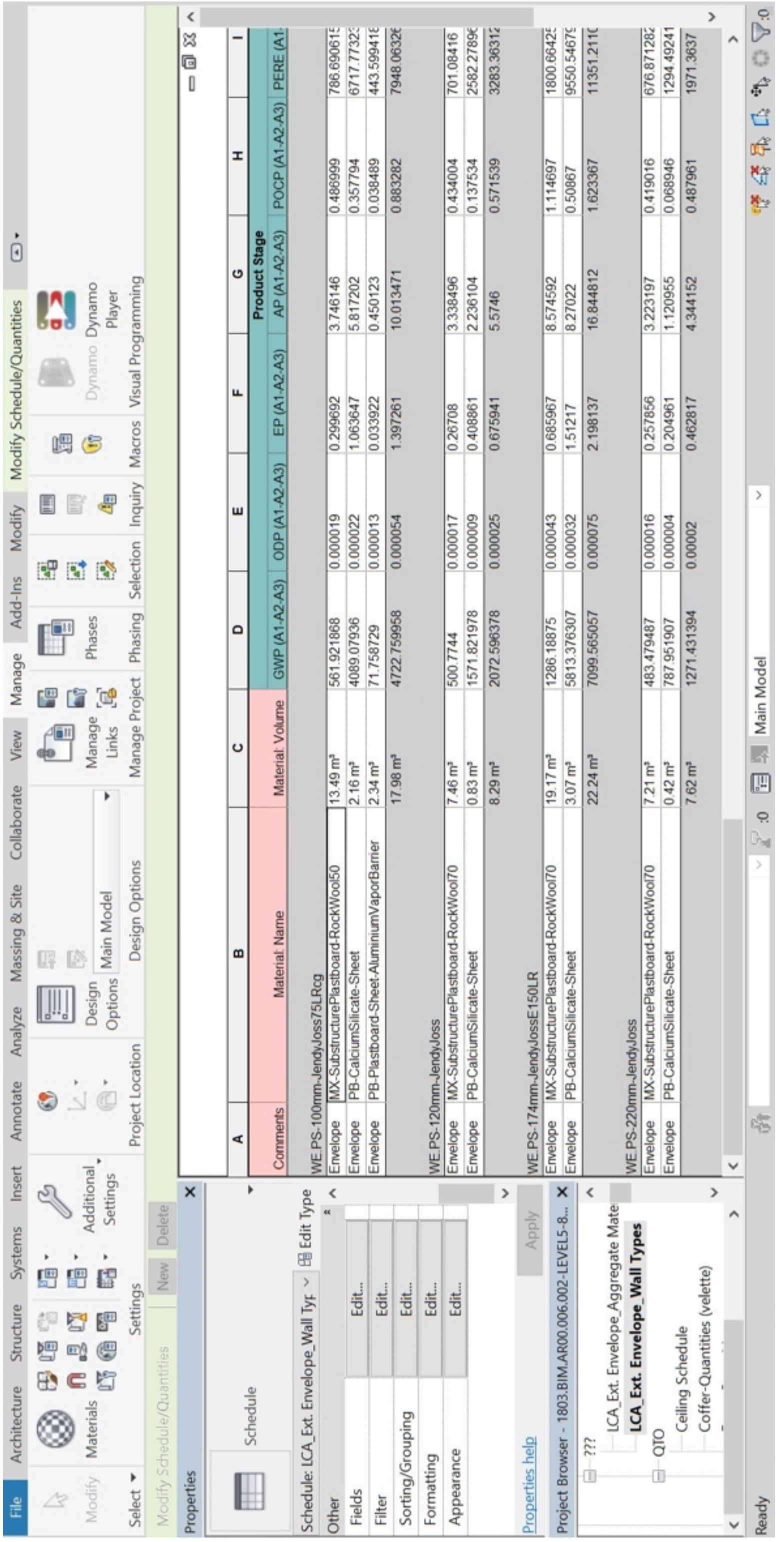
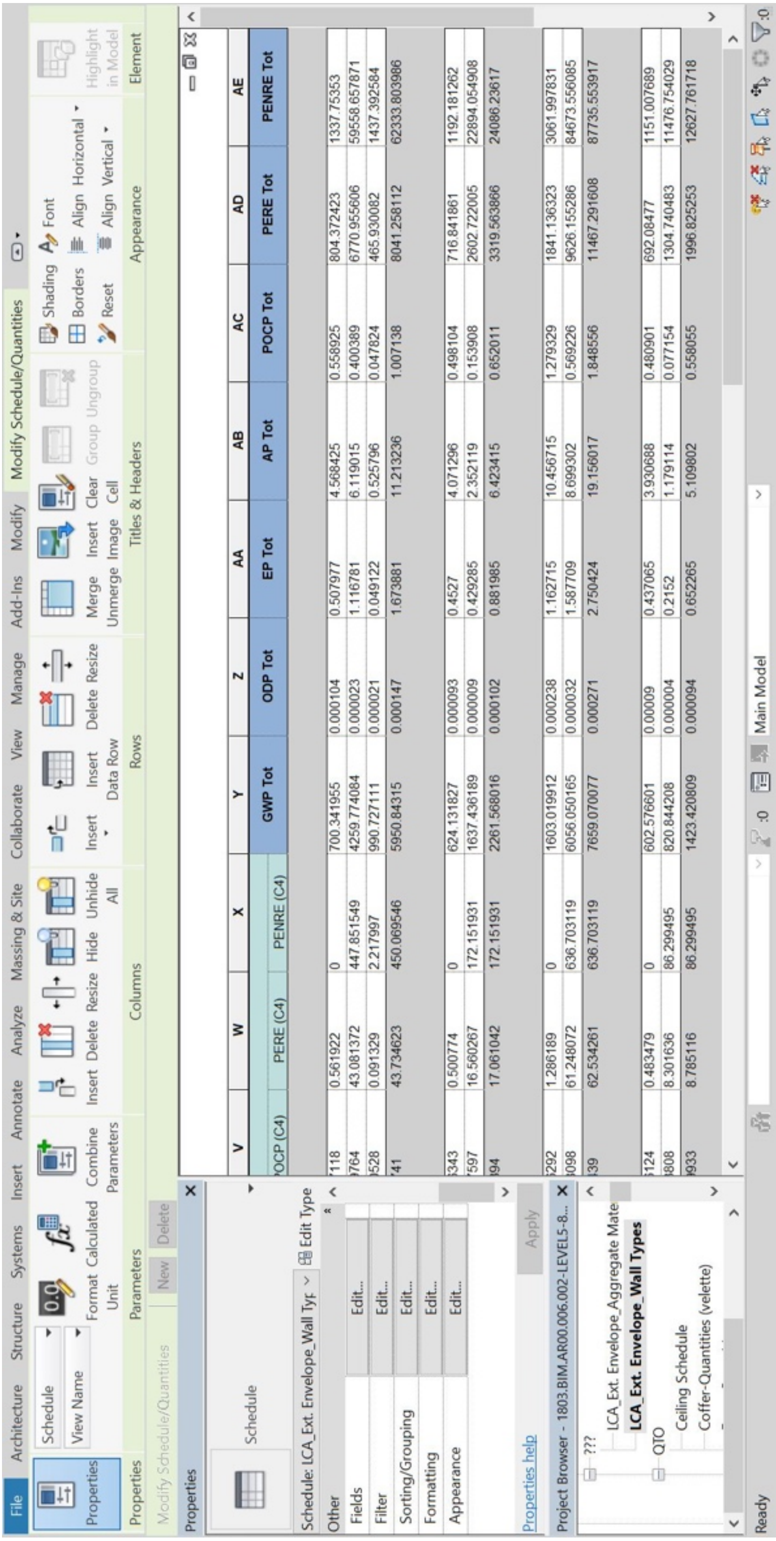


Fig. 4.14 a – Revit schedule of the opaque envelope sorted by wall assemblies - first part (Source: Author)



V	W	X	Y	Z	AA	AB	AC	AD	AE
OCP (C4)	PERE (C4)	PENRE (C4)	GWP Tot	ODP Tot	EP Tot	AP Tot	POCP Tot	PERE Tot	PENRE Tot
118	0.561922	0	700.341955	0.000104	0.507977	4.568425	0.558925	804.372423	1337.75353
764	43.081372	447.851549	4259.774084	0.000023	1.116781	6.119015	0.400389	6770.955606	59558.657871
528	0.091329	2.217997	990.727111	0.000021	0.049122	0.525796	0.047824	465.930082	1437.392584
41	43.734623	450.069546	5950.84315	0.000147	1.673881	11.213236	1.007138	8041.258112	62333.803986
343	0.500774	0	624.131827	0.000093	0.4527	4.071296	0.498104	716.841861	1192.181262
597	16.560267	172.151931	1637.436189	0.000009	0.429285	2.352119	0.153908	2602.722005	22894.054908
94	17.061042	172.151931	2261.568016	0.000102	0.881985	6.423415	0.652011	3319.563866	24086.23617
292	1.286189	0	1603.019912	0.000238	1.162715	10.456715	1.279329	1841.136323	3061.997831
098	61.248072	636.703119	6056.050165	0.000032	1.587709	8.699302	0.569226	9626.155286	84673.556085
39	62.534261	636.703119	7659.070077	0.000271	2.750424	19.156017	1.848556	11467.291608	87735.553917
124	0.483479	0	602.576601	0.00009	0.437065	3.930688	0.480901	692.08477	1151.007689
808	8.301636	86.299495	820.844208	0.000004	0.2152	1.179114	0.077154	1304.740483	11476.754029
933	8.785116	86.299495	1423.420809	0.000094	0.652265	5.109802	0.558055	1996.825253	12627.761718

Fig. 4.14 b – Revit schedule of the opaque envelope sorted by wall assemblies - second part (Source: Author)

4.2.4 Discussion

The case presented is a pilot application of the proposed workflow, consequently it suffers from a number of non-optimized operations. Further development, such as greater automation of the workflow, the inclusion within the workflow of other building life cycle phases (e.g. construction and demolition activities), or the possibility of easier access to materials and product environmental data, could boost the convenience of such an approach, leading to innovative, comprehensive and reliable applications. However, it is possible to identify a number of advantages and disadvantages resulting from implementation of the proposed workflow. The benefits that emerged from the proposed method are:

- easy access to the actual quantities and attributes of the construction materials and building products, thus avoiding manual data entry;
- autonomy to adapt the assessment variables (e.g. study boundaries, environmental indicators) to different analysis scopes, depending on personal expertise and evaluation goals;
- opportunity of comparing different design alternatives, especially with regard to materials and products, resulting in an effective decision-making tool;
- capacity of real-time assessment as the project level of detail evolves; from the early design stages to the conclusive ones, without re-importing the BIM model into the external LCA platform every time the model changes;
- opportunity of taking advantage of a structured spreadsheet for materials and products that can be updated with new elements and environmental information and, therefore, it can be re-employed in further analyses;

At the same time, as previously stated, this method also brings certain challenges such as:

- producing a spreadsheet implies having a robust system for naming and classifying materials and environmental impacts, resulting in accurate but time-consuming manual data entry since it is not yet feasible to obtain an automatic data import from EPDs or other LCA databases into the BIM models without employing specific commercial software;
- collecting reliable data from certified sources, such as EPDs, is still a delicate step since it depends on the availability of data for all the project materials and products;

- the accuracy of performing the LCA and the representativeness of the outcomes depends greatly on the quality of the BIM model;
- the issue of including aspects such as transportation information, realistic construction operations, materials and product maintenance etc., is still problematic due to the difficulties of developing reliable scenarios and the heterogeneity and variety of building project features;

This sample workflow, even if applied to one case study, does not limit the validation of the method, since the basic procedures for environmental data processing and its integration into the BIM environment do not depend on different building design processes or different buildings typologies (Röck et al., 2018).

4.3 Outcomes

In Part IV, the research addressed the implementation of the LCA-BIM integration approach proposed in Part III. In particular, an illustrative case study was tested, simulating the operation that practitioners should perform in order to deliver an environmental analysis through a BIM platform.

Starting from the indication presented in Part III, a detailed workflow was developed, firstly identifying three essential phases: Input, Analysis and Output, within which the workflow steps were organized.

After having collected the necessary environmental data (according to a certain LCA framework), through the use of BIM authoring software (i.e. Autodesk Revit) and a spreadsheet (such as Microsoft Excel), the Analysis phase led to the preparation of the BIM model, enabling it to host and manage the environmental life cycle information.

Subsequently, the Analysis phase, through the employment of a visual programming tool (i.e. Autodesk Dynamo) allows the interrelation between the BIM platform and the external spreadsheet and the consequent allocation of the environmental data to the model's materials.

This operation leads to the production of specific schedules within the BIM platform, capable of displaying the actual environmental impacts of the building's materials, possibly combined within building's assemblies (such as different external wall configurations) and sorted by impact category and life cycle stage.

During the Output phase (not addressed in this case), such schedules, which are completely customizable by the user, can provide valuable indications for project revisions and modifications or can be used to fulfil the environmental requirement of a GBRS protocol, facilitating the certification procedures.

The benefits and the inconveniences of this approach were finally discussed: on the one hand, this workflow represents a convenient decision-making method, suitable for designers without particular LCA expertise on a day-to-day basis which allows a real-time display of the environmental consequences of certain design choices, on the other hand, the approach still suffers from complexity in certain operative steps.

Furthermore, although a simplified framework has been adopted, certain drawbacks typical of the LCA methodologies, such as reliable data collection and management and the inclusion of complex scenarios that are hard to predict, still hinder achievement of an optimized analysis.

Future development of this kind of method should be undertaken, aimed at further improving the LCA-BIM integration and exploiting the numerous opportunities provided by new digital technologies in the building sector.

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Part V

Conclusions

5.0 Research Path Summary

The presented thesis project investigated recognition of the critical environmental footprint generated by construction projects, from their conception to their disposal. Several environmental dimensions are threatened by the fabrication and use of buildings, endangering natural balances and ecosystems.

The first part of the research was therefore centered on the study of environmental consequences arising from the construction industry, investigating the causes of such impacts and depicting the most important international initiatives aimed at tackling this situation.

What has emerged from sustainable development actions carried out over the last forty years is the need to mitigate the impacts especially within the building sector, with the aim of reducing resource and energy consumption, cutting hazardous emissions and consolidating waste reduction and recycling campaigns. From the World Commission on Environment and Development in 1987 to the United Nations Climate Change Conference (COP 21) in 2015, aimed at setting specific sustainable goals thus enforcing environmental policies and regulations, the definition of specific tools to measure the numerous environmental variables and comprehend the limit benchmarks have always emerged as priorities.

Buildings are responsible for a significant share of the global environmental impacts, however not all the burden should be placed upon the building operation phase, as all the phases associated with the manufacturing of construction products, transport, installation, maintenance and disposal, known as "embodied impacts", also play their part.

Along with the improvement of the operational energy performance, the embodied impacts on the other life cycle stages have also risen consistently. The principal tools adopted as study subjects to address this topic are sustainability assessment protocols or green buildings rating systems (GBRSs) which have been developed to evaluate the environmental, social and economic profiles of buildings.

The first investigation performed through a sample of GBRSs, selected among the most common ones for application on residential buildings, aimed to identify a "core set" of representative categories and building sustainability indicators.

This analysis has highlighted that the most relevant indicators, according to GBRSs protocols, concern building operations such as: energy, the comfort of the site for users and indoor environmental quality, thus less importance was attributed to environmental aspects.

Further insight into the GBRSs evaluation categories, performed in Part I, revealed that the relevance of impacts related to non-operational phases of the building life cycle, i.e. embodied impacts, is only 10%.

Although international initiatives and directives have typically targeted operating energy and carbon emissions (see the Energy Performance of Buildings Directives - EPBD 2002/91/EC, 2010/31/EU and the recent 2018/844/EU), recently attention has shifted towards consideration of the entire life cycle of buildings, with particular respect to building products, see European Regulation CPR 305/2011 and European Directives 2014/23/EU, 2014/24/EU and 2014/25/EU.

The growing interest within the EU context in the life cycle approach to buildings led this this research to focus on the Life Cycle Assessment (LCA) methodology, which emerged as an appropriate tool for measuring embodied impacts. Knowledge of its framework, as well as the conditions and the methods of its application to buildings has been deepened, with the aim of identifying the most characteristic aspects for building applications.

In Part II, an extensive in-depth analysis of the LCA regulatory and methodological framework was presented, including an overview of the principal LCA-based items for building products such as: Environmental Product Declarations (EPD) and Products Category Rules (PCR).

In addition, a comprehensive comparison between the LCA framework included in six international GBRSs (LEED v4, DGNB Core 14, BREEAM NC v.2016, Green Star v.1.1, Green Globes v.1.5 and Active House v.2) was performed. This comparison allowed us to draft a shared buildings LCA framework (with particular reference to Goal and Scope definition) indicating a number of common LCA modules, impact categories, building elements to be included in the assessment, reference functional units and reference life for buildings.

This study also investigated the GBRS rating methods, identifying two main approaches: one based on environmental impact reduction with respect to a reference building, and one centred on predefined impact benchmarks.

The first approach, which is more subjective and less restrictive, allows for more open management of the environmental variables, leaving greater discretion in the definition of the reference building but, on the other hand, it is more adaptable to different contexts. The second approach, which on the contrary is more rigid and objective, limits the scope of actions but enhances the achievement of more sustainable goals.

This study, despite having confirmed some evidence found in literature on a simplified and standardized approach to building applications has, however, underlined several discrepancies in the application of the method within a broad context and in the interpretation of the results.

Moreover, indications on the importance of adopting LCA approaches at the beginning of the design process, emphasized in the literature, emerged as particularly significant for the delineation of the environmental profiles of buildings. Part III of the thesis, therefore, starting with a series of considerations about LCA weaknesses at building scale, dealt with the development of a simplified approach capable of overcoming the drawbacks that emerged with the intent of facilitating the environmental evaluation in the early phases of the process.

This approach was developed in order to address both methodological and operational LCA issues. With respect to the methodological aspects, the outcomes from the GBRS comparison performed in Part II was considered and intersected with the indications contained in the recent voluntary communication framework developed by the European Commission, which defines a common "sustainable" workflow for the construction sector, called Level(s). The results of the GBRS comparison provide consistent evidence of the LCA features that could be considered particularly representative for building applications. At the same time, the indications offered by the Level(s) framework, in compliance with the most recent European standards on the evaluation of the environmental performance of buildings (such as EN 15978 and EN 15804), endorsed the approach of adaptability to the European context. As a consequence, a common and simplified building LCA framework, suitable for early design applications, was developed and proposed.

With respect to the operational aspects, as the complexity of the LCA assessment is an acknowledged restraint for non-expert practitioners, implementation of the proposed framework within the Building Information Modelling (BIM) environment was investigated, recognizing integration between the two approaches as a valuable opportunity (Habibi, 2017). The use of BIM is spreading rapidly, and, for designers and decision-makers, this technology can represent a valid means to facilitate LCA analysis at different scales. Moreover, the capacity of BIM tools to easily produce (and provide access to) the Bill of Quantities, allows the continuous real-time update of the LCA evaluation, as the project acquires a greater level of detail, hence a higher LOD. Furthermore, according to several authors (Basbagill et al., 2013; Antón and Díaz, 2014; Wong and Zhou, 2015; Soust-Verdaguer et al., 2017; Najjar et al, 2017; Dupuis et al., 2017; Meex et al., 2018; Bueno and Fabricio, 2018; Röck et al, 2018), LCA-BIM integration is considered a convenient and effective way to carry out environmental evaluations starting with the initial design phase, representing a beneficial means for fulfilling more responsible choices and achieving a greater number of sustainable goals.

After an in-depth study of the existing LCA-BIM integration approaches, the research addressed the development of a customizable and convenient approach, presenting a workflow based on interaction between a BIM platform and an LCA database (managed through a spreadsheet) with the support of a computational visual scripting tool, in line with other experiences found in the literature (Rock et al., 2018; Shadram and Mukkavaara, 2018; etc.).

Such an approach was designed in particular to meet the needs of practitioners who are familiar with a BIM environment, but who are neither LCA experts nor inclined to make expensive economic investments in specific LCA tools or LCA commercial databases. Moreover, the workflow intended to avoid combinations between the BIM platform and other external tools (such as those for LCA assessment) in order to perform the environmental evaluation within the BIM platform itself, thus avoiding possible interoperability issues.

With the fourth and final part of the research work, a specific workflow, therefore, was developed, relying on interaction between a BIM authoring software (i.e. Autodesk Revit) and a computational visual scripting tool (i.e. Autodesk Dynamo) in order to connect the BIM model with the building product environmental data managed through a spreadsheet (such as Microsoft Excel).

Finally, in Part IV, the proposed LCA-BIM integration was tested through an illustrative case study in order to demonstrate the process, identifying the potential advantages and disadvantages of such a method. With the aim, according to Antón and Diaz (2014), of achieving a convenient decision-making method, suitable for day-to-day use by designers with no particular LCA expertise, the operations that practitioners should perform in order to deliver an environmental analysis through a BIM platform were simulated and presented.

Three essential phases were identified first of all: Input, Analysis and Output, within which the workflow steps were organized.

After having collected the necessary environmental data (according to a certain LCA framework), through the use of Autodesk Revit and Microsoft Excel, the Input phase led to the preparation of the BIM model, enabling it to host and manage the environmental life cycle information.

Subsequently, the Analysis phase, through the use of Autodesk Dynamo, empowered the interrelation between the BIM platform and the external spreadsheet, and the consequent allocation of the environmental data to the model's materials.

This operation allowed us to produce specific schedules within the BIM platform, capable of displaying the actual environmental impacts of the building's materials, combined within the building assemblies (such as different external wall configurations) and sorted by impact category and life cycle stage.

During the Output phase (not addressed in this case), such schedules, which are fully customizable by the user, can be employed to provide valuable indications for project revisions and modifications or to fulfil the environmental requirement of a GBRS protocol, facilitating the certification procedures.

At the end of Part IV, the benefits and issues of this approach were discussed. On the one hand, the convenience of the workflow as a decision-making method is recognized, as it is particularly suitable for designers with no specific LCA expertise and allows the real-time display of the environmental consequences of certain design choices. Moreover, the outcomes resulting from the proposed approach may be used to revise design strategies and choices or to fulfil specific GBRS product environmental requirements.

On the other hand, it was shown that the approach still suffers from complexity in certain operative steps. Although a simplified framework has been adopted, certain drawbacks typical of the LCA methodologies, such as reliable data collection and management, and the inclusion of complex scenarios that are hard to predict, still hinder the application of a comprehensive analysis as well as optimized and fully automated operations. Interoperability between BIM models and LCA tools requires improvements, and data exchange for the automatic association of each building material and product with the unit processes during the life cycle is still a significant challenge (Soust-Verdaguer et al., 2016). Future development of this kind of method emerged as crucial in order to further improve LCA-BIM integration, exploiting the numerous opportunities provided by new digital technologies in the building sector.

5.1 Research Deliverables

In conclusion, retracing the path undertaken during the research, this thesis:

- Started with the aim of specifying the most representative characteristics of building sustainability as well as the most suitable methods for their measurement and evaluation (Research Question no. 1).
- Was then circumscribed to the most representative methods and metrics employed to evaluate a building's embodied impacts over its life cycle (Research Question no. 2).
- Finally, addressed the development of a possible methodological and operative framework with the aim of enabling an essential but indicative embodied impacts evaluation, optimized for the process phases that mainly affect the shaping of the environmental profiles of buildings (Research Questions no. 3).

Throughout the research, this work delivered the following outcomes:

- An overview of the aspects that may be considered the most relevant for building sustainability with an indication of the relative weight of each aspect, as well as particular insight into the environmental impacts.
- A detailed picture of the existing methodologies and tools (LCA, EPD etc.) capable of measuring, evaluating and displaying the magnitude of the environmental impacts related to a building's life cycle, reporting the regulatory and standard frameworks adopted internationally and identifying the most relevant strengths and weaknesses of the LCA method applied to buildings.
- A core set of LCA framework features that might be considered the most representative characteristics for building applications.
- The proposal of a simplified and essential framework to evaluate the embodied impacts over a building's life cycle, suitable for application within the EU context.
- An overview of recent technologies capable of digitizing the building process (BIM) with specific insight into the integration of such technologies with environmental assessment methods.
- The proposal of a customizable operative approach intended to integrate the proposed LCA framework (or a similar one) with a BIM platform, in order to

deliver real-time evaluations of the embodied impacts of a building as the design process advances.

Although the need for additional developments, improvements and optimization emerged as an ongoing issue, the results achieved may be considered a further step towards attainment of a comprehensive integrated project process, which represents a key factor for achieving sustainable objectives (Antón and Diaz, 2014) and enhancing the accomplishment of greater environmental quality of buildings.

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ANNEX A

Green Buildings Rating Systems comparison summary boards

A.1 Active House Summary Board

ACTIVE HOUSE 2013

Quantitative Parameters

Principles	Criteria Group	Criteria	Criteria Matches					Single Criteria Matches Percentage	Single Criterion Weight	Evaluation Area Weight
			DGNB	CSH	ITACA	GBC Home	HQE residential			
1. COMFORT	1.1. Daylight	1.1.1 Daylight Factor	3.1.5	7.1	4.3.1	5.4.1	10.2	5/5 100%	6,67%	33,33%
		1.1.2 Direct Sunlight Available	3.1.5	7.1	X	X	10.2	3/5 60%	6,67%	
	1.2. Thermal Environment	1.2.1 Maximum Operative temperature	3.1.2	X	4.2.1	X	8.2	3/5 60%	6,67%	
		1.2.2 Minimum Operative Temperature	3.1.1	X	X	X	8.1	2/5 40%	6,67%	
	1.3. Indor Air Quality	1.3.1 Standard Fresh Air Supply	3.1.3	X	4.1.1	5.1.1 5.1.2	11.2 13.2	4/5 80%	6,67%	
2. ENERGY	2.1. Energy demand	2.1.1 Annual Energy Demand	1.3.1 1.3.2	X	2.1.1 2.1.2 2.5.1	P.3.1 3.1.1 3.1.2	4.1.	4/5 80%	11,11%	33,33%
	2.2. Energy Supply	2.2.1 Origin of Energy Supply	1.3.2	X	2.2.1 2.2.2	3.2.1 3.1.1 2.2.1 2.3.1	4.1	4/5 80%	11,11%	
	2.3. Primary Energy Performance	2.3.1 Annual Primary Energy Performance	1.3.2	X	X	P.3.1 2.2.1 2.3.1	4.1	3/5 60%	11,11%	
3. ENVIRONMENT	3.1. Environmental Loads	3.1.1 Building's Primary Energy Consuption during Entire Lyfe Cylcle	1.3.1	1.2	2.1.1 2.1.2 2.5.1	3.1.1 3.1.2	X	4/5 80%	3,70%	33,33%
		3.1.2 Global Warming Potential (GWP) during Building's Life Cycle	1.1.1	1.1 6.1	3.1.1	5.3.1	2.2	5/5 100%	3,70%	
		3.1.3 Ozone Depletion Potentnial (ODP) during B.L.C.	1.1.2	X	X	5.3.1	2.2.	3/5 60%	3,70%	
		3.1.4 Photochemical Ozone Creation Potential (POCP) during B.L.C.	1.1.3	X	X	5.3.1	X	2/5 40%	3,70%	
		3.1.5 Acidification Potential (AP) during B.L.C.	1.1.4	X	X	5.3.1	2.2	3/5 60%	3,70%	
		3.1.6 Eutrophication Potential(EP) during B.L.C.	1.1.5	X	X	5.3.1	2.2	2/5 40%	3,70%	
	3.2. Fresh Water Consumption	3.2.1 Minimization of Fresh Water Consumption during Building's Use	1.3.3	2.1 2.2	2.4.1. 2.4.2	P.2.1 2.1 2.2	5.2 5.3	5/5 100%	3,70%	
	3.3. Sustainable Construction	3.3.1Recyclable Content	1.2.2	3.2 3.3	2.3.2 2.3.3 2.3.5	4.1.1 4.1.2	X	4/5 80%	3,70%	
		3.3.2 Responsible Sourcing	1.2.2	3.2 3.3 3.1	X	4.3.1 4.4.1	2.2	4/5 80%	3,70%	
		Common Matches	17/17	7/17	8/17	14/17	14/17	Tot:	100%	100%
		Matches Percentage	100,00%	41,18%	47,06%	82,35%	82,35%			

(Source: Author)

A.2 CSH Summary Board

CSH 2010 (+2014 Add.)

(M) denotes issues with mandatory elements.

Categories	Issues	Active House	DGNB	ITACA	GBC Home	HQE Residential	Single Criteria Matches Percentage	Credits Available	Single Criterion Weight	Category Weighting Factor
1. Energy and CO2 Emissions	1.1. Dwelling Emission rate (M)	3.1.2.	1.1.1	3.1.1	X	X	3/5 60%	10	11,74	36.40
	1.2.Fabric Energy Efficiency (M)	3.1.1	1.3.1	2.1.1 2.1.2 2.5.1	P.3.1 3.1.1 3.1.2	4.1-4.5	5/5 100%	9	10,57	
	1.3.Energy Displays Devices	X	X	X	X	4.6	1/5 20%	2	2,35	
	1.4. Drying Space	X	X	X	X	X	0%	1	1,17	
	1.5.Energy Labelled White Goods	X	X	X	4.3.1 4.4.1 4.4.2 3.3.1	2.2	2/5 40%	2	2,35	
	1.6.External Lighting	X	X	X	X	10.3	1/5 20%	2	2,35	
	1.7.Low and Zero Carbon technology	X	X	X	X	2.2	1/5 20%	2	2,35	
	1.8.Cycle Storage	X	X	1.1.2	X	X	1/5 20%	2	2,35	
	1.9.Home Office	X	X	X	X	X	0%	1	1,17	
2.Water	2.1.Indoor Waste Use (M)	3.2.1	1.3.3	2.4.2	P.2.1 2.1.1 2.1.2	5.2 5.4	5/5 100%	5	7,5	9.00
	2.2.External Water Use	3.2.1	1.3.3	2.4.1	2.2.1 2.2.2	5.2 5.4	5/5 100%	1	1,5	
3. Materials	3.1.Environmental Impact for Materials	3.3.2	1.2.2	X	4.4.1 4.4.2	2.2	4/5 80%	15	4,5	7.20
	3.2.Responsible Sourcing of Materials - Basic Building Elements	3.3.2 3.3.1	1.2.2	2.3.1 2.3.2 2.3.3	4.1.1	X	4/5 80%	6	1,8	
	3.3. Responsible Sourcing of Materials - Finishing Elements	3.3.2 3.3.1	1.2.2	2.3.4	4.1.2	X	4/5 80%	3	0,9	
4.Surface Water Run-Off	4.1.Management of Surface Water Run-Off from Developments (M)	X	X	3.3.1	1.4.1.	5.5	3/5 60%	2	1,1	2.20
	4.2.Flood Risk	X	X	3.3.2	X	X	1/5 20%	2	1,1	
5.Waste	5.1.Storage of non-recyclable waste and recyclable household waste (M)	X	4.1.5	3.2.1	P. 4.1	6.1-6.4 7.3	4/5 80%	4	3,2	6.40
	5.2.Construction site waste management	X	4.1.5	X	P. 4.2 4.2.1 4.2.2	3.3	3/5 60%	3	2,4	
	5.3. Composting	X	X	X	X	X	0%	1	0,8	
6. Pollution	6.1. Global warming potential (GWP) of insulants	3.1.2	1.1.1	3.1.1	4.4.1 4.4.2	2.2	5/5 100%	1	0,7	2.80
	6.2. NOX emissions	X	X	X	X	X	0%	3	2,1	
7. Health and Well-being	7.1.Daylighting	1.1.1 1.1.2	3.1.5	4.3.1	5.4.1	10.2	5/5 100%	4	4,67	14.00
	7.2.Sound insulation	X	3.1.4 4.1.2	4.4.1	5.5.2	9.1 9.2	4/5 80%	3	3,50	
	7.3. Private Space	X	X	X	1.6.2	1.2 12.1	2/5 40%	1	1,17	
	7.4.Lifetime Homes (M)	X	3.2.1	X	X	12.4	2/5 40%	4	4,67	
8.Management	8.1.Home user guide	X	5.1.5 4.1.4	5.3.2	6.1.4	7.1	4/5 80%	3	3,33	10.00
	8.2.Considerate Constructors Scheme	X	5.1.6	X	1.1.1	3.1 3.4 3.2	3/5 60%	2	2,22	
	8.3.Construction site impacts	X	5.1.6	X	Pre. 1.1 1.1.1 1.1.2 1.3.1 1.3.2	3.1 3.2 3.4	3/5 60%	2	2,22	
	8.4.Security	X	3.1.8	X	X	12.3	2/5 40%	2	2,22	
9. Ecology	9.1.Ecological value of site	X	3.1.7 6.1.2 6.1.1	6.1.1	1.3.1 1.3.2 1.1.1 1.1.3 1.1.4	X	3/5 60%	1	1,33	12.00
	9.2.Ecological enhancement	X	X	X	1.3.1 1.3.2 1.1.1 1.1.3 1.1.4	X	1/5 20%	1	1,33	
	9.3.Protection of ecological features	X	X	X	1.3.1 1.3.2 1.1.1 1.1.3	X	1/5 20%	1	1,33	
	9.4.Change in ecological value of site	X	X	X	X	X	0%	4	5,33	
	9.5.Building footprint	X	1.3.4	X	X	X	1/5 20%	2	2,67	
	Common Matches	9/34	19/34	15/34	20/34	20/34		Tot. 107		Tot. 100
	Matches Percentage	26,47%	55,88%	44,12%	58,82%	58,82%				

(Source: Author)

A.3 DGNB Summary Board

DGNB 2011

* meaning of the criterion not defined clearly

Evaluation Area	Criteria Group	Criteria	Matches					Single Criteria Matches Percentage	Weighting Factor	Weighting Factor (including site quality)	Group Points Max. Possible	Group Weigh
			Active House	CSH	ITACA	GBC Home	HQE Residential					
1. ENVIRONMENTAL QUALITY	1.1. Life Cycle Analysis	1.1.1 Global Warming Potential	3.1.2	1.1 6.1	3.1.1	5.3.1	2.2	5/5 100%	3	3,38	200.0	22.5
		1.1.2 Ozone Depletion Potential	3.1.3	X	X	5.3.1	2.2.	3/5 60%	1	1,13		
		1.1.3 Photochemical Ozone Creation Potential	3.1.4	X	X	5.3.1	X	2/5 40%	1	1,13		
		1.1.4 Acidification Potential	3.1.5	X	X	5.3.1	2.2.	3/5 60%	1	1,13		
		1.1.5 Eutrophication Potential	3.1.6	X	X	5.3.1	2.2.	3/5 60%	1	1,13		
	1.2. Global and Local Environmental Impact	1.2.1 Local Environmental Impact*	X	X	X	X	X	0%	3	3,38		
		1.2.2 Sustainable Use of Resource/ Wood	3.3.2 3.3.1	3.1 3.2 3.3	2.3.1 2.3.2 2.3.3 2.3.5	4.1.1 4.1.2 4.3.1 4.4.1	2.2	5/5 100%	1	1,13		
	1.3.Resource Consumption and Waste Generation	1.3.1 Nonrenewable Primary Energy Demand	2.1.1 3.1.1	1.2	2.1.1 2.1.2 2.5.1	P.3.1 3.1.1 3.1.2	4.1-4.5	5/5 100%	3	3,38		
		1.3.2 Total Primary Energy Demand and Proportion of Renewable Primary Energy	2.2.1 2.1.1 2.3.1	X	2.1.1 2.1.2 2.2.1 2.2.2 2.5.1	P.3.1 3.1.1 3.1.2 3.2.1 2.2.1 3.3.1	4.1	4/5 80%	2	2,25		
		1.3.3 Drinkig Water Demand and Volume of Waste Water	3.2.1	2.1 2.2	2.4.1 2.4.2	P.2.1 2.1 2.2	5.2 5.3	5/5 100%	2	2,25		
		1.3.4 Land Use	X	9.5	6.1.1	1.1.1.-1.1.4	X	3/5 60%	2	2,25		
2. ECONOMIC QUALITY	2.1. Life Cycle Costs	2.1.1 Building-Related Life Cycle Costs	X	X	X	X	X	0%	3	13,5	50.0	22.5
	2.2 Economic Performance	2.2.1 Sustainability for Third-Party Use	X	X	X	X	X	0%	2	9		
3. SOCIOCULTURAL AND FUNCTIONAL QUALITY	3.1. Health, Comfort and User Friendliness	3.1.1 Thermal Comfort in Winter	1.2.2	X	X	X	8.1	2/5 40%	2	1,61	280.0	22.5
		3.1.2 Thermal Comfort in Summer	1.2.1	X	4.2.1	X	8.2	3/5 60%	3	2,41		
		3.1.3 Indoor Air Quality	1.3.1	X	4.1.1	5.1.1 5.1.2	11.2 13.2	4/5 80%	3	2,41		
		3.1.4 Acoustic Comfort	X	7.2	4.4.1	5.5.1 5.5.2	9.1 9.2	4/5 80%	1	0,80		
		3.1.5 Visual Comfort	1.1.1 1.1.2	7.1	4.3.1	5.4.1	10.2	5/5 100%	3	2,41		
		3.1.6 User Influence on Building Operations	X	8.1	5.3.2	6.1.4	7.1	4/5 80%	2	1,61		
		3.1.7 Quality of Outdoor Spaces	X	9.1	6.1.1	1.3.1 1.3.2 1.1.1 1.1.3	1.2	4/5 80%	1	0,80		
		3.1.8 Safety and Security	X	8.4	X	X	12.3	2/5 40%	1	0,80		
	3.2. Functionality	3.2.1 Accessibility	X	7.4	X	X	12.4	2/5 40%	2	1,61		
		3.2.2 Efficinet Use of Floor Area	X	X	X	X	X	0%	1	0,80		
		3.2.3 Sustainability for Conversion*	X	X	X	X	X	0%	2	1,61		
		3.2.4 Public Access	X	X	6.1.3	1.2.1	1.3	3/5 60%	2	1,61		
		3.2.5 Cycling Convenience	X	X	1.1.2	1.2.4	1.3	3/5 60%	1	0,80		
	3.3. Aestethic Quality	3.3.1 Design and Urban Planning Quality trough Competition	X	X	X	X	X	0%	3	2,41		
		3.3.2 Integration of Public Art	X	X	X	X	X	0%	1	0,80		
4. TECHNICAL QUALITY	4.1. Techinical Quality of Building Design and Systems	4.1.1 Fire Prevention	X	X	X	X	X	0%	2	4,5	100.0	22.5
		4.1.2 Indoor Acoustic and Sound Insulation	X	7.2	4.4.1	5.5.1 5.5.2	9.1 9.2	4/5 80%	2	4,5		
		4.1.3 Building Envelope Quality*	X	X	X	X	X	0%	2	4,5		
		4.1.4 Ease of Cleaning ad Maintenance	X	8.1	5.3.2	6.1.4	7.1	4/5 80%	2	4,5		
		4.1.5 Ease of Dismanting and Recycling	X	5.1 5.2	3.2.1	P. 4.1 P. 4.2 4.2.1 4.2.2	3.3 6.1-6.4 7.3	4/5 80%	2	4,5		
5. PROCESS QUALITY	5.1. Quality of the Planning Process	5.1.1 Comprehensive Project Definition*	X	X	X	X	X	0%	3	1,30	230.0	10.0
		5.1.2 Integrated Planning*	X	X	X	X	X	0%	3	1,30		
		5.1.3 Comprehensive Building Design*	X	X	X	X	X	0%	3	1,30		
		5.1.4 Sustainable Aspects in Tender Phase*	X	X	X	X	X	0%	2	0,87		
		5.1.5 Documentation for Facility Management	X	8.1	5.3.2	6.1.4	7.1	4/5 80%	2	0,87		
		5.1.6 Environmelntal Impact of Construction Site/Construction Process	X	8.2 8.3	**2.3.1**	P. 1.1 1.1.1 1.1.2 1.3.1 1.3.2	3.1 3.4 3.2	4/5 80%	2	0,87		
		5.1.7 Prequalification of Contractors	X	X	X	X	X	0%	2	0,87		
	5.2. Constructon Quality	5.2.1 Construction Quality Assurance	X	X	X	X	X	0%	3	1,30		
		5.2.2 Systematic Commissioning	X	X	X	X	X	0%	3	1,30		
									Tot. 86		Tot. 860	Tot. 100
6. SITE QUALITY	6.1. Site Quality	6.1.1 Site Location Risks	X	9.1	6.1.1	1.1.1.-1.1.4	X	3/5 60%	2	2,31	130.0	15.0 assumption: 860:100=990:X
		6.1.2 Site Location Conditions	X	9.1	6.1.1	1.1.1.-1.1.4	X	3/5 60%	2	2,31		
		6.1.3 Public Image and Social Conditions	X	X	X	X	X		2	2,31		
		6.1.4 Access to Transportation	X	X	6.1.2	1.2.3 1.2.2	1.3	3/5 60%	3	3,46		
		6.1.5 Access to Specific Use Facilities	X	X	6.1.4	X	1.3	2/5 40%	2	2,31		
		6.1.6 Connection to Utilities	X	X	6.1.4	X	1.3	2/5 40%	2	2,31		
		Common Matches	13/48	17/48	23/48	25/48	27/48		99	115,00	Tot .990	
		Matches Percentage	27.08%	35,42%	47,92%	52,08%	56,25%					

(Source: Author)

A.4 GBC Home Summary Board

GBC Home 2014

(yellow) : One excludes the other within the same credit

Evaluation Area	Credits	Criteria	Active House	CSH	ITACA	DGNB	HQE Residential	Single Criteria Matches Percentage	Points Available	Total Points	Criteria weight	Evaluation Area Weight
1. SUSTAINABILITY OF THE SITE	Precondition 1	P.1.1 Pollution Prevention from Construction Site Activities	X	X	X	5.1.6	3.1 3.2 3.4	2/5 40%	/	/	/	/
	1.1 Site Selection and Building Density	1.1.1 Site Selection	X	8.2 8.3 9.1-9.3	6.1.1	1.3.4 3.1.7 5.1.6 6.1.1	X	3/5 60%	1	25	0,91	22,73%
		1.1.2 Building Density	X	8.3	6.1.1	1.3.4 5.1.6 6.1.1 6.1.2	X	3/5 60%	3		2,73	
		1.1.3 Recovery and Redevelopment of Contaminated Sites	X	9.1-9.3	6.1.1	1.3.4 3.1.7 6.1.1 6.1.2	X	3/5 60%	3		2,73	
		1.1.4 Filling, Reconstruction and Expansion	X	9.1-9.3	6.1.1	1.3.4 6.1.1 6.1.2	X	3/5 60%	2		1,82	
	1.2 Proximity to Collective Services and Alternative Mobility	1.2.1 Proximity to Services	X	X	1.1.1 6.1.3	3.2.4	1.3	3/5 60%	2		1,82	
		1.2.2 Proximity to Train Station	X	X	6.1.2	6.1.4	1.3	3/5 60%	1		0,91	
		1.2.3 Proximity to Bus Stops	X	X	6.1.2.	6.1.4	1.3	3/5 60%	2		1,82	
		1.2.4 Proximity to Alternative Mobility Services	X	X	1.1.2	3.2.5	1.3	3/5 60%	2		1,82	
	1.3 Site Menagement and Green Spaces	1.3.1 Site Menagement	X	8.3 9.1-9.3	X	3.1.7	1.2	3/5 60%	1		0,91	
		1.3.2 Green Spaces	X	8.3 9.1-9.3	X	3.1.7	1.2	3/5 60%	1		0,91	
	1.4 Rain Waters	1.4.1 Rain Waters	X	4.1	X	X	5.5.	2/5 40%	2		1,82	
	1.5 "Heat Island Effect"	1.5.1 "Heat Island Effect"	X	X	3.4.1	X	X	1/5 20%	2		1,82	
	1.6 Common Areas : relationship spaces and common spaces	1.6.1 Relationship Indoor Spaces	X	X	X	X	12.1	1/5 20%	2		1,82	
		1.6.2 Relationship Outdoor Spaces	X	7.3	X	X	1.2	2/5 40%	1		0,91	
2. WATER MENAGEMENT	Precondition 2	P.2.1 Reduction of Drinking Water for Domestic Uses Consuption	3.2.1	2.1	2.4.1 2.4.2	1.3.3	5.2	5/5 100%	/	/	/	/
	2.1 Reduction of Drinking Water for Domestic Uses Consuption	2.1.1 Comsuption reduction	3.2.1	2.1	2.4.2	1.3.3	5.2	5/5 100%	4	10	3,64	9,09%
		2.1.2 Non-drinking Water Reuse Strategies	X	2.1	3.3.1	1.3.3	5.4	4/5 80%	2		1,82	
	2.2 Efficient Management of Water for irrigation	2.2.1 Reduction of Irrigation trough Efficient Landscape Design	X	2.2	2.4.1	1.3.3	X	3/5 60%	2		1,82	
		2.2.2 No Use of Drinking Water for Irrigation	3.2.1	2.2	2.4.1	1.3.3	5.4 5.5	5/5 100%	4		3,64	
3. ENERGY AND ATHMOSPHERE	Precondition 3	P.3.1 Minimum Energetic Performance	2.1.1 2.3.1	1.2	2.1.1 2.1.2 2.5.1	1.3.1 1.3.2	4.1	5/5 100%	/	/	/	/
	3.1 Energetic Performance Optimization	3.1.1 Semplified Procedure	2.2.1 2.3.1	1.2	2.1.1 2.1.2	1.3.1 1.3.2	4.1	5/5 100%	16	30	14,54	27,27%
		3.1.2 Dynamic Thermal-Energetic Simulation	2.2.1 2.3.1	1.2	2.1.1 2.1.2	1.3.1 1.3.2	4.1	5/5 100%	22		20,00	
	3.2 In-site Renewable Energy Production	3.2.1 In-site Renewable Energy Production	2.2.1	X	2.2.1 2.2.2	1.3.2	4.1	4/5 80%	6		5,45	
	3.3 Appliances	3.3.1 Appliances	X	1.5	X	1.3.2	X	2/5 40%	2		1,82	
4. MATERIALS AND RESOURCES	Precondition 4	P.4.1 Collection and Storage of Recyclable Materials	X	5.1	2.3.2	4.1.5	6.1-6.4	4/5 80%	/	/	/	/
		P.4.2 Demolition/Costruction Waste Management	X	5.2	X	4.1.5	3.3	3/5 60%	/	/	/	/
	4.1 Reuse of Structural and Non-structural Building's Elements	4.1.1 Shell and Structures	3.3.1 (only for Existing Buildings)	3.2	2.3.1	1.2.2	2.2	5/5 100%	2	15	1,82	13,64%
		4.1.2 Interior partitions	3.3.1 (only for Existing Buildings)	3.3	X	1.2.2	2.2	4/5 80%	1		0,91	
	4.2 Construction and demolition waste management	4.2.1 Divert a Percentage of Waste	X	5.2	X	4.1.5	3.3	3/5 60%	2		1,82	
		4.2.2 m2 of Gross Surface Producted Waste	X	5.2	X	4.1.5	3.3	3/5 60%	2		1,82	
	4.3 Multicriteria Certification	4.3.1 Multicriteria Certification	3.3.2	1.5	2.3.3	1.2.2	2.2	5/5 100%	4		3,64	
	4.4 Environmental Optimization of Products	4.4.1 New Construction	3.1.2-3.1.6	1.5 3.1 6.1	2.3.3	1.2.2	2.2	5/5 100%	4		3,64	
		4.4.2 Refurbishment	3.1.2-3.1.6	1.5 3.1 6.1	2.3.3	1.1.1 1.2.2	2.2	5/5 100%	4		3,64	
	4.5 Materials Extracted, processed and Produced Nearby	4.5.1 Materials Extracted, processed and Produced Nearby	X	X	2.3.4	1.2.2	X	2/5 40%	2		1,82	
5. INDOOR ENVIRONMENTAL QUALITY	Precondition 5	P.5.1 Combustion Gas Emissions Control	X	X	X	X	13.1	1/5 20%	/	/	/	/
		P.5.2 Protection from Near Garages Pollution	X	X	X	X	X	0%	/	/	/	/
		P.5.3 Radon Protection	X	X	X	X	X	0%	/	/	/	/
		P.5.4 Extraction System in Kitchens and Bathrooms	X	X	X	X	8.1 8.2	1/5 20%	/	/	/	/
	5.1 Fresh Air Areation and Humidity Control	5.1.1 Fresh Air Areation Designed	1.3.1	X	4.1.1	3.1.3	X	3/5 60%	4	20	3,64	18,18%
		5.1.2 Mechanical Ventilation	1.3.1	X	4.1.1	1.1.1-1.1.5 3.1.3	11.2 13.2	4/5 80%	7		6,36	
		5.1.3 Humidity Control	X	X	X	X	8.3	1/5 20%	2		1,82	
	5.2 Indoor Pollution Control	5.2.1 During Construction Phase	X	X	X	X	3.4	1/5 20%	1		0,91	
		5.2.2 Before Occupancy	1.3.1	X	X	3.1.3	3.4	3/5 60%	1		0,91	
	5.3 Low Emission Materials	5.3.1 Low Emission Materials	X	X	X	X	2.3	1/5 20%	4		3,64	
	5.4 Daylight Factor (average)	5.4.1 Daylight Factor (average)	1.1.1	7.1	4.3.1	3.1.5	10.2	5/5 100%	2		1,82	
	5.5 Acustics	5.5.1 Noise Reduction Strategies during Construction Phase	X	X	4.4.1	3.1.4 4.1.2	9.1 9.2	3/5 60%	1		0,91	
		5.5.2 Regulation Acoustic Value Check up	X	7.2	4.4.1	3.1.4 4.1.2	9.1 9.2	4/5 80%	2		1,82	
6. DESIGN INNOVATION	6.1 Design Innovation	6.1.1 Design Innovation	X	X	X	X	X	0%	max3	6	0,91	5,45%
		6.1.2 ExemplaryPerformance	X	X	X	X	X	0%	max3		0,91	
		6.1.3 Integrated Design	X	X	X	X	X	0%	2		1,82	
		6.1.4 Building Use and Maintenance	X	8.1	5.3.2	3.1.6 4.1.4 5.1.5	7.1	4/5 80%	1		0,91	
	6.2 GBC Home AP Expert	6.2.1 GBC Home AP Expert	X	X	X	X	X	0%	1		0,91	
7.REGIONAL PRIORITY	7.1 Regional Priority	7.1.1 Specific Credit	X	X	X	X	X	0%	1	4	0,91	3,64%
		7.1.2 Specific Credit	X	X	X	X	X	0%	1		0,91	
		7.1.3 Specific Credit	X	X	X	X	X	0%	1		0,91	
		7.1.4 Specific Credit	X	X	X	X	X	0%	1		0,91	
		Common Matches	16/60	29/60	30/60	38/60	38/60			Tot. = 110		Tot. = 100%
		Matches Percentage	26,67%	48,33%	50%	63,33%	63,33%					

(Source: Author)

A.5 Protocollo ITACA Summary Board

PROTOCOLLO ITACA 2011 (V.2012)

Tool 1: Building and surrounding areas				Active House	CSH	DGNB	GBC Home	HQE Residential		Refurbishment		New Costruction	
Evaluation Area	Criteria Group	Criteria	ID	Matches					Single Criteria Matches Percentage	Waighting Factor [%] Single Tool	Waighting Factor [%] Complete Tool	Waighting Factor [%] Single Tool	Waighting Factor [%] Complete Tool
1. SITE QUALITY	1.1 Design of the Area	1.1.1 External Common Area Serviced	A.3.3	X	X	6.1.5 6.1.6	1.2.1	1.2	3/5 60%	1	1	1	1
		1.1.2 Bicycle's Use Support	A.3.4	X	1.8	3.2.5	1.2.4	X	3/5 60%	4	3	4	3
2.RESOURCES CONSUPTION	2.1 Primary Non-renewable energy Demand during the Buildig's Life Cycle	2.1.1 Heating Primary Energy Demand	B.1.2	2.1.1 3.1.1	1.2	1.3.1 1.3.2	P.3.1 3.1.1 3.1.2	4.1	5/5 100%	7	6	7	6
		2.1.2 Domestic Hot Water Energy Demand	B.1.5	2.1.1 3.1.1	1.2	1.3.1 1.3.2	P.3.1 3.1.1 3.1.2	4.1	5/5 100%	7	6	7	6
	2.2 Energy from Renewable Sources	2.2.1 Renewable Energy for thermal Uses	B.3.2	2.2.1	X	1.3.2	3.2.1	4.1	4/5 80%	2	2	2	2
		2.2.2 Energy Produced in the Site for Electric Uses	B.3.3	2.2.1	X	1.3.2	3.2.1	4.1	4/5 80%	2	2	2	2
	2.3 Eco-friendly Materials	2.3.1 Existing Structures Reuse	B.4.1	X	3.2	5.1.6 1.1.2	4.1.1	2.2	4/5 80%	3	2	0	0
		2.3.2 Recycled Materials	B.4.6	3.3.1	3.2	1.2.2	P.4.1	2.2	5/5 100%	2	2	3	2
		2.3.3. Materials from Renewable Sources	B.4.7	3.3.1	3.2	1.2.2	4.3.1 4.4.1 4.4.2	2.2	5/5 100%	2	2	3	3
		2.3.4 Local Materials for Finishing	B.4.9	X	3.3	1.2.2	4.5.1	2.2	4/5 80%	2	2	3	2
		2.3.5 Recyclable/removable Materials	B.4.10	3.3.1	X	1.2.2	X	2.2	3/5 60%	2	2	3	3
	2.4 Drinking Water	2.4.1 Drinking Water for Irrigation	B.5.1	3.2.1	2.2	1.3.3	P.2.1 2.2.1 2.2.2.	5.5	5/5 100%	4	4	4	4
		2.4.2 Indoor Drinking Water	B.5.2	3.2.1	2.1	1.3.3	P.2.1 2.1.1	5.3	5/5 100%	2	2	2	2
	2.5 Shell Performance	2.5.1 Net Energy for Cooling	B.6.2	2.1.1 3.1.1	1.2	1.3.2	P.3.1	X	4/5 80%	0	0	5	5
		2.5.2 Shell Thermal Trasmittance	B.6.3	X	X	X	X	X	0%	3	3	4	3
		2.5.3 Solar Radiation Control	B.6.4	X	X	X	X	X	0%	3	3	0	0
		2.5.4 Thermal Inertia of the Building	B.6.5	X	X	X	X	X	0%	3	3	0	0
3.ENVIRONMENTAL LOADS	3.1 CO2 eq. Emissions	3.1.1 Expected Emissions during Operative Phase	C.1.2	3.1.2	1.1 6.1	1.1.1	X	X	3/5 60%	6	5	6	5
	3.2 Solid Waste	3.2.1 Solid Waste during Operative Phase	C.3.2	X	5.1	4.1.5	X	6.1 6.3 6.4	3/5 60%	3	3	3	3
	3.3 Waste Water	3.3.1 Waste Water (Grey) Channeled Into Sewer	C.4.1	X	4.1	X	2.1.2	5.4	3/5 60%	5	4	5	4
		3.3.2 Soil Permeability	C.4.3	X	4.2	X	X	X	1/5 20%	2	2	2	2
	3.4 Surrounding Environment Impact	3.4.1 "Heat Island Effect"	C.6.8	X	X	X	1.5.1	X	1/5 20%	4	4	4	4
4. INDOOR ENVIRONMENTAL QUALITY	4.1 Ventilation	4.1.1 Ventilation and Air Quality	D.2.5	1.3.1	X	3.1.3	5.1.1 5.1.2	11.2 13.2	4/5 80%	4	4	4	4
	4.2 Hygrothermal Comfort	4.2.1 Air Temperature during Summer	D.3.2	1.2.1	X	3.1.2	X	8.2	3/5 60%	5	5	5	5
	4.3 Visual Comfrot	4.3.1 Daylighting	D.4.1	1.1.1	7.1	3.1.5	5.4.1	10.2	5/5 100%	4	4	4	4
	4.4 Acoustic Comfort	4.4.1 Acoustic Quality of the Building	D.5.6	X	7.2	3.1.4 4.1.2	5.5.1 5.5.2	9.1 9.2	4/5 80%	5	5	5	5
	4.5 Electromagnetic Pollution	4.5.1 Magnetic Fields at Industrial Frequency (50Hz)	D.6.1	X	X	X	X	12.1	1/5 20%	2	2	2	2
5.FACILITES QUALITY	5.1 Operative Phase Security	5.1.1. Integration of Home Automation Systems	E.1.9	X	X	X	X	7.5	1/5 20%	2	2	2	2
	5.2 Functionality and Efficiency	5.2.1 Cabling System Quality	E.2.4	X	X	X	X	X	0%	3	2	3	2
	5.3 Maintenance of Performance during Operative Phase	5.3.1 Shell Performances Maintenance	E.6.1	X	X	X	X	X	0%	4	3	4	3
		5.3.2 Availability of Technical Guides of the Building	E.6.5	X	8.1	3.1.6 4.1.4 5.1.5	6.1.4	7.1	4/5 80%	2	2	2	2
Tool 2: Site	6.1 Site Selection	6.1.1 Reuse of the Territory	A.1.5	X	9.1	1.3.4 3.1.7 6.1.1 6.1.2	1.1.1.-1.1.4	X	3/5 60%	0	0	34	3
SITE QUALITY		6.1.2 Accessibility to Public Transportation	A.1.6	X	X	6.1.4	1.2.3 1.2.2	1.3	3/5 60%	36	4	23	2
		6.1.3 Fuctional Mix of the Area	A.1.8	X	X	3.2.4	1.2.1	1.3	3/5 60%	34	3	23	2
		6.1.4 Proximity to Infrastructures	A.1.10	X	X	6.1.5 6.1.6	X	1.3	2/5 40%	30	3	20	2
		Common Matches Tool 1		14/31	18/31	21/31	19/31	21/31		100	92	101	91
		Common Mathches Tool 2		0/4	1/4	4/4	3/4	3/4		100	10	100	9
		Matches Percentage Complete Tool		40,00%	51,43%	71,43%	62,86&	68,57%		/	102	/	100

(Source: Author)

A.6 HQE Summary Board

HQE Bâtiment Résidentiel 2014

Topic	Targets	Criteria	Active House	CSH	ITACA	DGNB	GBC Home	Single Criteria Matches Percentage	Top Performing Points Available	Tot TP per Topic	Criteria Weight	Topic Weight
			Matches									
ENVIRONMENT 14	1. Building's relationship with its immediate environment	1.1. Site analysis	X	X	X	X	X	0%	2	36	1,59	28,57%
		1.2. Layout of the plot to promote a pleasant living environment	X	7.3	1.1.1	3.1.7	1.3.1 1.3.2	4/5 80%	1		0,79	
		1.3. Layout of the plot to encourage eco-mobility	X	X	6.1.2	3.2.4 3.2.5 6.1.4 6.1.5 6.1.6	1.2.1-1.2.4	3/5 60%	2		1,59	
	2. Quality of components	2.1. Technical quality of materials, products and equipment used	X	X	X	X	X	0%	1		0,79	
		2.2. Environmental quality of the materials, products and equipment used	3.3.2 3.1.2 3.1.3 3.1.5 3.1.6	1.5 1.7 3.1 6.1	2.3.1-2.3.5	1.1.1 1.1.2 1.1.4 1.1.5 1.2.2	4.3.1 4.1.1 4.1.2 4.4.1 4.4.2	5/5 100%	3		2,38	
		2.3. Sanitary quality of materials, products and equipment used	X	X	X	X	5.3.1	1/5 20%	3		2,38	
	3. Sustainable worksite	3.1. Commitments and objectives of the building site	X	8.2 8.3	X	5.1.6	P.1.1	3/5 60%	3		2,38	
		3.2. Organization of the building site	X	8.2 8.3	X	5.1.6	P.1.1	3/5 60%	3		2,38	
		3.3. Building-site waste management	X	5.2	X	4.1.5	P.4.2 4.2.1 4.2.2	3/5 60%	4		3,17	
		3.4. Limiting nuisance and pollution on the site	X	8.2 8.3	X	5.1.6	P.1.1 5.2.1	3/5 60%	4		3,17	
	6. Waste management	6.1. Choice of collective waste storage	X	5.1	3.2.1	4.1.5	P.4.1	4/5 80%	1		0,79	
		6.2. Reducing waste production and improving sorting	X	5.1	X	4.1.5	P.4.1	3/5 60%	2		1,59	
		6.3. Conditions of collective storage of waste	X	5.1	3.2.1	4.1.5	P.4.1	4/5 80%	6		4,76	
		6.4. Disposal of waste outside the influence of the operation (requirement to be complied with if the storage of waste is made within the enclosure of the operation)	X	5.1	3.2.1	4.1.5	P.4.1	4/5 80%	1		0,79	
ENERGY AND SAVINGS 15	4. Energy management	4.1. Thermal design	2.1.1 2.2.1 2.3.1	1.2	2.2.1 2.1.1 2.1.2	1.3.1 1.3.2	P.3.1 3.1.1 3.1.2 3.2.1	5/5 100%	3	33	2,38	26,19%
		4.2. Solar thermal energy and/or photovoltaic panels (requirements to be met if solar panels are installed)	X	1.2	X	1.3.1	X	2/5 40%	1		0,79	
		4.3. Thermal insulation of networks	X	1.2	X	1.3.1	X	2/5 40%	2		1,59	
		4.4. Artificial lighting	X	1.2	X	1.3.1	X	2/5 40%	4		3,17	
		4.5. Lift (if present)	X	1.2	X	1.3.1	X	2/5 40%	1		0,79	
		4.6. Control of energy consumption	X	1.3	X	X	X	1/5 20%	1		0,79	
	5. Water management	5.1. Metering of water consumption	X	X	X	X	X	0%	3		2,38	
		5.2. Reduction in consumption of water distributed	3.2.1	2.1 2.2	X	1.3.3	P.2.1 2.1.1	4/5 80%	3		2,38	
		5.3. Need for domestic hot water	3.2.1	X	2.4.2	1.3.3	X	2/5 40%	1		0,79	
		5.4. Waste water management	X	2.1 2.2	3.3.1	1.3.3	2.1.2 2.2.2	4/5 80%	2		1,59	
		5.5. Rainwater management	X	4.1	2.4.1	X	1.4.1 2.2.2	3/5 60%	2		1,59	
	7. Maintenance management	7.1 Information on maintenance	X	8.1	5.3.2	3.1.6 4.1.4 5.1.5	6.1.4	4/5 80%	1		0,79	
		7.2. Water flow control	X	X	X	X	X	0%	2		1,59	
		7.3. Maintenance of the waste storage area (if present)	X	5.1	X	4.1.5	X	2/5 40%	3		2,38	
		7.4. Design to ensure efficient maintenance of other equipment	X	X	X	X	X	0%	3		2,38	
		7.5. Technical management of the building and intelligent home systems	X	X	5.1.1	X	X	1/5 20%	1		0,79	
COMFORT 10	8. Hygrothermal comfort	8.1. Comfort during cold periods (if adapted to a specific country)	1.2.2	X	X	3.1.1	P.5.4	3/5 60%	3	21	2,38	16,67%
		8.2. Comfort during hot periods (if adapted to a specific country)	1.2.1	X	4.2.1	3.1.2	P.5.4	4/5 80%	3		2,38	
		8.3. Hygrometry measurement	X	X	X	X	5.1.3	1/5 20%	1		0,79	
	9. Acoustic comfort	9.1. Including acoustics in the architectural provisions	X	7.2	4.4.1	3.1.4 4.1.2	5.5.1 5.5.2	4/5 80%	1		0,79	
		9.2. Acoustic quality	X	7.2	4.4.1	3.1.4 4.1.2	5.5.1 5.5.2	4/5 80%	2		1,59	
	10. Visual comfort	10.1. Exterior visual context	X	X	X	X	X	0%	2		1,59	
		10.2. Natural lighting	1.1.1 1.1.2	7.1	4.3.1	3.1.5	5.4.1	5/5 100%	2		1,59	
		10.3. Artificial lighting	X	1.6	X	X	X	1/5 20%	1		0,79	
	11. Olfactory comfort	11.1. Controlling sources of unpleasant odour	X	X	X	X	X	0%	3		2,38	
		11.2. Ventilation	1.3.1	X	4.1.1	3.1.3	P.5.4 5.1.2	4/5 80%	3		2,38	
HEALTH AND SAFETY 9	12. Quality of spaces	12.1. Spaces quality and health	X	7.3	4.5.1	X	1.6.1	3/5 60%	4	36	3,17	28,57%
		12.2. Home amenities	X	X	X	X	X	0%	1		0,79	
		12.3. Safety/Security	X	8.4	X	3.1.8	X	2/5 40%	10		7,94	
		12.4. Accessibility and adaptability of the building	X	7.4	X	3.2.1	X	2/5 40%	3		2,38	
	13. Air quality and health	13.1. Control pollution sources	X	X	X	X	P.5.1	1/5 20%	2		1,59	
		13.2. Ventilation	1.3.1	X	4.1.1	3.1.3	P.5.4 5.1.2	4/5 80%	8		6,35	
		13.3. Measuring air quality	X	X	X	X	X	0%	1		0,79	
	14. Water quality and health	14.1. Water quality	X	X	X	X	X	0%	4		3,17	
		14.2. Reducing the risk of legionella	X	X	X	X	X	0%	3		2,38	
		Common Matches	9/49	28/49	19/49	30/49	27/49	TOT:	126		TOT:	100,00%
		Matches Percentage	18,37%	57,14%	38,78%	61,22%	55,10%					

(Source: Author)

ANNEX B

Green Buildings Rating Systems comparison: common categories reallocation

TOOLS COMPARISON

(yellow)	: One excludes the other within the same credit (GBCHome)
(light orange)	: Estimated values

Category	System	Crieria	N° of criteria	Single criterion weight	Single groups weight [615%]	Category weight [615%]	Tot. Groups weight in percentace [100%]	Total categories weight in percentage [100%]	Note
DESIGN QUALITY: USERS	DGNB	6.1.3 Public Image and Social Conditions	17	2,31	39,33	85,21	6,40	13,85	DGNB doesn't consider SITE QUALITY within the final result --> the "6.1." criteria weights have been estimated
		6.1.4 Access to Transportation		3,46					
		6.1.5 Access to Specific Use Facilities		2,31					
		6.1.6 Connection to Utilities		2,31					
		3.1.7 Quality of Outdoor Spaces		0,80					
		3.1.8 Safety and Security		0,80					
		3.2.1 Accessibility		1,61					
		3.2.2 Efficinet Use of Floor Area		0,80					
		3.2.4 Public Access		1,61					
		3.2.5 Cycling Convenience		0,80					
		3.3.1 Design and Urban Planning Quality trough Competition		2,41					
		3.3.2 Integration of Public Art		0,80					
		4.1.1 Fire Prevention		4,50					
		4.1.3 Building Envelope Quality		4,50					
		5.2.1 Construction Quality Assurance		1,30					
		4.1.4 Ease of Cleaning ad Maintenance		4,50					
		4.1.5 Ease of Dismanting and Recycling		4,50					
	CSH	8.4.Security	3	2,22	5,74		0,93		
		1.8.Cycle Storage		2,35					
		1.9.Home Office		1,17					
	Protocollo ITACA	1.1.1 External Common Area Serviced	6	1,00	12		1,95		
		1.1.2 Bicycle's Use Support		3,00					
		4.5.1 Magnetic Fields at Industrial Frequency (50Hz)		2,00					
		6.1.2 Accessibility to Public Transportation		2,00					
		6.1.3 Fuctional Mix of the Area		2,00					
		6.1.4 Proximity to Infrastructures		2,00					
	GBC Home	1.2.1 Proximity to Services	6	1,82	9,09		1,48		
		1.2.2 Proximity to Train Station		0,91					
		1.2.3 Proximity to Bus Stops		1,82					
		1.2.4 Proximity to Alternative Mobility Services		1,82					
		1.6.1 Relationship Indoor Spaces		1,82					
		1.6.2 Relationship Outdoor Spaces		0,91					
	HQE	1.2. Layout of the plot to promote a pleasant living environment	7	0,79	19,05		3,10		
		1.3. Layout of the plot to encourage eco-mobility		1,59					
		12.1. Spaces quality and health		3,17					
		12.2. Home amenities		0,79					
		12.3. Safety/Security		7,94					
		12.4. Accessibility and adaptability of the building		2,38					
		14.2. Reducing the risk of legionella		2,38					

(Source: Author)

DESIGN QUALITY: SITE	DGNB	1.2.1 Local Environmental Impact	5	3,38	11,12	57,54	1,81	9,36	
		1.3.4 Land Use		2,25					
		5.1.6 Environmelntal Impact of Construction Site/Construction Process		0,87					
		6.1.1 Site Location Risks		2,31					
		6.1.2 Site Location Conditions		2,31					
	CSH	4.1.Management of Surface Water Run-Off from Developments (M)	8	1,10	16,41		2,67		
		4.2.Flood Risk		1,10					
		8.3.Construction site impacts		2,22					
		9.1.Ecological value of site		1,33					
		9.2.Ecological enhancement		1,33					
		9.3.Protection of ecological features		1,33					
		9.4.Change in ecological value of site		5,33					
		9.5.Building footprint		2,67					
	Protocollo ITACA	3.3.2 Soil Permeability	3	2,00	9		1,46		
		3.4.1 "Heat Island Effect"		4,00					
		6.1.1 Reuse of the Territory		3,00					
	GBC Home	1.1.1 Site Selection	10	0,91	15,46		2,51		
		1.1.2 Building Density		2,73					
		1.1.3 Recovery and Redevelopment of Contaminated Sites		2,73					
		1.1.4 Filling, Reconstruction and Expansion		1,82					
		1.3.1 Site Menagement		0,91					
		1.3.2 Green Spaces		0,91					
		1.4.1 Rain Waters		1,82					
		1.5.1 "Heat Island Effect"		1,82					
		6.1.1 Design Innovation		0,91					
		6.1.2 ExemplaryPerformance		0,91					
	HQE	3.1. Commitments and objectives of the building site	2	2,38	5,55		0,90		
		3.4. Limiting nuisance and pollution on the site		3,17					
MATERIALS/PRODUCTS	Active House	3.3.1Recyclable Content	2	3,70	7,4	49,10	1,20	7,98	
		3.3.2 Responsible Sourcing		3,70					
	DGNB	1.2.2 Sustainable Use of Resource/ Wood	1	1,13	1,13		0,18		
	CSH	1.5.Energy Labelled White Goods	4	2,35	9,55		1,55		
		3.1.Environmental Impact for Materials		4,50					
		3.2.Responsible Sourcing of Materials - Basic Building Elements		1,80					
		3.3. Responsible Sourcing of Materials - Finishing Elements		0,90					
	Protocollo ITACA	2.3.1 Existing Structures Reuse	5	0,00	10		1,63		
		2.3.2 Recycled Materials		2,00					
		2.3.3. Materials from Renewable Sources		3,00					
		2.3.4 Local Materials for Finishing		2,00					
		2.3.5 Recyclable/removable Materials		3,00					
	GBC Home	4.1.1 Shell and Structures	7	1,82	15,47		2,51		
		4.1.2 Interior partitions		0,91					
		4.3.1 Multicriteria Certification		3,64					
		4.4.1 New Construction		3,64					
		4.4.2 Refurbishment		3,64					
		4.5.1 Materials Extracted, processed and Produced Nearby		1,82					
		5.3.1 Low Emission Materials		3,64					
	HQE	2.1. Technical quality of materials, products and equipment used	3	0,79	5,56		0,90		
		2.2. Environmental quality of the materials, products and equipment used		2,38					
		2.3. Sanitary quality of materials, products and equipment used		2,38					

(Source: Author)

ENERGY	Active House	2.1.1 Annual Energy Demand	4	11,11	37,03	116,75	6,02	18,98	
		2.2.1 Origin of Energy Supply		11,11					
		2.3.1 Annual Primary Energy Performance		11,11					
		3.1.1 Building's Primary Energy Consuption during Entire Lyfe Cylcle		3,70					
	DGNB	1.3.1 Nonrenewable Primary Energy Demand	2	3,38	5,63		0,92		
		1.3.2 Total Primary Energy Demand and Proportion of Renewable Primary Energy		2,25					
	CSH	1.2.Fabric Energy Efficiency (M)	3	10,57	14,09		2,29		
		1.4. Drying Space		1,17					
		1.6.External Lighting		2,35					
	Protocollo ITACA	2.1.1 Heating Primary Energy Demand	6	6,00	24		3,90		
		2.1.2 Domestic Hot Water Energy Demand		6,00					
		2.2.1 Renewable Energy for thermal Uses		2,00					
		2.2.2 Energy Produced in the Site for Electric Uses		2,00					
		2.5.1 Net Energy for Cooling		5,00					
		2.5.2 Shell Thermal Trasmittance		3,00					
	GBC Home	3.1.1 Semplified Procedure	4	14,54	27,27		4,43		
		3.1.2 Dynamic Thermal-Energetic Simulation		20,00					
		3.2.1 In-site Renewable Energy Production		5,45					
		3.3.1 Appliances		1,82					
	HQE	4.1. Thermal design	5	2,38	8,73		1,42		
		4.2. Solar thermal energy and/or		0,79					
		4.3. Thermal insulation of networks		1,59					
		4.4. Artificial lighting		3,17					
		4.5. Lift (if present)		0,79					
WATER	Active House	3.2.1 Minimization of Fresh Water Consumption during Building's Use	1	3,70	3,7	43,56	0,60	7,08	
	DGNB	1.3.3 Drinkig Water Demand and Volume of Waste Water	1	2,25	2,25		0,37		
	CSH	2.1.Indoor Waste Use (M)	2	7,50	9		1,46		
		2.2.External Water Use		1,50					
	Protocollo ITACA	2.4.1 Drinking Water for Irrigation	3	4,00	10		1,63		
		2.4.2 Indoor Drinking Water		2,00					
		3.3.1 Waste Water (Grey) Channeled Into Sewer		4,00					
	GBC Home	2.1.1 Comsuption reduction	4	3,64	9,09		1,48		
		2.1.2 Non-drinking Water Reuse Strategies		1,82					
		2.2.1 Reduction of Irrigation trough Efficient Landscape Design		1,82					
		2.2.2 No Use of Drinking Water for Irrigation		3,64					
	HQE	5.2. Reduction in consumption of water distributed	5	2,38	9,52		1,55		
		5.3. Need for domestic hot water		0,79					
		5.4. Waste water management		1,59					
		5.5. Rainwater management		1,59					
		14.1. Water quality		3,17					
ENVIRONMENTAL IMPACTS	Active House	3.1.2 Global Warming Potential (GWP) during Building's Life Cycle	5	3,70	18,5	48,265	3,01	7,85	
		3.1.3 Ozone Depletion Potentnial (ODP) during B.L.C.		3,70					
		3.1.4 Photochemical Ozone Creation Potential (POCP) during B.L.C.		3,70					
		3.1.5 Acidification Potential (AP) during B.L.C.		3,70					
		3.1.6 Eutrophication Potential(EP) during B.L.C.		3,70					
	DGNB	1.1.1 Global Warming Potential	5	3,38	7,88		1,28		
		1.1.2 Ozone Depletion Potential		1,13					
		1.1.3 Photochemical Ozone Creation		1,13					
		1.1.4 Acidification Potential		1,13					
		1.1.5 Eutrophication Potential		1,13					
	CSH	1.1. Dwelling Emission rate (M)	4	11,74	16,89		2,75		
		6.1. Global warming potential (GWP) of insulants		0,70					
		6.2. NOX emissions		2,10					
		1.7.Low and Zero Carbon technology		2,35					
	Protocollo ITACA	3.1.1 Expected Emissions during Operative Phase	1	5,00	5		0,81		

(Source: Author)

INDOOR ENVIRONMENTAL QUALITY	Active House	1.1.1 Daylight Factor	5	6,67	33,35	118,674	5,42	19,30	
		1.1.2 Direct Sunlight Available		6,67					
		1.2.1 Maximum Operative temperature		6,67					
		1.2.2 Minimum Operative Temperature		6,67					
		1.3.1 Standard Fresh Air Supply		6,67					
	DGNB	3.1.1 Thermal Comfort in Winter	7	1,61	15,75		2,56		
		3.1.2 Thermal Comfort in Summer		2,41					
		3.1.3 Indoor Air Quality		2,41					
		3.1.4 Acoustic Comfort		0,80					
		3.1.5 Visual Comfort		2,41					
		3.1.6 User Influence on Building		1,61					
		4.1.2 Indoor Acoustic and Sound Insulation		4,50					
	CSH	7.1.Daylighting	4	4,67	14,01		2,28		
		7.2.Sound insulation		3,50					
		7.3. Private Space		1,17					
		7.4.Lifetime Homes (M)		4,67					
	Protocollo ITACA	2.5.3 Solar Radiation Control	6	0,00	18,00		2,93		
		2.5.4 Thermal Inertia of the Building		0,00					
		4.1.1 Ventilation and Air Quality		4,00					
		4.2.1 Air Temperature during Summer		5,00					
		4.3.1 Daylighting		4,00					
		4.4.1 Acoustic Quality of the Building		5,00					
	GBC Home	5.1.1 Fresh Air Areation Designed	8	3,64	14,54		2,36		
		5.1.2 Mechanical Ventilation		6,36					
		5.1.3 Humidity Control		1,82					
		5.2.1 During Construction Phase		0,91					
		5.2.2 Before Occupancy		0,91					
		5.4.1 Daylight Factor (average)		1,82					
		5.5.1 Noise Reduction Strategies during Construction Phase		0,91					
		5.5.2 Regulation Acoustic Value Check up		1,82					
	HQE	8.1. Comfort during cold periods (if adapted to a specific country)	11	2,38	23,02		3,74		
		8.2. Comfort during hot periods (if adapted to a specific country)		2,38					
		8.3. Hygrometry measurement		0,79					
		9.1. Including acoustics in the architectural provisions		0,79					
		9.2. Acoustic quality		1,59					
		10.1. Exterior visual context		1,59					
		10.2. Natural lighting		1,59					
		10.3. Artificial lighting		0,79					
		11.1. Controlling sources of unpleasant odour		2,38					
		11.2. Ventilation		2,38					
		13.2. Ventilation		6,35					
ECONOMY	DGNB	2.1.1 Building-Related Life Cycle Costs	2	13,50	22,50	22,50	3,66	3,66	
		2.2.1 Sustainability for Third-Party Use		9,00					
MANAGEMENT	DGNB	5.1.5 Documentation for Facility Management	2	0,87	2,17	35,85	0,35	5,83	
		5.2.2 Systematic Commissioning		1,30					
	CSH	1.3.Energy Displays Devices	3	2,35	7,9		1,28		
		8.1.Home user guide		3,33					
		8.2.Considerate Constructors Scheme		2,22					
	Protocollo ITACA	5.1.1. Integration of Home Automation Systems	4	2,00	9		1,46		
		5.2.1 Cabling System Quality		2,00					
		5.3.1 Shell Performances Maintenance		3,00					
		5.3.2 Availability of Technical Guides of the Building		2,00					
	GBC Home	6.1.4 Building Use and Maintenance	1	0,91	0,91		0,15		
	HQE	3.2. Organization of the building site	10	2,38	15,87		2,58		
		4.6. Control of energy consumption		0,79					
		5.1. Metering of water consumption		2,38					
		13.1. Control pollution sources		1,59					
		13.3. Measuring air quality		0,79					
		7.1 Information on maintenance		0,79					
		7.2. Water flow control		1,59					
		7.3. Maintenance of the waste storage area (if present)		2,38					
		7.4. Design to ensure efficient maintenance of other equipment		2,38					
		7.5. Technical management of the building and intelligent home systems		0,79					

(Source: Author)

WASTE	CSH	5.1.Storage of non-recyclable waste and recyclable household waste (M)	3	3,20	6,4	22,33	1,04	3,63	
		5.2.Construction site waste management		2,40					
		5.3. Composting		0,80					
	Protocollo ITACA	3.2.1 Solid Waste during Operative Phase	1	3,00	3		0,49		
	GBC Home	4.2.1 Divert a Percentage of Waste	2	1,82	1,82		0,30		
		4.2.2 m2 of Gross Surface Producted Waste		1,82					
	HQE	3.3. Building-site waste management	5	3,17	11,11		1,81		
		6.1. Choice of collective waste storage		0,79					
		6.2. Reducing waste production and improving sorting		1,59					
		6.3. Conditions of collective storage of waste		4,76					
		6.4. Disposal of waste outside the influence of the operation (requirement to be complied with if the storage of waste is made within the enclosure of the operation)		0,79					
OTHER	DGNB	3.2.3 Sustainability for Conversion*	6	1,61	7,25	15,21	1,18	2,47	
		5.1.1 Comprehensive Project Definition*		1,30					
		5.1.2 Integrated Planning*		1,30					
		5.1.3 Comprehensive Building Design*		1,30					
		5.1.4 Sustainable Aspects in Tender Phase		0,87					
		5.1.7 Prequalification of Contractors		0,87					
	GBC Home	6.1.3 Integrated Design	6	1,82	6,37		1,04		
		6.2.1 GBC Home AP Expert		0,91					
		7.1.1 Specific Credit		0,91					
		7.1.2 Specific Credit		0,91					
		7.1.3 Specific Credit		0,91					
		7.1.4 Specific Credit		0,91					
	HQE	1.1. Site analysis	1	1,59	1,59		0,26		
						615,00	100,00	100,00	

(Source: Author)

ANNEX C

Green Buildings Rating Systems comparison: operational vs non-operational environmental impacts

Active House			
Use - Total (%)	3,7	Other phase - Total (%)	29,6
3.2.1 Minimization of Fresh Water Consumption during Building's Use	3,7	3.3.1Recyclable Content	3,7
		3.3.2 Responsible Sourcing	3,7
		3.1.1 Primary Energy LC	3,7
		3.1.2 Global Warming Potential (GWP) during Building's Life Cycle	3,7
		3.1.3 Ozone Depletion Potentnial (ODP) during B.L.C.	3,7
		3.1.4 Photochemical Ozone Creation Potential (POCP) during B.L.C.	3,7
		3.1.5 Acidification Potential (AP) during B.L.C.	3,7
		3.1.6 Eutrophication Potential(EP) during B.L.C.	3,7
CSH			
Use - Total (%)	23,09	Other phase - Total (%)	10
		3.1.Environmental Impact for Materials	4,5
1.1 Dwelling Emssion Rate	11,74	3.2.Responsible Sourcing of Materials - Basic Building Elements	1,8
1.7 Low and Zero Carbon technology	2,35	3.3. Responsible Sourcing of Materials - Finishing Elements	0,9
2.1.Indoor Waste Use (M)	7,5	6.1. Global warming potential (GWP) of insulants	0,7
2.2.External Water Use	1,5	6.2. NOX emissions	2,1
DGNB			
Use - Total (%)	3,38	Other phase - Total (%)	7,9
1.2.2 Sustainable Use of Resource/ Wood	1,13	1.1.1 Global Warming Potential	3,38
1.3.3 Drinkig Water Demand and Volume of Waste Water	2,25	1.1.2 Ozone Depletion Potential	1,13
		1.1.3 Photochemical Ozone Creation Potential	1,13
		1.1.4 Acidification Potential	1,13
		1.1.5 Eutrophication Potential	1,13
ITACA			
Use - Total (%)	28	Other phase - Total (%)	0
2.3.1 Existing Structures Reuse	0		
2.3.2 Recycled Materials	2		
2.3.3. Materials from Renewable Sources	3		
2.3.4 Local Materials for Finishing	2		
2.3.5 Recyclable/removable Materials	3		
3.1.1 Expected Emissions during Operative Phase	5		
3.2.1 Solid Waste during Operative Phase	3		
2.4.1 Drinking Water for Irrigation	4		
2.4.2 Indoor Drinking Water	2		
3.1.1 Expected Emissions during Operative Phase	4		
HQE			
Use - Total (%)	19,84	Other phase - Total (%)	2,38
3.3. Building-site waste management	3,17	2.2. Environmental quality of the materials, products and equipment used	2,38
6.1. Choice of collective waste storage	0,79		
6.2. Reducing waste production and improving sorting	1,59		
6.3. Conditions of collective storage of waste	4,76		
6.4. Disposal of waste outside the influence of the operation	0,79		
2.1. Technical quality of materials, products and equipment used	0,79		
2.3. Sanitary quality of materials, products and equipment used	2,38		
5.2. Reduction in consumption of water distributed	2,38		
5.4. Waste water management	1,59		
5.5. Rainwater management	1,59		
GBC			
Use - Total (%)	9,1	Other phase - Total (%)	86,1
2.1.1 Comsuption reduction	3,64	4.4 Environmental Optimization of Products	4
2.1.2 Non-drinking Water Reuse Strategies	1,82	4.3 Multicriteria Certification	4
2.2.1 Reduction of Irrigation trough Efficient Landscape Design	3,64	4.2 Construction and demolition waste management	2
		4.1 Reuse of Structural and Non-structural Building's Elements	3
USE Phase TOTAL [615%]	87,11	OTHER Phases TOTAL [615%]	62,88
USE Phase TOTAL [100%]	14.16	OTHER Phases TOTAL [100%]	10,22

(Source: Author)