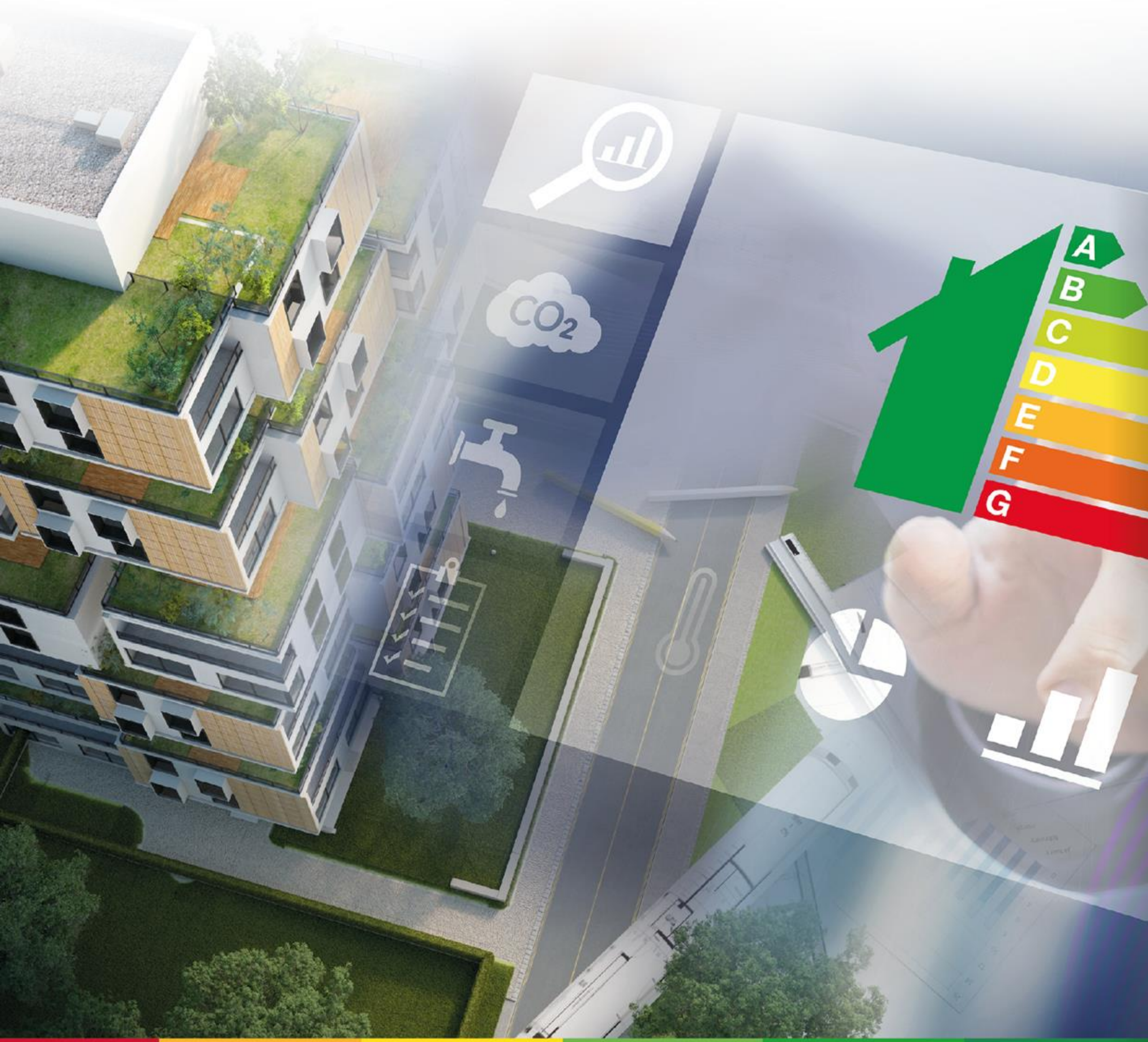
Ref. Ares(2023)5343936 - 02/08/2023

D2.1 Asset methodology assessment in building level



Project Acronym:	SmartLivingEPC
Project Full Title:	Advanced Energy Performance Assessment towards Smart Living in Building and District Level
Grant Agreement:	101069639
Project Duration:	36 months (01/07/2022 – 30/06/2025)

Deliverable 2.1

Asset methodology assessment in building level

Work Package:	WP2 Smart Living EPCs Framework Asset Methodology
Task:	T2.1 SRI analysis and integration to SmartLivingEPC T2.2 Energy and non-energy resources analysis and integration to SmartLivingEPC T2.3 Environmental life-cycle assessment and integration to SmartLivingEPC T2.4 Technical audits and inspections integration to SmartLivingEPC
Document Status:	Draft v0.1
File Name:	SLE_D2.1
Due Date:	30.07.2023
Submission Date:	31.07.2023
Lead Beneficiary:	FRC

Dissemination Level	
Public	☒
Confidential, only for members of the Consortium (including the Commission Services)	☐

Authors List

Leading Author				
First Name		Last Name	Beneficiary	Contact e-mail
Phoebe-Zoe		Georgali	FRC	res.gp@frederick.ac.cy
Paris		Fokaides	FRC	eng.fp@frederick.ac.cy
Co-Author(s)				
#	First Name	Last Name	Beneficiary	Contact e-mail
1	Cătălin	Lungu	AIIR	vicepresedinte@aiiro.ro
2	Tiberiu	Catalina	AIIR	tiberiu.catalina@aiiro.ro
3	Pablo	Carnero	REHVA	pcm@rehva.eu
4	Paul	Waide	WSE	paul@waide-europe.eu
5	Corin	Waide	WSE	corin@waide-europe.eu

Reviewers List

Reviewers			
First Name	Last Name	Beneficiary	Contact e-mail
Aggeliki	Veliskaki	CERTH	aveliskaki@iti.gr

Version History

v	Author	Date	Brief Description
1	Phoebe-Zoe Georgali Paris Fokaides	04.07.2023	First draft version of the document
2	Pablo Carnero	04.07.2023	Input from REHVA
3	Paul Waide	14.07.2023	Input from WSE
4	Cătălin Lungu	18.07.2023	Input from AIIR
5	Phoebe-Zoe Georgali	24.07.2023	Circulation for review
6	Phoebe-Zoe Georgali Paris Fokaides	30.07.2023	Document finalization

Copyright

Table of Contents

List of Figures

List of Tables

List of Acronyms, Abbreviations and other Terms used in the document

Term	Description
AC	Air-conditioning
AHU	Air-handling unit
API	Application Programming Interfaces
BAC	Building automation and control Products, software, and engineering services for automatic controls, monitoring and optimization, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services equipment. "Control" does not imply that the system or device is restricted to input/output, processing, optimization, management, and operator functions. Processing of data and information is possible.
BACS	Building automation and control system **BACS** is also referred to as **BMS** (building management system) **BEMS** (building energy management system) is part of a **BMS**
BAPV	Building Attached Photovoltaics
BEMS	Building energy management system Comprises data collection, logging, alarming, reporting, and analysis of energy usage, etc. The system is designed to reduce energy consumption, improve utilization, increase reliability, and predict the performance of the technical building systems, as well as optimize energy usage and reduce its cost.
BESS	Battery Energy Storage Systems
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaics
BM	Building management The totality of services involved in the management operation and monitoring of buildings (including plats and installations). Building management can be assigned as part of facility management.
Building fabric	All physical elements of a building, excluding technical building systems. It is often described as the building as such. It includes elements both inside and outside the thermal envelope, including the thermal envelope itself.
Building service	Service is provided by technical building systems and by appliances to provide acceptable indoor environment conditions, domestic hot water, illumination levels, and other services related to the use of the building. The services included in EPB assessments are referred to as "EPB services". Contrarily those not included as "non-EPB services".
CA	Concerted Action (of the EPBD)
CAV	Constant Air Volume
CB	Chilled Beams
CE	"Conformité Européenne" (European conformity marking)
CEN	French: Comité Européen de Normalisation; English: European Committee for Standardization
CENELEC	French: Comité Européen de Normalisation Électrotechnique; English: European Committee for Electrotechnical Standardization
COP	Coefficient of Performance
DC	Direct Current
DCV	Demand-Controlled Ventilation
Distant	Not on-site nor nearby.
DG	Directorate-General
DHW	Domestic Hot Water
DR	Demand Response

DX	Direct Expansion
EC	European Commission
ED	Ecodesign Directive
EED	Energy Efficiency Directive
EEI	Energy Efficiency Index
EER	Energy Efficiency Ratio
ELR	Energy Labelling Regulation
EMS	Energy Monitoring System
EN	European Norm
ENER	Directorate-General for Energy
EPB	Energy performance of Buildings (Directive)
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPREL	European Product Database for Energy Labelling
EU	European Union
EU27	27 Member countries of the EU
EU28	The former 28 Member countries of the EU
EUR	Euro (currency)
FCU	Fan Coil Unit
FM	Facility Manager
FP	Flue Pipe
Functionality level	As a term within the SRI calculation methodology, means the level of smart readiness of a smart-ready service.
GHG	greenhouse gases
H2020	Horizon 2020
HIU	Heat Interface
HP	Heat Pump
HR	Heat Recovery
HRS	Heat Recovery System
HVAC	Heating, Ventilation, and Air-Conditioning
HVAC&R	Heating, Ventilation, Air-Conditioning, and Refrigeration
IAQ	Indoor Air Quality
ICT	Information and Communications Technology
IEC	International Electrotechnical Committee
ISO	International Organization for Standardization
IT	Information Technology
KPI	Key Performance Indicator
LENI	Lighting Numerical Indicator
LPHE	Liquid-to-liquid Plate Heat Exchangers
lx	Lux
MFH	Multi-Family Housing
MS	Member State
MSA	Market Surveillance Authority
Nearby	On the local or district level
NZEB	Nearly Zero-Energy Building
O&M	Operation & Maintenance
OJ	Official Journal (of the EU)
On-site	Premises and the parcel of land on which the building(s) is located and the building itself. On-site defines a strong link between the energy source (localization and interaction) and the building.
PDI	Lighting Power Density
PI	Performance Indicator
PR	Performance Ratio
PSFP	Average Specific Fan Power

PV	Photovoltaic
QR	QR code
RAC	Room Air Conditioner
RE	Renewable Energy
RES	Renewable Energy Systems/Sources
RT	Rooftop
SEER	Seasonal Energy Efficiency Ratio
SFP	Specific Fan Power
Smart-ready service	A term within the SRI calculation methodology; means a function or an aggregation of functions provided by one or more technical components or systems. A smart-ready service makes use of smart-ready technologies and orchestrates them into higher-level functions.
Smart-ready technology	A term within the SRI calculation methodology; means a technological enabler for one or more smart-ready services.
SRI	Smart Readiness Indicator
STC	Standard Test Conditions
TABS	Thermally activated building system Massive building fabric is actively heated or cooled by integrated air- or water-based systems.
TBM	Technical building management Processes and services related to the operation and management of building and technical building systems through the interrelationships between the different disciplines and trades.
TBS	Technical building systems Technical equipment for heating, cooling, ventilation, humidification, dehumidification, domestic hot water, lighting, and electricity production. A technical building system is composed of different subsystems.
TC	Technical Committee
Technical domain	As a term within the SRI calculation methodology, it means a collection of smart-ready services that, together, realize an integrated and consistent part of the services expected from the building or building unit.
TES	Thermal Energy Systems
Thermal envelope area	The total area of all elements of a building that enclose thermally conditioned spaces through which thermal energy is transferred, directly or indirectly, to or from the external environment. The thermal envelope area depends on whether internal, overall internal, or external dimensions are being used.
TRV	Thermostatic Radiator Valves
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow

The terms and definitions outlined above reflect those used in standardization. ISO and IEC maintain terminological databases at the following addresses:

1. ISO online browsing platform: available at https://www.iso.org/obp
2. IEC Electropedia: available at https://www.electropedia.org/

Executive Summary

SmartLivingEPC aims to deliver a holistic smart Energy Performance Certificate (EPC) spanning relevant life-cycle performance aspects of the built environment. The certificate’s scope will transcend energy performance, including the certification procedure's smartness, sustainability, and inspection dimension. Consequently, the smart energy performance certification scheme shall integrate the Smart Readiness Indicator (SRI) assessment, Life Cycle Analysis (LCA), and Life Cycle Cost (LCC) assessment, as well as additional human-centric indicators (e.g., Indoor Environmental Quality, thermal comfort, etc.), and others within the Level(s) framework. Furthermore, *SmartLivingEPC* will produce a dual enhanced methodology based on the existing CEN standards for delivering asset and operational ratings. These assessments will be applicable at both the building and the district scale.

The smart EPCs shall be issued with the use of digital tools and retrieving quality input data from BIM literacy, energy audits, and technical inspections, including enriched energy and sustainability-related information for the as-designed and actual performance of the building. Compatibility with Digital Building Logbooks (DBL) protocols will be ensured. The project will also use the digital twin approach to integrate BIM and inverse modeling by employing operational data to ensure that building models are enhanced and evolved in accordance with their actual performance during the complete life cycle. To that end, data coming from sensors and smart meters, as well as innovations related to the Internet of Things (IoT) and Artificial Intelligence (AI), will be leveraged.

Within WP2, “SmartLivingEPC Framework Asset Methodology”, the actions for the establishment of the smart EPC asset methodology will be performed. In short, smartness, sustainability, and audit and technical inspection aspects are integrated into one uniform rating system of the energy performance of buildings as well as the introduction of a new rating scheme at a building complex level. In that sense, the building level classification will result in a weighted average of four other indicators: the SRI, the Level(s), the energy performance rating, and the results from technical audits.

1 Introduction

1.1 Work package and Task description

The built environment constitutes a substantial proportion of global energy consumption and greenhouse gas emissions. Recognizing the urgency to mitigate climate change and reduce energy usage, the *Advanced Energy Performance Assessment towards Smart Living in Building and District Level – SmartLivingEPC* project—a transformative initiative aimed at enhancing energy efficiency in buildings. The central tenet of this project is the development of a novel Energy Performance Certificate (EPC) framework that goes beyond conventional energy rating systems.

Work Package 2 (WP2) assumes a pivotal role in establishing the asset methodology assessment at the building level by addressing several pressing challenges that have impeded the holistic evaluation of energy performance in buildings. Traditionally, energy ratings have been based solely on energy consumption data, neglecting other essential aspects that contribute to buildings' overall sustainability and performance. By incorporating cutting-edge practices and integrating diverse evaluation parameters, this integrated approach aims to create a comprehensive and harmonized rating system. Such a system will enable stakeholders, including property owners, investors, and policymakers, to make informed decisions, promote sustainable practices, and facilitate the transition toward a low-carbon future. This integrated approach embraces various aspects that significantly influence building performance and occupant satisfaction by implementing its tasks (T). Notably, it emphasizes the incorporation of additional critical characteristics, such as (SRI) – T2.1, energy and non-energy aspects – T2.2, LCA tools – T2.3, and introduction of a new building complex level rating scheme through technical audits and inspections – T2.4.

Conventional energy rating systems have undoubtedly played a critical role in fostering awareness of energy consumption in buildings. However, their narrow focus on energy usage fails to capture the broader spectrum of factors influencing a building's environmental impact and overall performance. As the global focus shifts towards sustainable development and responsible resource utilization, there is an imperative to rethink the current evaluation methodologies and develop a more inclusive approach. The asset methodology assessment at the building level seeks to address this need by encompassing a multifaceted evaluation paradigm. Integrating the principles of SRI analysis enables a more comprehensive understanding of a building's environmental, social, and governance implications. Concurrently, LCA tools facilitate a holistic examination of a building's environmental footprint over its entire life cycle, from construction to end-of-life considerations. Additionally, the incorporation of non-energy aspects, such as indoor air quality, thermal comfort, and occupant well-being, ensures a people-centric approach to building assessment.

A critical facet of this deliverable is the introduction of a new scheme building rating at the complex level. Recognizing that buildings rarely function in isolation, the Asset Methodology Assessment aims to extend its impact to encompass entire building complexes. This novel approach fosters more accurate and relevant ratings by evaluating the collective energy performance and sustainability attributes of interconnected structures.

1.2 Background and Objectives

Buildings account for a substantial portion of total energy consumption in Europe, and enhancing their energy performance is pivotal in achieving sustainability goals and combating climate change. Despite various existing rating systems and assessment tools, a coherent, comprehensive, and uniform methodology is still lacking to gauge the energy performance of buildings accurately. Moreover, the available frameworks often fail to consider vital non-energy aspects and fail to integrate multiple evaluation parameters into a single, cohesive rating system. With the integration of SRI analysis, LCA tools, technical audits, and inspections into a unified system, the project aspires to develop an all-encompassing assessment scheme that not only measures energy efficiency but also encompasses sustainability, environmental impact, and overall building performance.

1.3 Scope of the deliverable

This deliverable is an integral part of WP2, aiming to establish a unified and comprehensive approach to assess the energy performance and sustainability of buildings at individual and complex levels.

T2.1 - *SRI analysis and integration into SmartLivingEPC* focuses on examining smart technologies in buildings and analyzing SRIs with the aim of integrating them into the energy certification methodology of buildings. The first step involves conducting a detailed overview of the current status of SRIs, including their definition and methodologies. The examination will encompass the capacity of buildings to adapt their operation to occupants' needs, energy efficiency, and overall performance based on SRI schemes. SRIs will be classified according to the Energy Performance of Buildings Directive (EPBD) recast, categorizing aspects like heating, cooling, lighting, and more. The task also entails linking SRI certifications with EPC data, enabling the extraction of SRI information from intelligent Building Information Modeling (BIM) documents, thus facilitating the integration of SRI results into the new SmartLivingEPCs.

T2.2 - *Energy and non-energy resources analysis and integration into SmartLivingEPC* seeks to incorporate both energy performance and non-energy aspects into the classification of buildings. Building upon the technical documentation derived from the EN52000 standards series and other energy-related standards, this task aims to develop an integrated asset-based methodology for assessing building energy performance. The procedures developed will encompass the building's life cycle, integrate energy-related performance data, and data concerning non-energy resource consumption, such as water, noise, and acoustic quality issues. The assessment will be conducted in the BIM environment, leading to the development of necessary Application Programming Interfaces (APIs) to support the process. The expected outcome is a comprehensive energy and non-energy asset assessment of buildings, which will be further integrated into the SmartLivingEPC rating scheme.

The objective of T2.3 - *Environmental life-cycle assessment and integration into SmartLivingEPC* is to analyze the environmental life-cycle assessment and sustainability aspects of buildings to include sustainability ratings in the SmartLivingEPC rating procedure. Building and construction sustainability tools and technical standards, including the Level(s) scheme, will be employed to achieve this. The task will primarily focus on defining specific sustainability indicators for quantifying the environmental impact of buildings during their design and construction stages, utilizing a cradle-to-gate rationale. BIM documents will be utilized for the environmental assessment of buildings, necessitating the development of appropriate APIs to extract relevant building information from the IFC documents. The deliverable's outcome will consist of defined indicators and calculation processes, enabling the integration of life cycle performance aspects into the SmartLivingEPC calculation procedures.

T2.4 - *Technical audits and inspections integration into SmartLivingEPC* aims to integrate the findings from technical audits and inspections into the EPCs. It acknowledges the significance of up-to-date data on building systems' performance and its relevance to the energy rating process. By analyzing the input and outcomes of technical audits for building systems, such as the EN 15378, EN 16798, EN 16946, and EN 16947 standards series, this task seeks to identify relevant findings that can be utilized for energy classification. The outcome will be the development of necessary procedures and methodologies to incorporate the periodic audit findings of building systems into the process of calculating the asset energy class of the building, complementing the tasks in T2.1, T2.2, and T2.3.

The deliverable’s scope aims to revolutionize the evaluation of energy performance and sustainability of buildings by creating an integrated approach that includes SRIs, energy and non-energy aspects, LCA, and technical audits. Once integrated into the SmartLivingEPC rating procedure, this comprehensive assessment scheme will pave the way toward more energy-efficient and environmentally responsible buildings throughout Europe.

2 SRI analysis and integration to SmartLivingEPC

In this chapter, a detailed description of the SRI assessment is included. The remaining is structured as follows: Section 2.1 includes a documentation of current practices for SRI; Section 2.2 discusses the SRI certificate; Section 2.3 deals with the data and parameters for SRI analysis; and Section 2.4 outlines the SRI indicators used in the scope of the SmartLivingEPC project.

In future updates of this document the link between the SRI and EPB assessments and certification schemes and the extraction of data from IFC files to serve as an input for the SRI assessment will be dealt with.

2.1 Documentation of current practices for SRI

This Section aims to facilitate the integration of the SRI calculation into the SmartLivingEPC asset rating calculation methodology at the building, concerning the development, methodologies, and related procedures for the issuance of SRI certification. The process is to describe the SRI assessment methodology in detail, outlining the relevance at the building level. Certain conclusions are drawn, and possible future advances are outlined.

2.1.1 Context

The amendment of Directive 2010/31/EU on the energy performance of buildings (EPBD) [1] outlined the impact of energy system digitalization in the energy landscape, from the integration of renewables to smart grids and smart-ready buildings. As a result, smart-ready systems and digital solutions in the built environment are to be promoted through the provision of targeted incentives. Consequently, the Smart Readiness Indicator was introduced as a common European scheme for rating the smart readiness of buildings.

The power to adopt acts to supplement the directive and to establish the definition of the SRI and the calculation methodology was delegated to the European Commission (EC). The powers regarding the modalities for its implementation were also conferred to the Commission. As preparatory work, a first SRI technical study had been requested by the EC to VITO, WSEE, ECOFYS, and OFFIS, including a preliminary definition of the SRI and calculation methodology, as well as an extensive stakeholder consultation. A second SRI technical study was later commissioned by VITO and WSEE for the finetuning of the definition and calculation methodology [2]. As a result, the Commission Delegated Regulation 2020/2155 [3] and the Commission Implementing Regulation (EU) 2020/2156 [4] were published.

The Delegated Regulation established a common definition and calculation methodology for the SRI. Consequently, the *smartness* of a building or building unit was defined as its ability to sense, interpret, communicate, and actively respond in an efficient manner to changing conditions in relation to the operation of technical building systems, the external environment, and demands from building occupants. The calculation methodology and smart readiness rating were described in annexes I to VIII; though striving for consistency and comparability of building ratings across the EU, flexibility to adapt the calculation to specific conditions is enabled. The SRI scheme was labeled as optional, leaving the decision for its implementation to the Member

States (MSs). The SRI calculation methodology enables the connection or integration of the SRI scheme with national EPB schemes, particularly EPCs.

Nevertheless, the SRI can never substitute, only complement, energy performance, and sustainability assessments. Furthermore, digital building models shall be allowed to be used to facilitate the calculation of a building's SRI. The SRI certificate was defined as the document for communicating the smart readiness indicator of a building or building unit. It was established that only qualified or accredited experts could issue SRI certificates. If implemented, the SRI ought to have an independent control system, which may be linked to that in place for the energy performance certification schemes.

The Implementing Regulation detailed the accreditation and qualification of SRI experts. It indicated that the experts accredited or qualified for issuing energy performance certificates, carrying out an inspection of heating, air conditioning, combined heating or air conditioning and ventilation systems under Directive 2010/31/EU, or performing energy audits under Directive 2012/27/EU, are also competent for issuing smart readiness indicator certificates. It posed that additional requirements may be set, particularly in relation to training. Regarding the validity of the SRI certificate, the Regulation indicated that it should not exceed ten (10) years. It indicated that self-assessment by building owners, users, and other interested stakeholders ought to be enabled. However, any smart readiness assessment without the intervention of an expert may not lead to the issue of a smart readiness indicator certificate. Article 9 outlines the details of the national testing of the smart readiness indicator scheme.

In 2021, the SRI support team was set up by VITO, WSEE, R2M Solution, and LIST. The objective is to provide technical assistance for the testing and implementation of the SRI. In 2022, some countries launched a voluntary test phase of the SRI.

2.1.2 SRI core methodology

As indicated by the Commission Delegated Regulation 2020/2155 [5], the smart readiness of a building or building unit is determined based on the assessment of **smart-ready services** present or planned in, or relevant for, the building or building unit and their **functionality level**. The smart readiness of a building or building unit is expressed by a rating that derives from a total smart readiness score expressed as a percentage and represents the ratio between the smart readiness of the building or building unit compared to the maximum smart readiness it could reach. Therefore, it assesses the effective capabilities of the building or building unit to adapt its operation to the needs of the occupants and the grid and to improve its energy efficiency and overall in-use performance compared to a given potential.

The SRI methodology is structured in **three key smart readiness functionalities** (f), as highlighted in point 2 of Annex Ia, to Directive 2010/31/EU, within which certain **impact criteria** exist (ic).

1. Energy performance and operation
    - Energy efficiency
    - Maintenance and fault prediction
2. Response to user needs
    - Comfort

- Convenience
- Health, well-being, and accessibility
- Information to occupants

3. Energy flexibility
   - Energy flexibility and storage

The relevant impact criteria per key smart readiness functionality are depicted visually in **Figure 1**.

The SRI assesses **nine technical domains** (d), also defined by [5] are listed below and depicted in **Figure 2**.

1. Heating
2. Domestic hot water
3. Cooling
4. Ventilation
5. Lighting
6. Dynamic building envelope
7. Electricity
8. Electric vehicle charging
9. Monitoring and control

For each technical domain (d), **smart-ready services** $(S_{i,d})$ shall be defined by the MSs as part of smart-ready catalogs, including their related **functionality levels** $(FL(S_{i,d}))$, and corresponding individual scores for each impact criterion $(I_{ic}\left(FL(S_{i,d})\right))$. The smart-ready catalogs shall reflect the state-of-the-art of **smart-ready technologies**, which may be different among building types. Hence, several smart-ready catalogs may exist. The smart-ready service catalog shall define the maximum score of each technical domain for each impact criterion $(I_{max}(d, ic))$.

MSs shall define the respective **weighting factors** $(W_{d,ic})$ characterizing the influence of each technical domain (d) on each impact criterion (ic). Such factors ought to be expressed as a percentage, the sum of which ought to be 100% for each impact criterion. Weighting factors may be different between building types. As a result, it is possible to obtain the **smart readiness score for each impact criterion** (SR_{ic}).

Member States shall define the respective **weighting factors** $(W_{f,ic})$ of relevant impact criteria (ic) within each key functionality (f), which enables to obtain **smart readiness scores** $\left(SR_f\right)$ along the three key functionalities. Next, the **weighting factor** (W_f) indicates the influence of each key functionality (f) on the **total smart readiness score**(SR). Ultimately, the ratio between the smart readiness of the building or building unit compared to the maximum smart readiness that it could reach results in the **smart readiness rating**. The ratio yields a rating based on the **seven-class scale**: 90-100%; 80-90%; 65-80%; 50-65%; 35-50%; 20-35%; <20%, ranging from highest to lowest smart readiness.

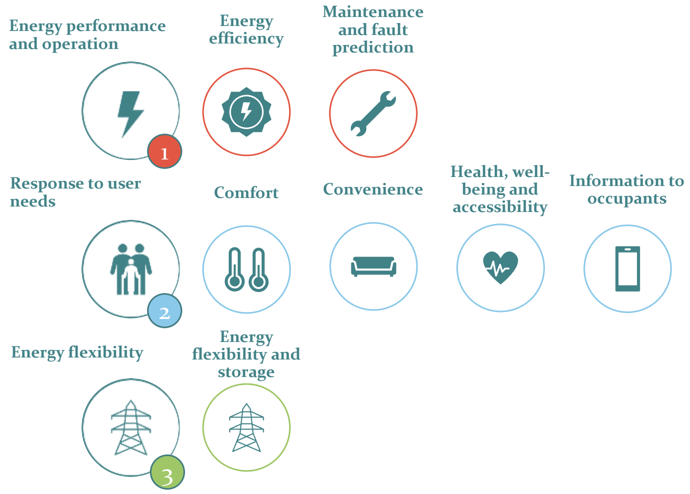


Figure 1: Relevant impact criteria per key functionality

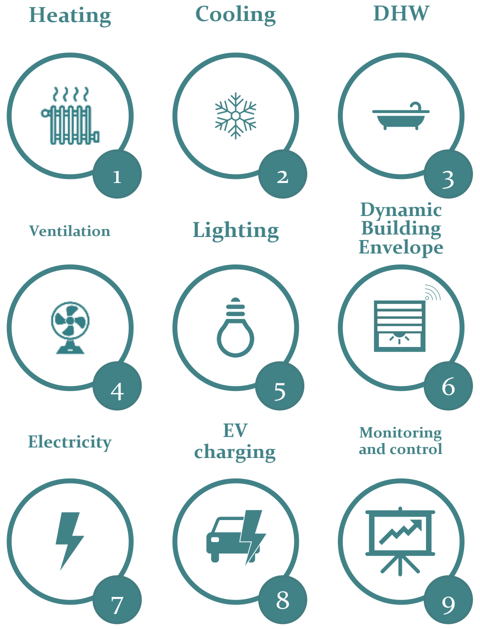


Figure 2: SRI technical domains

In the subsequent Sections of the document, when using the terms technical domains, service groups, smart ready services, and functionality levels in italics, they shall be understood as referred to their meaning within the SRI calculation methodology.

2.2 SRI certificate

The content of the smart readiness indicator certificate, as defined by Annex IX of the Commission Delegated Regulation 2020/2155 [5], includes the following:

- General certificate information
    - Unique ID of the certificate
    - Date of issue and date of expiration of the certificate
    - An informational text clarifies the smart readiness indicator's scope, particularly about energy performance certificates. Where available, the energy performance class of the building or building unit as specified by a valid energy performance certificate.
- General building or building unit information
    - Type of building or building unit
    - Surface area
    - Year of construction and, where relevant, of renovation
    - Location
- Smart readiness of the building
    - Smart readiness class of the building or building unit. Optionally, the total smart readiness score of the building or building units.

  - Smart readiness scores along the three key functionalities and per impact criterion. Optionally, scores of each technical domain for each impact criterion.

An informational text clarifying that the certificate reflects smart readiness at the date of issuance and that any significant modifications to the building and its systems would affect smart readiness and would therefore require an update of the information given on the certificate.

Optionally, additional information on the assumptions made in the calculation of scores, such as weighting factors of impact criteria used for calculating smart readiness scores for key functionalities.

- Where possible, available information on connectivity, in particular on the existence of high-speed-ready in-building physical infrastructure, such as the voluntary 'broadband ready' label. Also, where possible, available information on interoperability, cybersecurity of systems, and data protection, including where relevant on conformity to commonly agreed standards and information on related risks.
- Optionally, recommendations on improving the smart readiness of the building or building unit considering, where relevant, the heritage value.

Note how there is information in the SRI certificate that directly comes from input data retrieved by the assessor and specific to the assessed object (i.e., general building or building unit information, information on connectivity and in-building physical infrastructure, recommendations to improve the smart readiness of the building or building unit), general information to be provided by the assessor that is not explicitly linked to the assessed object (i.e., assessor identification, additional information on financial opportunities, etc.), and information related to the result of the assessment (i.e., smart readiness class, score, etc.). This situation is similar to that found in energy performance certificates.

2.2.1 Contextual adaptations

Service catalogs ought to be defined by the MSs. As a result, different *smart ready services* per technical domain may be considered among European countries.

The definition of **weighting factors** of *technical domains* per impact criterion is the prerogative of Member States as well. The standard approach defines the weighting factors of certain technical domains (i.e., *heating*, *domestic hot water*, *cooling*, *ventilation*, *lighting*, and *electricity*) as the energy balance per climatic zones. The remaining technical domains' weighting factors per impact criterion (i.e., *dynamic building envelope*, *electric vehicle charging*, and *monitoring and control*) are either fixed or equally distributed. For the calculation of the energy balance, energy performance in building assessments as per the energy performance certificates may be used. The climatic zones are defined by the MSs, and it is possible to have diverse sets of weighting factors depending on the building type. Approaches for the weighting factors definition that deviate from the standard approach are also possible.

MSs shall also define the **weighting factors** related to the influence of each *key functionality* in the total smart readiness score. To avoid unfairly penalizing a building or building unit, some smart-ready services may be omitted in the calculation of the smart readiness scores if those services are not relevant for that building or building unit. MSs shall define the conditions for allowing such adaptations of the calculation procedure. MSs may define additional considerations in terms of inclusiveness, connectivity, interoperability, cybersecurity, data protection, etc.

2.3 Data and parameters for SRI analysis

The SRI support team has produced the SRI assessment package (v4.5 being the latest) [6]. It is comprised of a practical guide for the SRI calculation framework and a calculation spreadsheet. The spreadsheet is a representation of the methodology for calculating the SRI based on the multi-criteria assessment method defined in the Commission Delegated Regulation 2020/2155 [7]. The spreadsheet is a tool to support SRI testing and implementation in EU Member States. It includes a default **service catalog** and **weighting factors** while enabling the use of customized values.

2.3.1 Service Catalog

The SRI assessment package produced by the SRI support team defines a **service catalog** in which each *technical domain* comprises several service groups containing *smart-ready services,* as in **Table 1**.

Table 1: Default service catalog - SRI assessment package (v4.5)

Technical domain	Service group	Smart-ready service
Heating	Heat control – demand side	Emission control
		Control of distribution fluid temperature
		Control of distribution pumps in networks
		TES for building heating, excluding TABS
	Heat control – supply side	Generator control
		Sequencing in the case of different generators
	Information to occupants and facility managers	Report regarding system performance
	Flexibility and grid interaction	
Domestic hot water	Heat control – supply side	Storage - generator control
		Sequencing in the case of different generators
	Information to occupants and facility managers	Report regarding system performance
Cooling	Cooling control – demand side	Emission control
		Control of distribution fluid temperature
		Control of distribution pumps in networks
		TES for building heating, excluding TABS
		Interlock avoiding
	Cooling control – supply side	Generator control
		Sequencing in the case of different generators
	Information to occupants and facility managers	Report regarding system performance
	Flexibility and grid interaction	
Ventilation	Air flow control	Supply air flow control at room level
		Supply air flow control at the air handling unit level
	Air temperature control	Heat recovery control

		Supply air temperature at the air handling unit level
	Free cooling	
	Information to occupants and facility managers	Report regarding system performance
Lighting	Artificial lighting control	Occupancy control for indoor lighting
	Control artificial lighting based on daylight levels	
Dynamic building envelope	Window control	Solar shading control
		Opening control, combined with an HVAC system
	Information to occupants and facility managers	Report regarding system performance
Electricity	Locally generated electricity storage	
	Locally generated electricity self-consumption optimization	
	Combined Heat and Power generation control	
	Demand Side Management	Support of (micro) grid operation
	Information to occupants and facility managers	Report regarding local electricity generation.
		Report regarding local electricity storage.
		Report regarding local electricity consumption
Electric vehicle charging	EV Charging	Capacity
		Grid balancing
		Connectivity
Monitoring and control	HVAC interaction control	Run time management of HVAC systems
	Fault detection	
	Technical building system interaction control	Occupancy detection
	Smart Grid integration	
	Information to occupants and facility managers	Report regarding demand side management performance and operation.
		Report regarding demand side management performance and operation.
	Override DSM control	
	Single platform that allows automated control, coordination between TBS, and optimization of energy flow	

Several incremental **functionality levels**, ranging from 0 to 4, are defined in a technology-neutral manner for each technical domain's smart-ready service. A higher functionality level reflects smarter performance. The SRI calculation spreadsheet enables user-defined *smart-ready services*.

2.3.2 Weighting factors

The SRI assessment package produced by the SRI support team defines default **weighting factors** for each technical domain per impact criterion for five (5) climatic zones in Europe (i.e., South-East Europe, North-East Europe, South Europe, West Europe, and North Europe). Such factors are different for residential and non-residential buildings; furthermore, the **weighting factors** of each *key functionality* in the total smart readiness score. The SRI calculation spreadsheet enables user-defined **weighting factors**.

2.4 SmartLivingEPC SRI Indicators

The final report of the second SRI technical study [8] investigated three potential SRI assessment methods (i.e., Method A, Method B, and Method C). Methods A and B are based on the assessment of the *smart-ready services* that are present or planned at the design stage and their *functionality level*. The assessment aims to determine with sufficient reliability what services are present or planned, and if so, the functionality level for each of those services. For this purpose, digital models of buildings, including building information models or digital twins, may be used when available. The main difference is that Method A considers a reduced **service catalog** and thus spans a subset of the *smart-ready services* considered in Method B. Consequently, Method A requires less effort, time, and potential expertise. By default, Method B would require an on-site inspection of the assessed object. Alternatively, Method C aims to be based on measured data, quantifying the operational *smartness* of in-use buildings.

Methods A and B are methodologies included in the SRI assessment package produced by the SRI support team, whereas Method C is considered a potential future evolution. The generic process of the SRI assessment following Method A or B is outlined in **Figure 3**.

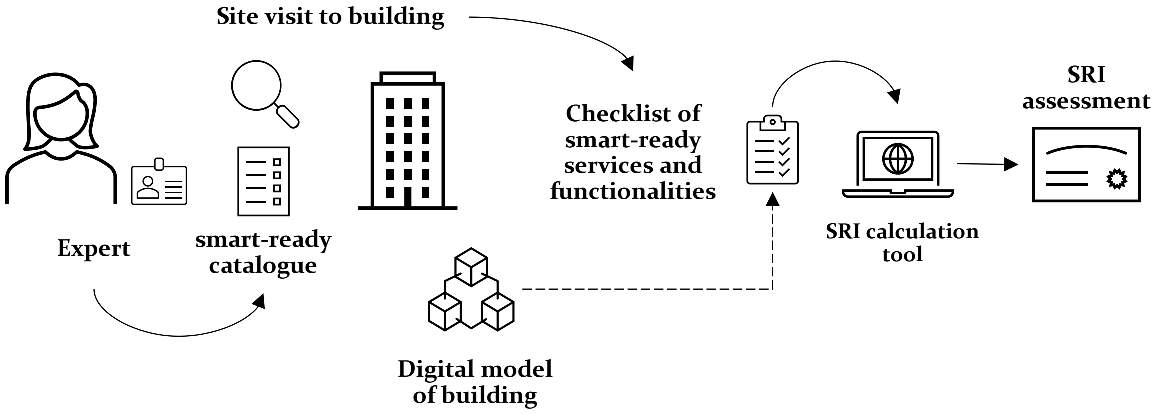


Figure 3: Generic SRI assessment process. Method A or B

The following sub-sections will explain the SRI assessment procedure taken as reference Method B and the default calculation methodology.

2.4.1.1 Input data

Performing an SRI assessment requires the identification of general information about the assessed object as well as retrieving the inputs needed for the calculations, similar to that required for the issue of energy performance certificates. The SRI assessment, as per the calculation spreadsheet developed by the SRI support team, requires the definition of certain input data, which can be structured according to the following:

- Assessor information.
- General building information.
- Methodology selection.

- Definition of applicability of smart-ready services and main functionality levels
- Assessment date.

The input data regarding **assessor information**, the **methodology selection**, and the **assessment data** are trivial and, therefore, not of interest in this document. The **general building information** contains items that correlate with overarching preparation steps for EPB assessments [9]. The **definition of the applicability of smart ready service and main functionality level** is the core calculation methodology for the SRI. Certain *functionality levels* may be defined for each *technical domain's smart-ready service*. Such *functionality levels* are enabled by certain smart-ready technologies either present or planned at the building or building unit. Depending on the applicable smart service catalog, the input data-gathering process may be variable in terms of time and effort needed. Furthermore, where they are available, digital models of buildings, including building information models or digital twins, may be used to increase reliability and reduce the time of the assessment.

2.4.1.2 Calculation

Once the main *functionality level* has been defined for each applicable *technical domain's smart-ready service*, the calculation proceeds as indicated in Section 2.1.2.

Each *smart-ready service* ($S_{i,d}$) has a certain *functionality level* ($FL(S_{i,d})$), which is equivalent to a score for each *impact criterion* (ic). The scores $I_{ic}(FL(S_{i,d}))$ of each *technical domain* (d) and *impact criterion* are defined by **Equation 1**, as the sum of the scores of the *smart-ready services* within a given *technical domain*.

$$I(d, ic) = \sum_{i=1}^{Nd} I_{ic}\left(FL(S_{i,d})\right) \qquad \textbf{Equation 1.}$$

The calculation is reproduced considering the maximum *functionality level* per applicable *smart-ready service* contained in the *smart-ready service catalog* ($FL_{max}(S_{i,d})$). It is indicated in Equation 2.

$$I_{max}(d, ic) = \sum_{i=1}^{Nd} I_{ic}\left(FL_{max}(S_{i,d})\right) \qquad \textbf{Equation 2.}$$

It is possible to produce the smart readiness score per *technical domain* and *impact criterion* following Equation 3.

$$SR_{d,ic} = \frac{I(d, ic)}{I_{max}(d, ic)} \cdot 100 \qquad \textbf{Equation 3.}$$

Next, the scores per *technical domain* are summed, considering their respective contribution to each *impact criterion*. The result is divided by the maximum possible score, resulting in the smart readiness score per *impact criterion* (SR_{ic}) as per Equation 4.

$$SR_{ic} = \frac{\sum_{d=1}^{N} W_{d,ic} \cdot I(d, ic)}{\sum_{d=1}^{N} W_{d,ic} \cdot I_{max}(d, ic)} \cdot 100 \qquad \textbf{Equation 4.}$$

The smart readiness per technical domain follows Equation 4.

$$SR_d = \frac{\sum_{ic=1}^{M} W_{d,ic} \cdot I(d,ic)}{\sum_{ic=1}^{M} W_{d,ic} \cdot I_{max}(d,ic)} \cdot 100 \qquad \textbf{Equation 5.}$$

The smart readiness score per *smart readiness functionality* (f) is obtained as the weighted addition of the scores per *impact criterion* as per Equation 6.

$$SR_f = \sum_{ic=1}^{M} W_f(ic) \cdot SR_{ic} \qquad \textbf{Equation 6.}$$

Finally, the total smart readiness score is obtained as the weighted addition of the scores per *smart readiness functionality,* as in Equation 7.

$$SR = \sum W_f \cdot SR_f \qquad \textbf{Equation 7.}$$

The contextual adaptations outlined in Section 2.2.1 may have a significant impact on the calculation process. The total smart readiness score corresponds to a smart readiness rating (SR_{class}), expressed based on seven smart readiness classes; namely, 90-100%; 80-90%; 65-80%; 50-65%; 35-50%; 20-35%; <20%, ranging from highest to lowest smart readiness.

2.4.1.3 Output data

The results of the SRI assessment are included in the SRI certificate, as indicated in sub-Section 2.3.1. The output data of the calculations is depicted in **Table 2**.

Table 2: SRI assessment output data

Description	Symbol	Unit
Total smart readiness score	SR	%
Total smart readiness rating	SR_{class}	-
Smart readiness score, per key functionality Energy performance and operation Response to user needs Energy flexibility	SR_f	%
Smart readiness score, per impact criterion Energy efficiency Maintenance and fault prediction Comfort Convenience Health, well-being, and accessibility Information to occupants Energy flexibility and storage	SR_{ic}	%
Smart readiness score, per technical domain Heating Domestic hot water Cooling Ventilation Lighting Dynamic building envelope	SR_d	%

Electricity Electric vehicle charging Monitoring and control		

3 Energy and non-energy resources analysis and integration to SmartLivingEPC

3.1 Current technical documentation for a joint asset-based methodology

Building Energy Simulation (BES) is a reliable computational tool for calculating a building's energy consumption accurately. It estimates energy consumption based on several factors, including building geometry, orientation, envelope properties, HVAC systems, lighting systems, and occupancy patterns. BES can predict energy consumption under different operating conditions and can simulate a building's energy performance over its entire life cycle. BES's ability to model complex systems and interactions and its adaptability to specific building types, climates, and operating conditions make it a valuable tool for building owners and designers to make informed decisions about a building's energy efficiency and identify energy-saving opportunities. Non-energy assessment evaluates aspects that impact the comfort and quality of life in a building, such as indoor air quality, acoustics, thermal comfort, lighting, accessibility, and functionality.

The state of the environment throughout buildings is known as indoor environmental quality (IEQ). Poor indoor environmental quality has been associated with respiratory problems, allergies, headaches, and fatigue. IEQ is affected by things including air, lighting, sound, and temperature. IEQ may be enhanced by ensuring adequate ventilation, air filtration, lighting, acoustics, and thermal comfort. Multiple factors influence indoor environmental quality (IEQ), including the ventilation system, window type, building location, building occupancy, and building use. Improvements in occupant health and productivity may be achieved by increasing attention to IEQ factors including natural light and noise levels.

The design and layout of a building may influence the health, productivity, and satisfaction of the people who live there. Important non-energy factors that contribute to IEQ include things like air quality, temperature, illumination, and noise. Important non-energy issues include safety, radon danger, earthquake potential, accessibility, flexibility, and ecological sustainability. A structure's carbon footprint may be further reduced by using sustainable building materials, installing rainwater collecting systems, installing green roofs, and installing solar panels. Noise may be reduced in buildings without sacrificing the comfort or productivity of their occupants via the use of sound-absorbing materials and strategic wall placement. As a whole, a building's usefulness, security, and comfort may benefit by attending to these non-energy elements.

The entire asset calculation engine is based on a rating from I to IV (categories) for non-energy parameters and A to G for energy parameters or CO_2 emissions. The recommended color scheme, consisting of the same RGB colors as proposed in the project, proves to be the most suitable choice as it aptly embodies the distinctive essence of the project’s undertaking.

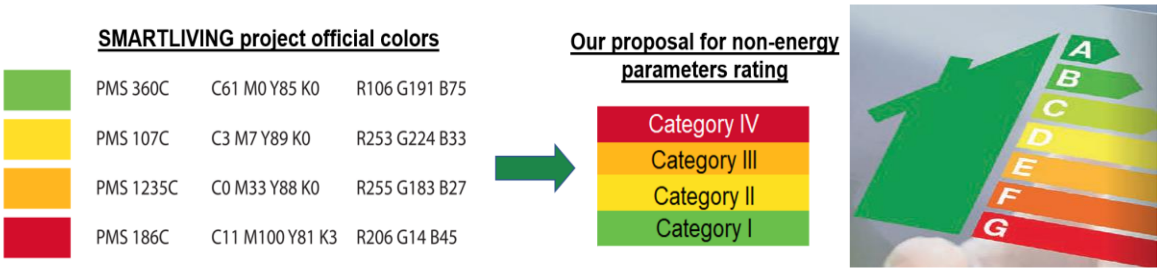


Figure 4: a) Proposed colour scheme for non-energy parameters (e.g. IEQ or other) b) energy scheme from SmartLivingEPC proposed for energy scale

In the present-day context of heightened awareness of climate change and the need to minimize energy use, energy efficiency has become an increasingly important factor in the design and construction of buildings. Certification programs that analyze and score buildings based on specified energy characteristics are one technique to encourage energy efficiency in buildings. In order to better understand the energy efficiency of their buildings, both owners and tenants may benefit from these certification schemes.

One of the most important parts of the asset calculation is the energy consumption of the buildings, including the calculation of heating, domestic hot water, lightning, ventilation and air conditioning. The calculation is based on the EPBD standards with the following parts: EPB standards ISO 52000-1, 52003-1, 52010-1, 52016-1 and 52018-1.

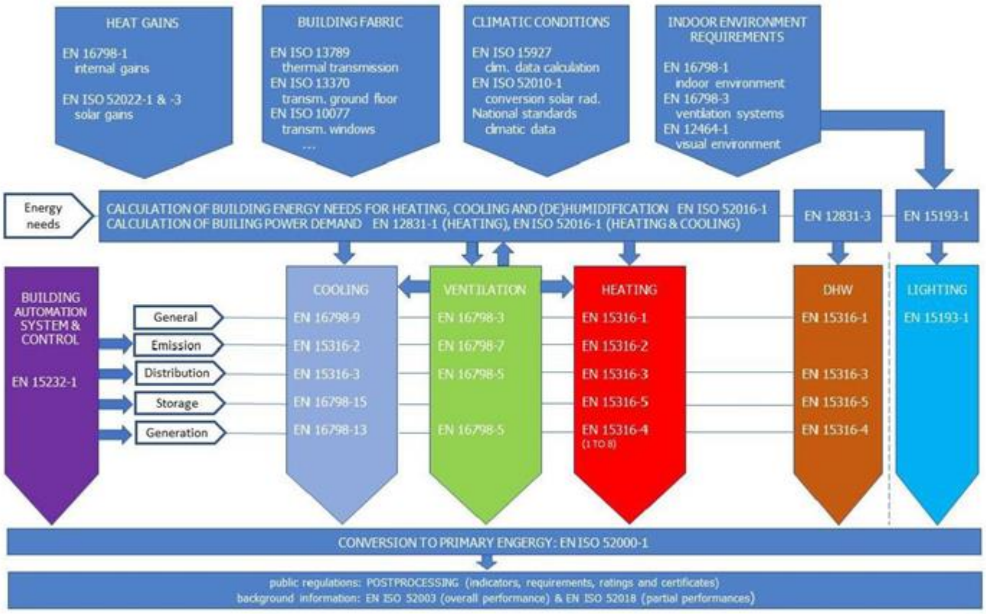


Figure 5: Logical scheme of energy calculation using EN ISO standards [https://epb.center/]

It is generally agreed that the most precise way to estimate a building's energy usage is via the use of Building Energy Simulation. BES is a computer method for modelling the energy efficiency of buildings. The geometry, orientation, envelope qualities, heating, ventilation, and air conditioning (HVAC), lighting, and occupancy patterns of a structure are only some of the variables that might affect an estimate of its energy consumption.

One of BES's key benefits is its capacity to foretell a building's energy usage under various scenarios. In this way, architects and building owners can evaluate the relative energy efficiency of several design possibilities. It is essential for long-term planning and decision-making to be able to simulate a building's energy performance across its full life cycle, and BES makes this possible.

Another advantage of BES is that it may replicate complicated systems and interactions, such as those between the envelope and HVAC systems of a building. Improved energy consumption forecasts and the potential for new energy-saving strategies are the consequences of this approach. Because of their flexibility and configurability, BES tools may be adapted to meet the needs of a wide variety of buildings and environments. Because of this, they may be installed in a wide variety of buildings, from residences to factories.

When estimating a building's energy usage, Building Energy Simulation (BES) provides the best precision. It is a useful tool for building owners and designers since it can anticipate energy consumption under varied operating situations, simulate complicated systems and relationships, and be adapted to specific building types. BES provides owners and architects with data on a building's energy use so they may make educated choices about how to improve efficiency and save costs.

For the rating the following energy parameters are proposed based on the new EPBD standards:

- **Final energy consumption of a building (kWh/m^2/year)**
  1. Heating
  2. Cooling
  3. Domestic Hot Water
  4. Lighting
  5. Ventilation
- **Primary energy consumption of a building (kWhep/m^2/year)**
  1. Heating
  2. Cooling
  3. Domestic Hot Water
  4. Lighting
  5. Ventilation
- **Renewable energy production of a building (kWh/m^2/year) and share by utilities and total (%)**
  1. Heating
  2. Cooling
  3. Domestic Hot Water
  4. Lighting (e.g. from photovoltaic energy)
  5. Ventilation (similar to d.)
- **Exported energy (kWh/m^2/year)**
  1. Thermal energy
  2. Electric energy
  3. Thermal energy from renewable sources

4. Electric energy from renewable sources

3.2 Collection of performance data generated over the building's life cycle concerning the consumption of non-energy resources

A building's design and layout may have a significant impact on the wellness, fulfilment, and productivity of its residents. Buildings may be described using a wide range of metrics, not only energy-related ones like energy efficiency and carbon emissions. Indoor environmental quality, safety, radon risk, earthquake potential, ease of access, adaptability of design, lifetime of construction materials, and ecological sustainability are all factors to consider.

The comfort, health, and productivity of building occupants may also be affected by indoor environmental quality (IEQ), an important non-energy parameter. The term "indoor environmental quality" (IEQ) is used to describe the state of a building's air, temperature, lighting, and levels of background noise. Health concerns including asthma flare-ups, migraines, and exhaustion may result from inadequate indoor environmental quality (IEQ). The use of high-quality materials, appropriate ventilation, and temperature and humidity management are all ways in which building owners may improve indoor environmental quality.

The safety of the building's inhabitants and the structure itself makes security a significant non-energy component. Access control systems, video cameras, and locked doors are just some of the security features that may be built into a building to keep unwanted visitors out. Security systems in buildings may safeguard their residents from more than just physical injury; they can also deter criminal activity like theft and vandalism.

The radon threat is an additional important non-energy component that may impact the occupant's health. Accumulated radon gas poses health hazards, including an increased risk of lung cancer recognized by WHO as the second source after smoking. The location and geology of the building site, as well as the building's construction and ventilation systems, may all affect the chance of being exposed to radon. Radon testing and, if required, the installation of radon mitigation solutions by building owners will reduce radon risk.

The possibility of earthquakes is another non-energy factor that should be considered when assessing a building's resilience. Seismic bracing or reinforced foundations are two examples of how buildings in earthquake-prone areas may be made safer for residents. Seismic retrofitting is an option for building owners looking to increase their structures' resilience to earthquakes. Thus, an important non-energy parameter may be represented by the seismic risk class (SR1 to SR4).

One further non-energy factor that might impact a building's functionality and acceptability to the public is its level of accessibility. The term "accessibility" refers to the convenience with which visitors and residents may use the building's facilities. Buildings that are accessible to all users, including those with physical limitations, tend to have more fulfilled and productive occupants.

The longevity and usefulness of a structure may also be affected by another non-energy factor: adaptability. The capacity of a structure to accommodate its occupants' and the building's changing requirements through time is what is meant by the term "adaptability." Owners might avoid spending a lot of money on costly upgrades and retrofits by designing their buildings to be flexible.

Materials used in construction and long-term upkeep are two more crucial factors outside of energy use. Recycled or low-emission materials are only two examples of the types of sustainable construction supplies that might lessen a structure's negative influence on the environment. Sustainable elements, such as rainwater collection systems, green roofs, and solar panels, may help building owners further reduce their carbon footprint.

The above-mentioned energy-related criteria aren't the only ones that may be utilized to characterize a structure. Buildings may be constructed with features like sound-absorbing materials or smart wall placement to decrease noise, for instance, which can have a significant impact on occupant comfort and productivity. Natural light, vistas, and colour schemes are all examples of aesthetic and design aspects that might improve tenant pleasure.

Security, radon danger, seismic risk, IEQ, ADA compliance, adaptability, sustainable materials, acoustics, and aesthetics are just a few of the numerous non-energy factors that may be used to characterize a structure. Addressing these factors and designing places that satisfy the demands of users over the long term may enhance the functioning, safety, and comfort of buildings. In the following chapters we will present each of these along with the asset assessment method.

3.3 Non-energy resources assessment

When people talk about how they feel inside a building, they often talk about the indoor environmental quality (IEQ) [10]. Numerous adverse health effects, including respiratory issues, allergies, headaches, and weariness, have been linked to low IEQ [11].

- Indoor environmental quality (IEQ) is determined by a number of variables [12], including but not limited to air quality, illumination, sound, and temperature.
- Poor indoor air quality has been linked to decreased lung and brain function [13].
- Indoor air pollution is often caused by things like cigarette smoke, cleaning chemicals, and materials used in construction [14].
- Indoor air quality may be enhanced and health risks mitigated with the aid of proper ventilation and air filtration [15].
- IEQ is affected not just by the air quality but also by the amount of light. Poor lighting may cause discomfort to the eyes, head, and body [16].
- The mental and physical well-being of building residents may also be affected by the acoustics, or level of noise, within the structure.
- Too much noise may be stressful and inhibit work output, while too little can lead to feelings of isolation and a breakdown in communication [17].

- Comfort and efficiency may also be affected by the building's thermal comfort, which includes the temperature and humidity levels within.
- High humidity encourages the formation of mold and other indoor air pollutants [18], while very high temperatures may be uncomfortable and impair mental performance.

Thus, indoor environmental quality (IEQ) is vital to the well-being of building occupants. A healthy interior environment is the result of several factors coming together, including proper ventilation, air filtration, lighting, acoustics, and thermal comfort [19]. In the asset assessment have been considered the 4 main parts of the IEQ thus we have the following schematic diagram that includes also the proposed non-energy parameters for each part:

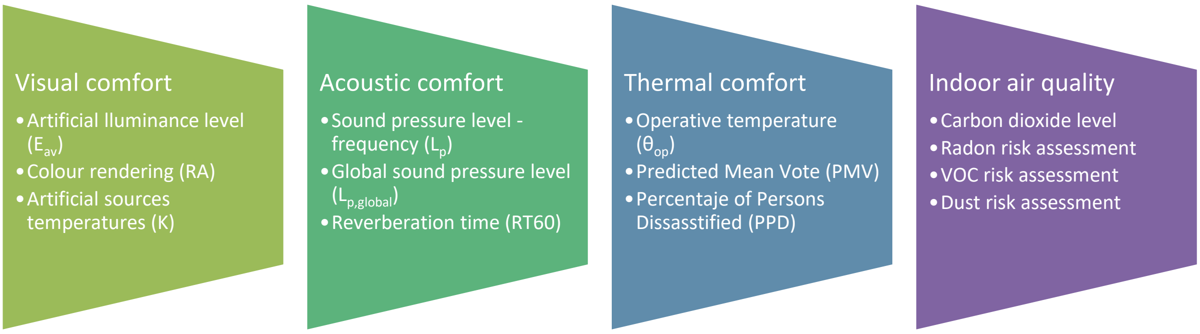


Figure 6: Main non-energy parameters for IEQ

The IEQ level varies widely throughout a building based on a number of factors. The ventilation system of a building is a key factor since it modulates the amount of outside air brought in and removes contaminants. Moreover, the window type and frame may increase or decrease air infiltration and thus impact the air quality. IEQ may also be affected by other factors, such as where in the building you happen to be. It's possible, for instance, that upper-floor residents will be subjected to higher temperatures and more intense solar radiation than ground-floor residents. In addition, the interior air quality may be lower for those who are closer to sources of indoor air pollutants such as photocopiers (e.g., ozone production) or cleaning chemicals (higher VOC levels). Occupant density is another factor that might affect IEQ. IEQ may also be affected by the kind of occupancy and the actions (metabolic rate) that occur inside it. The presence of natural light has been shown to improve the mood, productivity, and energy efficiency of building occupants. A building's interior may be divided into several zones, with those closest to windows getting more natural light than those furthest from the windows. Natural lighting may also be difficult to provide in buildings with deep floor plates or narrow floor designs. IEQ may also be affected by other crucial factors, like noise level. Occupant comfort, focus, and productivity may all take a hit when noise levels are too high.

External noise levels in a building may be affected by its proximity to a ***busy road*** or an industrial region, while *inside noise levels may be affected by HVAC systems or elevators*. Daylight and noise levels are two crucial elements that might affect the indoor environmental quality (IEQ) of a building. The health and productivity of the building's residents depend on these factors being properly addressed.

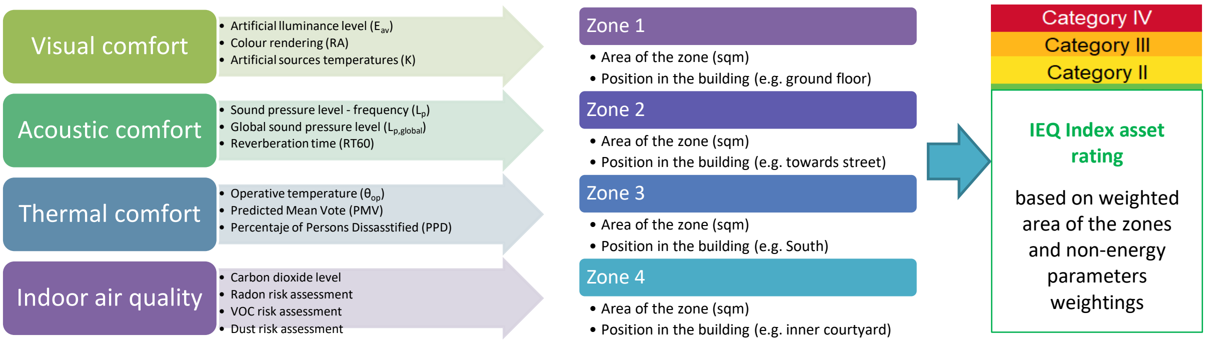


Figure 7: Analysis of indoor environmental quality throughout an entire building based on four reference zones

In previous research conducted during the last years the indoor parameters can vary considerably within the same building and thus it is important to choose reference zones that describe the best the destination of the studied building. In the example below we can observe the variation of temperature and illuminance for different rooms and floors for the same building.

More details about the paper are found here: https://www.rric.ro/reviste/articole/vol4nr3art7.pdf

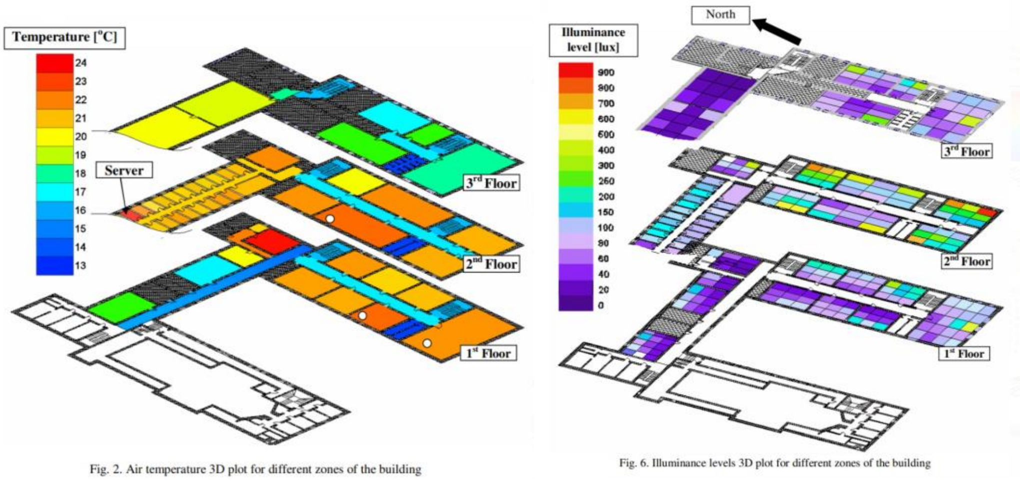


Fig. 2. Air temperature 3D plot for different zones of the building

Fig. 6. Illuminance levels 3D plot for different zones of the building

Figure 8: Variation of air temperature and daylight illuminance within the same building

Considering the above data, we consider it mandatory to rate a building in terms of IEQ based on at least four reference zones. For the following assessment procedure, all the calculations are based on four reference zones.

3.3.1 Thermal comfort

Thermal comfort, which refers to a person's degree of satisfaction with the thermal environment they reside in, is an important component of indoor environmental quality. It is a complex process that is impacted by several variables, including radiant temperature, air temperature, humidity, and air velocity. The health, productivity, and well-being of building inhabitants depend on maintaining thermal comfort [20][21].

Research has repeatedly shown that the temperature within buildings has a substantial impact on the well-being and satisfaction of individuals [22][23]. Unfavourable interior thermal conditions, including extreme heat or cold, may impair comfort, raise stress, and impair cognitive performance [24]. According to the World Health Organization (WHO), exposure to very high temperatures may result in several health issues, such as heat stroke, dehydration, and cardiovascular illnesses [25]. Therefore, it is essential to control interior temperatures to maintain the comfort and safety of inhabitants.

Variations in temperature may also affect how comfortable occupants are. According to Kim et al. (2019), office employees' ratings of thermal comfort were strongly impacted by changes in air temperature [26]. Like this, Choi et al.'s research from 2019 found that temperature variation might cause pain and dissatisfaction among building inhabitants [27]. These results underline how crucial it is to keep interior temperatures stable to increase occupant wellbeing and comfort.

Thermal comfort, as a crucial component of indoor environmental quality, has a substantial influence on the health, productivity, and well-being of occupants. Understanding all the variables that affect interior thermal conditions is essential to achieving and sustaining thermal comfort. Building owners and facility managers may guarantee resident satisfaction by controlling interior temperatures and reducing temperature variability.

In order to evaluate people's thermal comfort in enclosed spaces, the Predicted Mean Vote (PMV) model is often utilized. It is a tool that assesses how people perceive the thermal environment and offers a thermal comfort index based on a variety of environmental and individual characteristics. PMV is generally acknowledged and regularly used in research applications, HVAC systems, and building design. The calculating method for PMV and its importance in foretelling human thermal comfort will be covered in this work.

Measuring environmental variables such as air temperature, mean radiant temperature, air velocity, humidity, and garment insulation, which is measured in Clo units, is one of many phases in the PMV calculation technique [28] [29]. The PMV model predicts an individual's thermal experience using these metrics together with personal elements like metabolic rate, degree of clothing, and personal preferences. The PMV is a scale with a 0 signifying a neutral temperature feeling and a range from -3 (cold) to +3 (hot).

The PMV model has been verified by several experiments, which demonstrate its potency in forecasting thermal comfort [30] [31]. Additionally, studies have shown that the PMV model is a superior thermal comfort indicator than other models [32] [33]. The PMV model, however, has certain drawbacks, such as the inability to take into account individual variances and variations in thermal sensitivity [34]. Additionally, psychological elements like light, sound, and air quality that may affect thermal comfort are not taken into consideration by the PMV model. Despite these drawbacks, the PMV model continues to be a popular tool for HVAC system design and gives a quantitative evaluation of thermal comfort. Additionally, it enables engineers and designers to evaluate how well various HVAC systems and architectural designs affect how comfortable occupants are.

We have considered a non-energy parameter the PMV model as it provides a trustworthy method for estimating people's thermal comfort in enclosed spaces and it is mentioned in multiple EN standards. The PMV model is still a commonly used tool in building design and HVAC systems since it has been well proven in multiple research.

The PMV model, despite its drawbacks, is nevertheless a useful tool for designers, engineers, and researchers for evaluating and enhancing occupant thermal comfort and thus can be proposed for our project.

How the procedure was prepared

The key PMV components that are utilized to forecast an individual's thermal perception are environmental and personal characteristics. Air temperature, mean radiant temperature, air velocity, humidity, and clothing insulation are all environmental influences. Metabolic rate, degree of clothing, and personal preferences are all personal aspects. To anticipate an individual's thermal feeling, these parameters are integrated using the PMV computation process. Several assumptions and simplifications were necessary for the procedure.

Air temperature

The PMV model relies heavily on the indoor air temperature as a predictor of thermal comfort [29]. According to the PMV model, the average temperature of the air around people is what constitutes the "indoor air temperature". The model works on the assumption that there is no appreciable change in air temperature with elevation. Consequently, effective thermal comfort in buildings requires precise monitoring and management of internal air temperatures. Keeping the temperature of the indoor air between 20 and 23 degrees Celsius is advised for sedentary work [34]. According to EN 16798-1:2019 the conventional heating set-point temperature depends on the building category and room destination (e.g., residential buildings: living area and bedroom, the air temperature is 20°C, office is also 20°C, classrooms the air temperature is 18°C, hospital rooms 22°C, hotels 20°C, commercial non-food 18°C and 15°C for commercial food)..

Mean radiant temperature

The average surface temperature across all objects in an area is known as the Mean Radiant Temperature (MRT). Walls, ceilings, flooring, and even furniture may all fall within this category. Since MRT influences the rate at which heat is transferred to and from the human body, it is an essential factor in establishing thermal comfort. The human body loses heat to the environment through radiation, convection, and evaporation, making this heat exchange crucial. The MRT is accounted for in the PMV model's computation of heat exchange between the human body and the environment, which is extensively used to forecast thermal comfort. The asymmetry factor, which indicates the discrepancy between the operative temperature and the MRT, is also calculated from the MRT inside the model. Optimal thermal comfort in buildings requires precise MRT measurement and regulation. Achieving an equilibrium between the air temperature and MRT and improving thermal comfort in buildings may be accomplished via the employment of strategies such as radiant heating and cooling systems. The key to thermal comfort is keeping the air temperature and MRT in equilibrium.

Operative temperature

The operative temperature of a zone is a measure of what temperature the air and surfaces are, on average. It is commonly utilized in the design and evaluation of buildings because of its importance in determining occupant thermal comfort. By **averaging the air temperature and the mean radiant temperature**, we can get the operational temperature, which is representative of what a human would feel if they were placed in an environment with the same heat transfer properties. Different kinds of rooms have varying thermal comfort needs, hence, European standards for IEQ divide the operational temperature into a number of categories. The following are examples of categories defined by EN standards:

Category I ("comfort zone") refers to the optimal temperature range in which an individual may work without excessive sweating or shivering. Example: for residential buildings at 1 clo the $\theta_{op,min}$ is 21°C while for summer period for 0.5 clo is $\theta_{op,max}$ is 25.5°C.

Category II ("acceptable zone") is the range of working temperatures within which a person has only little discomfort. Example: for residential buildings at 1 clo the $\theta_{op,min}$ is 20°C while for summer period for 0.5 clo is $\theta_{op,max}$ is 26°C.

Category III ("border zone") is the temperature gray area where a person may need supplemental heating or cooling to feel comfortable. Example: for residential buildings at 1 clo the $\theta_{op,min}$ is 18°C while for summer period for 0.5 clo is $\theta_{op,max}$ is 27°C.

Category IV ("critical zone") the temperature range where workers may experience symptoms of thermal stress, which may have serious health consequences. Example: for residential buildings at 1 clo the $\theta_{op,min}$ is less than 18°C while for summer period for 0.5 clo is $\theta_{op,max}$ is higher than 27°C.

Air velocity

The speed and direction of airflow are what we call its "air velocity." Because it impacts how quickly heat is transported from the body to the environment, it is a crucial aspect in establishing a person's level of thermal comfort. One of the factors used to determine thermal comfort in the Predicted Mean Vote (PMV) model is air velocity. Convective heat loss from the skin accelerates in response to an increase in air velocity, making one feel cold and even chilly. However, low air velocities may make people feel stuffy and slow down the pace at which they cool down via evaporation, leading to discomfort and even heat stress.

According to the thermal comfort needs of various locations, the European standards for indoor environmental quality divide air velocity into a number of distinct classes. The following are examples of categories defined by EN 15251 and EN16798-1 in three categories (v_{air_max}=0.1 m/s, v_{air_max}=0.16 m/s, v_{air_max}=0.21 m/s for winter case and (v_{air_max}=0.12 m/s, v_{air_max}=0.19 m/s, v_{air_max}=0.24 m/s for summer case)

A person's thermal comfort zone is the range of air velocities at which they experience only mild discomfort. The tolerance zone is broader than the comfort zone and includes a range of acceptable air velocities.

This zone of air velocities is the limit beyond which a human would experience thermal discomfort and may need extra ventilation or air conditioning to reach a state of thermal comfort. In this range of air velocities, a human may experience thermal stress, which may lead to serious health issues.

Clothing level

As concerns the clothing factor in various seasons, maintaining thermal comfort requires the right clothes. People often dress in lightweight, breathable clothes in the summer when the temperature is high, with a recommended clothing level of 0.5 clo (where 1clo is equivalent to 0.155 m2·°C/W). In contrast, people dress in warmly in insulating clothes during the winter when the air is cold. The degree of clothing that is suggested for winter is 1 clo. It is important to note that suggested clothing levels may change based on individual parameters including age, gender, and amount of physical activity. To maintain thermal comfort in various seasons inside a heated/cooled building, the basic rule of thumb **of 0.5 clo for summer** and **1 clo for winter** is a suitable starting point.

Metabolic rate

The Predicted Mean Vote (PMV) of thermal sensation is calculated using the metabolic rate which primarily measures how much heat the human body produces. Most widely accepted standards provide the metabolic rates for different activities. The unit "Met" is often used to quantify the metabolic rate, also known as human body heat or power generation. One Met is the metabolic rate of a calm, sitting individual. **Table 3** lists typical metabolic rates for various popular activities:

Table 3: Metabolic rates included in the procedure

Activity	W/m^2	CO2 exhalation (m^3/h)	Met
Resting	46	0.013	0.8
Light activity	70	0.02	1.2
Moderate activity	93	0.1	1.6
Heavy activity	116	0.33	2

Calculation of PMV

To estimate how most individuals in a specific area would feel about the thermal comfort the Predicted Mean Vote (PMV) takes into account individual and environmental variables. To determine PMV, one uses the following formula:

$$\begin{aligned}\mathrm{PMV} = (0.303e^{0.303} + 0.028)\{&(\mathrm{M}-\mathrm{W}) - 3.05\,[5.37 - 0.007\,(\mathrm{M}-\mathrm{W}) - \mathrm{p_a}] \\ &- 0.42\,[(\mathrm{M}-\mathrm{W}) - 58.15] - 0.0173\mathrm{M}\,(5.87 - \mathrm{p_a}) \\ &- 0.0014\mathrm{M}\,(34 - \mathrm{t_a}) - 3.96 \\ &* 10^{-8}\mathrm{f_{cl}}[(\mathrm{t_{cl}} + 273)^4 - (\mathrm{t_{mr}} + 273)^4] - \mathrm{f_{cl}}\mathrm{h_c}(\mathrm{t_{cl}} - \mathrm{t_a})\}\end{aligned}$$

Equation 8.

$$\begin{aligned}\mathrm{t_{cl}} = 35.7 - 0.0275(\mathrm{M}-\mathrm{W}) - \mathrm{I_{cl}}\{&(\mathrm{M}-\mathrm{W}) \\ &- 3.05\,[5.73 - 0.007(\mathrm{M}-\mathrm{W}) - \mathrm{p_a}] \\ &- 0.42\,[(\mathrm{M}-\mathrm{w}) - 58.15] - 0.0173\mathrm{M}\,(5.87 - \mathrm{p_a}) \\ &- 0.0014\mathrm{M}\,(34 - \mathrm{t_a})\}\end{aligned}$$

Equation 9.

$$\mathrm{PPD} = 100 - 95\exp[-(0.003353\mathrm{PMV}^4 + 0.29179\mathrm{PMV}^2)]$$

Equation 10.

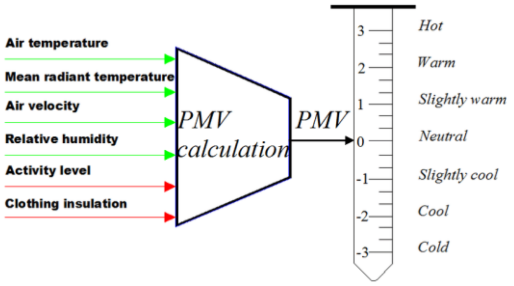
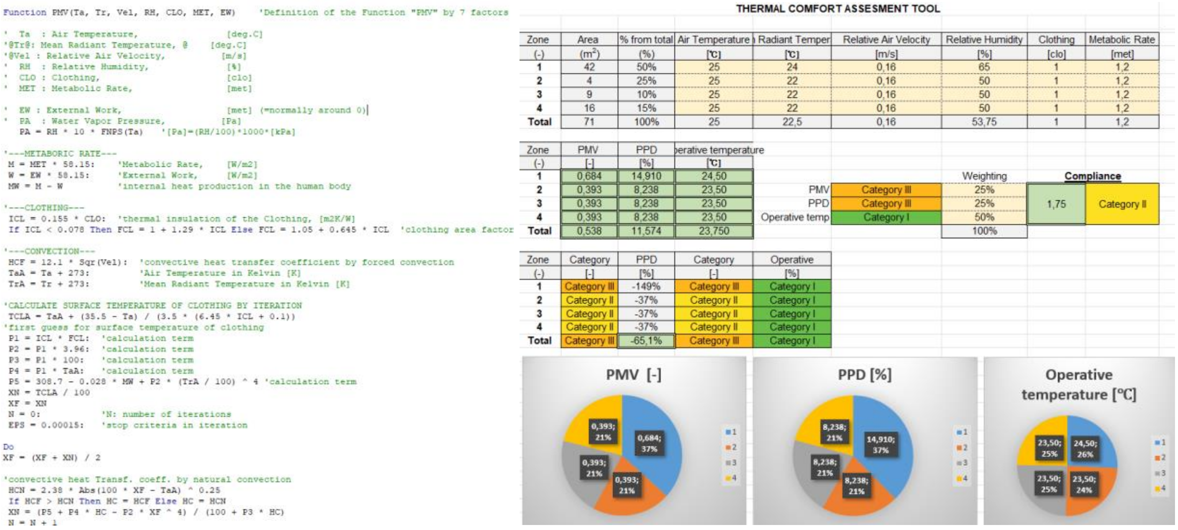


Figure 9: Calculation formulas/factors and value scale of PMV and PPD [35]

Calculation of the PMV and PPD was realized under VBA code in Excel based on the reference proposed by Takahiro Sat [245], thus below a part of the code and on the right is the proposed assessment of thermal comfort based on 3 non-energy parameters (PMV, PPD, Operative temperature).



```
Function PMV(Ta, Tr, Vel, RH, CLO, MET, EW)    'Definition of the Function "PMV" by 7 factors

'  Ta  : Air Temperature,                   [deg.C]
'@Tr@: Mean Radiant Temperature, @     [deg.C]
'@Vel : Relative Air Velocity,            [m/s]
'  RH  : Relative Humidity,                [%]
'  CLO : Clothing,                         [clo]
'  MET : Metabolic Rate,                   [met]

'  EW : External Work,                     [met] (=normally around 0)
'  PA  : Water Vapor Pressure,            [Pa]
   PA = RH * 10 * FNPS(Ta)    '[Pa]=(RH/100)*1000*[kPa]

'---METABORIC RATE---
 M = MET * 58.15:     'Metabolic Rate,     [W/m2]
 W = EW * 58.15:      'External Work,      [W/m2]
 MW = M - W           'internal heat production in the human body

'---CLOTHING---
 ICL = 0.155 * CLO:  'thermal insulation of the Clothing, [m2K/W]
 If ICL < 0.078 Then FCL = 1 + 1.29 * ICL Else FCL = 1.05 + 0.645 * ICL  'clothing area factor

'---CONVECTION---
 HCF = 12.1 * Sqr(Vel):  'convective heat transfer coefficient by forced convection
 TaA = Ta + 273:         'Air Temperature in Kelvin [K]
 TrA = Tr + 273:         'Mean Radiant Temperature in Kelvin [K]

'CALCULATE SURFACE TEMPERATURE OF CLOTHING BY ITERATION
 TCLA = TaA + (35.5 - Ta) / (3.5 * (6.45 * ICL + 0.1))
'first guess for surface temperature of clothing
 P1 = ICL * FCL:  'calculation term
 P2 = P1 * 3.96:  'calculation term
 P3 = P1 * 100:   'calculation term
 P4 = P1 * TaA:   'calculation term
 P5 = 308.7 - 0.028 * MW + P2 * (TrA / 100) ^ 4 'calculation term
 XN = TCLA / 100
 XF = XN
 N = 0:           'N: number of iterations
 EPS = 0.00015:   'stop criteria in iteration

Do
XF = (XF + XN) / 2

'convective heat Transf. coeff. by natural convection
 HCN = 2.38 * Abs(100 * XF - TaA) ^ 0.25
 If HCF > HCN Then HC = HCF Else HC = HCN
 XN = (P5 + P4 * HC - P2 * XF ^ 4) / (100 + P3 * HC)
 N = N + 1
```

THERMAL COMFORT ASSESMENT TOOL

Zone	Area	% from total	Air Temperature	Radiant Temper	Relative Air Velocity	Relative Humidity	Clothing	Metabolic Rate
(-)	(m^2)	(%)	[°C]	[°C]	[m/s]	[%]	[clo]	[met]
1	42	50%	25	24	0,16	65	1	1,2
2	4	25%	25	22	0,16	50	1	1,2
3	9	10%	25	22	0,16	50	1	1,2
4	16	15%	25	22	0,16	50	1	1,2
Total	71	100%	25	22,5	0,16	53,75	1	1,2

Zone	PMV	PPD	perative temperature
(-)	[-]	[%]	[°C]
1	0,684	14,910	24,50
2	0,393	8,238	23,50
3	0,393	8,238	23,50
4	0,393	8,238	23,50
Total	0,538	11,574	23,750

		Weighting	Compliance	
PMV	Category III	25%	1,75	Category II
PPD	Category III	25%		
Operative temp	Category I	50%		
		100%		

Zone	Category	PPD	Category	Operative
(-)	[-]	[%]	[-]	[%]
1	Category III	-149%	Category III	Category I
2	Category II	-37%	Category II	Category I
3	Category II	-37%	Category II	Category I
4	Category II	-37%	Category II	Category I
Total	Category III	-65,1%	Category III	Category I

Figure 10: a) VBA code calculation for PMV/PPD and b) proposed calculation sheet for Thermal Comfort Rating and weighting (example)

Future parameters that are to be implemented: overheating hours if no cooling, mean radiant temperature estimation based on regression models.

3.3.2 Visual comfort

Visual comfort is a crucial element of building design that can impact occupant productivity and well-being. The term "visual comfort" describes the nature of the visual environment, which includes elements like illumination, glare, and colour. While good visual comfort can increase occupant satisfaction and performance, poor visual comfort can cause eye strain, headaches, and fatigue [36]. Lighting is a crucial component of visual comfort. Comfort, mood, and productivity of occupants can be impacted by lighting levels and quality. High-quality illumination can increase clarity of vision, lessen strain on the eyes, and increase attentiveness. Lighting systems should be created to offer adequate illumination without producing glare or other unpleasant visual effects [37]. Glare is another factor in visual comfort. Glare occurs when the visual environment has an excessive amount of brightness or contrast, which causes pain to the eyes and reduces visibility. Direct sunlight, reflection off of surfaces, and poorly positioned lighting fixtures are all potential sources of glare. The incidence of glare can be decreased through proper building fenestration and shading systems, while glare from artificial lighting can be diminished through the installation of light fixtures with proper shielding [38].

Another crucial element for visual comfort is colour. Colour can influence perception and mood; some hues encourage relaxation while others encourage energy and production. When choosing colours for a structure, designers should consider both the intended purpose of the area and the inhabitant experience [39].

The daylight factor quantifies the quantity of daylight that enters a structure during the course of a typical day. Under an overcast sky, it is defined as the comparison of the indoor illuminance of a horizontal surface to the outside illuminance of the same surface. To determine how well a building takes advantage of its natural lighting, architects and designers might utilize the daylight factor [40].

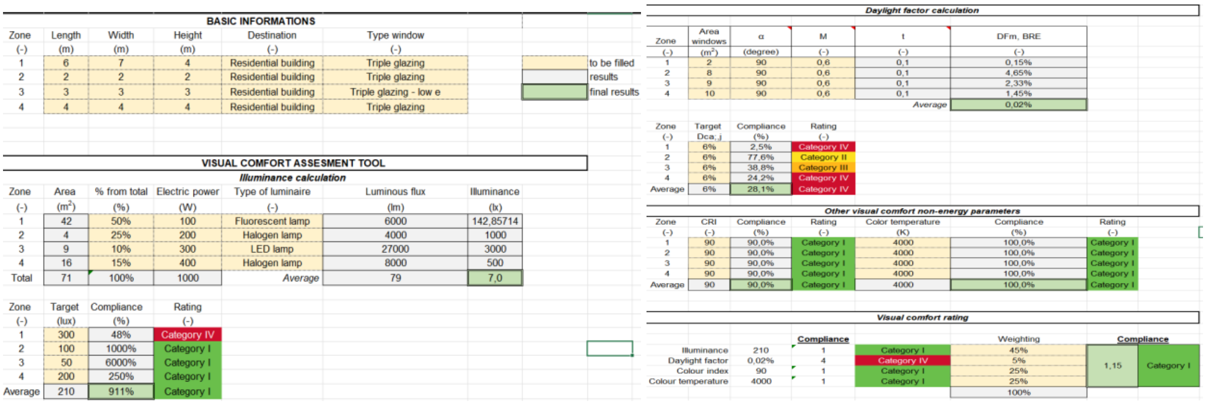
Orientation, window size and placement, shading devices, and glazing characteristics are only a few of the variables that might affect the daylight factor in a building. High-performance glazing, such as low-e glass, can improve a building's energy efficiency by allowing more natural light inside while keeping the inside cooler and decreasing glare [41]. Depending on the room's function, a different amount of natural light is ideal. The daylight component in circulation areas may just need to be 2%, whereas in offices it may ideally be between 5% and 10% [42]. Building occupants can obtain numerous benefits from well-designed daylighting systems, including enhanced visual comfort, enhanced productivity, and decreased energy use. Daylighting systems, which let in outside light during the day, can save a lot of money on electricity by reducing the need for artificial lighting [42]. The daylight factor is an essential indicator of how well a building makes use of its natural sunlight. There are numerous energy savings and occupant benefits that can result from well-designed daylighting systems. In order to create efficient shading and daylighting systems, architects and designers of buildings should take into account the recommended daylight factor for the planned use of each room. Thus, visual comfort is a crucial non-energy parameter of building design that can have an impact on occupant satisfaction and efficiency. For inhabitants, places can be made that are both useful and enjoyable with the help of good lighting design, glare reduction, and colour selection.

We have prepared a calculation sheet with the following parameters:

- Illuminance level (lx)
- Daylight factor (%)
- Colour Rendering Index (CRI)
- Colour temperature

Based on the destination of the building, type of window, electric consumption, type of luminaire, target of illuminance from international norms (e.g. 300 lx), area of windows, angle of visible sky from the mid-point of the window, maintenance factor, target Dca;j, CRI target (e.g. 90), Colour temperature target (e.g. 4000 K) the compliance and rating was possible.

It must be mentioned that users can modify the weighting scheme for the 4 non-energy parameters available for visual comfort. Below are presented some of the screenshots from the calculation sheet:



BASIC INFORMATIONS

Zone	Length	Width	Height	Destination	Type window
(-)	(m)	(m)	(m)	(-)	(-)
1	6	7	4	Residential building	Triple glazing
2	2	2	2	Residential building	Triple glazing
3	3	3	3	Residential building	Triple glazing - low e
4	4	4	4	Residential building	Triple glazing

to be filled
results
final results

VISUAL COMFORT ASSESMENT TOOL

Illuminance calculation

Zone	Area	% from total	Electric power	Type of luminaire	Luminous flux	Illuminance
(-)	(m^2)	(%)	(W)	(-)	(lm)	(lx)
1	42	50%	100	Fluorescent lamp	6000	142,85714
2	4	25%	200	Halogen lamp	4000	1000
3	9	10%	300	LED lamp	27000	3000
4	16	15%	400	Halogen lamp	8000	500
Total	71	100%	1000	*Average*	79	7,0

Zone	Target	Compliance	Rating
(-)	(lux)	(%)	(-)
1	300	48%	Category IV
2	100	1000%	Category I
3	50	6000%	Category I
4	200	250%	Category I
Average	210	911%	Category I

Daylight factor calculation

Zone	Area windows	α	M	t	DFm, BRE
(-)	(m^2)	(degree)	(-)	(-)	(-)
1	2	90	0,6	0,1	0,15%
2	8	90	0,6	0,1	4,65%
3	9	90	0,6	0,1	2,33%
4	10	90	0,6	0,1	1,45%
				Average	0,02%

Zone	Target	Compliance	Rating
(-)	Dca;,j	(%)	(-)
1	6%	2,5%	Category IV
2	6%	77,6%	Category II
3	6%	38,8%	Category III
4	6%	24,2%	Category IV
Average	6%	28,1%	Category IV

Other visual comfort non-energy parameters

Zone	CRI	Compliance	Rating	Color temperature	Compliance	Rating
(-)	(-)	(%)	(-)	(K)	(%)	(-)
1	90	90,0%	Category I	4000	100,0%	Category I
2	90	90,0%	Category I	4000	100,0%	Category I
3	90	90,0%	Category I	4000	100,0%	Category I
4	90	90,0%	Category I	4000	100,0%	Category I
Average	90	90,0%	Category I	4000	100,0%	Category I

Visual comfort rating

		Compliance		Weighting	**Compliance**	
Illuminance	210	1	Category I	45%	1,15	Category I
Daylight factor	0,02%	4	Category IV	5%		
Colour index	90	1	Category I	25%		
Colour temperature	4000	1	Category I	25%		
				100%		

Figure 11: Proposed calculation sheet for Visual Comfort Rating and weighting (example)

3.3.3 Acoustic comfort

Acoustic comfort is a crucial component of indoor environmental quality that may significantly affect building occupants' productivity and general well-being. It deals with the volume of sound or noise in a place and how its inhabitants react to it [43]. High noise levels might interfere with communication and focus, increase tension, and make speech less understandable. On the other side, a place that is completely silent or without sound may also be unsettling and confusing [44]. Depending on the way the room will be used, different acoustic comfort levels are advised. For instance, a school could need less noise than a restaurant or a mall [43].

Structure materials, room acoustics, HVAC systems, and outside noise sources are just a few of the elements that might influence how comfortable it is to hear within a structure. Noise levels may be decreased and acoustic comfort can be increased by thoughtfully arranging the design of acoustic systems such as walls, ceilings, and floors [45].

Furthermore, using sound-absorbing furnishings like carpets, curtains, and acoustic panels may decrease noise levels and enhance acoustic comfort [46]. In conclusion, acoustic comfort is a crucial component of indoor environmental quality that may have an impact on building occupants' productivity and general well-being. Building designers should take into account the appropriate levels of acoustic comfort for each space's intended usage when designing efficient acoustic systems to lower noise levels and enhance acoustic comfort.

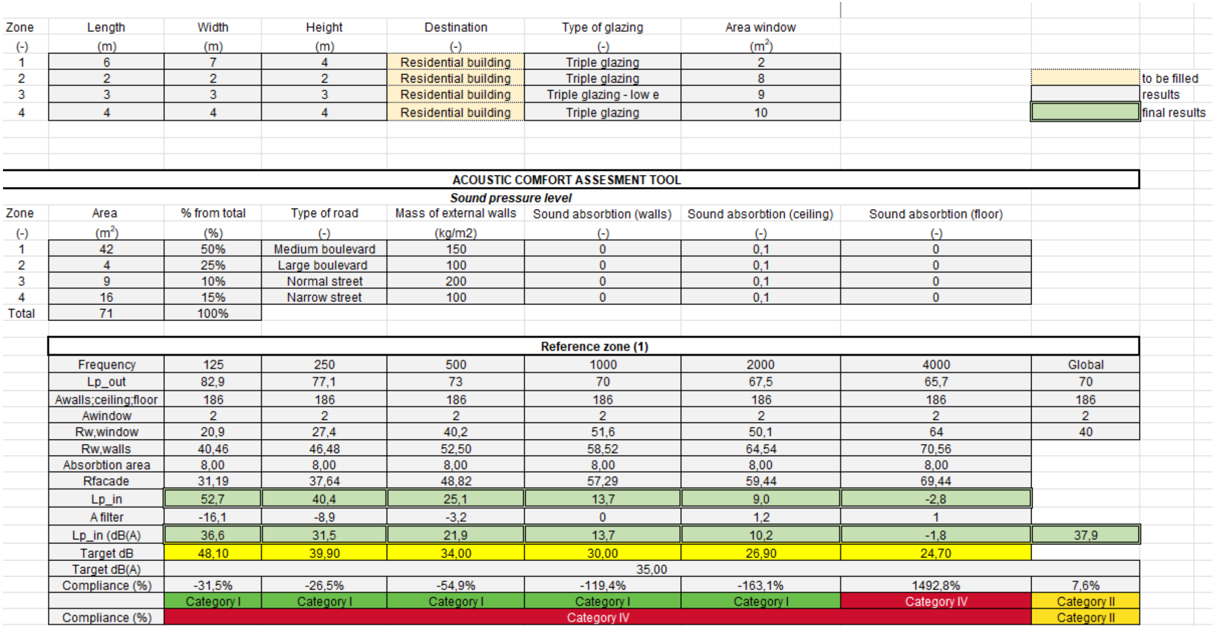
In the proposed procedure, we have proposed 3 non-energy parameters:

1) Global Sound pressure level (dB(A))
2) Noise curve compliance – sound pressure by frequency (dB)
3) Reverberation time RT60

The analyzed frequencies were 125 Hz to 4000 Hz. The input data is the destination, type of glazing, area of the windows, type of road – noise exposure (e.g., large boulevard), mass of external walls, sound absorption coefficient and area for walls, ceiling, and floor. The calculation formula for the theoretical assessment of sound attenuation of walls is presented below:

$$R = 20 * log_{10}(f) + 20 * log_{10}(p_{s)}) - 45$$ **Equation 11.**

Below is presented a screenshot from the calculation sheet:



Zone	Length	Width	Height	Destination	Type of glazing	Area window
(-)	(m)	(m)	(m)	(-)	(-)	(m^2)
1	6	7	4	Residential building	Triple glazing	2
2	2	2	2	Residential building	Triple glazing	8
3	3	3	3	Residential building	Triple glazing - low e	9
4	4	4	4	Residential building	Triple glazing	10

🟨	to be filled
☐	results
🟩	final results

ACOUSTIC COMFORT ASSESMENT TOOL

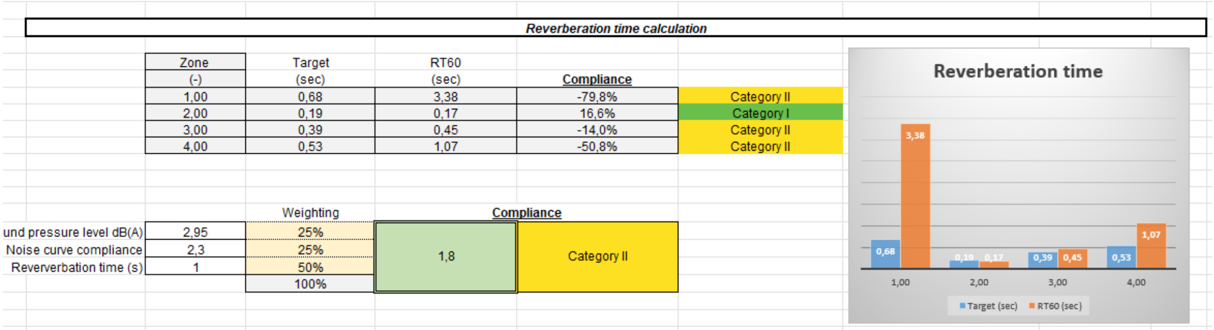
Sound pressure level

Zone	Area	% from total	Type of road	Mass of external walls	Sound absorbtion (walls)	Sound absorbtion (ceiling)	Sound absorbtion (floor)
(-)	(m^2)	(%)	(-)	(kg/m2)	(-)	(-)	(-)
1	42	50%	Medium boulevard	150	0	0,1	0
2	4	25%	Large boulevard	100	0	0,1	0
3	9	10%	Normal street	200	0	0,1	0
4	16	15%	Narrow street	100	0	0,1	0
Total	71	100%					

Reference zone (1)

Frequency	125	250	500	1000	2000	4000	Global
Lp_out	82,9	77,1	73	70	67,5	65,7	70
Awalls;ceiling;floor	186	186	186	186	186	186	186
Awindow	2	2	2	2	2	2	2
Rw,window	20,9	27,4	40,2	51,6	50,1	64	40
Rw,walls	40,46	46,48	52,50	58,52	64,54	70,56	
Absorbtion area	8,00	8,00	8,00	8,00	8,00	8,00	
Rfacade	31,19	37,64	48,82	57,29	59,44	69,44	
Lp_in	52,7	40,4	25,1	13,7	9,0	-2,8	
A filter	-16,1	-8,9	-3,2	0	1,2	1	
Lp_in (dB(A)	36,6	31,5	21,9	13,7	10,2	-1,8	37,9
Target dB	48,10	39,90	34,00	30,00	26,90	24,70	
Target dB(A)	35,00						
Compliance (%)	-31,5%	-26,5%	-54,9%	-119,4%	-163,1%	1492,8%	7,6%
	Category I	Category I	Category I	Category I	Category I	Category IV	Category II
Compliance (%)	Category IV						Category II

Figure 12: proposed calculation sheet for Acoustic Comfort Rating



Reverberation time calculation

Zone	Target	RT60	Compliance	
(-)	(sec)	(sec)		
1,00	0,68	3,38	-79,8%	Category II
2,00	0,19	0,17	16,6%	Category I
3,00	0,39	0,45	-14,0%	Category II
4,00	0,53	1,07	-50,8%	Category II

		Weighting	Compliance	
und pressure level dB(A)	2,95	25%	1,8	Category II
Noise curve compliance	2,3	25%		
Reververbation time (s)	1	50%		
		100%		

Figure 13: Proposed calculation sheet for Reverberation time calculation and weighting of the non-energy parameters (example)

3.3.4 Indoor air quality

Indoor air quality (IAQ) is the state of the air within the building and how it affects the health and comfort of the people who are housed there [47]. Problems with breathing, allergies, and headaches are only some of the outcomes of low levels of indoor air quality (IAQ) [48]. Pollutants in the air may originate either from outside or within, including in construction materials, cleaning products, combustion appliances, and traffic exhaust [49]. Locating and removing the origins of IAQ-detrimental contaminants is essential. Ventilation, filtering, and eliminating the original source are all viable options for doing this [50]. Ventilation is the process of bringing in fresh air from outside to mix with the stale air within. Natural ventilation, mechanical ventilation, or a mix of the two may all provide adequate ventilation [51]. Cleaning using non-toxic materials and reducing the amount of cooking and heating done indoors are two examples of source control measures that may be taken to improve indoor air quality [53].

Carbon dioxide (CO2) levels within buildings have been demonstrated to adversely affect the well-being and health of people. Symptoms like this may be brought on by excessive amounts of CO2 [54].

Indoor CO2 levels may be controlled in part via ventilation. By leaving the windows and doors open, as well as using other naturally occurring ventilation approaches, indoor air quality is enhanced. On the other hand, mechanical ventilation involves the use of mechanical components like fans and air handlers to transport and condition the air within a building [55].

Natural ventilation has been proven to be an efficient method of reducing CO2 concentrations within buildings. A Swedish research showed that opening classroom windows for only 10 minutes each hour may cut CO2 emissions by 40-50% [56]. In buildings where natural ventilation is impractical or insufficient, mechanical ventilation systems may be an efficient alternative for maintaining safe indoor CO2 levels. Researchers at an Italian hospital discovered that CO2 levels were considerably lower in-patient rooms when mechanical ventilation was used [57].

Maintaining secure amounts of carbon monoxide within buildings benefits the health and satisfaction of everyone inside. Building-specific and occupant-specific factors should inform the decision between natural and mechanical ventilation for CO_2 management. Indoor air quality (IAQ) is an essential non-energy parameter of IEQ since it may have a direct impact on people's health and comfort within a structure. The risk of health issues caused by indoor air pollutants may be greatly reduced by maintaining adequate IAQ by proper ventilation, filtration, and source management.

The proposed procedure takes into account the air infiltration rate based on the type of windows, building exposure to wind, destination, target CO_2, etc.

Using the calculation procedure, we are also able to predict the air infiltration rate of the zones. For that, we have used the **Table 4** (valid in general for residential buildings at a pressure difference of 4 Pa):

Table 4: Buildings' calculation procedure (Romanian methodology)

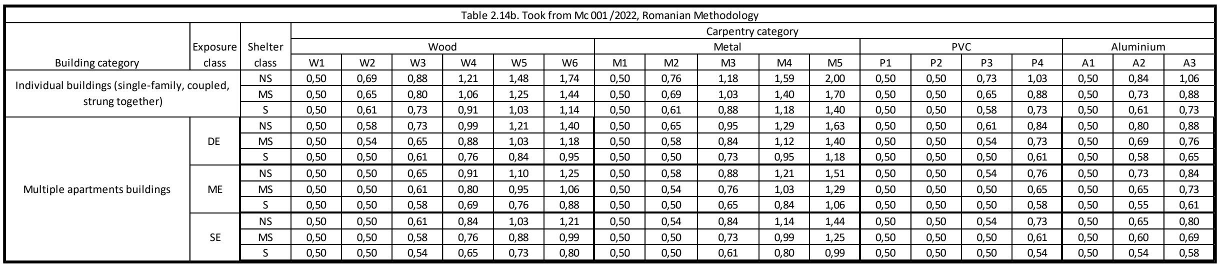


Table 2.14b. Took from Mc 001 /2022, Romanian Methodology

Building category	Exposure class	Shelter class	Carpentry category																
			Wood						Metal					PVC				Aluminium		
			W1	W2	W3	W4	W5	W6	M1	M2	M3	M4	M5	P1	P2	P3	P4	A1	A2	A3
Individual buildings (single-family, coupled, strung together)		NS	0,50	0,69	0,88	1,21	1,48	1,74	0,50	0,76	1,18	1,59	2,00	0,50	0,50	0,73	1,03	0,50	0,84	1,06
		MS	0,50	0,65	0,80	1,06	1,25	1,44	0,50	0,69	1,03	1,40	1,70	0,50	0,50	0,65	0,88	0,50	0,73	0,88
		S	0,50	0,61	0,73	0,91	1,03	1,14	0,50	0,61	0,88	1,18	1,40	0,50	0,50	0,58	0,73	0,50	0,61	0,73
Multiple apartments buildings	DE	NS	0,50	0,58	0,73	0,99	1,21	1,40	0,50	0,65	0,95	1,29	1,63	0,50	0,50	0,61	0,84	0,50	0,80	0,88
		MS	0,50	0,54	0,65	0,88	1,03	1,18	0,50	0,58	0,84	1,12	1,40	0,50	0,50	0,54	0,73	0,50	0,69	0,76
		S	0,50	0,50	0,61	0,76	0,84	0,95	0,50	0,50	0,73	0,95	1,18	0,50	0,50	0,50	0,61	0,50	0,58	0,65
	ME	NS	0,50	0,50	0,65	0,91	1,10	1,25	0,50	0,58	0,88	1,21	1,51	0,50	0,50	0,54	0,76	0,50	0,73	0,84
		MS	0,50	0,50	0,61	0,80	0,95	1,06	0,50	0,54	0,76	1,03	1,29	0,50	0,50	0,50	0,65	0,50	0,65	0,73
		S	0,50	0,50	0,58	0,69	0,76	0,88	0,50	0,50	0,65	0,84	1,06	0,50	0,50	0,50	0,58	0,50	0,55	0,61
	SE	NS	0,50	0,50	0,61	0,84	1,03	1,21	0,50	0,54	0,84	1,14	1,44	0,50	0,50	0,54	0,73	0,50	0,65	0,80
		MS	0,50	0,50	0,58	0,76	0,88	0,99	0,50	0,50	0,73	0,99	1,25	0,50	0,50	0,50	0,61	0,50	0,60	0,69
		S	0,50	0,50	0,54	0,65	0,73	0,80	0,50	0,50	0,61	0,80	0,99	0,50	0,50	0,50	0,54	0,50	0,54	0,58

Some of the tables used depend on the exposure to wind:

- No other buildings around (town building or holiday house)
- Few buildings around (building at city's border).
- Many buildings around (downtown, adjacent building or inside forest)

Type of carpentry and frame type (PVC, metal, wood, Aluminium)

- New carpentry with sealing gasket
- Good carpentry (without seal or slightly degraded)
- Old carpentry without seal

Operation scenarios for occupational period:

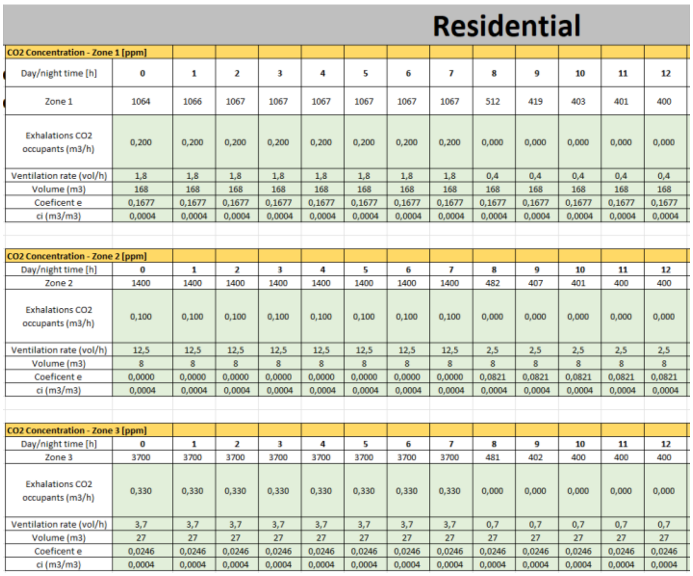
- Residential (24h)
- Office (8-17h, 5 days/week)
- Restaurant (8-22h, 7days/week)
- Hospital (24h)

The CO2 concentration level was considered as our non-energy parameter that define the IAQ quality thus using the following formula:

$$c = \left(\frac{\mathrm{q}}{\mathrm{n\ V}}\right)\left[1 - \left(\frac{1}{e^{n\,t}}\right)\right] + (c_0 - c_i)\left(\frac{1}{e^{n\,t}}\right) + c_i$$

Equation 12.

Based on CO_2 exhalation rate, volume, air change rate, time of calculation, c0 – concentration of 0 moment, ci – variable CO_2 level.



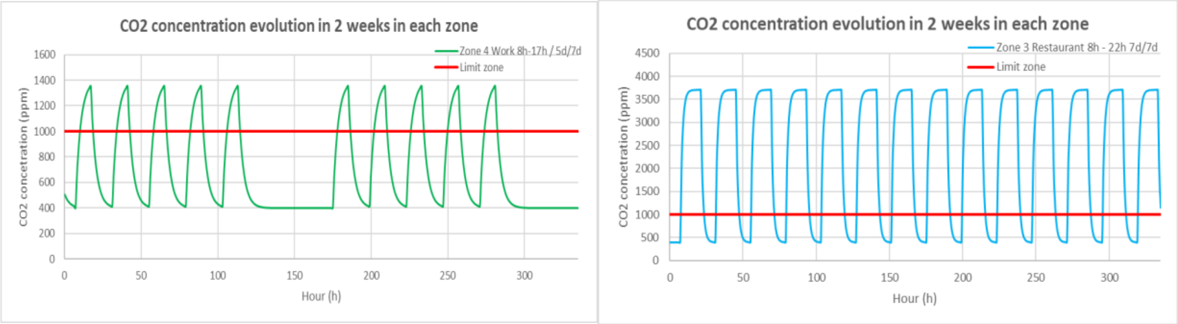
Residential

CO2 Concentration - Zone 1 [ppm]													
Day/night time [h]	0	1	2	3	4	5	6	7	8	9	10	11	12
Zone 1	1064	1066	1067	1067	1067	1067	1067	1067	512	419	403	401	400
Exhalations CO2 occupants (m3/h)	0,200	0,200	0,200	0,200	0,200	0,200	0,200	0,200	0,000	0,000	0,000	0,000	0,000
Ventilation rate (vol/h)	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	0,4	0,4	0,4	0,4	0,4
Volume (m3)	168	168	168	168	168	168	168	168	168	168	168	168	168
Coeficent e	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677	0,1677
ci (m3/m3)	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004

CO2 Concentration - Zone 2 [ppm]													
Day/night time [h]	0	1	2	3	4	5	6	7	8	9	10	11	12
Zone 2	1400	1400	1400	1400	1400	1400	1400	1400	482	407	401	400	400
Exhalations CO2 occupants (m3/h)	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,000	0,000	0,000	0,000	0,000
Ventilation rate (vol/h)	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5	2,5	2,5	2,5	2,5	2,5
Volume (m3)	8	8	8	8	8	8	8	8	8	8	8	8	8
Coeficent e	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0821	0,0821	0,0821	0,0821	0,0821
ci (m3/m3)	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004

CO2 Concentration - Zone 3 [ppm]													
Day/night time [h]	0	1	2	3	4	5	6	7	8	9	10	11	12
Zone 3	3700	3700	3700	3700	3700	3700	3700	3700	481	402	400	400	400
Exhalations CO2 occupants (m3/h)	0,330	0,330	0,330	0,330	0,330	0,330	0,330	0,330	0,000	0,000	0,000	0,000	0,000
Ventilation rate (vol/h)	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7	0,7	0,7	0,7	0,7	0,7
Volume (m3)	27	27	27	27	27	27	27	27	27	27	27	27	27
Coeficent e	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246	0,0246
ci (m3/m3)	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004

Figure 14: Example of calculation sheet for 3 zones (period 0-12 hours) – the proposed method takes into account 2-week period



Zone	Target (ppm)	**Compliance**		**Compliance**	
1	1000	109,20%	Category I	74,3%	Category III
2	1000	71,58%	Category III		
3	1000	28,69%	Category IV		
4	1000	87,57%	Category II		

Figure 15: a) Example for an office zone (mechanical ventilation) and b) Restaurant (only air infiltration – windows and doors) calculated with the propose worksheet

For all the zones the category of IAQ based on EN16798-1 (Cat I - CO2 level <=400 + CO$_{2\_outdoor}$, Cat II - CO2 level between 400-600 + CO$_{2\_outdoor}$, Cat II - CO2 level between 600-1000 + CO$_{2\_outdoor}$, Cat IV - CO2 level > 1000 + CO$_{2\_outdoor}$). For the 4 analyzed zones

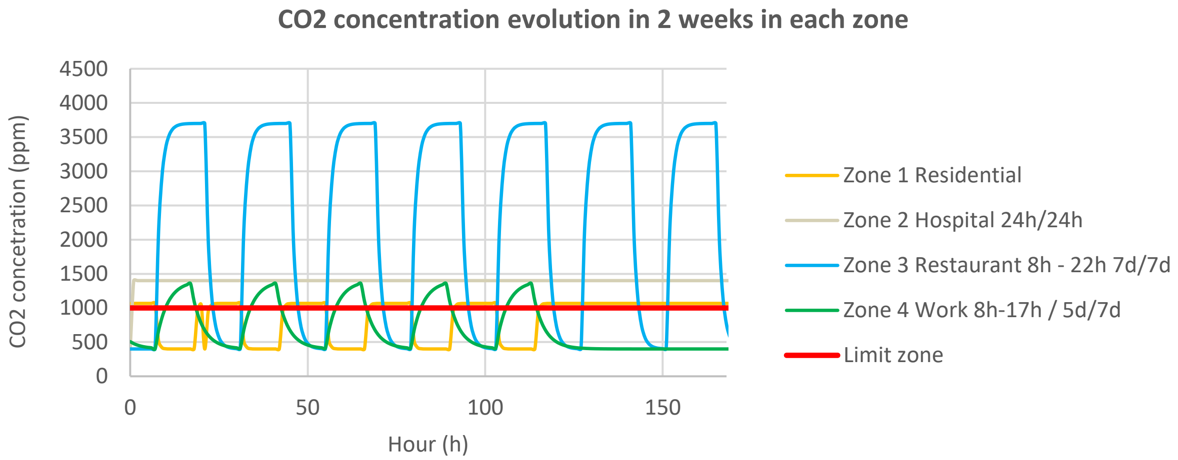


Figure 16: Example of a graphical representation of the CO$_2$ evolution for 168 hours (theoretical) based on multiple input data (e.g. occupants, exhalation rate – activity, type of air sealing – window, wind exposure, building type, fresh air flow – HVAC system, scenario of occupation)

3.3.4.1 Indoor Environmental quality Index

Calculating the indoor environmental quality of a building or interior space is rarely an easy task, given that the designer has to deal with numerous theoretical equations and simulation software for each of the IEQ parameters (operative temperature, illuminance and sound level) [58]. In addition, depending on what the occupants have highlighted, certain weights have to be given to the individual parameters. The ensuing weighting schemes attempt to combine the interrelated IEQ categories, into one performance model that can be used for ranking purposes. While there maybe value in combined indices for benchmarking and rating purposes, according to some studies there is also a loss of information and consequently a danger of misinterpretation. Many factors influence the relative importance of IEQ categories and that is why devising a universal weighting scheme that applies to all buildings at all times would seem difficult and unlikely. However, this should not deter the current study or further research dealing with weighting schemes from being pursued. While indeed some researchers argue that one-to-one comparisons of individual environmental parameters provide more information and are less likely to result in a conclusion that is inconsistent with occupant responses, the current study went forth with the holistic approach. An important remark has to be made when using the weighting values found in literature. These were derived especially for office buildings and their usability can thus be limited when applied to educational facilities. One key difference between the two building types comes from the importance placed on aural comfort. Whilst it is evident that office workers will place more emphasis on having a quiet working environment, school children will rank thermal comfort higher. A similar comment can be made for the lighting comfort.

Although no one discredits the importance of adequate light levels, survey respondents tend to crudely assess this aspect. It appears that a certain threshold exists below which insufficient lighting becomes bothersome depending on the activity employed. From one of our previous paper we have extracted the following weighting schema for the four non-energy parts of the IEQ (acoustic, IAQ, Visual, and Thermal).

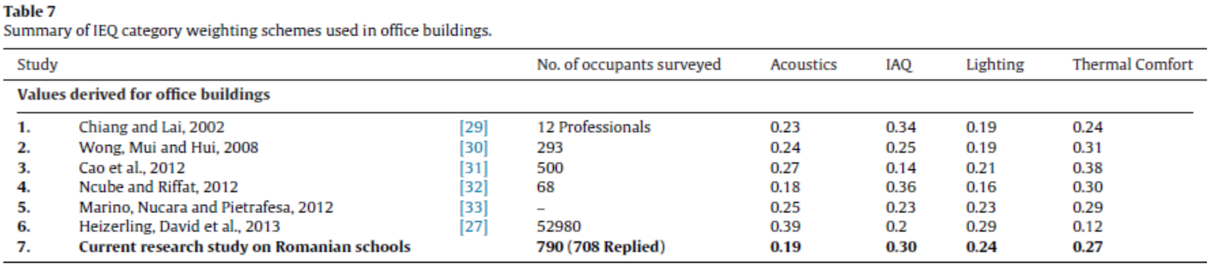
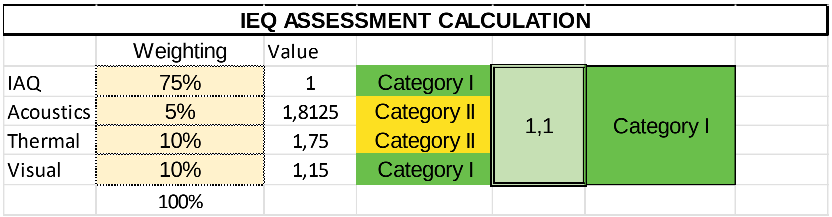


Table 7
Summary of IEQ category weighting schemes used in office buildings.

Study			No. of occupants surveyed	Acoustics	IAQ	Lighting	Thermal Comfort
Values derived for office buildings							
1.	Chiang and Lai, 2002	[29]	12 Professionals	0.23	0.34	0.19	0.24
2.	Wong, Mui and Hui, 2008	[30]	293	0.24	0.25	0.19	0.31
3.	Cao et al., 2012	[31]	500	0.27	0.14	0.21	0.38
4.	Ncube and Riffat, 2012	[32]	68	0.18	0.36	0.16	0.30
5.	Marino, Nucara and Pietrafesa, 2012	[33]	–	0.25	0.23	0.23	0.29
6.	Heizerling, David et al., 2013	[27]	52980	0.39	0.2	0.29	0.12
7.	**Current research study on Romanian schools**		**790 (708 Replied)**	**0.19**	**0.30**	**0.24**	**0.27**



IEQ ASSESSMENT CALCULATION						
	Weighting	Value				
IAQ	75%	1	Category I	1,1	Category I	
Acoustics	5%	1,8125	Category II			
Thermal	10%	1,75	Category II			
Visual	10%	1,15	Category I			
	100%					

Figure 17: Proposed calculation sheet for IEQ Index (example)

3.3.5 Radon risk assessment

Radon is a radioactive gas that occurs naturally and is often found inside, particularly in poorly ventilated structures. Research has connected radon exposure to lung cancer, and it is thought to be the second largest cause of mortality from lung cancer in the United States, after smoking [59]. Indoor radon levels may change based on things like soil type, building age and construction, and ventilation practices. The World Health Organization (WHO) advises that indoor radon levels not go over 100 Bq/m3 [60]. Building owners and occupants can take a number of steps to reduce radon levels in indoor environments, including increasing ventilation rates, sealing foundation and wall cracks and openings, and installing radon mitigation systems like active soil depressurization and ventilation systems [61]. Research shows that by taking these steps, indoor radon levels may be drastically lowered. In a British school, for instance, radon levels were found to drop from an average of 300 Bq/m3 to less than 10 Bq/m3 when a radon mitigation system was installed [62]. Radon poses a significant threat to human health in enclosed spaces, and steps should be taken to minimize exposure by both building owners and tenants. Reducing radon levels inside may be accomplished by improved ventilation, the sealing of cracks and crevices, and the installation of radon mitigation equipment.

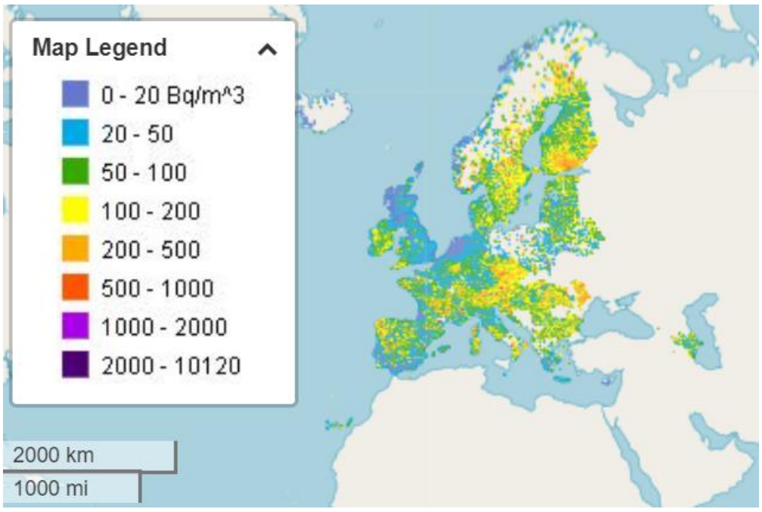


Figure 18: Indoor radon concentration averaged levels for a part of EU map (https://remap.jrc.ec.europa.eu/Atlas.aspx?layerID=3)

It can be seen that with this map we can identify with a resolution of 10 x 10 km the are that are most likely with the highest risk of radon problems inside a building.

A four-category risk assessment of radon exposure may be provided based on the European Indoor Radon Map, which offers data on indoor radon concentrations throughout Europe at a resolution of 10 km by 10 km.

Category I: Low risk- less than 100 Bq/m3

Indoor radon levels below 100 Bq/m3 are deemed safe for habitation. However, regular radon monitoring by residents is still advised to guarantee that the gas never rises over acceptable levels.

Category II: Moderate risk **–** levels within 100–300 Bq/m^3

Indoor radon levels between 100 and 300 Bq/m3 are considered a moderate concern for occupants of a building. Increased ventilation, sealing of cracks and holes, and radon mitigation devices are some of the actions that tenants may take to lower radon levels.

Category III – High risk levels within 300–1000 Bq/m3

High-risk regions include structures with indoor radon concentrations of 300 to 1000 Bq/m3. Residents should immediately begin taking action to lower radon levels, such as those described for category 2 or even relocate to a safer area if required.

Category IV – Very high risk (above 1000 Bq/m3) Radon levels within a building are considered very dangerous if they are more than 1000 Bq/m3. Urgent steps are needed to lower radon levels, and residents may want to look elsewhere for shelter.

The European Indoor Radon Map's four-category radon risk assessment may be used by building owners and occupants to determine the degree of radon risk in their building and take the necessary steps to minimize it.

3.3.6 Earthquake risk assessment

Europe is not a very seismic zone, although it does experience the occasional tremor. Considering both anticipated ground motion and the features of structures, Eurocode 8 sets standards for seismic design in Europe [63]. Several elements, including Europe's tectonic setting, geology, and seismicity history, affect the continent's seismic danger [64].

Seismic activity is highest in the Mediterranean and Balkan regions [63] [64], and severe earthquakes are more likely to occur there. Some of the most devastating earthquakes in modern European history have occurred in Italy, Greece, and Turkey [63]. Therefore, these nations have improved the seismic resilience of structures by establishing norms and laws [63] [65].

Europe's seismic hazard maps are created alongside the building rules to assist pinpoint high-risk locations and educate on earthquake-proof construction. These maps predict the potential for ground motion in various places by taking into account historical earthquake data, geological data, and seismological information [63] [64]. The most recent seismic hazard model for Europe, SHARE (Seismic Hazard Harmonization in Europe), was created as a joint effort between various European nations and offers a standardized hazard assessment for the area [64].

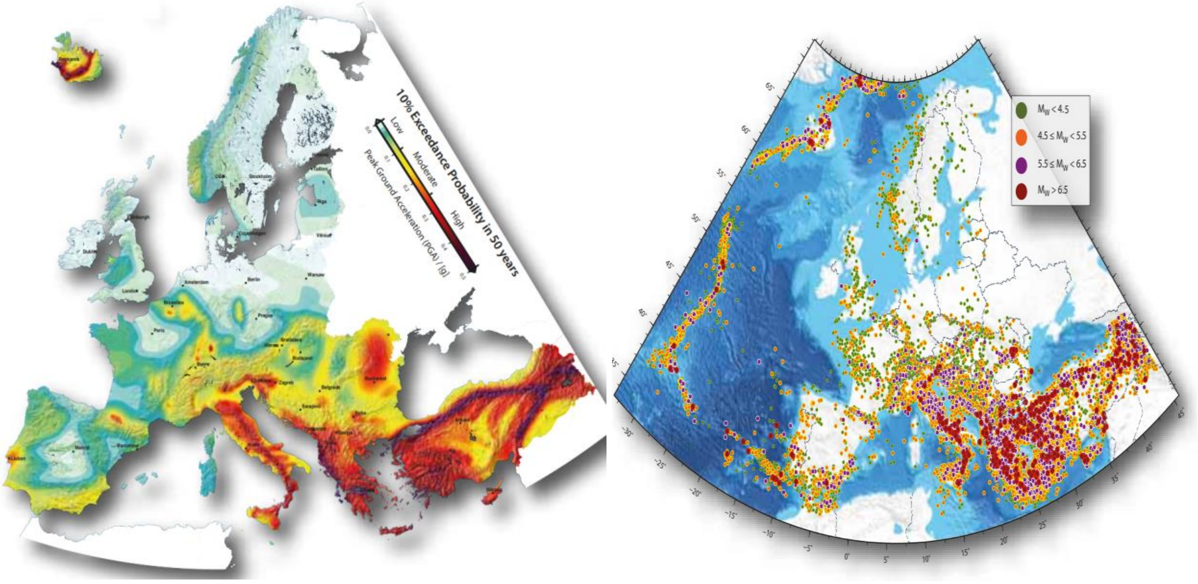


Figure 19: European Seismic Hazard Map (ESHM) displays the ground motion and b) earthquakes in Europe (major disasters in Italy, Greece, Romania or Turkey) – http://www.share-eu.org/sites/default/files/SHARE_Brochure_public.web_.pdf

Although Europe as a whole is not particularly prone to earthquakes, the danger varies from area to region. In Europe, designing and constructing structures that can withstand earthquakes requires the use of certain instruments, such as building rules, laws, and seismic hazard maps [63] [64] [65].

Any surveyed building falls into one of the following four risk classes:

- **R1** Class Rs I, which includes buildings with a high risk of collapse at the design earthquake corresponding to the ultimate limit state;
- **R2** Class Rs II, which includes buildings that are likely to suffer major structural degradation under the design earthquake but where loss of stability is unlikely;
- **R3** Class Rs III, which comprises buildings that under the effect of the design earthquake, may show structural degradation that does not significantly affect structural safety, but in which non-structural degradation may be significant;
- **R4** Class Rs IV, corresponding to constructions in which the expected seismic response is similar to that obtained in constructions designed on the basis of the requirements in force.

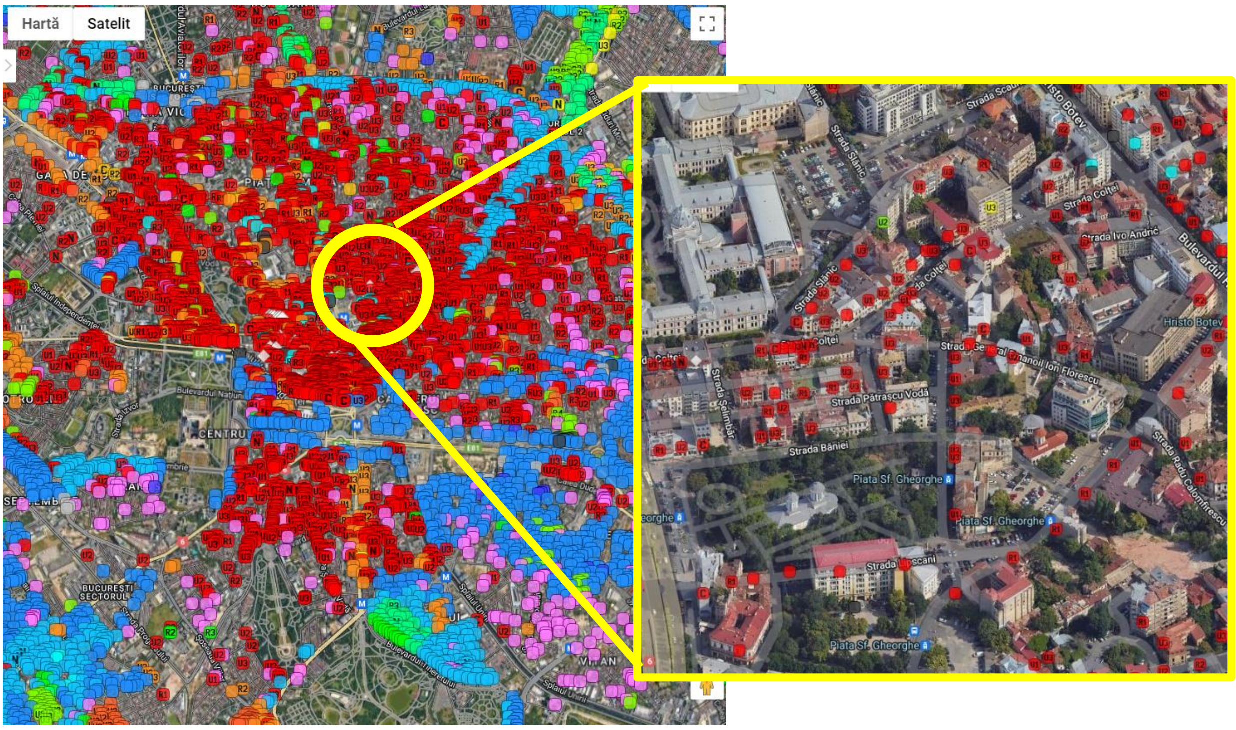


Figure 20: Seismic Risk (example for Bucharest, Romania) and zoom on a certain area with multiple building rated at earthquake hazard

Thus, it is proposed as a **non-energy parameter to measure the seismic risk of a building**.

3.3.7 Security assessment

Regarding the safety of people within and outside of the building, security measures must be taken very seriously. Access control systems, security cameras, and intrusion detection systems are just a few of the components that go into the construction of safe buildings. Whether the threat is real or digital, these systems can help you identify it and take action [66].

Authorized staff are the only ones who can enter restricted areas thanks to access control systems. Swipe cards, biometric scanners, and personal identification numbers are all viable options for this system. Cameras for monitoring the premises are another vital component of any adequate security system. They allow for constant surveillance of the building's inside and outside and may discourage illegal behaviour [67].

Perimeter-based and area-based intrusion detection systems are also viable options. All unlawful attempts to enter the building are detected by the perimeter-based security system. However, area-based systems may monitor a specific region within the structure for suspicious activity [68].

The safety of occupants is paramount throughout the construction and maintenance of any structure. Access control systems, security cameras, and intrusion detection systems are just a few of the components that go into the construction of safe buildings. Whether the threat is real or digital, these systems can help you identify it and take action. Protecting against cyber threats is another important function of a building's security system.

Based on the current security measures, a four-tiered risk assessment may be presented. Following is a breakdown of the classes:

Category I: A high-security facility is one that uses sophisticated security measures, such as a 24-hour security guard, surveillance cameras in all public areas, keypad-accessible automated doors, and other similar methods.

Category II: Moderately secure facilities include basic security features like staffed security during business hours, security cameras at strategic locations, automatic doors that need a key card to open, and so on.

Category III: Low-security buildings are those that only have the most fundamental security features, such as simple locks and no security cameras at the major entrances.

Category IV: No-security buildings are those that lack any kind of security, whether it be in the form of security cameras, guards, automated doors, or anything else.

All of the above-mentioned security measures, taken together, may increase or decrease a building's overall degree of security. Automatic doors may limit access to particular areas and prevent unwanted entrance, while security cameras can dissuade attackers and provide proof in the event of an incident. Manned security guards may serve as a visible deterrent by just being there. The value of the assets or information housed in a facility, as well as its location and the kind of operations conducted there, determine the degree of protection required. Banks, data centers, and other buildings storing valuable assets, as well as government and other sensitive sites, often demand a greater security level. Buildings may be categorized according to their degree of security using the results of a risk assessment, which are divided into four categories. Proposed rating of this non-energy parameter

Security, Lower-Level (Low Risk)

- No cameras (-), some cameras (-1) or full coverage (2-points) for security purposes. (2)
- Guards for Safety (out of a possible two points): None (-), Part-Time (1), and Full-Time (2) (2)
- Zero-Point-One-Point Automatic Doors: Absent (), Present (1)
- Access Restriction Levels: Restricted (-) or Full (+1) (1)

Second-Rate Protection (Moderate Risk)

- Score Security Cameras from 0 to 3: 0 = no cameras, 3 = some cameras, and 5 = all cameras. (5)

- Guards for Safety (from -3) to (3-5): None, Part-Time, and Full-Time (5)
- Zero-Point-One-Point Automatic Doors: Absent (), Present (1)
- Access Restriction Levels: Restricted (-) or Full (+1) (1)

Third-Grade Protection (High Risk)

- No cameras (-), few cameras (-6), or extensive coverage (--8): security cameras. (8)
- No security (-8 points), reduced security (-6 points), and full-time security (-8 points) (8)
- Zero-Point-One-Point Automatic Doors: Absent (), Present (1)
- Access Restriction Levels: Restricted (-) or Full (+1) (1)

Security, Level 4 (Very High Risk)

- No cameras (-), some cameras (9), or all cameras (10 points) for security. (10)
- None (-10 points), Part-Time (9), and Full-Time (10 points) (10)
- Zero-Point-One-Point Automatic Doors: Absent (), Present (1)
- Assorted (out of ten): Restricted access (-), Full authorization (1)

Each of the four aspects of security is given a score out of a possible 10, and the result is averaged. A higher score indicates a greater potential for breaching security measures. Low-risk structures have a total score of 0-2; moderate-risk structures have a score of 3-5; high-risk structures have a score of 6-8; and extremely high-risk structures have a score of 9-10. The weights assigned to each consideration may be modified to fit the needs of a certain structure.

4 Environmental life-cycle assessment and integration to SmartLivingEPC

4.1 Review of the sustainability performance of buildings

Life cycle assessment (LCA) is a relatively new field of study, having a history of only 50 years but having seen significant research and application within the past 30 years. Over the course of decades, the technique and applications have progressed to the point that there is now a consensus among scientists and established guidelines for how to conduct an LCA. In many countries, including the European Union (EU), Australia, Japan, Korea, the United States of America (USA), Canada, and, in developing economies such as India and, more recently, China, LCA is emerging as an essential component of climate change policy or voluntary actions. In the 1970s, LCA expanded from being simply an energy overview to an extensive investigation of the environmental burden of a product. In the 1980s and 1990s, complete LCA assessment and life cycle costing (LCC) concepts were initiated. During the first decade of the 21st century, social-LCA (SLCA) and — in particular, consequential LCA gained a foothold. Despite the fact that LCA provides us with the extremely valuable potential of selecting the most eco-efficient means of providing a particular feature or service, this framework does have some significant constraints when it comes to ensuring that a system is sustainable from an environmental perspective.

Life-cycle-oriented methodologies have been developed for the environmental characterization of products in response to rising awareness of environmental degradation, as well as a lack of energy and raw materials. LCA enables the assessment of the environmental impact of any system throughout its life cycle by considering the system's required input and associated output resources. LCA is frequently utilized in the decision-making process when actions extending either close or long into the future are at issue. Nonetheless, the typical technique for LCA needs to be modified in order to accommodate future and change-oriented aims. However, even so, there is not yet a standardized approach to accomplishing this goal.

Some of the critical moments in the history of LCA are outlined in **Table 5**.

Table 5: Moments in LCA history (selective)

Event	Year	Reference
Possibly the first-oriented LCA study concerning Energy requirements for the manufacturing of chemical intermediates and products	1963	World Energy Conference, Harold Smith
Coca-Cola Company conducts its very first investigation into the various types of beverage containers.	1969	Unpublished
The cornerstone of the methodological approach for environmentally extended input/output analysis is constructed.	1970	Leontief [69]
First LCA publications appeared, describing methodology & data sets	1972	
First computer program funded by MRI client	1973	

Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives, the first publicly available and peer-reviewed LCA report commissioned by the US EPA.	1974	US EPA [70]
EPA decided REPA/LCA was impractical as a regulatory tool (EPD)	1975	Hunt, Franklin, et al. [71] (1996)
Franklin Associates was established (first LCA company)	1975	Founded by William E. Franklin and Marjorie A. Franklin
Coca Cola published their LCA study (1969) in Science Magazine	1976	Baumann and Tillman [72] (2004)
Goodyear Tire and Rubber Company LCA on PET drink containers	1978	Unpublished
The first impact assessment method based on critical volumes introduced	1984	BUS (1984)
GaBi, which went on to become the first widely used commercial LCA program, had its first version launched.	1989	Thinkstep [73] (2016)
International forum by The Conservation Foundation debated role of REPA	1990	
The First edition of the commercial LCA program SimaPro was launched.	1990	PRé [74] (2016)
The concept of a "life cycle assessment" was initially conceived.	1990	SETAC [75] (1991)
Establishment of a variety of LCI databases, each of which is overseen by a separate organization	Early 1990s	
Franklin Associates published first methodology of LCA article	1992	Curran and Young [76] (1996)
EPA developed guidance manual for conducting and evaluating life cycle inventory	1992	Vigon et al. [77] (1993)
CML92, the first approach to impact assessment with a focus on environmental themes.	1992	Heijungs et al. [78]
The LCA framework, nomenclature, and methodology were standardized by the publication of the SETAC Code of Practice.	1993	SETAC [79]
The International Journal of Life Cycle Assessment, an academic journal devoted entirely to LCA, was established.	1996	IJLCA [80]
ISO 14040 standard on LCA principles and framework released	1997	ISO 14040 [81]
ISO 14041 standard on goal and scope definition released	1998	ISO 14041 [82]
Eco-indicator 99, methodology based on the extent of the damage appears	1999	Goedkoop and Spriensma [83] (2000)
ISO 14042 standard on life cycle impact assessment released	2000	ISO 14042
ISO 14043 standard on life cycle interpretation released	2000	ISO 14043
UNEP/SETAC Life Cycle Initiative launched	2002	UNEP [84]
The LCI database Ecoinvent version 1.01 is available	2003	Ecoinvent [85] (2016)
Through the use of ISO 14040 and ISO 14044, a broad methodological framework and guidelines for LCA were established	2006	
A framework for Life Cycle Sustainability Analysis was proposed	2008	Klöpffer [86]
“Guidelines to S-LCA", the first and most important steps towards standardization produced by the UNEP-SETAC Life Cycle Initiative	2009	UNEP/SETAC
International Reference Life Cycle Data System (ILCD) handbook released	2010	EC [87]

PAS 2050 standard on the assessment of the life cycle greenhouse gas emissions of goods and services	2011	World Resource Institute and World Business Council for Sustainable Development [88]
PEF and OEF guidelines launched	2012 and later	
ISO 14071 standard on critical review processes and reviewer competencies	2014	ISO 14071 [89]
ISO 14072 standard on requirements and guidelines for organizational LCA	2014	ISO 14072 [90]
Level(s); the European Commission’s first-ever framework to improve the sustainability of buildings.	2021	EC [91]

4.2 Overview of the current state of LCA

4.2.1 LCA conception

In the 1960s, when concerns about environmental deterioration and, more specifically, scarce resources began to surface, the concept of LCA was established. It was in the 1960s and 1970s that researchers first began looking at the effects that consumer goods had on the natural world [92]. More specifically, at the World Energy Conference in 1963, Harold Smith presented his "cumulative energy concept," which is credited with laying the groundwork for LCAs. The idea spread into environmental impacts in the 1970s in the US with "Resource and Environmental Profile Analysis," followed by the 1980s in Europe with the concepts of Ecobalances and industrial ecology, which demonstrated the increasing waste problem as a potential resource [93]. Both of these ideas contributed to the expansion of the concept. During this period, in which environmental issues like saving energy and resources, controlling pollution, and cutting down the use of waste and other unnecessary materials became important to the broader public, the earliest investigations, which were later classified as (partial) LCAs, were published [94]. There was an absence of uniformity and harmonization in the methodologies tended to fluctuate with public concerns. International forums for scholarly discourse and exchange around LCA were clearly lacking. There was a pause in the activity of the scientific community throughout the 1970s; LCAs were conducted without a unified conceptual perspective and using various methodologies. Even though the study's objectives were essentially the same, the acquired results varied substantially, which hindered LCA from being an even more widely recognized and used analysis method [95]. At the beginning of the 1980s and continuing throughout the 1990s, there was a marked increase in the development of new methodologies, as well as increased international coordination and collaboration. Thus, in the 1980s and 1990s, product life cycle management emerged as a critical concern. This gave rise to the concept of life cycle assessment (LCA), which is translated as the systematic gathering and analysis of information about a product system's inputs, outputs, and possible environmental implications [81] [96].

At the beginning of this era, companies commissioned the majority of the research, employed it internally, and shared relatively little of it with outside parties.

Materials and energy accountancy were early approaches that were influenced by material flow accountancy and tallied up each industrial process's resources and energy requirements (crude oil, steel, etc.), emissions, and solid waste. The Midwest Research Institute (MRI) undertook one of the earliest (unpublished) studies estimating the resource needs, pollutant load conditions, and waste streams of various beverage containers in 1969 for the Coca-Cola Company. Instead of openly sharing study results with consumers, they were mostly utilized for internal decision-making purposes, such as advising on the mitigation of life cycle consequences. The MRI referred to this type of study as Resource and Environmental Profile Analysis (REPA), involved analyzing the entire production process, "from cradle-to-grave", for the products under examination [92].

LCA attracted the attention of the government as well. For instance, a follow-up investigation to this study was carried out in 1974 for the United States Environmental Protection Agency (US EPA) by the same institute, with the intention of contributing to the formation of packaging regulations [97] [98]. A comparable study carried out by Basler and Hofman [99] in Switzerland is often seen as the impetus for the growth of LCA as we currently understand it. More widespread use of LCA was spurred by a study issued in 1984 by the Swiss Federal Laboratories for Materials Testing and Research (EMPA) [100]. This paper included a thorough list of the data required for LCA research [94]. The United Nations World Commission on Environment and Development released its report Our Common Future in 1987; this document is often known as the Brundtland Report in honor of its chairperson, Gro Harlem Brundtland [101]. Although the International Union for the Conservation of Nature first used the phrase "sustainable development" in 1980, it was not until the release of Our Common Future that the concept gained wider attention and received its most well-known description: "… development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The notion of sustainable growth provides a foundation for conceiving of these two increasingly urgent global crises as one tremendously powerful word by combining the concerns of current and future generations [102].

4.2.2 LCA standardization

Before LCA became commonplace in the 1990s, we had the development of the first life-cycle-oriented methods through a joint effort between academics and businesses in the 1960s. These analyses were known as Resource and Environmental Profile Analysis (REPA) [103] or Ecobalances or else as the precursors of today's LCA. For reasons including the need to protect proprietary data and the intricacy of translating technical findings into layman's terms, many of the earliest studies commissioned by businesses were never made public.

In spite of the fact that this decade is predominately one of convergence, it also represents a time of scientific inspection, investigation of LCA's theoretical underpinnings, and investigation of its synergies with other fields. Several life cycle inventory databases spanning various industries were also established in the early 1990s; these were administered by various institutes and associations. However, due to data specifications and quality discrepancies, databases may report vastly different amounts of resources used and emissions produced by the same industrial activity [104]. There are a number of well-known life cycle impact assessment methodologies that originated during this time period. These include environmental topic approaches [78] [105], end point or destruction approaches [106] [107], and the now-standard multidimensional practice [108] [109] of evaluating potential human and ecotoxic pollutants [110].

There was a significant increase in research and coordinating efforts across the globe in the 1990s (12-17), as seen by the proliferation of seminars, conferences, and LCA manuals and handbooks (18-25) published in the field. The international Journal of LCA (the first scholarly publication that is solely devoted to LCA); Resources, Conservation, and Recycling; Environmental Science & Technology; Journal of Industrial Ecology; Journal of Cleaner Production; and other journals also began publishing the first papers in their scientific series during this era. One of the most important outcomes of a coordinated effort to bring LCA specialists, clients, and academics together for the purpose of improving and harmonizing the LCA concept, nomenclature, and methods was the SETAC "Code of Practice" [111]. Since 1994, ISO has worked in conjunction with SETAC to advance LCA. Over the course of the years, ISO drafted and published four standards — principles and framework (ISO 14040), goal and scope definition (ISO 14041), life cycle impact assessment (ISO 14042), and life cycle interpretation (ISO 14043). The last three were incorporated in the ISO 14044 standard in 2006 as part of a revision that detailed the guidelines and specifications. This revision did not alter any of the provisions that were included in the standards. Since the introduction of the ISO 14040 series of standards for LCA, it has become standard procedure for businesses to disseminate LCA reports that have undergone peer review in order to substantiate their environmental claims. However, the complete revelation of source data remains uncommon due to confidentiality considerations. Instead of focusing on process validation and harmonization, as SETAC working groups did, ISO has taken on the formal responsibility of standardizing techniques and processes. The applicable standards will be analyzed in detail in the relevant sub-section. Due to SETAC's coordination and ISO's standardization operations, which provided a defined framework and nomenclature as well as a space for discussion and unification of LCA methodologies, the years 1990-2000 might be considered an era of convergence [92]. Furthermore, LCA was also incorporated into several policy documents and pieces of legislation, which had as their primary focus the legislation pertaining to packaging.

It was not until about 1990 that the first versions of SimaPro and GaBi, two popular LCA software, were produced. This requirement arose from the modeling of incredibly challenging product systems, as well as the expansion of LCI information and impact analysis methodology [73] [74]. CML92 was the first impact assessment technique to include a full spectrum of modern intermediate effect classifications [78]. It was released by Leiden University's Institute of Environmental Sciences in 1992. The Swedish EPS methodology [112] [113], which examined the damages, adopted a different tack by emphasizing human health and environmental harm instead of financial impacts; the Dutch Eco-indicator 99 method, introduced in 1999, fell into line by adopting a rather more science-based perspective to risk analysis [83]. To remedy this, in 2003, the first version of the Ecoinvent database (v1.01) was released, encompassing all major industries and seeking uniform data quality and standards [85]. The introduction of the EDIP2003 technique [114] with geographically heterogeneous impact assessment methodologies addressing non-global impacts reflects the recognition that there might be quite considerable disparities in the vulnerability of the environment enduring the consequences. In the 2000s and 2010s, much work will be done on methodologies for impact assessment of extraction-related effects such as water consumption and land use. In order to combine the best features of process-based and input/output-focused inventory classification, hybrid LCA will arise [104]. For the purpose of conducting assessments, a life cycle sustainability assessment (LCSA) framework will evolve, with the overarching goal of factoring in the environmental, social, and financial aspects of sustainability.

4.2.3 LCA elaboration

Although there is a growing need for LCA, the contemporary era is marked by a variety of different approaches. During the time that the ISO standardization process was taking place in the 1990s, LCA methodology was still infancy and rather immature. As a direct consequence, the standards that were produced of this process are not particularly thorough on certain methodological approaches; rather, they are mainly concentrated on the structure and the underlying values of LCA. Due to the wide range of interpretations that could be taken from the ISO standards, the Institute for Environment and Sustainability at the EU Commission's Joint Research Centre created a thorough guideline for LCA that describes scientific options left undetermined by the ISO standards [104].

Due to the absence of a consistent approach, different evaluations of the same material could provide inconsistent findings based on the specific technical decisions that were made. The American Center for LCA [115] and the Australian LCA Network [116], both of which were founded in 2001, are only two examples of the many national LCA networks that have since been launched. During the same time span, environmental policy is becoming more life-cycle-focused everywhere in the world (e.g., [117] [118] [119]). The Life Cycle Initiative [120] was first introduced in 2002 by the Society for Environmental Toxicology and Chemistry (SETAC) and the United Nations Environment Program (UNEP). Conforming to the definition provided in the ISO standard [81], LCA is the process of compiling and analyzing the inputs, outputs, and potential negative consequences on the environment that a product system has during its entire lifespan.

Using a life cycle thinking (LCT) approach, LCA can effectively evaluate and promote environmentally responsible production and consumption by providing comprehensive and balanced data concerning the environmental efficiency of products and services. LCT is a conceptual framework that refers to the requirements of analyzing the burdens of products, sectors, and projects using a holistic and all-encompassing viewpoint, beginning with the extraction of raw materials and ending with product disposal, and it is often seen as being crucial for assisting in the process of better-incorporating sustainability into policy decisions [121] [122]. Putting LCT into reality and enhancing the supporting instruments through solid information and metrics were established as the key goals of the Life Cycle Initiative. In anticipation of the European Integrated Product Policy (IPP) to be enacted at the EU level in 2003 with national policies such as environmental product declarations, ecolabels, green public procurements, and the incorporation of sustainability issues into standardization, multiple European countries established national product-oriented environmental initiatives employing LCA as the scientific basis. The European Commission emphasized the significance of LCA and the necessity of encouraging the implementation of life cycle thinking among the many parties involved in IP [123]. In 2005, the European Union (EU) established the European Platform on LCA [124] with the goal of increasing access to and use of high-quality LCA knowledge, methodologies, and research in order to better inform public policy and commercial actions. The United States Environmental Protection Agency (EPA) began advocating for LCA's adoption in the country [125]. The European

Commission's Joint Research Centre (EC-JRC) deserves special recognition for its efforts to provide this policy encouragement through a variety of programs and actions dating all the way back to 2004.

Building efficiency can be improved by including LCA alongside integrated project delivery (IPD) and Building Information Modeling (BIM) [126] [127] [128]. When properly integrated, BIM models can become part of building automation systems, providing the building operator with a comprehensive picture of all the building's systems. Through the implementation of LCT, which improves both IPD and BIM, puts people, profits, and the environment at the forefront of decision-making so that all three can be considered simultaneously. The essential parts of the IPD and LCA process are broken down and illustrated in **Figure 21** [129] [130].

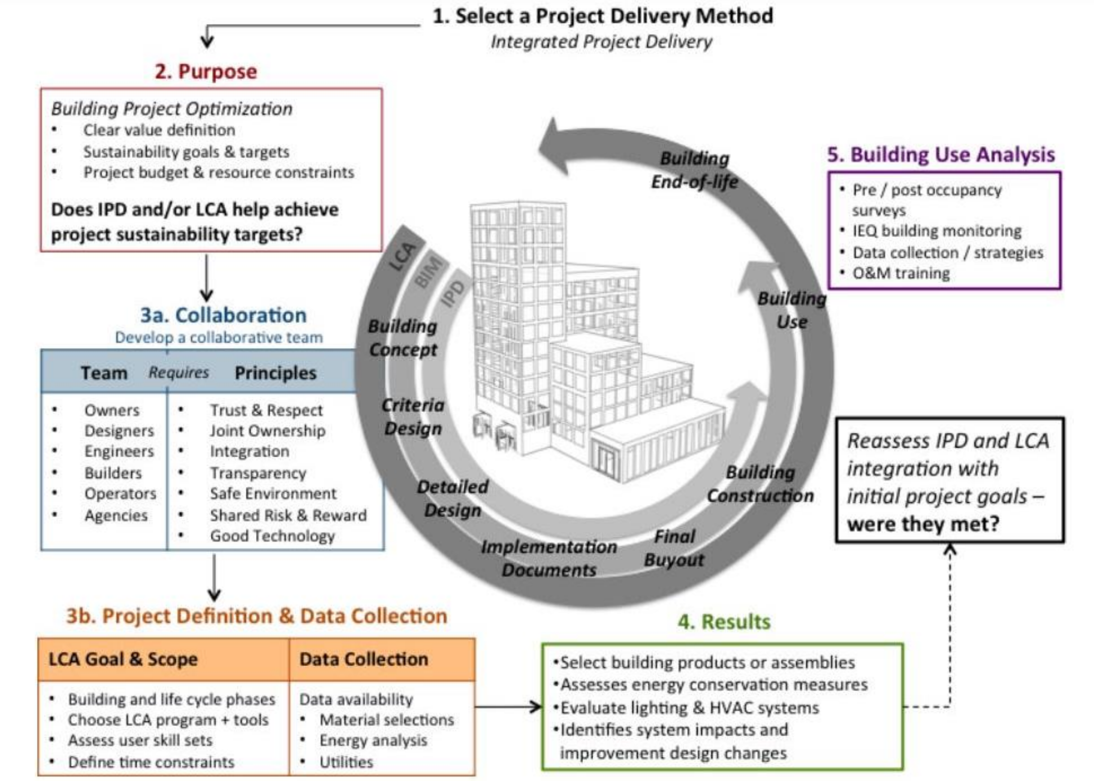


Figure 21: IPD and LCA structure [131]

As a result of using LCT at the inception of a construction project, all phases of the endeavor are guided by a comprehensive perspective. However, LCA's lack of comprehensiveness in answering all the concerns that a building owner needs to consider before making a decision is one of its few drawbacks. In particular in the construction sector, the LCA application business can benefit from extending the function of conventional LCAs through the use of a wider range of tools and approaches. As can be seen in **Figure 22**, an exploratory approach in the form of a decision tree was designed to assist users in selecting an optimal LCA enhancement strategy for their specific endeavors [92]. The IPD team will keep improving project life cycle thinking and increasing effect consciousness by utilizing the decision tree to identify the most relevant LCA optimization approach. The decision tree is meant to graphically connect how several LCA techniques can be combined to achieve a certain objective, like product choice or energy usage.

Since the International Organization for Standardization (ISO) never intended to define LCA methodologies in depth, and due to the lack of consensus on how to perceive parts of the ISO standards, many approaches have been created with regard to system boundaries and allocation methods [132]. These include risk-based LCA [133] [134] [135] [136], dynamic LCA [137] [138] [139] [140], hybrid LCA [131] [141] [142], and spatially differentiated LCA [143] [144]. The term LCC refers to a financial evaluation that factors in all agreed-upon predicted major and pertinent cost flows across the time of the study. The estimated expenditures are those expected to be incurred to accomplish the desired performance goals (such as those related to reliability, safety, and availability) [145]. Further, methods for social life cycle assessment (SLCA) [146] and life cycle costing (LCC) [147] have been suggested and/or implemented that might be inconsistent with environmental LCA with respect to temporal perspectives, system boundaries, calculation methodologies, etc. [143] [148]. Each of these methods addresses a unique set of questions and builds on the life-cycle foundation in unique ways. In 2006, in response to this challenge, the European Commission initiated the Co-ordination Action for innovation in Life Cycle Analysis for Sustainability (CALCAS) [149] initiative in order to standardize the wide variety of LCA methods and establish research priorities and directions.

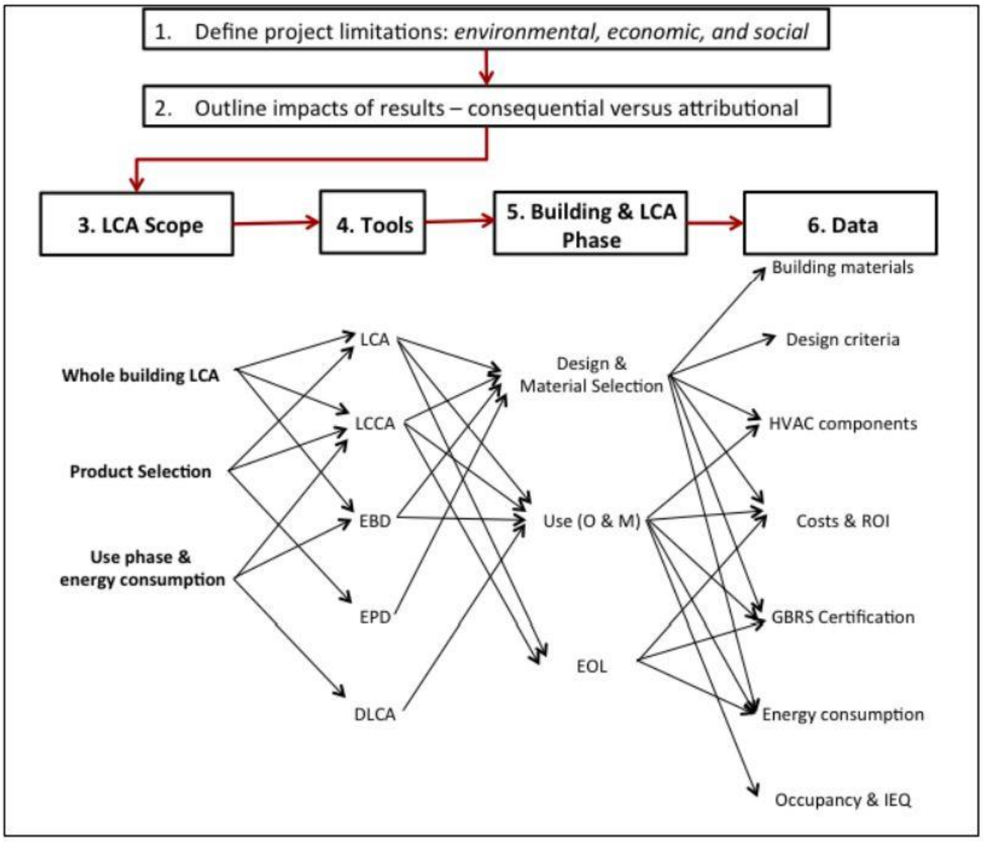


Figure 22: Decision tree of optimal LCA enhancement strategy [150]

In 2008, the European Commission launched its Sustainable Consumption and Production and Sustainable Industrial Policy (SCP/SIP) Action Plan [151], marking a watershed moment in the development of LCA for policy support. As a result, LCA emerged as the scientific core alongside IPP and resource and waste management policies from the past, but without the micromanagement legislative extent investigated by the US EPA in the 1980s. Following the publication of the guidelines for ILCD [152] in 2012, the EU Commission issued recommendations for Product Environmental Footprint (PEF) [153] and Organizational Environmental Footprint (OEF) [154]. The European Platform on LCA (EPLCA) [155] is an important resource in this context; the platform's stated mission is to enhance life cycle thinking in the industry and policy decisions in the EU, and it has been instrumental in the growth of both PEF and OEF [156] by ensuring adequate data and methodologies.

4.2.4 LCA sustainability

Since the beginning of this millennium, efforts have been made to broaden the scope of the LCA framework so that it takes into account the effects of the product or system on social entities like workers, consumers, and communities. This is being done in order to be able to provide a more in-depth evaluation of the ability to contribute that a product or system makes to the concept of sustainability. S-LCA is the abbreviation for Social Life Cycle Assessment (SLCA), which refers to this augmentation of LCA.

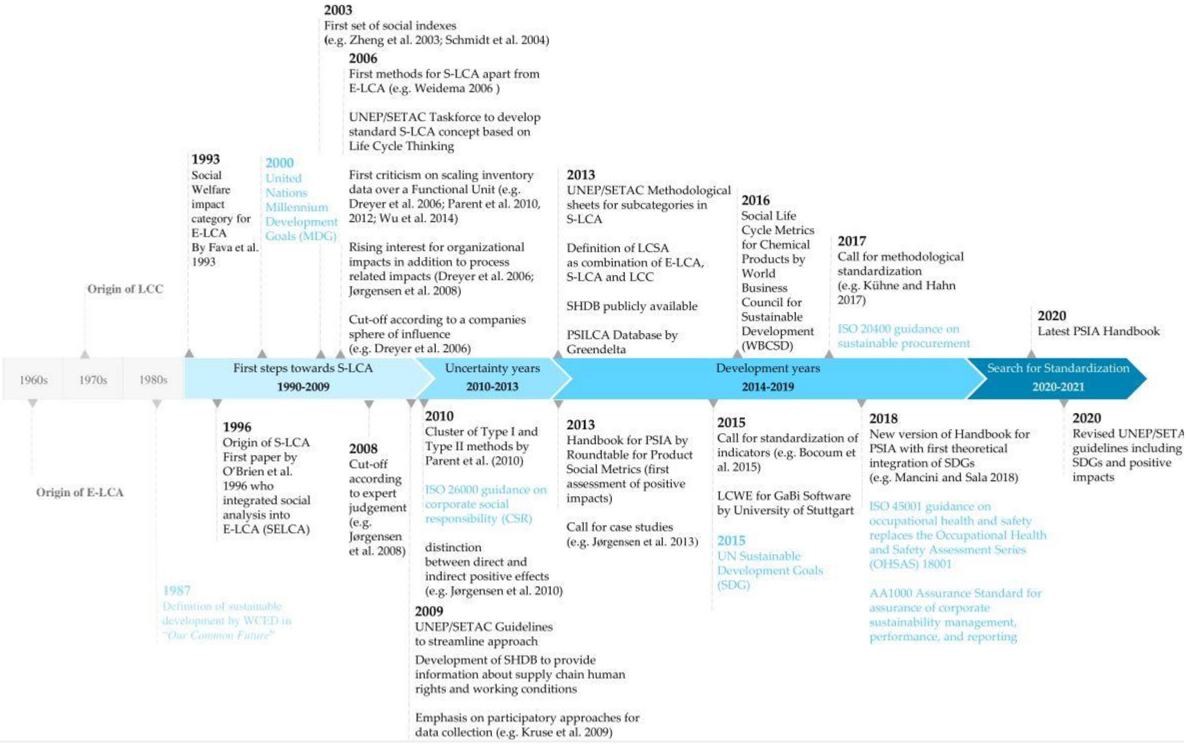


Figure 23: S-LCA progress 1996-2020 (adapted by [159] [160] [161] [162] [163] [164])

S-LCA is still developing. Thus, a wide range of strategies for the aforementioned methodological stages are presented in the extant S-LCA literature. As a result, it would be inaccurate to refer to it as a consistent and unanimous process. The "Guidelines to S-LCA" developed under the UNEP-SETAC Life Cycle Initiative represent the most significant step towards standardization to date and can be seen as a backbone for future research on S-LCA [157]. Early S-LCA development was heavily inspired by LCA, with the research community presuming that S-LCA could analyze social implications in the same manner that LCA could examine environmental ones. A comprehensive history of the developments and turning points that led to the present-day situation of SLCA has been laid forth. Accordingly, Huarachi et al. [158] broad classification of S-LCA history under four periods was refined and supported by scientific, political, and social benchmarks (**Figure 23**).

The main objective of an S-LCA is to determine how different aspects of a product or system influence human well-being at different points during its life cycle [165] [166] [167]. In light of this, S-LCA should offer a way that allows not only recognizing the social alterations generated by a product or system yet also for characterizing them and assessing them in terms of how they lead to a certain collective human wealth. If a person's welfare is in any way influenced by an action taken at any point in the product's life cycle, then that action must be accounted into the S-LCA [168]. This means that any impacted individual is regarded as a stakeholder, be it workers throughout the life cycle, local or regional people impacted by the various phases of the product life cycle, consumers [156], as well as interested parties who have the potential to influence or be influenced by decisions made during the product's life cycle, such as other decision-makers or business owners [169].

Figure 24: Impact areas identified by UNEP/SETAC [169]

According to Pollok et al. [169], All categories suggested by the methodology sheets have been employed in certain studies when evaluating them at the sub-category level, however their use is quite uneven. It is worth noting that UNEP/SETAC has not released a new set of methodology sheets at this time. Consequently, **Figure 24** does not include the evaluation of the new subcategories indicated by the Guideline 2020. One of the most significant flaws of the S-LCA paradigm is that it risks glossing over crucial distinctions between social and environmental concerns. Nevertheless, it cannot avoid its objective as a life cycle-oriented approach that aims for social evaluation, irrespectively of whether it will successfully incorporate essential values from the social sciences.

To incorporate social and economic sustainability dimensions into product life cycle analyses alongside environmental ones (three pillars), LCA has been recommended to be expanded into LCSA [170] [171]. It shifts the focus from challenges at the production level to those at the industry level and beyond, potentially albeit at the economic growth level. This way of thinking became more popular when Elkington [172] came up with the idea of the "Triple bottom line". He said that enterprises should control the environmental, social, and financial elements of sustainability in the same quantifiable manner that they actually manage the financial implications. The LCSA is rather a structure for the synthesis of concepts that span multiple disciplines. The main difficulty, then, lies in organizing, choosing, and making available the multiplicity of models in regard to various sorts of life cycle sustainability concerns.

Consequently, Kloepffer [170] presented the subsequent plan for LCSA, where LCSA necessitates that all three aspects of sustainability be evaluated in the same context, taking into account the same aspects of a product's life cycle in each evaluation.

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA} \qquad \textbf{Equation 13.}$$

4.2.5 LCA further development

The EU has been at the forefront of incorporating LCA into product design and application to a considerably larger degree compared to any other part of the world [122] [173]. Over the course of the next ten years, it is believed that LCA will be developed further in a wide range of ways. Additionally, it is possible that LCSA will have matured enough to provide a conceptual model for questions spanning multiple product, sector, and economic levels, as well as for tackling these issues across the entire sustainability scope (citizens, earth, and wealth) and with a more comprehensive set of processes.

Since the release of ISO 14040 [174], EN 15978 [175], which explains LCA methodology for structures, and, more recently, Level(s) [91], which is a reporting tool for assessing building sustainability, the implementation of LCA within the built environment has seen tremendous growth over the course of the past years [176]. Challenges remain to LCA's extensive industry implementation. This is partially because traditional LCA requires a lot of time and resources [177] [178]; thus, it is usually performed after a design has been agreed on [179] [180]. Life cycle thinking and assessment are making their way from academic applications and ad hoc deployments (mainly in-house in large corporations) to complex applications in the community as a whole [181]. This shift is occurring gradually. "Responsible consumption and production" is the focus of Sustainable Development Goal (SDG) (**Figure 25**) number 12 of the United Nations Agenda 2030, and the LCT is at the center of this goal. This objective intends to encourage individuals to embrace more environmentally friendly lifestyles by the year 2030, and accomplishing this objective will require a significant amount of attention on the supply chain, from primary producers to final consumers [182].

According to the findings of the review by Roberts et al. [184], LCA is typically applied later in the design phase when it is already too belated to have a significant contribution to the design. Despite the progress that has been made, the analysis showed that LCA still has a long way to go before it can effectively guide early-stage design decisions and significantly improve the built environment's performance. When designing a structure, it is important to consider how our choices will affect the building's carbon footprint over its lifetime. Considering the estimation that the built environment is responsible for over 40% of global greenhouse gas emissions [185], there is considerable space for improvement in this area [186]. Recommendations for achieving a net-zero carbon-built environment by 2050 have been released by the World Green Building Council (WorldGBC) [187]. Following applicable policies, the term carbon is commonly used to refer to all anthropogenic greenhouse gases equivalent to carbon dioxide [188].

LCA is frequently used in the decision-making process when addressing operations that will actually occur in the near or far future during every stage of the manufacturing, usage, and eventual disposal of products [189] [190]. Despite their differences, foresight approaches may provide valuable insights into a range of issues associated with future-oriented LCAs. However, the conventional technique for LCA needs to be modified for the prospective and change-oriented aims; even so, a standardized approach has not yet been developed to accomplish this goal. The term "prospective" or "future-oriented" LCA is used to describe a methodical evaluation of forthcoming events and developments that takes into account potential changes in the product system (and/or functional unit), its socioeconomic structures, and policy decisions that could have a consequence for the environment in the future. The LCA of upcoming technologies will yield a number of responses rather than "the" solution.

Figure 25: Links of Sustainable Development Goals [183]

LCA, a similar tool or a suite of tools, appears likely to expand in the near future due to the variety of policy variables and implications on stakeholder choices [191]; this is an interesting and promising period for the method [92] [192]. The expected mediating feedback mechanisms between methodology and policy are depicted in **Figure 26.**

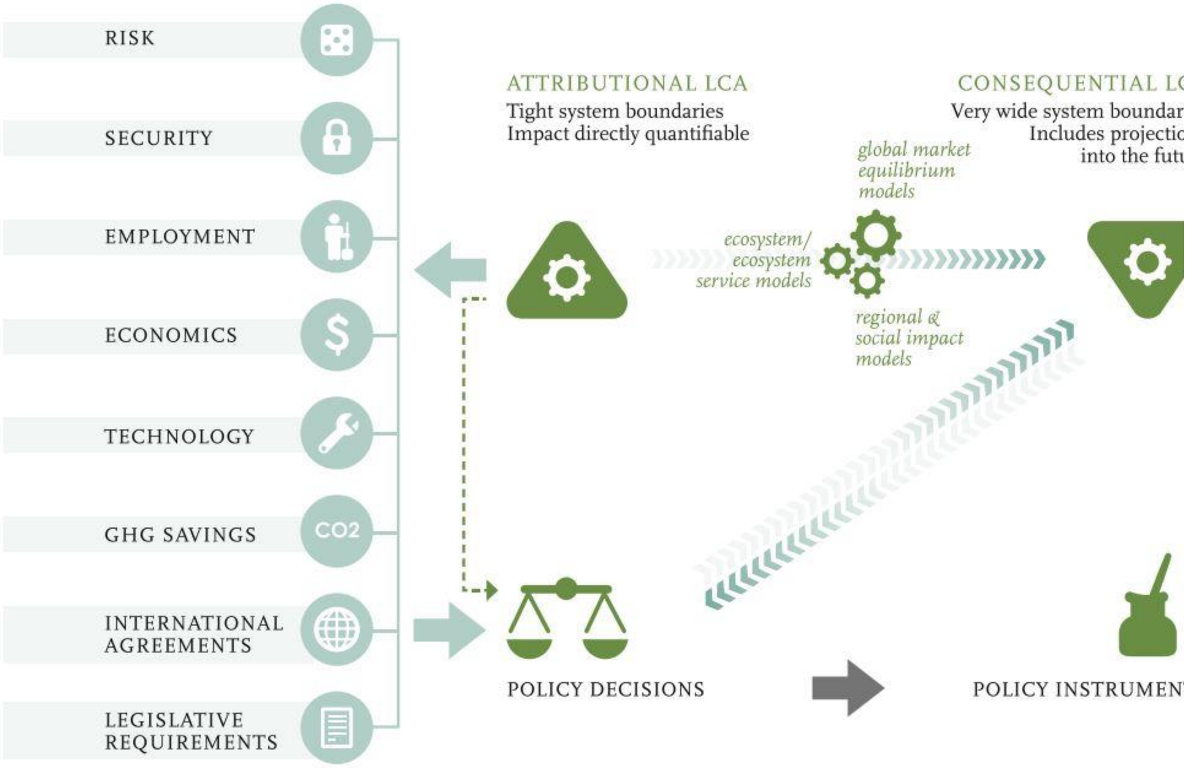


Figure 26: Feedback mechanisms between methodology and policy [193]

There are commonalities to be seen between LCSA and the field of integrated assessment (IA). When it comes to particular concerns of sustainability, risk assessment (RA) is very relevant and should either be performed in addition to or instead of LCSA tools. IA is an interdisciplinary method that combines, analyzes, and distributes knowledge from several scientific fields in such a manner that the entire cause-effect sequence of a challenge can be assessed. This definition comes from Van der Sluijs [194], who describes IA as thus. As such, LCSA can be understood as the reincarnation of IA inside the life-cycle context. The international scientific community and international political agencies have a formidable challenge in developing the LCSA framework; effective international cooperation is essential if we are not to return to an impasse of the multiplicity of various theories and techniques.

Pomponi and Moncaster [195] showed that the use and end-of-life stages of a building are commonly left out of embodied carbon LCA research. This highlights the importance of focusing on the impacts that buildings have when they are initially constructed. All of the effects that occur before the materials exit the plant or processing facility are included in the cradle-to-gate emissions [196]. According to the findings, more research is required to offer designers with context-specific knowledge to make informed judgments about all aspects that can be modified by design and management, which vary depending on time and location [197]. The incorporation of LCA into the design phase will be of tremendous assistance to designers in meeting the targets for 2030 and 2050 [198] concerning (i) guaranteeing that designs will be able to contribute to the establishment of a built environment with a net-zero carbon footprint, (ii) having knowledge of the environmental effects that will be caused by constructions prior to their building, and (iii) enabling designers to get rid of undesired influences at any point in the design phase [185] [199]. Whole-life carbon analysis is an analogous approach that also incorporates elements from LCA theory and practice; however, it narrows its attention to a specific concern, namely the potential for global warming, which is more commonly known as the carbon footprint [200] [201].

Finally, the Masterplan to Limiting Building Life Cycle Hazards, depicted in **Figure 27**, can be utilized to determine which critical steps should be taken and which major design milestones should be reached at each phase of a building's development.

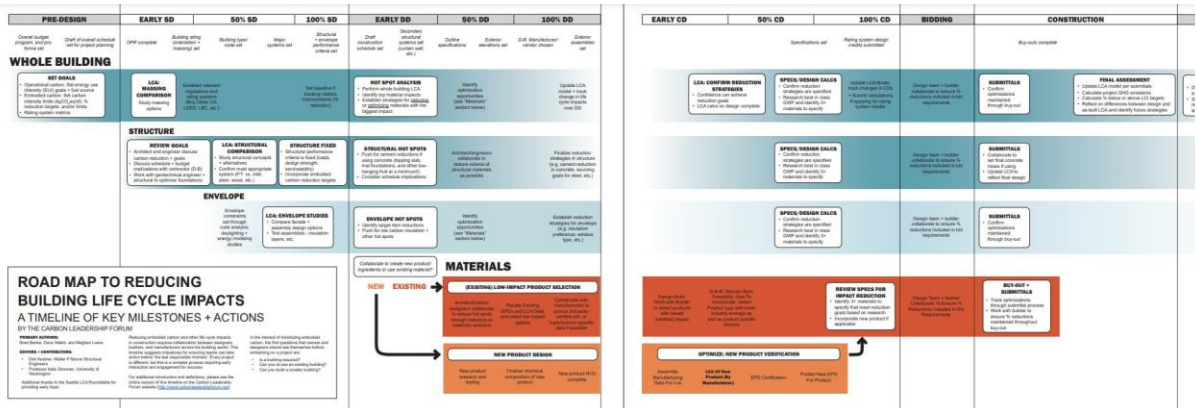


Figure 27: Masterplan to Limiting Building Life Cycle Hazards [202]

4.3 Overview of existing BIM to LCA

Since there is a growing interest in integrating LCA and BIM to steer the building sector toward environmental sustainability, the BIM-based LCA methods are analyzed to propose a workflow based on data input, data analysis, and data output that would support a holistic approach to buildings while minimizing wasted time and effort. The goal is to provide professionals with cutting-edge methods for assessing environmental implications, such as energy analysis, cost estimation, and green building certifications.

There have been multiple attempts to categorize BIM and LCA [203] [204] [205] [206]. Anton and Diaz [204] proposed two different ways in which BIM and LCA could be combined. First, data from building information models (BIMs) is used directly in environmental performance calculations—the second kind requests that environmental attributes be incorporated into the BIM objects. Wastiels and Decuypere [206] put forward the most exhaustive taxonomy. A total of five subtypes focused on the medium via which data is exchanged between BIM and LCA tools were identified; the Bill of Quantities report, the IFC format, BIM viewer tools, LCA plug-ins, and attribute values.

In the most recent studies, there were found to be three distinct ways of handling the interchange of data between BIM and LCA (**Figure 28**). Using a third-party tool, Type I combines information from BIM and LCA to provide carbon results. Material amounts can be included in models made with BIM programs like Autodesk Revit [207] [208], ArchiCAD [209], and Rhinoceros [210], and then exported to be integrated with carbon emission values found in numerous LCA databases [211] [212]. Excel spreadsheets and other custom tools written in programming languages [213] [214] [215] are commonly used to perform calculations. Despite being easy to implement and providing immediate results, this method can only be used for very basic forms of LCA.

Type II integrates carbon emission variables into the BIM system through the creation of plug-ins and APIs (APIs) [216] [217] [218]. The data mapping process between carbon emission components and BIM objects is still time-consuming due to differences in material characteristics like units, types, and names, but this method makes effective use of BIM technology as a data repository and visualization platform [219] [220]. Professionally and reliably, Type III has the overwhelming advantage since it imports the essential BIM data into specialized LCA software tools, resulting in an accurate and thorough LCA. Since it connects the relevant BIM model to expert LCA implementation and offers sufficient LCA information with in-tool databases, this strategy should receive more attention.

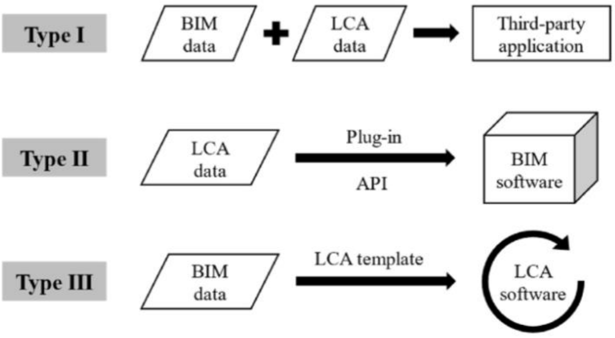


Figure 28: Three BIM-integrated LCA data-flow methodologies [221]

Construction design makes Revit the most popular BIM tool. Athena Impact Estimator, eBalance, openLCA, and SimaPro are other LCA tools. Revit, SketchUp, Tekla, and ArchiCAD are just a few of the available various BIM software packages that allow for property modification and IFC export. SimaPro, one of the best LCA software programs, can pull in data from numerous LCA databases, including the widely-used Ecoinvent, ETH-ESU 96, and US LCI, to generate accurate estimates of carbon emissions from raw materials and energy use [222]. There are also various licensed, automated LCA-BIM software, such as OneClickLCA [223].

A BIM-integrated LCA approach (Figure 29) was created in the Xu et al. [224] study, incorporating three components: (i) BIM data preprocessing, (ii) information extraction and incorporation, and (iii) embodied carbon evaluation. Pan et al. [225] propose a five-level analytical framework that divides buildings into (i) materials, like concrete and steel, (ii) components, like prefabricated concrete surfaces or staircases, (iii) assemblies, like non-volumetric precast facades, (iv) flats, like a residential unit, and (v) whole buildings.

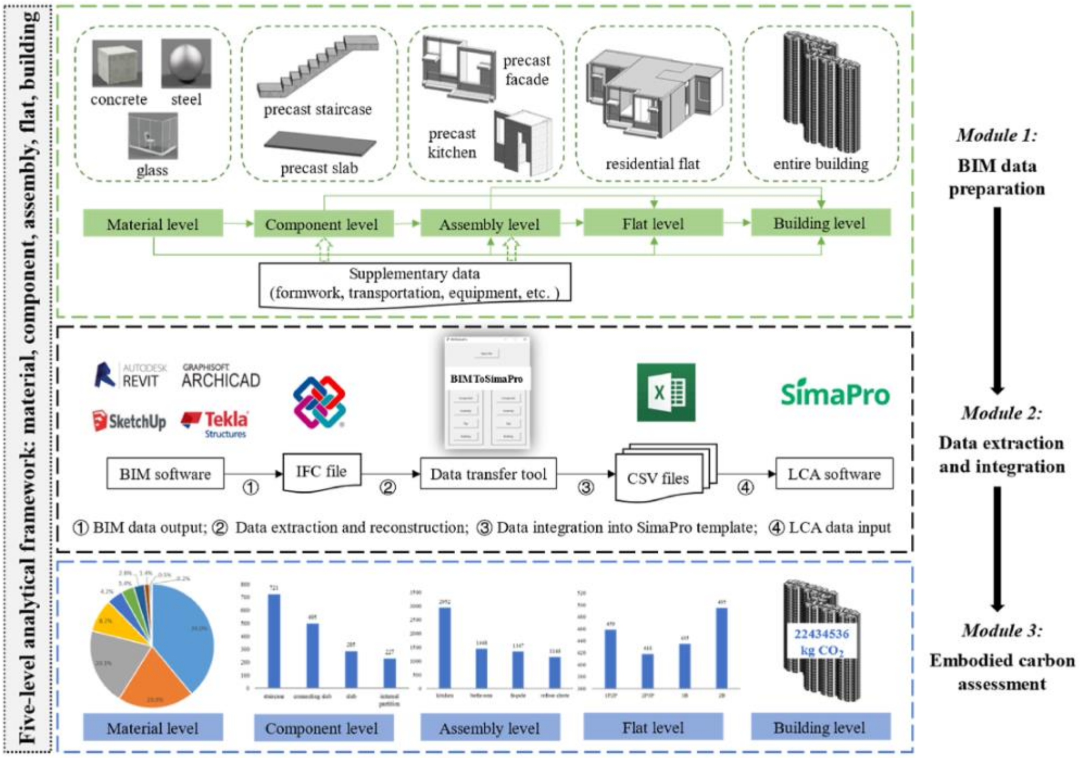


Figure 29: The framework of the developed BIM-integrated LCA solution [224]

In the future, it will be impossible to disregard the need to incorporate LCA and BIM in the process of decision-making at an early stage. The incorporation and LCA hold great promise for the building industry’s long-term sustainability. When all relevant building data is combined with existing LCA databases, the possible environmental influence of building professionals’ actions becomes clear. The methodological difficulties and restrictions of currently available LCA-BIM technologies demonstrate the seemingly limitless potential for the creation of new assessment tools and approaches. Once the integration is established, information-based building modeling will ensure that LCA is performed continually in real-time throughout all phases of construction planning.

The challenges with BIM-LCA development and sustainability (Table 6) leading to inefficiency [226] include, among others, the lack of a uniform database platform and the employment of databases that are too different from one another. Using the same or similar databases offers more consistent outcomes [227]. Although relative tools have been developed, they are still not widely used, and it is not common practice for engineers at the design stage to also perform LCA. Region-specific databases are useful since some of them provide automated material classification, which is essential for assigning and measuring potential environmental consequences. Some of these difficulties can be traced to an absence of management or standardization of the concepts in regard to LCA; for example, the most frequently cited barriers have been pointed out to be the absence of a method for extracting quantities, specifications for the input of material data, and high-quality models at the time they necessitate them for LCA. Consequently, the necessary collaborative modeling effort is not being undertaken since there is no motivation to model for quantity take-off.

Table 6: BIM and sustainability assessment: opportunities and constraints for discussion [228] [229]

Challenges	Comments	
Improper administration of construction models in a collaborative process	▪ Time-consuming	▪ No minimum demands for LOD on material information
	▪ Model not designed by users	▪ Inability to edit models
	▪ Lack of responsibility for the quantities in models	▪ No standardization for extraction of quantities
	▪ Late commencement of models	
Modelling errors	▪ Errors in the model	▪ Wrong mensuration from modelling errors
	▪ Wrong dimension of elements	▪ Double modelling
	▪ No reinforcement in concrete elements	
Manual workflow and large models	▪ Too much information	▪ Extracting quantities/checking data is the most time-consuming process
	▪ Time consuming with manual BIM–LCA workflow	
Workflow errors	▪ Paint areas are wrong if the suspended ceiling is not accounted for	▪ Difficult to check models for errors by third parties
	▪ Human error when manually typing	▪ Inability to detect missing quantities in Revit quantities extraction
Data exchange and matching model data with LCIA data	▪ Matching quantities with LCIA data from LCA by creating generic plug-in scripts for all models	▪ Difficulty using quantity outputs units from models for LCA
	▪ Issues with stability and workflow	▪ Difficulty in future workflow prediction to user-friendly tools
Variations in the structure of models	▪ Difference in modelling across nations	▪ Structurally different models
Lack of data availability and quality in models	▪ Incorrect modelling	▪ Difficulty in extracting correct quantities from the models
	▪ Incorrect quantities	▪ Materials are not in the models
	▪ Varying details	▪ Not all materials are modelled in the model
	▪ Data in models is not good enough	▪ Varying models quality
	▪ MEP model is not used for the LCA because it is not good enough	▪ Insufficient details in models
	▪ Getting information from the right source	▪ Incomplete data availability in Revit
	▪ Information is not in the Revit model; only geometry	▪ Incorrect models in terms of extracting quantities

4.4 Data and Parameters for Environmental Analysis

In the context of the SmartLivingEPC project, **Figure 31** demonstrates the process of extracting LCA results for a building's environmental indicators, encompassing various stages such as construction materials, transportation, construction/installation, and deconstruction. These results are obtained from a BIM file and are informed by the environmental indicators outlined in Level(s) guidelines.

The comprehensive analysis conducted reveals detailed values for the environmental indicators during distinct stages of the building's life cycle (Figure 30): (a) the phase involving construction materials, (b) transportation of materials to the site, (c) the construction and installation process, and (d) the end-of-life phase. Additionally, the total values for each indicator are provided. As a result of this analysis, the environmental footprint associated with each construction material and structural element category can be discerned.

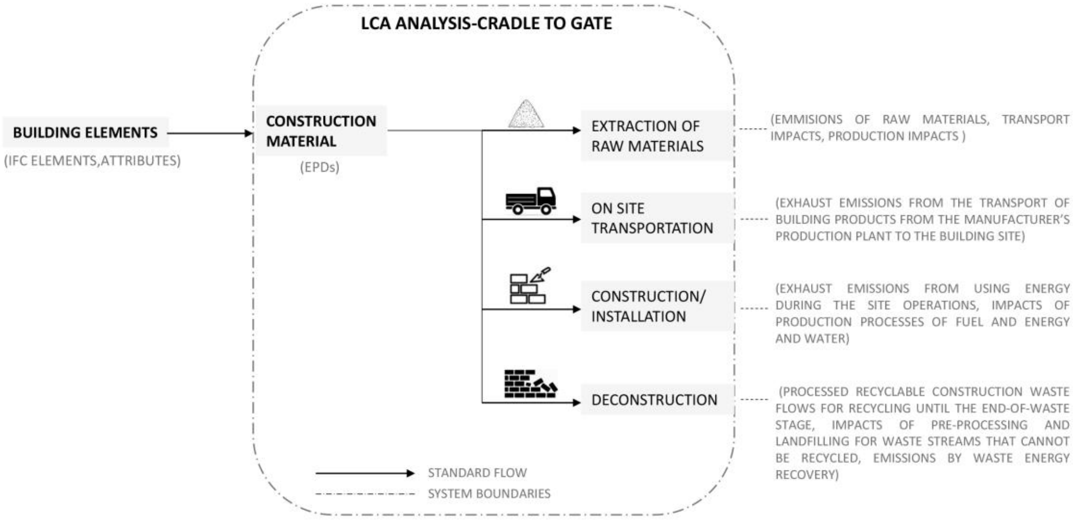


Figure 30: System's boundaries for the LCA analysis materials

4.4.1 Methodology

The SmartLivingEPC project aims to incorporate a comprehensive set of indicators concerning the environmental aspects of buildings. This endeavor underscores the significance of integrating LCA methodologies into the efficient energy design of buildings. The EPCs primarily cater to pertinent stakeholders, practicing engineers, and EPC assessors, with the ultimate goal of implementing the principles of SmartLivingEPC in building certification processes.

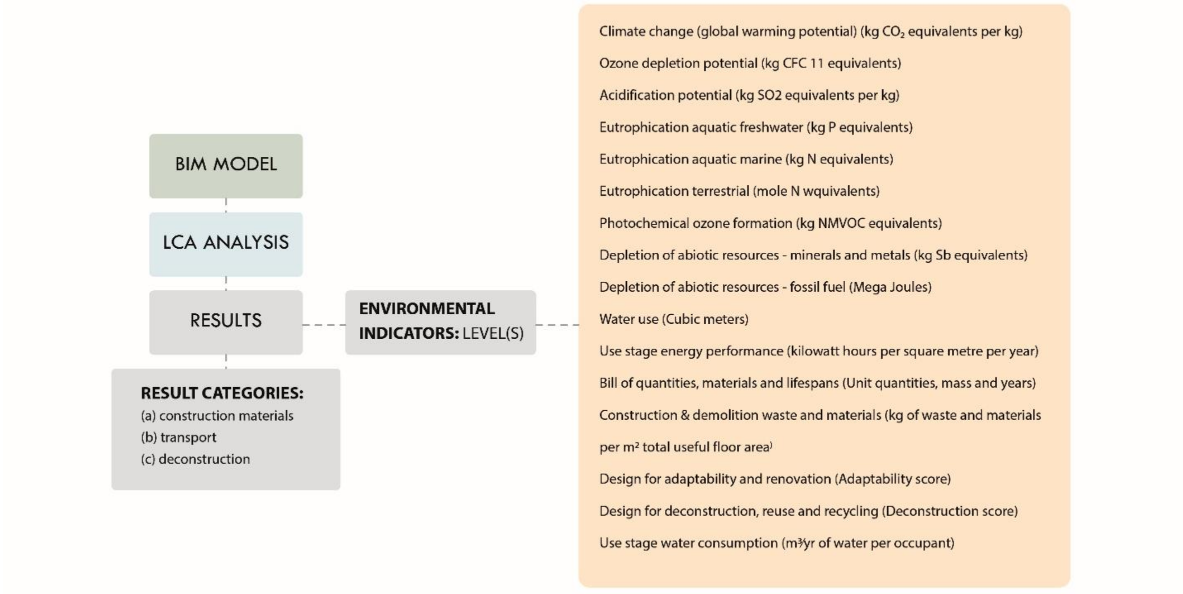


Figure 31: Environmental indicators extraction

The development of environmental indicators for SmartLivingEPC is rooted in the Level(s) scheme, which serves as the European Union's framework for assessing and reporting on the sustainability performance of buildings across their entire life cycle. The Level(s) approach aligns its evaluations with European sustainability objectives and employs existing standards, thereby providing a cohesive platform for quantifying, analyzing, and comprehending the life cycle of buildings. This approach targets various circularity aspects and furnishes indicators that offer valuable insights into enhancing building functionality. Consequently, Level(s) constitutes a constructive framework devoted to bolstering environmental performance, optimizing resource utilization, and diminishing the overall impact of the built environment on global resources.

4.5 SmartLivingEPC Environmental Indicators

4.5.1 Level(s) scheme indicators

Level(s) offers a comprehensive framework of indicators and standardized metrics aimed at assessing the environmental efficacy of buildings throughout their entire life cycle. In addition to gauging environmental performance, the methodology facilitates the evaluation of other crucial facets pertaining to building performance, such as health and comfort indicators, life cycle cost analysis, and the anticipation of potential future performance risks.

Level(s) endeavors to establish a comprehensive lexicon of sustainability concerning edifices. This universally accepted terminology is intended to facilitate the implementation of measures at the individual building scale, which can effectively align with and support overarching environmental policy imperatives within the European context. The framework of Level(s) is organized as in **Figure 32**.

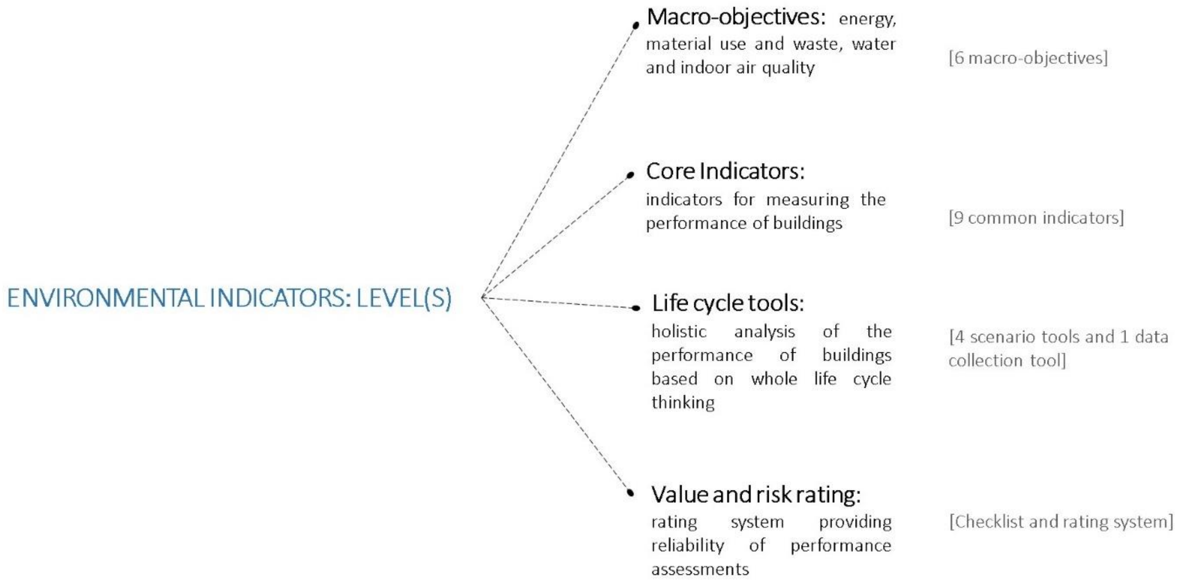


Figure 32: Diagram of Level(s) objectives

Moreover, the Level(s) framework endeavors to foster life cycle thinking by directing users to progress from a preliminary concentration on discrete facets of building performance to a more comprehensive outlook. The ultimate objective lies in its potential to attain broader adoption of Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) practices throughout Europe. The indicators are explained in more detail below:

Climate change (global warming potential) (kg CO_2 equivalents per kg): Indicator of potential global warming due to air emissions of greenhouse gases. Climate change is defined as the impact of human emissions on the radiative forcing (i.e., heat radiation absorption) of the atmosphere. This may, in turn, have adverse impacts on ecosystem health, human health, and material welfare. Most of these emissions enhance radiative forcing, causing the temperature at the earth’s surface to rise, i.e., the greenhouse effect. The areas of protection are human health, the natural environment, and the man-made environment.

Ozone depletion potential (kg CFC 11 equivalents): Indicator of air emissions that causes the destruction of the stratospheric ozone layer.

Acidification potential (kg SO2 equivalents per kg): Decrease in the pH-value of rainwater and fog measure, which has the effect of ecosystem damage due to, for example, nutrients being washed out of soils and increased solubility of metals into soils. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems, and materials (buildings). The major acidifying pollutants are SO_2, NO_x, and NH_x. Areas of protection are the natural environment, the man-made environment, human health, and natural resources.

Eutrophication aquatic freshwater (kg P equivalents): Excessive growth measurement of aquatic plants or algal blooms due to high levels of nutrients in freshwater. Freshwater ecotoxicity refers to the impacts of toxic substances on freshwater aquatic ecosystems.

Eutrophication aquatic marine (kg N equivalents): marine ecosystem reaction measurement to excessive availability of a limiting nutrient.

Eutrophication terrestrial (mole N equivalents): increased nutrient availability measurement in the soil as a result of the input of plant nutrients.

Photochemical ozone formation (kg NMVOC equivalents): emissions of nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOC) measurement and consequent effects on the 'Human Health' and 'Terrestrial ecosystems' areas of protection. The photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health, and ecosystems may also damage crops. The relevant areas of protection are human health, the man-made environment, the natural environment, and natural resources.

Depletion of abiotic resources - minerals and metals (kg Sb equivalents): Indicator of the depletion of natural non-fossil resources. "Abiotic resources" are natural sources (including energy resources) such as iron ore, crude oil, and wind energy, which are regarded as non-living. Abiotic resource depletion is one of the most frequently discussed impact categories, and there is consequently a wide variety of methods available for characterizing contributions to this category. To a large extent, these different methodologies reflect differences in problem definition. Depending on the definition, this impact category includes only natural resources, or natural resources, human health, and the natural environment, among its areas of protection.

Depletion of abiotic resources – fossil fuel (Mega Joules): Indicator of the depletion of natural fossil fuel resources.

Water use (Cubic meters): Indicator of the amount of water required to dilute toxic elements emitted into water or soil.

Use stage energy performance (kilowatt-hours per square meter per year): 'operational energy consumption': primary energy demand measurement of a building in the use stage, generation of low-carbon or renewable energy.

Life cycle Global Warming Potential (kg CO_2 equivalents per square meter per year): 'carbon footprint assessment' or 'whole life carbon measurement': building's contribution to greenhouse gas (GHG) emissions measurement associated with earth's global warming or climate change.

Bill of quantities, materials, and lifespans (Unit quantities, mass, and years): The quantities and mass of construction products and materials, as well as the estimation of the lifespan measurements necessary to complete defined parts of the building.

Construction & demolition waste and materials (kg of waste and materials per m^2 of total useful floor area): The overall quantity of waste and materials generated by construction, renovation, and demolition activities; used to calculate the diversion rate to reuse and recycling, in line with the waste hierarchy.

Design for adaptability and renovation (Adaptability score): Building design extent assessment of facilitation future adaptation to changing occupier needs and property market conditions; a building proxy capacity to continue to fulfill its function and for the possibility to extend its useful service life into the future.

Design for deconstruction, reuse, and recycling (Deconstruction score): Building design extent assessment of facilitation future recovery of materials for reuse or recycling, including assessment of the disassembly for a minimum scope of building parts ease, followed by the reuse and recycling for these parts and their associated sub-assemblies and materials ease.

Use stage water consumption (m^3/yr of water per occupant): The total consumption of water measurement for an average building occupant, with the option to split this value into potable and non-potable supplied water, as well as support measurement of the identification of the water-scarce location.

The findings pertain to the various **life stages of the building**, encompassing: (a) A1-A3, involving construction materials; (b) A4, concerning transportation to the construction site; (c) A5, encompassing the construction/installation process; (c) B1, during the utilization phase; (d) B3, involving repair activities; (e) B4-B5, encompassing material replacement and refurbishment; (f) B6, pertaining to energy consumption; (g) B7, involving water usage; and (h) C1-C4, during the end-of-life stage. By employing a specialized process for the computation of environmental indicators, the results primarily pertain to the following four life stages of the building: (1) A1-A3, concerning construction materials; (2) A4, relating to transportation to the site; (3) B5, encompassing construction and installation; and (4) C1-C4, during the end-of-life phase. A comprehensive account of the principal life cycle stages and the scope of analysis is furnished in the accompanying Table 7.

Table 7: Table of life-cycle stages description [OneClick LCA]

Life-cycle stages	Description
A1-A3 Construction Materials	Raw material supply (A1) includes emissions generated when raw materials are taken from nature transported to industrial units for processing, and processed. Loss of raw material and energy are also taken into account. Transport impacts (A2) include exhaust emissions resulting from the transport of all raw materials from suppliers to the manufacturer's production plant as well as impacts on the production of fuels. Production impacts (A3) cover the manufacturing of the production materials and fuels used by machines, as well as the handling of waste formed in the production processes at the manufacturer's production plants until the end-of-waste state.
A4 Transportation to the site	A4 includes exhaust emissions resulting from the transport of building products from the manufacturer's production plant to the building site as well as the environmental impacts of the production of the used fuel.
A5 Construction/installation process	A5 covers the exhaust emissions resulting from using energy during the site operations, the environmental impacts of production processes of fuel and energy and water, as well as handling of waste until the end-of-waste state.
B1-B5 Maintenance and material replacement	The environmental impacts of maintenance and material replacements (B1-B5) include environmental impacts from replacing building products after they reach the end of their service life. The emissions cover impacts from raw material supply, transportation, and production of the replacing new material as well as the impacts from manufacturing the replacing material as well as handling of waste until the end-of-waste state.
B6 Energy use	The considered use phase energy consumption (B6) impacts include exhaust emissions from any building-level energy production as well as the environmental impacts of production processes of fuel and externally produced energy. Energy transmission losses are also taken into account.
B7 Water use	The considered use phase water consumption (B7) impacts include the environmental impacts of the production processes of fresh water and the impacts from wastewater treatment.
C1-C4 Deconstruction	The impacts of deconstruction include impacts for processing recyclable construction waste flows for recycling (C3) until the end-of-waste stage or the impacts of pre-processing and landfilling for waste streams that cannot be recycled (C4) based on the type of material. Additionally, deconstruction impacts include emissions caused by waste energy recovery.
D External impacts/end-of-life benefits	The external benefits include emission benefits from recycling recyclable building waste. Benefits for re-used or recycled material types include the positive impact of replacing virgin-based material with recycled material and benefits for materials that can be recovered for energy cover positive impact for replacing other energy streams based on average impacts of energy production.

In the context of the SmartLivingEPC project, the LCA Level(s) tool is employed for the purpose of conducting assessments. Within this framework, a comprehensive compilation of seventeen distinct data result terms is meticulously outlined in Annex **A.2 Environmental life-cycle Indicators**.These environmental indicators primarily constitute asset indicators, amenable to computation through the amalgamation of the materials bill of quantities derived from a BIM document, along with the pertinent Environmental Product Declarations (EPDs) of the building materials under consideration.

5 Technical audits and inspections integration to SmartLivingEPC

5.1 Introduction

Noting that the objective of this Section is to facilitate the integration of information derived from energy performance inspections/audits of HVAC systems (such as those conducted under the auspices of the EPBD Article 14 and 15 provisions) into the SmartLivingEPC asset rating's calculation methodology, both at the building and complex level. In broad terms, the methodology entails:

- Conducting an analysis of the inputs and findings (outputs) of the technical inspection audits for building systems, such as the EN 15378, the EN 16798, the EN 16946, and the EN 16947 standards series
- Identifying and listing the main findings from the technical inspection audits which can be used for the energy classification
- Developing the necessary procedures and methodology, to enable the utilization of the findings of building systems periodic audits in the process of calculating the asset energy class of buildings, complementing Tasks T2.1, T2.2, and T2.3.

Noting that the scope is focused on the inspections/audits applied when assessing HVAC systems in line with the EPBD article 14 and 15 provisions, for each primary HVAC TBS, the methodology comprises the following steps:

- Acquisition and review of relevant TBS audit standards for HVAC TBS
- Clarification of the generic EPB EPC asset methodology per EN standards for each related HVAC type that has an audit standard
- Mapping of inputs/outputs of the EN TBS inspection/audit standards against the generic EPC asset assessment methodology – identification within each specific case where the EN audit standards:
    - produce inputs (or outputs) that could be used in the generic EPC asset methodology
    - where they do not and could not be adapted to do so
    - where they do not but could be adapted to do so
    - for the latter case, propose potential adaptations in procedure and method
- Note that this is to be done for each inspection level (per the annexes in the audit standards)
- Reporting of findings.

This is complemented by an additional step that considers how the inspection findings could be used as inputs into the SmartLivingEPC asset methodology and the proposal of procedures for how to do so.

5.1.1 Specific audit standards

This first (M13) version of the report focuses on the following inspection standards for HVAC systems:

- EN 15378-1:Energy performance of buildings - Heating systems and DHW in buildings - Part 1: Inspection of boilers, heating systems and DHW, Module M3-11, M8-11
- EN 16798-17:Energy performance of buildings. Ventilation for buildings Guidelines for inspection of ventilation and air conditioning systems (Module M4-11, M5-11, M6-11, M7- 11)

And:

- EN 16798-1:Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics - Module M1-6.

Later editions will include the standard:

- Energy Performance of Buildings - Inspection of Automation, Controls and Technical Building Management - Part 1: Module M10-11

5.1.2 Specific HVAC calculation standards

The principal HVAC calculation standards and their relationship to the EPB EPC calculation methodology are shown in **Figure 33**.

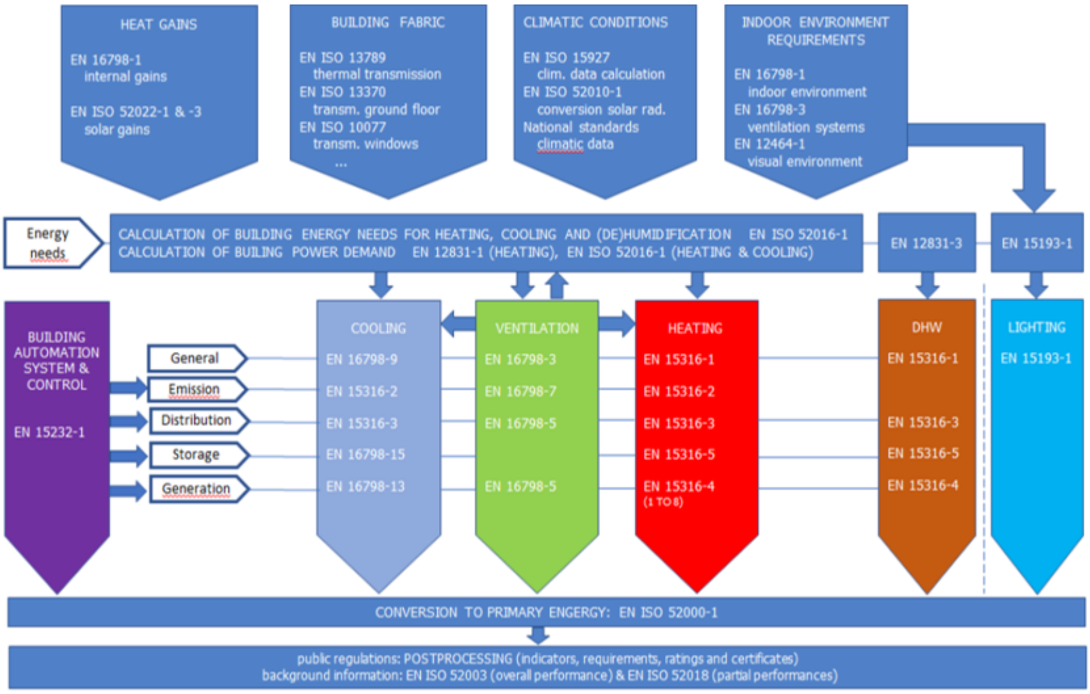


Figure 33: HVAC, BACS & lighting within the EPB calculation framework [230]

5.1.3 Respecting copyright

Drafting Section 5 is challenging due to the copyright of the EN standards. The mapping analysis underpinning this work is very detailed and hence necessarily includes the content of the standards in analytical mapping matrices (TBS inspection procedure steps and outputs mapped to inputs/outputs of the EPC asset assessment methodologies). Putting this into a public report (unless as a less meaningful synthesis) carries copyright risk.The text in this Section aims to avoid any copyright breach by only relaying synthetic tables in EPB standards that are of types already widely in the public domain, such as those on public view within the EPB center documents. Moreover, by summarising relevant outputs of the standards and (when relevant) their main objectives. At no stage does it report any details of the methodologies used to conduct the assessments except in the most general terms. Thus, the IP in the standards is fully protected.

5.2 Audits of technical building systems under the EPBD

5.3 Technical Audits for building systems analysis

5.3.1 Audits of space heating (and hot water) systems

This Section sets out the information on the inspections/audits of space heating and hot water systems and considers the outputs that could be integrated into the SmartLivingEPC asset methodology.

5.3.1.1 Standards and assessment procedures

This sub-section cites the standards that are used to calculate the energy performance of space heating and hot water systems when determining building energy performance via an EPC asset methodology and also cites the standards that are used to conduct audits/inspections of the space heating and hot water systems. It also reports the standards that are relevant to the EPBD Article 8(1) TBS measures.

5.3.1.2 Space heating and hot water within the overall EPB standards framework

Space heating is the largest contributor to building energy use in Europe, and domestic hot water heating is the second largest contributor, so collectively, their assessment is critical to the determination of any building's primary energy consumption and performance under an EPC rating. The assessment methods applicable to them sit within the following broad building energy performance evaluation framework.

Thus, from the left, a set of standards exists to determine the boundary conditions with regard to the indoor/outdoor conditions and the component and product characteristics. Another set of standards builds into these to determine the energy needs of the building (including the space heating and hot water). The energy use is determined for this energy need by applying calculation standards, 12 of which apply to space heating and domestic hot water. Then all the results from across all the technical building systems (including space heating and hot water) are aggregated to determine the primary energy use, which then allows the energy performance class under an EPC to be established. The energy calculations under the EPB standards asset assessment methodological framework are shown in **Figure 35**.

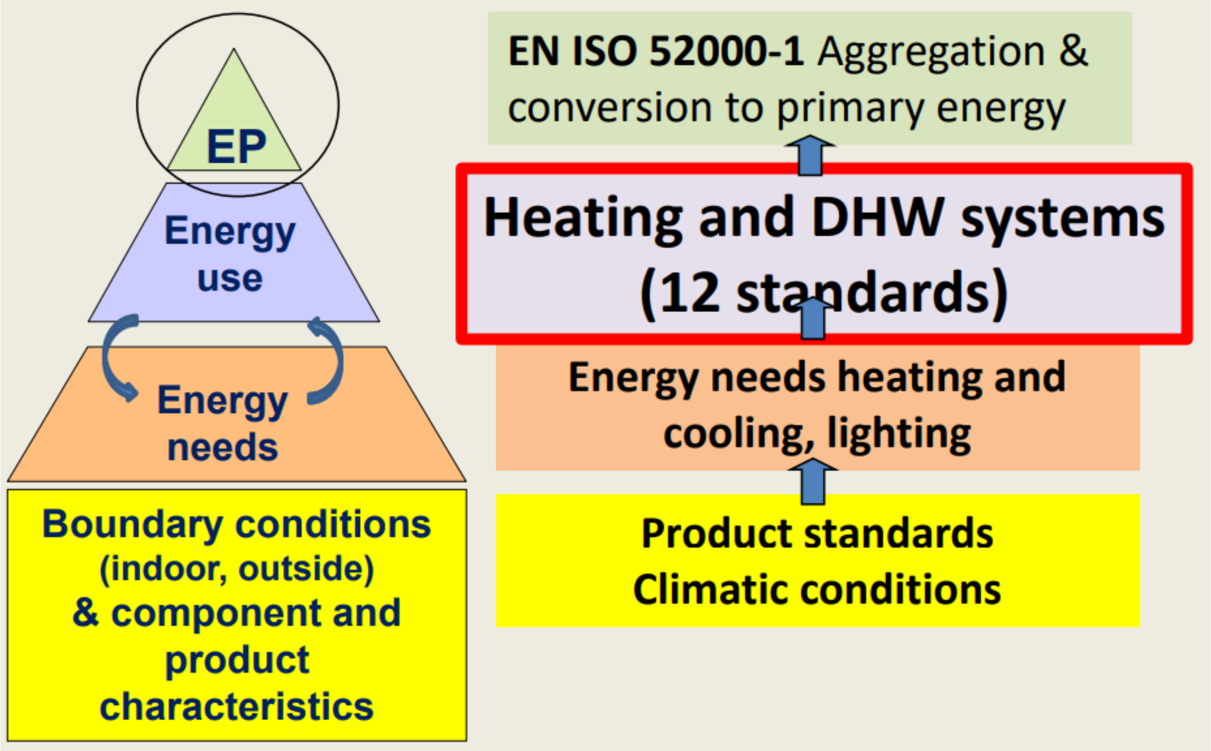


Figure 34: Space heating and hot water within the EPB calculation framework [243]

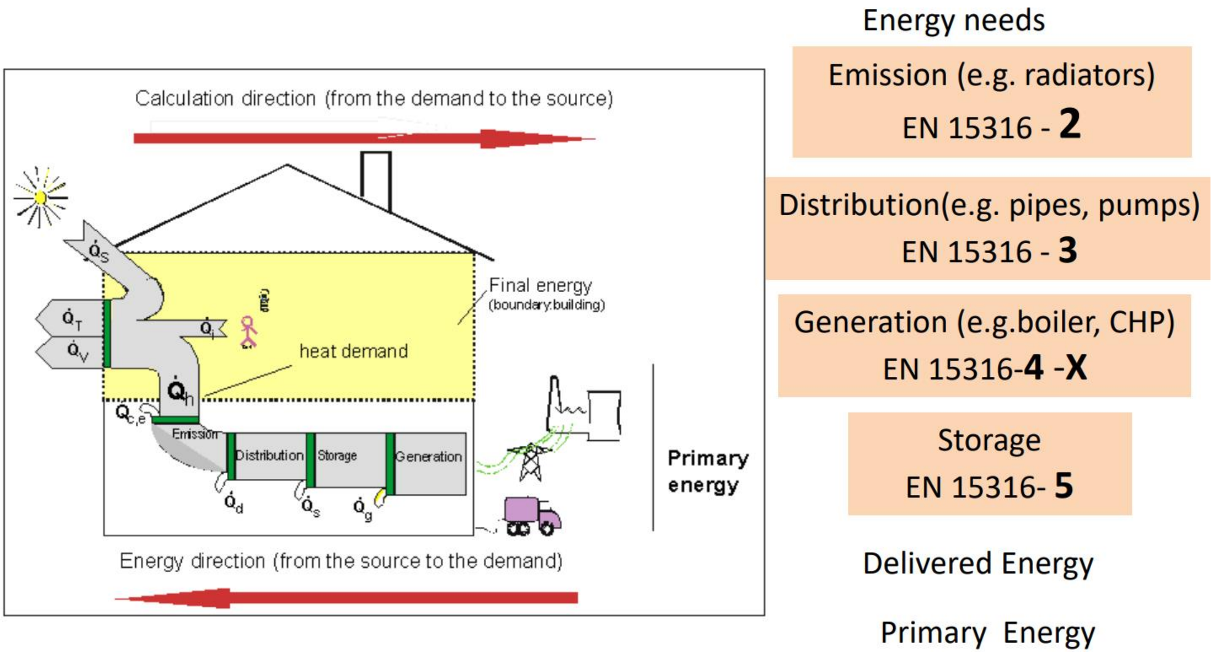


Figure 35: Energy calculation: General structure of heating and DHW standards - EN 15316 – series [243]

The following standards are concerned:

- EN 15316–1 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 1: General and Energy performance expression, Module M3–1, M3–4, M3–9, M8–1, M8–4
- EN 15316–2 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 2: Space emission systems (heating and cooling), Module M3–5, M4–5
- EN 15316–3 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 3: Space distribution systems (DHW, heating, and cooling), Module M3–6, M4–6, M8–6
- EN 15316–4-1 (heat. & DHW generation, combust. systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–1: Space heating and DHW generation systems, combustion systems (boilers, biomass), Module M3–8-1 and M 8–8-1
- EN 15316–4-2 (heat. & DHW generation, heat pump systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–2: Space heating generation systems, heat pump systems, Module M3–8-2, M8–8-2
- EN 15316–4-3 (heat generation, th. solar & PV systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–3: Heat generation systems, thermal solar and photovoltaic systems, Module M3–8-3, M8–8-3, M11–8-3
- EN 15316–4-4 (heating generation, cogen systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–4: Heat generation systems, building-integrated cogeneration systems, Module M8–3-4, M8–8-4, M8–11-4
- EN 15316–4-5 (heating generation, district H&C) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–5: District heating and cooling, Module M3–8-5, M4–8-5, M8–8-5, M11–8-5
- EN 15316–4-8 (heating generation, air heat. & ovhead rad. systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–8: Space heating generation systems, air heating and overhead radiant heating systems, including stoves (local), Module M3–8-8
- EN 15316–5 (heating and DHW storage systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 5: Space heating and DHW storage systems (not cooling), Module M3–7, M8–7

And additionally:

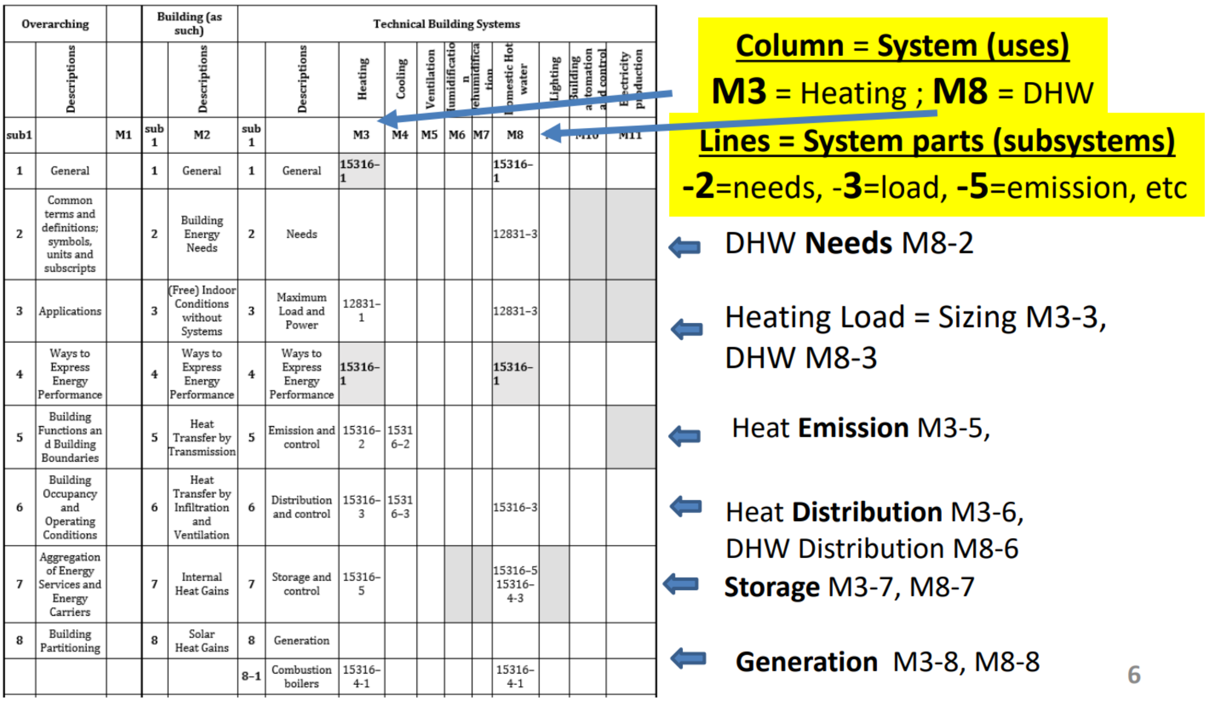
- CEN/TR 15316-6-1 (technical report)
- CEN/TR 15316-6-2 (technical report)
- CEN/TR 15316-6-3 (technical report)
- CEN/TR 15316-6-4 (technical report)
- CEN/TR 15316-6-5 (technical report)
- CEN/TR 15316-6-7 (technical report)
- CEN/TR 15316-6-8 (technical report)
- CEN/TR 15316-6-9 (technical report)
- CEN/TR 15316-6-10 (technical report)
- EN 12831–1 (heat. design load)

- CEN/TR 15316-6-6 (technical report)
- CEN/TR 12831-2 (technical report)

The following calculation standards are applicable:

- EN 15316-1: M3 Space heating: general
- EN 15316-1: M8 DHW: general
- EN 12831-3: M8-2 DHW: needs
- EN 12831-1: M3-3 Space heating: needs (sizing)
- EN 12831-3: M8-3 DHW: needs (sizing)
- EN 15316-2: M3-5 Space heating: emission and control
- EN 15316-3: M3-6 Space heating: Distribution and control
- EN 15316-5: M3-7 Space heating: Storage and control
- EN 15316-5: M8-7 DHW: Storage and control
- EN 15316-4-1: M3-8 Space heating: generation
- EN 15316-4-1: M8-8 DHW: generation

The relationship between these and the EPB methodological framework is shown in **Figure 36**.



Overarching			Building (as such)		Technical Building Systems										
	Descriptions			Descriptions		Descriptions	Heating	Cooling	Ventilation	umidification	ehumidification	omestic Hot water	Lighting	Building automation and control	Electricity production
sub1		M1	sub 1	M2	sub 1		M3	M4	M5	M6	M7	M8		M10	M11
1	General		1	General	1	General	**15316-1**					15316-1			
2	Common terms and definitions; symbols, units and subscripts		2	Building Energy Needs	2	Needs						12831-3			
3	Applications		3	(Free) Indoor Conditions without Systems	3	Maximum Load and Power	12831-1					12831-3			
4	Ways to Express Energy Performance		4	Ways to Express Energy Performance	4	Ways to Express Energy Performance	**15316-1**					**15316-1**			
5	Building Functions and Building Boundaries		5	Heat Transfer by Transmission	5	Emission and control	15316-2	15316-2							
6	Building Occupancy and Operating Conditions		6	Heat Transfer by Infiltration and Ventilation	6	Distribution and control	15316-3	15316-3				15316-3			
7	Aggregation of Energy Services and Energy Carriers		7	Internal Heat Gains	7	Storage and control	15316-5					15316-5 15316-4-3			
8	Building Partitioning		8	Solar Heat Gains	8	Generation									
					8-1	Combustion boilers	15316-4-1					15316-4-1			

Figure 36: Relationships between EPB energy calculation standards for space heating and hot water [243]

It should be noted that while most MS use monthly calculation methods in their EPCs, the new EN standards support hourly calculations. Using an hourly calculation interval enables several new possibilities, including:

- it is easier to determine and handle priorities when dealing with several generators, e.g., determining the load to the next generator in the sequence - the monthly method necessitates a "turn-around" such as calculating critical generators like heat pumps with monthly bins to check if they can fulfill the load
- the ability to take into account storage and thermal solar dynamics
- in connection with EN ISO 52016, taking into account the effect of intermittent operation and limited power.

There are also the following additional aspects to consider when defining the comfort schedule and operation schedule:

- comfort schedule: at what time a certain level of comfort is required to achieve a standard service i.e. the reference to evaluate a discomfort
- system operation schedule: at what time the system is turned on, e.g., the set-point is set on comfort level. This has to anticipate the comfort schedule to enable recovery of comfort conditions.

However, the EPB space heating and DHW standards are not only energy calculation standards but also include EN 15378-1-Inspection of boilers, heating systems, and DHW, M3-11, M8-11 with the aim of:

- supporting transposition of the EPBD article 14 and 15 requirements on inspection
- supporting transposition of EPBD requirement on economic feasibility via EN 15459 Economic evaluation procedure for energy systems, M1_14
- supporting measured energy performance via EN 15378-3 Measured energy performance, Module M3-10, M8-10
- helping to close the gap between measured and calculated energy.

Commission guidance on the interpretation of Article 8(1) measures

When setting Article 8(1) requirements, it is helpful to consider the Commission's guidance [244] on the possible interpretation of system requirements for space heating, as shown in **Table 8**. In principle, energy inspections and audits inform the extant situation of heating systems with regard to each of these aspects.

Table 8: Commission Article 8(1) guidance for space heating

Type of requirement	A possible interpretation for space heating	Useful references
Overall energy performance	In this context, overall performance refers to the performance of the whole process of energy transformation in heat generators, heat distribution across the building, heat emission in individual rooms or spaces of the building, and, where applicable, heat storage. In particular, it is not limited to the performance of heat generators and can include requirements that affect other parts of the system (e.g. insulation of distribution piping network).	▪ EN 15316 standard series e.g. ▪ EN 15316-1 ▪ EN 15316-2 ▪ EN 15316-3 ▪ EN 15316-4-1 ▪ EN 15316-4-2 ▪ EN 15316-4-5 ▪ EN 15316-4-8 ▪ EN 15316-5 ▪ EN 15316-4-8 ▪ EN 15316-5
Appropriate dimensioning	For heating systems, 'appropriate dimensioning' would refer to determining heating needs, taking into account relevant parameters (in particular, intended usage of the building and its spaces), and translating these requirements into design specifications for heating systems.	▪ EN 12831-1, EN 12831–3 ▪ Module M8–2, M8–3EN 12828 ▪ EN 14337 ▪ EN 1264-3:2009
Proper installation	Proper installation refers to the need to ensure the system can operate according to design specifications. Ensuring proper installation can rely e.g., on national technical guidelines, product manufacturer documentation, and certification of installers.	▪ EN 14336 ▪ EN 1264-4 ▪ EN 14337
Adjustment	The adjustment refers here to the test and fine-tuning of the system under real-life conditions, in particular, to check and possibly adjust system functions that can impact performance (e.g., control capabilities – see below).	▪ EN 15378-1 ▪ EN 14336 ▪ EN 15378–3

Appropriate control	Concerns control capabilities that heating systems can include in order to optimize performance, e.g., automatic adaptation of heat output of emitters in individual rooms or spaces, the adaptation of system temperature based on outside temperature (‘weather compensation’), or time schedules, dynamic and static hydronic balancing, system operation monitoring, adjustment of water/air flow depending on needs, etc.	▪ EN 15500-1 ▪ EN 15316-2 ▪ EN 15232, space heater energy labeling regulations

Applicable inspection standards

The applicable inspection (audit) standard for space heating and hot water systems is:

- EN 15378-1: Energy performance of buildings - Heating systems and DHW in buildings - Part 1: Inspection of boilers, heating systems and DHW, Module M3-11, M8-11

For operational ratings, the following calculation standard is used:

- EN 15378-3: Energy performance of buildings - Heating and DHW systems in buildings - Part 3: Measured energy performance, Module M3-10, M8-10

In addition, the EN 153780-1 standard sets out procedures to inspect:

- Heat generator inspection procedure
- Heating system inspection procedure.

Elements to be inspected

The heat generator inspection procedure includes inspection methods and procedures on:

- Heat generator inspection level identification
- Heat generator identification
- Document identification
- Heat generator visual inspection
- Heat generator functionality check
- Heat generator maintenance status
- Heat generator controls, sensors, and indicators
- Meter readings
- Heat generator performance evaluation
- Heat generator inspection report and advice
- Heat generator performance advice

The heating system inspection procedure includes the following steps, which comprise the actions, in order, that could be included in an inspection.

- Heating system inspection level identification
- Heating system inspection preparation
- Heating system and inspection identification
- Document collection and system identification
- Heating system functionality check
- Heating system maintenance status
- Heating system central controls, sensors, and indicators
- Meter readings
- Energy ware consumption
- Space heating emission subsystem
- Space heating emission control subsystem
- Space heating distribution subsystem
- Generation subsystem
- Storage subsystem
- Generation subsystem sizing
- Heating system global efficiency or rating
- Domestic hot water systems
- Heating system inspection report and advice

Elements to be inspected as a function of the designated inspection level

The standard proposes that a set of “inspection levels” be determined (ostensibly by inspection mandating authorities) that determine what should be inspected as a function of the level. The implicit notion is that the inspection level would depend on the nature of the building and heating/hot water system, such that higher energy-using systems with higher savings potentials from inspection would be subject to more comprehensive inspections than those with lower saving potentials.

While the standard leaves it up to the user (practically the inspection mandating authorities) to decide what items should be inspected using the standard through the establishment of inspection levels; however, it includes an informative annex that identifies three optional inspection levels according to the following cases:

- if the property is: a) single-family house or b) any other building type
- the nature of the heating/hot water system i.e., a) autonomous system, b) autonomous system per building unit, c) centralized system

Combinations of the above lead to three inspection levels, two basic and one detailed as follows:

- Basic 1(a) is for single-family homes
- Basic 1(b) for all other properties with an autonomous heating/hot water system per building unit
- Detailed is for all other properties (than single-family homes) but with a centralized heating/hot water system.

5.3.1.3 Mapping audit outputs with EPC inputs

From the inspection content reported in Section 5.2.2, the following key space energy heater performance aspects can be reported (depending on the level of inspection adopted)

- Sizing of the space heat generator (specifically the degree of oversizing in relation to the need)
- Seasonal efficiency of the space heat generator
- Correct positioning of the heat emitters
- Quality of insulation of the distribution system piping
- Information on the characteristics/energy performance of the pumping system
- Information on the spatial resolution of the control of the heat emitters
- Information on the appropriateness of the positioning of the sensors
- Information on the amount and appropriate sizing of the hot water storage
- Information on the insulation quality of the hot water storage

Table 9: Inclusion of heating and hot water elements within an inspection as a function of the informative inspection level per EN 15378-1

A/A	Subject of inspection	Inspection Level		
		Basic - 1 Single Family Home	Basic - 1 Other (autonomous)	Detailed - 2 Other – (centralized)
1.	Heating system inspection level identification	Y	Y	Y
2.	Heating system inspection preparation	Y	Y	Y
3.	Heating system and inspection identification			
	▪ Collect and record the information on inspection, building (i.e. address, location), and heating system identification as specified in the inspection level definition.	Y	Y	Y
	▪ Identify the service(s) provided by the heating system	Y	Y	Y
4.	Document collection and system identification			
	▪ If required by the inspection level, collect and identify available relevant documents according to inspection-level specifications.	Y	Y	Y
5.	Heating system functionality check	N	N	Y
6.	Heating system maintenance status	Y	Y	Y
	Heating system central controls, sensors, and indicators	N	N	Y
	Meter readings	Y	Y	Y
	Energyware consumption	N	N	Y
	Space heating emission subsystem	Y	Y	Y
	Space heating emission control subsystem	Y	Y	Y
	Space heating distribution subsystem	Y	Y	Y
	Generation subsystem	Y	Y	Y
	Heat generators identification	Y	Y	Y
	Heat generators inspection			
	1. Boiler inspection	Y	Y	Y
	1. Thermal solar inspection	Y	Y	Y
	2. Heat pump inspection	N	N	Y
	3. Heat exchangers	N	N	Y
	4. Other generation sub-systems	N	N	Y
	5. Generation subsystem control inspection	N	N	Y
	Storage subsystem	Y	Y	Y
	Generation subsystem sizing	Y	Y	Y
	▪ Other generators sizing	N	N	N
7.	Heating system global efficiency or rating	N	N	N
8.	Domestic hot water systems	Y	Y	Y
9.	Heating system inspection report and advice	Y	Y	Y

For the DHW system:

- type and size of heat generator used for domestic hot water production
- sizing, thermal insulation, temperature levels, and control strategy of any storage vessel
- sizing, performance (including fouling and scaling), thermal insulation, and temperature control of the heat exchanger
- auxiliary energy requirements (e.g. circulation pump)
- temperature levels, operation timing, and control strategy of circulation lines

Each of the above can be mapped to corresponding parameters in the EPB asset-based energy performance calculation standards, which will be shown in the M20 version of this report (subject to clarification of the issues mentioned in Section 5.2.3). Thus, they can be used to adjust and improve the accuracy of heating and hot water energy performance calculations used to generate EPCs providing the EPCs are generated in accordance with the EPB calculation standards.

5.3.2 Audits of air conditioning systems

This Section sets out the information on the inspections/audits of air conditioning systems and considers the outputs that could be integrated into the SmartLivingEPC asset methodology.

5.3.2.1 Standards and assessment procedures

This sub-section cites the standards that are used to calculate the energy performance of air conditioning systems when determining building energy performance via an EPC asset methodology and also cites the standards that are used to conduct audits/inspections of the air conditioning systems. It further reports the standards that are relevant to the EPBD Article 8(1) TBS measures.

The applicable audit standards for air conditioning/cooling systems are:

- EN 16798-17: Energy performance of buildings. Ventilation for buildings Guidelines for inspection of ventilation and air conditioning systems (Module M4-11, M5-11, M6-11, M7- 11), and
- EN 16798-1: Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics - Module M1-6

For asset ratings, the following calculation standards are used:

- EN 16798–9 Energy performance of buildings. Ventilation for buildings Calculation methods for energy requirements of cooling systems (Modules M4-1, M4-4, M4-9). General
- CEN/TR 16798-10 Energy performance of buildings – Ventilation for buildings – Part 10: Interpretation of the requirements in EN 16798-9 – Calculation methods for energy requirements of cooling systems (Module M4-1, M4-4, M4-9) – General
- EN 16798–13 Energy performance of buildings. Ventilation for buildings Calculation of cooling systems (Module M4-8). Generation

- CEN/TR 16798-14 Energy performance of buildings – Ventilation for buildings - Part 14: Interpretation of the requirements in EN 16798-13 – Calculation of cooling systems (Module M4-8) – Generation
- EN 16798–15 Energy performance of buildings. Ventilation for buildings Calculation of cooling systems (Module M4-7). Storage
- CEN/TR 16798-16 Energy performance of buildings – Ventilation for buildings – Part 16: Interpretation of the requirements in EN 16798-15 – Calculation of cooling systems (Module M4-8) – Storage

Table 10: Relationships between EPB energy calculation standards for space cooling

Overarching		**Building (as such)**		**Technical Building Systems**										
	Descriptions		Descriptions		Descriptions	Heating	**Cooling**	Ventilation	Humidification	Dehumidification	Domestic Hot water	Lighting	Building automation and control	PV, wind, ..
sub1	M1	sub1	M2	sub1		M3	**M4**	M5	M6	M7	M8	M9	M10	M11
1.	General	1.	General	1.	General									
2.	Common terms and definitions; symbols, units, and subscripts	2.	Building Energy Needs	2.	Needs									
3.	Applications	3.	(Free) Indoor Conditions without Systems	3.	Maximum Load and Power									
4.	Ways to Express Energy Performance	4.	Ways to Express Energy Performance	4.	Ways to Express Energy Performance									
5.	Building Functions and Building Boundaries	5.	Heat Transfer by Transmission	5.	Emission and control									
6.	Building Occupancy and Operating Conditions	6.	Heat Transfer by Infiltration and Ventilation	6.	Distribution and control									
7.	Aggregation of Energy Services and Energy Carriers	7.	Internal Heat Gains	7.	Storage and control									
8.	Building Partitioning	8.	Solar Heat Gains	8.	Generation and control									

9.	Calculated Energy Performance	9.	Building Dynamics (thermal mass)	9.	Load dispatching and operating conditions									
10.	Measured Energy Performance	10.	Measured Energy Performance	10.	Measured Energy Performance									
11.	Inspection	11.	Inspection	11.	Inspection									
12.	Ways to Express Indoor Comfort			12.	BMS									
13.	Outdoor Environment Conditions													
14.	Economic Calculation													

Commission guidance on the interpretation of Article 8(1) measures

When setting Article 8(1) requirements, it is helpful to consider the Commission's guidance[3] on the possible interpretation of system requirements for space cooling, as shown in **Table 11**. In principle, energy inspections and audits inform the extant situation of cooling systems with regard to each of these aspects

Table 11: Commission Article 8(1) guidance for space cooling

Type of requirement	A possible interpretation for space cooling	Useful references
Overall energy performance	In this context, overall performance refers to the performance of the whole process of energy transformation in cooling generators, cooling distribution across the building, cooling emission in individual rooms or spaces of the building, and, where applicable, cool storage. In particular, it is not limited to the performance of cooling generators but can include requirements that affect other parts of the system (e.g. insulation of distribution piping network).	▪ EN 16798 standard series on cooling systems, e.g. ▪ EN 16798–9, ▪ EN 16798–13 ▪ EN 16798–15
Appropriate dimensioning	Dimensioning refers to the optimal sizing of the cooling system with regard to the cooling needs of the building and its spaces.	▪ EN 1264-3:2009
Proper installation	Proper installation refers to the need to ensure the system can operate according to design specifications. Ensuring proper installation can rely e.g. on national technical guidelines, product manufacturer documentation, and certification of installers.	▪ EN 1264-4
Adjustment	The adjustment refers here to the test and fine-tuning of the system under real-life conditions (6), in particular to check and possibly adjust system functions that can impact performance (e.g. control capabilities – see below).	▪ EN 16798–17

Appropriate control	Concerns control capabilities that systems for space cooling can include in order to optimize performance, e.g. automatic adaptation of cooling output of emitters in individual rooms or spaces	▪ EN 15500-1 ▪ EN 15316-2 ▪ EN 15232

Applicable inspection standards

The applicable inspection (audit) standard for cooling systems is:

- EN 16798-17: Energy performance of buildings. Ventilation for buildings Guidelines for inspection of ventilation and air conditioning systems (Module M4-11, M5-11, M6-11, M7- 11)

For asset ratings, the following calculation standard is used:

- EN 16798-1:Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics - Module M1-6

The EN 16798-17 standard sets out procedures to inspect:

- Method 2 – Air conditioning systems

The inspection's principal purpose is to advise building operators and owners on reducing their energy consumption while maintaining acceptable indoor environmental conditions. Accordingly, each inspection should produce an inspection report explaining the advantages gained from implementing the recommendations.

The inspection report includes:

- recommendations for improvements with an indication of their probable cost-effectiveness and any other benefits
- an assessment of the system's efficiency, including maintenance and controls
- an assessment of the sizing compared to the cooling and ventilation requirements of the building
- characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations.

Elements to be inspected

The air conditioning system inspection procedure includes inspection methods and procedures on:

1) refrigeration equipment
2) pump and chilled water pipework
3) outdoor heat rejection devices
4) water and refrigerant-based terminal units
5) mechanical ventilation
6) building systems controls and parameters
7) metering.

The refrigeration equipment inspection procedure is specified in CEN/TR 16798-18:20.

The pumps and chilled water pipework inspection procedure includes steps on

1) condition and operation of chilled water pipework and its insulation
2) signs of leakage from the pipe work

3) pumps and valves for the distribution of water as an energy carrier.

The outdoor heat rejection devices inspection procedure includes steps on

1) location, condition, and operation of the outdoor heat rejection devices
2) condition and operation of water pipework and its insulation
3) signs of leakage from the pipe work and casing of the heat rejection device
4) pumps and valves for the distribution of water as an energy carrier
5) fans
6) cleanliness of the heat exchanger.

The water and refrigerant-based terminal units include steps on

1) condition and operation of water and refrigerant-based terminal units.

The mechanical ventilation inspection procedure includes steps on

1) externally or internally mounted air transfer devices
2) ductwork
3) air handling unit
4) air filters
5) heat exchanger
6) exhaust opening
7) outdoor air intake.

The building systems controls and parameters inspection procedure includes steps:

1) All controls, sensors, and indicators relevant to energy performance, as well as the Building Management System, shall be identified. If the air conditioning system provides ventilation, the controls shall be inspected as a whole, taking into account the requirements for ventilation systems
2) Guidance per EN15232 may be given on: location; function; settings; operating time.

Elements to be inspected as a function of the designated inspection level

The standard sets out a set of three “inspection levels” (**Table 12**) to be determined (ostensibly by inspection mandating authorities) that determine what should be inspected as a function of the level. The implicit notion is that the inspection level would depend on the nature of the building and ventilation system, such that higher energy-using systems with higher savings potentials from inspection would be subject to more comprehensive inspections than those with lower saving potentials.

Table 12: Inspection levels for air conditioning systems per EN 16798-17

Inspection level	Type of inspection	Description
1	Pre-inspection and functional checks	This basic level of inspection has two purposes, to: ▪ gather all relevant documentation on the system type and size and to identify any priority inspection areas where the design, installation, or operation of the system departs from good practice in a manner likely to affect its energy consumption; ▪ non-intrusively identify on-site (normally visually) features of system operation that are wasteful of energy. It does not include measurements.

2	Functional measurements	This level requires measurements in addition to level 1 to check that the system is operating as intended and to identify sources of energy wastage. These can include, for example, specified design conditions and set points.
3	Special measurements	This level requires, in addition to levels 1 and 2, additional measurements to provide more detailed assessments of system performance. Such measurements can, for example, cover extended periods of time or technical aspects such as *in situ* component performance.

Aspects to be included in the inspection report as a function of the designated inspection level

Table 13 shows the elements to be included in the cooling system inspection reports as a function of the designated inspection level.

Table 13: Contents of the cooling system inspection report per EN 16798-17

Information	Method		Part
	1	2	
General			
Name, address, and status of the person and organization in charge of the inspection	X	X	—
Official designation and address of the property	X	X	—
Name and address of the building owner	X	X	—
Date of the inspection	X	X	—
Parts of the system that could not be inspected	X	X	5.4
Pre-inspection / Compliance with design documentation			
Status of the documentation or information, including identification of lacking and outdated documentation	X	X	5.3.6
Priority areas for the collection of missing information during the inspection on site	X	X	5.3.6
Priority areas for the inspection where the design installation appears to depart from good practice in a manner likely to affect its performance	X	X	5.3.6
Any difference between documentation and actually installed components	X	X	6.3, 7.3
Any difference between working or as-installed drawings and the actual system	X	X	6.3, 7.3
Aspects of the inspections simplified or reduced because of clear evidence that a good practice program of maintenance is being carried out	X	X	6.4.1.1, 7.4.2
Check the system			
Evidence showing why parts could not be checked because they were not accessible	X	X	5.4
Building parts and components inspected and number of measurements performed	X	X	5.5
In case of the presence of specific ventilation systems for the reduction in the concentration of specific gas (e.g. radon), the operation or not of these specific ventilation systems during the inspection	X	NA	6.4.1.4
State, integrity, and cleanliness of the ductwork (including observations)	X	NA	6.4.1.5, 6.4.2.2
Total air flow rate extracted and/or supplied by the air handling unit	X	NA	6.2, 6.4.2.3
Electrical power consumed by the fan(s)	X	NA	6.2, 6.4.2.3
In the case of a central system, the pressure before and after the unit and the air filter	X	NA	6.4.2.3

Missing, blocked, damaged air filters and blanking plates in place	X	NA	6.4.2.4
Frequency of air filter changing or cleaning, and time elapsed since the last change or cleaning, as well as discrepancies between written records of air filter changes and visual evidence	X	NA	6.4.2.4
In the case of the use of manometers or magnehelic gauges to monitor pressure drop across the air filter, their condition and issues. Presence and conditions of air filter change warning devices or control systems (if existing).	X	NA	6.4.2.4
Condition and cleanliness of the heat exchangers	X	X	6.4.2.5

Information	**Method**		**Part**
	1	2	
Any evidence that occupants find the air delivery arrangement unacceptable	X	NA	6.4.2.6
Cleanliness and correct functioning of the air inlets and outlets	X	NA	6.4.2.6
The adequacy of air inlets and outlets, according to 6.4.2.6	X	NA	6.4.2.6
If air flow rate measurements are performed, guidance to the selection of air inlets/exhausts to be measured	X	NA	6.4.2.6
Results of the comparison of the settings of control that limit the operation of the ventilation systems with the periods when the building is in use	X	NA	6.4.2.8
In cases where the ventilation system is considered to be producing excessive noise or vibration, or allowing cross-talk between spaces, the probable cause	X	NA	6.4.2.10.1
Assessment of the system			
The specific cooling load	NA	X	7.2
The specific cooling capacity	NA	X	7.2
Assessment of the air-conditioning efficiency	NA	X	7.2
Assessment of the sizing compared to the cooling and ventilation requirements of the building	X	X	5.1, 7.2
Assessment of the system efficiency, including maintenance and controls	X	X	5.1
Characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations	X	X	5.1
Information on any parameters suspected to be useful to measure concerning the energy efficiency of the refrigerator	NA	X	7.4.2
Measurements carried out	X	X	—
Comments on faults found	X	X	—
Recommendations and advice			
Advice to keep any documentation determined in 5.3, any survey or calculation in a file so they are available for subsequent inspections	X	X	5.3.5
Advice to the building manager on issues to address when developing a plan to complete the documentation	X	X	5.3.6
Advice regarding the cleaning of exhaust and supply systems to ensure a good air quality	X	NA	6.4.1.5
Advice for improvement, including the adjustments to be made to ensure that it agrees with the design	X	X	6.5, 7.5
Proposals to improve the results in terms of energy impact, including possible replacement of the system, subsystems, or components and the economic justification of choices	X	X	6.5, 7.5
Advice on location, function, and settings of controls, sensors, and indicators	NA	X	7.4.7

Advice to the owner to reduce energy consumption if energy consumption recordings show that the equipment in not running in accordance with the use of the building	NA	X	7.4.8
Advice to record meter readings on a regular basis if meters are installed but no consumption records are available	NA	X	7.4.8
Advice on the use of shading devices	NA	X	7.5
Final comment about the system's performance	X	X	—

5.3.2.2 Mapping audit outputs with EPC inputs

From the inspection content reported in Section 5.5.1, the following key air conditioner system energy performance aspects can be reported (depending on the level of inspection adopted):

- The specific cooling load
- The specific cooling capacity
- Assessment of the air-conditioning efficiency
- Assessment of the sizing compared to the cooling and ventilation requirements of the building
- Assessment of the system’s efficiency, including maintenance and controls
- Characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations
- Information on any parameters suspected to be useful to measure concerning the energy efficiency of the refrigerator

Each of the above can be mapped to corresponding parameters in the EPB asset-based energy performance calculation standards, which will be shown in the M20 version of this report (subject to clarification of the issues mentioned in Section 5.2.3). Thus, they can be used to adjust and improve the accuracy of air conditioning energy performance calculations used to generate EPCs, provided the EPCs are generated in accordance to the EPB calculation standards.

Furthermore, the following advice may improve the system's energy performance:

- Advice on location, function, and settings of controls, sensors, and indicators
- Advice to the owner to reduce energy consumption if energy consumption recordings show that the equipment is not running in accordance with the use of the building
- Advice to record meter readings on a regular basis if meters are installed but no consumption records are available
- Advice on the use of shading devices.

5.3.3 Audits of ventilation systems

This Section sets out the information on the inspections/audits of ventilation systems and considers the outputs that could be integrated into the SmartLivingEPC asset methodology.

5.3.3.1 Standards and assessment procedures

This sub-section cites the standards used to calculate the energy performance of ventilation systems when determining building energy performance via an EPC asset methodology and also cites the standards used to conduct audits/inspections of the ventilation systems. It further reports the standards that are relevant to the EPBD Article 8(1) TBS measures.

Table 14: Relationships between EPB energy calculation standards for ventilation systems

Overarching		**Building (as such)**		**Technical Building Systems**										
	Descriptions		Descriptions		Descriptions	Heating	Cooling	**Ventilation**	Humidification	Dehumidification	Domestic Hot water	Lighting	Building automation and control	PV, wind, ..
sub1	M1	sub1	M2	sub1		M3	M4	**M5**	M6	M7	M8	M9	M10	M11
1.	General	1.	General	1.	General									
2.	Common terms and definitions; symbols, units, and subscripts	2.	Building Energy Needs	2.	Needs									
3.	Applications	3.	(Free) Indoor Conditions without Systems	3.	Maximum Load and Power									
4.	Ways to Express Energy Performance	4.	Ways to Express Energy Performance	4.	Ways to Express Energy Performance									
5.	Building Functions and Building Boundaries	5.	Heat Transfer by Transmission	5.	Emission and control									
6.	Building Occupancy and Operating Conditions	6.	Heat Transfer by Infiltration and Ventilation	6.	Distribution and control									
7.	Aggregation of Energy Services and Energy Carriers	7.	Internal Heat Gains	7.	Storage and control									
8.	Building Partitioning	8.	Solar Heat Gains	8.	Generation and control									

9.	Calculated Energy Performance	9.	Building Dynamics (thermal mass)	9.	Load dispatching and operating conditions									
10.	Measured Energy Performance	10.	Measured Energy Performance	10.	Measured Energy Performance									
11.	Inspection	11.	Inspection	11.	Inspection									
12.	Ways to Express Indoor Comfort			12.	BMS									
13.	Outdoor Environment Conditions													
14.	Economic Calculation													

When setting Article 8(1) requirements, it is helpful to consider the Commission's guidance on the possible interpretation of system requirements for ventilation, as shown in **Table 15**.

Table 15: Commission Article 8(1) guidance for ventilation

Type of requirement	A possible interpretation for space heating	Useful references
Overall energy performance	The energy performance of the ventilation system as a whole, taking into account e.g. fans' energy efficiency, the characteristics of the ventilation duct network, heat recovery, etc.	▪ EN 16798–3 ▪ EN 16798–5–1 ▪ EN 16798–5–2
Appropriate dimensioning	Dimensioning refers to the optimal sizing of the ventilation system with regard to the ventilation needs of the building and its spaces.	▪ EN 16798-7 ▪ CEN/TR 14788 ▪ CR 1752
Proper installation	Proper installation refers to the need to ensure the system can operate according to design specifications. Ensuring proper installation can rely e.g. on national technical guidelines, product manufacturer documentation, and certification of installers.	N/A
Adjustment	The adjustment refers here to the test and finetuning of the system under real-life conditions (8), in particular, to check and possibly adjust system functions that can impact performance (e.g. control capabilities – see below).	▪ EN 12599 ▪ EN 16798-17 ▪ EN 14134
Appropriate control	Concerns control capabilities that ventilation systems can include in order to optimize performance, e.g. airflow modulation	▪ EN 15232 ▪ EN 15500-1

Applicable inspection standards

The applicable inspection (audit) standard for ventilation systems is:

- EN 16798-17: Energy performance of buildings. Ventilation for buildings Guidelines for inspection of ventilation and air conditioning systems (Module M4-11, M5-11, M6-11, M7- 11)

For asset ratings, the following calculation standard is used:

- EN 16798-1:Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics - Module M1-6

The EN 16798-17 standard sets out procedures to inspect:

- Method 1 – Ventilation-only systems

The inspection's principal purpose is to advise building operators and owners on reducing their energy consumption while maintaining acceptable indoor environmental conditions. Accordingly, each inspection should produce an inspection report explaining the advantages gained from implementing the recommendations.

The inspection report includes:

- recommendations for improvements with an indication of their probable cost-effectiveness and any other benefits
- an assessment of the system's efficiency, including maintenance and controls
- an assessment of the sizing compared to the cooling and ventilation requirements of the building
- characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations.

Elements to be inspected

The ventilation system inspection procedure for Mechanical exhaust and/or supply systems includes inspection methods and procedures on:

- ductwork
- air handling unit or fan
- air filters
- heat exchangers and heat recovery
- externally or internally mounted air transfer device/supply or exhaust in rooms
- air intakes and air exhaust openings of the system
- controls and settings
- recirculated air
- noise vibration

There are also inspection procedures for balanced systems, those using natural ventilation, and those using hybrid systems.

Elements to be inspected as a function of the designated inspection level

The standard sets out a set of three “inspection levels”, see the table below, to be determined (ostensibly by inspection mandating authorities) that determine what should be inspected as a function of the level. The implicit notion is that the inspection level would depend on the nature of the building and ventilation system, such that higher energy-using systems with higher savings potentials from inspection would be subject to more comprehensive inspections than those with lower saving potentials.

Table 16: Inspection levels for ventilation systems per EN 16798-17

Inspection level	Type of inspection	Description
1	Pre-inspection and functional checks	This basic level of inspection has two purposes, to: ▪ gather all relevant documentation on the system type and size and to identify any priority inspection areas where the design, installation, or operation of the system departs from good practice in a manner likely to affect its energy consumption; ▪ non-intrusively identify on-site (normally visually) features of system operation that are wasteful of energy. It does not include measurements.
2	Functional measurements	This level requires measurements in addition to level 1 to check that the system is operating as intended and to identify sources of energy wastage. These can include, for example, specified design conditions and set points.
3	Special measurements	This level requires, in addition to levels 1 and 2, additional measurements to provide more detailed assessments of system performance. Such measurements can, for example, cover extended periods of time or technical aspects such as *in situ* component performance.

Aspects to be included in the inspection report as a function of the designated inspection level

Table 17 shows the elements to be included in the ventilation system inspection reports as a function of the designated inspection level.

Table 17: Contents of the ventilation system inspection report per EN 16798-17

Information	Method		Part
	1	2	
General			
Name, address, and status of the person and organization in charge of the inspection	X	X	—
Official designation and address of the property	X	X	—
Name and address of the building owner	X	X	—
Date of the inspection	X	X	—
Parts of the system that could not be inspected	X	X	5.4
Pre-inspection / Compliance with design documentation			
Status of the documentation or information, including identification of lacking and outdated documentation	X	X	5.3.6
Priority areas for the collection of missing information during the inspection on site	X	X	5.3.6
Priority areas for the inspection where the design installation appears to depart from good practice in a manner likely to affect its performance	X	X	5.3.6
Any difference between documentation and actually installed components	X	X	6.3, 7.3
Any difference between working or as-installed drawings and the actual system	X	X	6.3, 7.3
Aspects of the inspections simplified or reduced because of clear evidence that a good practice program of maintenance is being carried out	X	X	6.4.1.1, 7.4.2
Check the system			
Evidence showing why parts could not be checked because they were not accessible	X	X	5.4
Building parts and components inspected and number of measurements performed	X	X	5.5
In case of the presence of specific ventilation systems for the reduction in the concentration of specific gas (e.g. radon), the operation or not of these specific ventilation systems during the inspection	X	NA	6.4.1.4
State, integrity, and cleanliness of the ductwork (including observations)	X	NA	6.4.1.5, 6.4.2.2

Total air flow rate extracted and/or supplied by the air handling unit	X	NA	6.2, 6.4.2.3
Electrical power consumed by the fan(s)	X	NA	6.2, 6.4.2.3
In the case of a central system, the pressure before and after the unit and the air filter	X	NA	6.4.2.3
Missing, blocked, damaged air filters and blanking plates in place	X	NA	6.4.2.4
Frequency of air filter changing or cleaning, and time elapsed since the last change or cleaning, as well as discrepancies between written records of air filter changes and visual evidence	X	NA	6.4.2.4
In the case of the use of manometers or magnehelic gauges to monitor pressure drop across the air filter, their condition and issues. Presence and conditions of air filter change warning devices or control systems (if existing).	X	NA	6.4.2.4
Condition and cleanliness of the heat exchangers	X	X	6.4.2.5

Information	**Method**		**Part**
	1	2	
Any evidence that occupants find the air delivery arrangement unacceptable	X	NA	6.4.2.6
Cleanliness and correct functioning of the air inlets and outlets	X	NA	6.4.2.6
The adequacy of air inlets and outlets, according to 6.4.2.6	X	NA	6.4.2.6
If air flow rate measurements are performed, guidance to the selection of air inlets/exhausts to be measured	X	NA	6.4.2.6
Results of the comparison of the settings of control that limit the operation of the ventilation systems with the periods when the building is in use	X	NA	6.4.2.8
In cases where the ventilation system is considered to be producing excessive noise or vibration, or allowing cross-talk between spaces, the probable cause	X	NA	6.4.2.10.1
Assessment of the system			
The specific cooling load	NA	X	7.2
The specific cooling capacity	NA	X	7.2
Assessment of the air-conditioning efficiency	NA	X	7.2
Assessment of the sizing compared to the cooling and ventilation requirements of the building	X	X	5.1, 7.2
Assessment of the system efficiency, including maintenance and controls	X	X	5.1
Characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations	X	X	5.1
Information on any parameters suspected to be useful to measure concerning the energy efficiency of the refrigerator	NA	X	7.4.2
Measurements carried out	X	X	—
Comments on faults found	X	X	—
Recommendations and advice			
Advice to keep any documentation determined in 5.3, any survey or calculation in a file so they are available for subsequent inspections	X	X	5.3.5
Advice to the building manager on issues to address when developing a plan to complete the documentation	X	X	5.3.6
Advice regarding the cleaning of exhaust and supply systems to ensure a good air quality	X	NA	6.4.1.5

Advice for improvement, including the adjustments to be made to ensure that it agrees with the design	X	X	6.5, 7.5
Proposals to improve the results in terms of energy impact, including possible replacement of the system, subsystems, or components and the economic justification of choices	X	X	6.5, 7.5
Advice on location, function, and settings of controls, sensors, and indicators	NA	X	7.4.7
Advice to the owner to reduce energy consumption if energy consumption recordings show that the equipment is not running in accordance with the use of the building	NA	X	7.4.8
Advice to record meter readings on a regular basis if meters are installed but no consumption records are available	NA	X	7.4.8
Advice on the use of shading devices	NA	X	7.5
Final comment about the system's performance	X	X	—

5.3.3.2 Mapping audit outputs with EPC inputs

From the inspection content reported in Section 5.3.3, the following key ventilation system energy performance aspects can be reported (depending on the level of inspection adopted)

- Assessment of the sizing compared to the cooling and ventilation requirements of the building
- Assessment of the system efficiency, including maintenance and controls
- Characteristics of the air conditioning and/or ventilation system that can be compared to design specifications or inputs of energy calculations
- Electrical power consumed by the fan(s)

Each of the above can be mapped to corresponding parameters in the EPB asset-based energy performance calculation standards, which will be shown in the M20 version of this report (subject to clarification of the issues mentioned in Section 5.2.3). Thus, they can be used to adjust and improve the accuracy of heating and hot water energy performance calculations used to generate EPCs providing the EPCs are generated in accordance with the EPB calculation standards.

Furthermore, the following advice may improve the system's energy performance:

- Proposals to improve the results in terms of energy impact, including
- possible replacement of the system, subsystems, or components and the economic justification of choices
- Advice on location, function, and settings of controls, sensors, and indicators
- Advice to the owner to reduce energy consumption if energy consumption recordings show that the equipment is not running in accordance with the use of the building
- Advice to record meter readings on a regular basis if meters are installed but no consumption records are available
- Advice on the use of shading devices.

In addition, the following aspects have relevance for the IAQ and IEQ of the ventilation system:

- State, integrity, and cleanliness of the ductwork (including observations)
- Total air flow rate extracted and/or supplied by the air handling unit

- In case of the presence of specific ventilation systems for the reduction in the concentration of specific gas (e.g. radon), the operation or not of these specific ventilation systems during the inspection
- In the case of a central system, the pressure before and after the unit and the air filter
- Missing, blocked, damaged air filters and blanking plates in place
- Frequency of air filter changing or cleaning, and time elapsed since the last change or cleaning, as well as discrepancies between written records of air filter changes and visual evidence
- Any evidence that occupants find the air delivery arrangement unacceptable
- Cleanliness and correct functioning of the air inlets and outlets.

Furthermore, the following advice may improve the IAQ/IEQ:

- Advice regarding the cleaning of exhaust and supply systems to ensure a good air quality
- Advice for improvement, including the adjustments to be made to ensure that it agrees with the design.

5.3.4 Definition of building systems periodic audits procedures and methodology

To boost the energy performance of buildings [2031], the EU established a legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU [232]. The Directive amending the Energy Performance of Buildings Directive (2018/844/EU) [233] (the so-called EPBD recast) introduced new elements and sent a strong political signal on the EU’s commitment to modernize the building sector in light of technological improvements and to increase building renovations.

In October 2020, the Commission presented its Renovation wave strategy [234] as part of the European Green Deal [235]. It contains an action plan with concrete regulations, financing, and enabling measures to boost building renovation. Its objective is to at least double the annual energy renovation rate of buildings by 2030 and to foster deep renovation. A revision of the Energy Performance of Buildings Directive is one of its key initiatives. A revision of the Energy Performance of Buildings Directive is one of its key initiatives.

Some of the key provisions in the original EPBD of direct relevance to the SmartLivingEPC project and the work reported in this task on inspections/audits include:

- Article 3, Adoption of a methodology for calculating the energy performance of buildings
- Article 8 Technical building systems
- Article 11 Energy performance certificate
- Article 14 Inspection of heating systems
- Article 15 Inspection of air-conditioning systems
- Article 16 Reports on the inspection of heating and air-conditioning systems.

5.3.4.1 Measures introduced in the 2018 EPBD recast

The amending directive (2018/844/EC) covers a broad range of policies and support measures that will help national EU governments boost the energy performance of buildings and improve the existing building stock. EU countries must, for example, establish strong **long-term renovation strategies**, aiming at decarbonizing the national building stocks by 2050, with indicative milestones for 2030, 2040, and 2050. The strategies should contribute to achieving the national energy and climate plans (NECPs) energy efficiency targets. The directive also requires that EU countries set cost-optimal **minimum energy performance requirements** for new buildings, for existing buildings undergoing a major renovation, and for replacing or retrofitting building elements like heating and cooling systems, roofs, and walls.

As of 2021, all new buildings must be nearly zero-energy buildings (NZEB) [236], and since 2019, all new public buildings should be NZEB. When a building is sold or rented, energy performance certificates must be issued, and inspection schemes for heating and air conditioning systems must be established. The directive supports **electro-mobility** by introducing minimum requirements for car parks over a certain size and other minimum infrastructure for smaller buildings. There is also an optional European scheme for rating the smart readiness of buildings, and **smart technologies** are promoted. The directive introduced requirements for the installation of building automation and control systems and devices that regulate temperature at room level. It addresses the health and well-being of building users, for instance, by considering air quality and ventilation.

5.3.4.2 Proposal for a revision of the directive

In December 2021, the Commission proposed a revision of the directive (COM(2021) 802 final). It upgrades the existing regulatory framework to reflect higher ambitions and more pressing needs in climate and social action while providing EU countries with the flexibility needed to take into account the differences in the building stock across Europe.

It also sets out how Europe can achieve a zero-emission and fully decarbonized building stock by 2050. The proposed measures will increase the rate of renovation, particularly for the worst-performing buildings in each country. The revised directive will modernize the building stock, making it more resilient and accessible. It will also support better air quality, the digitalization of energy systems for buildings, and the roll-out of infrastructure for sustainable mobility. Crucially, the revised directive facilitates more targeted financing to investments in the building sector, complementing other EU instruments supporting vulnerable consumers and fighting energy poverty.

In order to make sure that buildings are fit for the enhanced climate ambition, as presented in the 2030 Climate Target Plan and reflected in the “Delivering the European Green Deal Package” [237] in July 2021, the Commission’s new proposal aims to contribute to reaching the target of at least -60% emission reductions by 2030 in the building sector in comparison to 2015 and achieve climate neutrality by 2050. It will work hand in hand with other initiatives of the European Green Deal package, in particular with the review of the proposed new emissions trading system for fuels used in buildings, the Energy Efficiency Directive, the Renewable Energy Directive, as well as the Alternative Fuels Infrastructure Regulation.

The main measures in the new proposal are:

- the gradual introduction of minimum energy performance standards to trigger renovation of the worst-performing buildings
- a new standard for new buildings and a more ambitious vision for buildings to be zero-emission
- enhanced long-term renovation strategies [238], to be renamed national Building Renovation Plans
- increased reliability, quality, and digitalization of Energy Performance Certificates [239], with energy performance classes to be based on common criteria
- a definition of deep renovation and the introduction of building renovation passports
- modernization of buildings and their systems, and better energy system integration (for heating, cooling, ventilation, charging of electric vehicles, renewable energy)

The Council and the European Parliament are now considering the proposed revision of the directive.

5.3.5 Inspection provisions

5.3.5.1 EPBD provisions on inspections of HVAC

The Energy Performance of Buildings Directive [240] sets out the following provisions with regard to the inspection of heating and cooling systems (including ventilation) and their reporting:

Article 14: Inspection of heating systems

1. Member States shall lay down the necessary measures to establish regular inspections of the accessible parts of heating systems or systems for combined space heating and ventilation, with an effective rated output of over 70 kW, such as the heat generator, control system, and circulation pump(s) used for heating buildings. The inspection shall include an assessment of the efficiency and sizing of the heat generator compared with the heating requirements of the building and, where relevant, consider the capabilities of the heating system or the system for combined space heating and ventilation to optimize its performance under typical or average operating conditions.

Where no changes have been made to the heating system or to the system for combined space heating and ventilation or to the heating requirements of the building following an inspection carried out pursuant to this paragraph, MSs may choose not to require the assessment of the heat generator sizing to be repeated.

2. Technical building systems that are explicitly covered by an agreed energy performance criterion or a contractual arrangement specifying an agreed level of energy efficiency improvement, such as energy performance contracting, or that are operated by a utility or network operator and therefore subject to performance monitoring measures on the system side, shall be exempt from the requirements laid down in paragraph 1, provided that the overall impact of such an approach is equivalent to that resulting from paragraph 1.

3. As an alternative to paragraph 1 and provided that the overall impact is equivalent to that resulting from paragraph 1, Member States may opt to take measures to ensure the provision of advice to users concerning the replacement of heat generators, other modifications to the heating system or to the system for combined space heating and ventilation and alternative solutions to assess the efficiency and appropriate size of those systems. Before applying the alternative measures referred to in the first subparagraph of this paragraph, each Member State shall, by submitting a report to the Commission, document the equivalence of those measures' impact to the measures referred to in paragraph 1. Such a report shall be submitted to the Commission as part of the Member States' integrated national energy and climate plans referred to in Article 3 of Regulation (EU) 2018/1999.

4. Member States shall lay down requirements to ensure that, where technically and economically feasible, non-residential buildings with an effective rated output for heating systems or systems for combined space heating and ventilation of over 290 kW are equipped with building automation and control systems by 2025. The building automation and control systems shall be capable of:

- continuously monitoring, logging, analyzing, and allowing for adjusting energy use;
- benchmarking the building's energy efficiency, detecting losses in efficiency of technical building systems, and informing the person responsible for the facilities or technical building management about opportunities for energy efficiency improvement; and
- allowing communication with connected technical building systems and other appliances inside the building and being interoperable with technical building systems across different types of proprietary technologies, devices, and manufacturers.

5. Member States may lay down requirements to ensure that residential buildings are equipped with:

- the functionality of continuous electronic monitoring that measures systems' efficiency and informs building owners or managers when it has fallen significantly and when system servicing is necessary; and
- effective control functionalities to ensure optimum energy generation, distribution, storage, and use.
- Buildings that comply with paragraph 4 or 5 shall be exempt from the requirements laid down in paragraph 1.

Article 15: Inspection of air-conditioning systems

1. Member States shall lay down the necessary measures to establish regular inspections of the accessible parts of air-conditioning systems or systems for combined air-conditioning and ventilation with an effective rated output of over 70 kW. The inspection shall include an assessment of the efficiency and sizing of the air-conditioning system compared with the cooling requirements of the building and, where relevant, consider the capabilities of the air-conditioning system or the system for combined air-conditioning and ventilation to optimize its performance under typical or average operating conditions.

Where no changes have been made to the air-conditioning system or the system for combined air-conditioning and ventilation or to the cooling requirements of the building following an inspection carried out under this paragraph, MSs may choose not to require the assessment of the sizing of the air-conditioning system to be repeated. MSs that maintain more stringent requirements according to Article 1(3) shall be exempt from the obligation to notify them to the Commission.

2. Technical building systems that are explicitly covered by an agreed energy performance criterion or a contractual arrangement specifying an agreed level of energy efficiency improvement, such as energy performance contracting, or that are operated by a utility or network operator and therefore subject to performance monitoring measures on the system side, shall be exempt from the requirements laid down in paragraph 1, provided that the overall impact of such an approach is equivalent to that resulting from paragraph 1.

3. As an alternative to paragraph 1 and provided that the overall impact is equivalent to that resulting from paragraph 1, MSs may opt to take measures to ensure the provision of advice to users concerning the replacement of air-conditioning systems or systems for combined air-conditioning and ventilation, other modifications to the air-conditioning system or system for combined air-conditioning and ventilation and alternative solutions to assess the efficiency and appropriate size of those systems.

Before applying the alternative measures referred to in the first subparagraph of this paragraph, each MS shall, by means of submitting a report to the Commission, document the equivalence of the impact of those measures to the impact of the measures referred to in paragraph 1. Such a report shall be submitted to the Commission as part of the Member States' integrated national energy and climate plans referred to in Article 3 of Regulation (EU) 2018/1999.

4. MSs shall lay down requirements to ensure that, where technically and economically feasible, non-residential buildings with an effective rated output for systems for air-conditioning or systems for combined air-conditioning and ventilation of over 290 kW are equipped with building automation and control systems by 2025. The building automation and control systems shall be capable of:

- continuously monitoring, logging, analyzing, and allowing for adjusting energy use;
- benchmarking the building’s energy efficiency, detecting losses in efficiency of technical building systems, and informing the person responsible for the facilities or technical building management about opportunities for energy efficiency improvement; and
- allowing communication with connected technical building systems and other appliances inside the building and being interoperable with technical building systems across different types of proprietary technologies, devices, and manufacturers.

5. MSs may lay down requirements to ensure that residential buildings are equipped with:

- the functionality of continuous electronic monitoring that measures systems’ efficiency and informs building owners or managers when it has fallen significantly and when system servicing is necessary, and

- effective control functionalities to ensure optimum energy generation, distribution, storage, and use.
- buildings that comply with paragraph 4 or 5 shall be exempt from the requirements laid down in paragraph 1.

Article 16: Reports on the inspection of heating and air-conditioning systems

1. An inspection report shall be issued after each heating or air-conditioning system inspection. The inspection report shall contain the result of the inspection performed in accordance with Article 14 or 15 and include recommendations for the cost-effective improvement of the energy performance of the inspected system.

The recommendations may be based on a comparison of the energy performance of the system inspected with that of the best available feasible system and a system of a similar type for which all relevant components achieve the level of energy performance required by the applicable legislation.

2. The inspection report shall be handed over to the owner or tenant of the building. Thus, a regular mandatory inspection of HVAC systems of 70 kW or greater heating (or cooling) capacity is required using a standardized inspection process unless MSs put in place alternative measures that will produce equivalent energy savings. In addition, MSs shall lay down requirements to ensure that, where technically and economically feasible, non-residential buildings with an effective rated output for systems for air-conditioning or systems for combined air-conditioning and ventilation of over 290 kW are equipped with building automation and control systems by 2025.

5.3.5.2 EPBD provisions on technical building systems under Article 8(1) and 8(9)

Technical building systems (TBS) are defined in the Energy Performance of Buildings Directive (EPBD) as 'technical equipment for space heating, space cooling, ventilation, domestic hot water, built-in lighting, building automation and control, on-site electricity generation, or a combination thereof, including those systems using energy from renewable sources of a building or building unit' (Article 2(3)). Inspections and audits of technical building systems are a key aspect of determining their energy performance, as will be made clear in the later text; however, here, the characteristics and linkages to EPB standards will be made clear as this explains the policy and standardization context that links the Article 14 and 15 HVAC inspections/audits to the other EPBD measures that address HVAC (Article 8 TBS, the EPC measures and the minimum energy performance standards measures).

The main function of the TBS in a building is to provide a comfortable, healthy, and functional indoor environment when the building is occupied. There can be large differences in energy performance between TBSs designed to deliver the same functionality. These performance differences arise, for example, by the extent to which: the overshooting of comfort temperature or air quality set points is minimized, energy demand is reduced by matching service delivery with occupancy, hydronic heating or cooling distribution system losses are minimized, and heat or cold generation efficiency is optimized. Therefore, the energy efficiency community and related policy-making process need to be aware that very significant energy savings in buildings can be obtained by measures that improve the performance of technical building systems (TBS). Furthermore, the rate at which TBS is renewed or retrofitted is greater than that of building fabric renovation and/or new construction, and thus, measures that target TBS can access a much greater proportion of the building stock in any given period than those that concern major renovation.

The performance of technical building systems has a very significant impact on the overall building energy performance and therefore needs to be a major focus of building energy performance policy measures. For this reason, the 2018[1] amendment of the EPBD strengthened the measures applicable to TBS. In particular:

- Article 8(1) of the EPBD requires MSs to set system requirements for overall energy performance, proper installation, appropriate dimensioning, adjustment, and control of technical building systems.
- Article 8(9) of the EPBD requires MSs to ensure that when a technical building system is installed, replaced, or upgraded, the overall energy performance of the altered part or (where relevant) of the complete altered system is assessed.

These provisions are very relevant to the SmartLivingEPC framework because the SmartLivingEPC methodology can be designed to help speed up the recognition of the Article 8(1)/(9) impacts within EPCs, as is explained later in this report.

5.3.5.3 Article 8(1) provisions

Article 8(1) specifies requirements as set out in the sub-sections below:

5.3.5.3.1 Appropriate dimensioning

Article 8(1) requires MSs to set appropriate TBS dimensioning requirements because oversized systems will often operate far from the optimal efficiency level and create unnecessary energy wastage. In practice, this requires obligations to be imposed on system designers and installers to conduct an adequate dimensioning assessment according to specified procedures and to document the outcome. The dimensioning assessment needs to determine the realistic (not overly inflated) maximum load based on the actual characteristics of the building, its occupants and how it is to be used, and climate. It also needs to determine the system's efficiency in delivering that load so it can be sized accordingly.

For thermal systems (space heating and cooling), the sizing requirements should be based on specified design temperatures. For example, Spain requires space heating systems to be sized to deliver a 21°C indoor temperature and space cooling systems to be sized to deliver a 25°C indoor temperature and requires the outdoor temperature to be based on the 99% most extreme thermal conditions [241].

5.3.5.3.2 Proper installation

The quality of installation often has a significant impact on the delivered performance of a TBS; thus, Article 8(1) requires MSs to set proper system installation requirements to minimize the risk of poor installation outcomes.

As an example, Flanders, Belgium [242], apply installation correction factors to the overall system performance requirements for ventilation for:

- the airtightness of the air group, e.g., of the Air Handling Unit
- the airtightness of the ducts
- the insulation of the ducts.

These correction factors penalize poor adjustment practices and reward good practices, thereby creating an incentive to implement higher-quality system adjustment practices.

5.3.5.3.3 Adjustment

Many/most TBS's require proper adjustment to perform at or near their optimal operational levels; thus, Article 8(1) requires Member States to set adjustment requirements.

For example, Flanders applies correction factors to the overall system performance requirements for space heating for adjustment for:

- the control of boiler temperature
- the regulation of a normal regimen
- self-regulating equipment
- hydraulic balancing.

These correction factors penalize poor adjustment practices and reward good practices, thereby creating an incentive to implement higher-quality system adjustment practices.

5.3.5.3.4 Control

The quality of system control has a very large impact on the TBS energy consumption and quality of service provision. Accordingly, Article 8(1) requires MSs to set TBS control requirements. The system boundary at which the control provisions apply can have a large bearing on the energy-saving impact, as can the sophistication of the control requirements.

Many of the largest energy savings opportunities for system operation concern control, and to a large degree, these options are applicable at a system boundary level that is not captured by control provisions in product policy instruments such as Ecodesign for TBS components and energy labeling for space and water heating.

5.3.5.3.5 Relation to inspections/audits

In principle, TBS inspections and audits (specifically the HVAC-related ones of Articles 14 and 15) inform the understanding of the extant situation of HVAC systems with regards to each of these aspects and thus can help with the implementation of Article 8(1) measures. As discussed later, in principle, this information could also be reflected within a dynamic "living" EPC in the spirit of the SmartLivingEPC concept.

5.3.5.3.6 Need for a meaningful Article 8(1)

All building energy is consumed in technical building systems, and space heating alone accounts for by far the largest share of primary energy use in EU buildings (~65% of the total). Whole building minimum energy performance measures only affect new buildings or major renovations, while Ecodesign and energy labeling apply to components or part of the system but do not address much of the savings opportunity from optimization of the technical building system as a whole. In the case of space heating, it is estimated that the adoption of comprehensive Article 8(1) requirements could reduce total EU building primary energy consumption in 2040 by between 6.5% and 16%, in addition to the savings triggered by the other policy measures. Therefore, MSs are required to set such measures for space heating systems with regard to overall performance, dimensioning, installation, adjustment, and control to abide by the terms of Article 8(1).

5.3.5.4 Article 8(9) provisions

Article 8(9) specifies 3.2.3 Performance assessment and documentation provisions as set out below.

Article 8(9) of the EPBD stipulates that:

> “Member States shall ensure that, when a technical building system is installed, replaced or upgraded, the overall energy performance of the altered part, and where relevant, of the complete altered system, is assessed. The results shall be documented and passed on to the building owner so that they remain available and can be used for the verification of compliance with the minimum requirements laid down pursuant to paragraph 1 of this Article and the issue of energy performance certificates. Without prejudice to Article 12, Member States shall decide whether to require the issuing of a new energy performance certificate.”
>
> The European Commission’s guidance [14] states:
>
> “Article 8(9) of the EPBD requires that the results of the assessment of the system (or of an altered part of it) performance are documented and passed on to the building owner. Member States are free to determine the form and content of this documentation, which can vary depending on the type of intervention considered. However, in this context, Member States should ensure that the documentation covers the scope of the assessment performed and can be useful for the verification of compliance with the minimum requirements on energy performance laid down pursuant to Article 8(1) of the EPBD and for energy performance certification (see next paragraph). Member States are also free to determine how the documentation is to be passed on to the building owner.
>
> The obligations in Article 8(9) of the EPBD on documenting system (or altered part) performance aim to ensure that up-to-date information on technical building system performance is made available to building owners. Such information can be used, for instance, for energy performance certification or to verify compliance with minimum

> energy performance requirements (e.g., when a building undergoes a major renovation). It is up to MSs to decide whether a new energy performance certificate (EPC) will have to be issued as a result of the energy performance assessment of the technical building system (or an altered part of it)."

Thus, it is up to the MSs to define in their national legislation the cases where it is relevant to assess the performance of the whole system, as opposed to those where only the assessment of the performance of the altered part is required. Noting that the following cases can be defined:

- a new system is installed
- a whole system is replaced
- a part or parts of a system undergo a major upgrade that can significantly affect the overall performance of the system.

5.4 Benefits of technical audits

HVAC audits are currently required under Articles 14 and 15 of the EPBD for buildings with certain characteristics. The frequency with which mandatory HVAC audits are conducted is set at the MS level, but they are likely to be more frequent than the issuance of an EPC in most cases. Nor do the audits generally occur at the same time as an EPC assessment, calculation, and certificate are issued. In part, for this reason, audit information is not currently used in EPCs. Nonetheless, this presents an opportunity as, in principle, the information these audits contain could be used to refine the EPC HVAC performance calculations. Doing so would make the audit information more salient as it could affect the EPC rating, and building owners (and the market in general) are known to place value on higher EPC ratings. For the above to happen from a procedural perspective, the EPC would need to be amendable in light of the information gathered from the audit, as shown in **Figure 37**.

Under this schematic, if an EPC has been calculated using a standard asset calculation methodology (e.g., aligned with the EN ISO asset calculation methodology for the energy performance of buildings), then the EPC would need to be capable of being updated each time an HVAC energy performance audit is conducted to reflect the additional information contained within the audit.

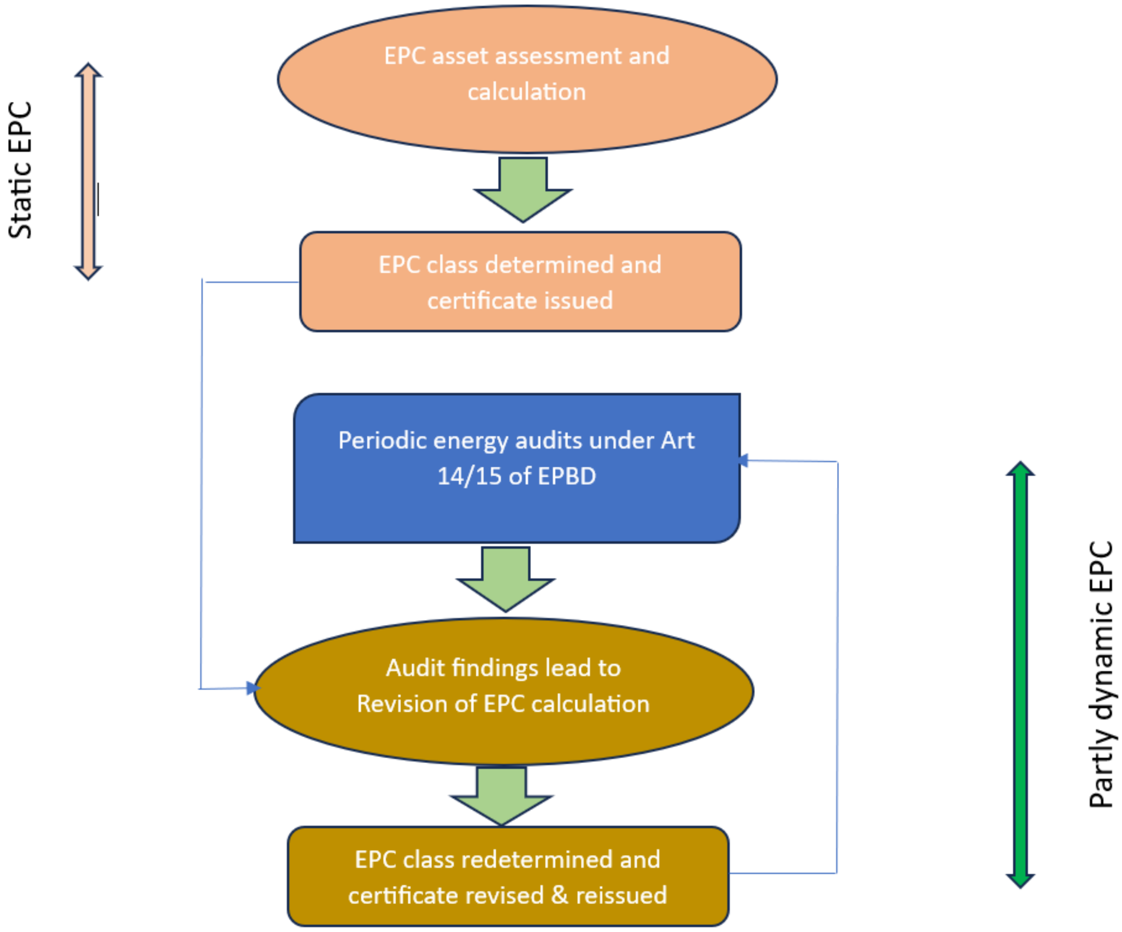


Figure 37: Energy calculation: General structure of heating and DHW standards - EN 15316 - series

Permitting this to happen would be beneficial for the following reasons:

- The HVAC is the dominant part of almost all buildings' energy use, and thus, EPC ratings are sensitive to the performance attributed to it
- The EPBD asset methodology makes a number of assumptions about how the HVAC is operated that may be inaccurate – inclusion of the HVAC audit data would allow the actual performance characteristic to be captured, leading to more accurate EPC
- HVAC systems performance can be adjusted (especially in response to audit recommendations), which would alter the real energy efficiency of the building
- HVAC systems are likely to be upgraded or replaced much more rapidly than the building fabric thus, are inherently more dynamic – significant changes in the HVAC characteristics can lead to significant changes in the real energy efficiency of a building, and EPCs ought to be better at reflecting (and hence encouraging) upgrades
- Such upgrades or replacements should also be subject to EPBD Article 8(1) and 8(9) requirements regarding the energy performance of technical building systems; thus, the audit could both serve as a

means of determining the impact that such measures have had while acting as a means of verifying that they have been respected.

- Electronic EPC registration systems are already in use in some MSs, and in principle, such systems could be structured to allow EPCs to be recalculated and reissued (electronically) every time significant changes in the building's energy performance are reported in the system.
- Were such systems to already include the default EPC asset information for the HVAC systems, then it would be possible to adapt the data in the system to reflect the audit findings each time an audit is conducted – this would encourage building owners/managers to act upon audit recommendations as doing so would lead to an improved EPC rating
- Such a system would also encourage the owners/managers of buildings subject to periodic HVAC audits to consider upgrading the HVAC system (perhaps through a replacement of all or part of the system) faster than may otherwise be the case as the impact on the EPC rating would be reported at the frequency of the audit. This could be an important stimulus for building owners looking to upgrade the performance to meet minimum EPC rating requirements (now under consideration in the EPBD recast proposals), or simply to demonstrate faster progress in the energy performance of a portfolio of buildings.

For all of the above reasons, it makes sense to leverage the value of the HVAC audits and to use them to both enable a more dynamic (and hence valuable) EPC rating and also to allow audits and EPCs to support the critical Article 8 objectives which are one of the key mechanisms to accelerate the transformation of Europe’s buildings to higher energy efficiency levels. On top of this, the potential value of such audits in reflecting real service delivered, particularly informing insights into the quality of ventilation delivered, can also be leveraged through the SmartLivingEPC IAQ/IEQ KPIs. The experience of the Covid-19 pandemic has demonstrated how critical IAQ is to minimizing transmission of viruses and hence to health and productivity, and hence the value of this aspect alone is very significant, and it should be a big motivating factor towards both more common and frequent audits and dynamic EPCs.

6 Conclusions

The SmartLivingEPC project represents a transformative and pioneering initiative aimed at revolutionizing the assessment of energy performance in the built environment. By addressing the limitations of asset energy rating systems, this project has developed a novel EPC framework that encompasses a wide range of critical indicators. Through the implementation of the asset methodology assessment at the building level, several key conclusions can be drawn.

Firstly, the integration of diverse evaluation parameters in the SmartLivingEPC framework has led to a comprehensive and harmonized rating system. Unlike traditional energy rating systems that focus solely on energy consumption, the SmartLivingEPC framework incorporates cutting-edge practices and embraces multiple aspects that significantly influence a building's performance. The inclusion of SRI analysis allows for a more holistic understanding of a building's environmental, social, and governance implications, promoting sustainable practices and responsible resource utilization.

Secondly, the adoption of Life Cycle Assessment (LCA) tools within the SmartLivingEPC framework enables a more thorough examination of a building's environmental impact throughout its entire life cycle. By considering factors in cradle-to-gate boundaries, stakeholders can make informed decisions regarding building materials, energy sources, and waste management, contributing to a low-carbon future.

Thirdly, the incorporation of non-energy aspects, such as indoor air quality, thermal comfort, and occupant well-being, underscores the project's commitment to a people-centric approach to building assessment. Recognizing that buildings are spaces for human occupancy, the SmartLivingEPC framework places occupant satisfaction and well-being at the forefront, aiming to enhance the overall quality of life for building users.

One of the significant contributions of the SmartLivingEPC project lies in the introduction of a new rating scheme at the building complex level. By recognizing the interconnectedness of buildings within a complex, this innovative approach ensures a more accurate and relevant evaluation of collective energy performance and sustainability attributes. The possibility of using audit data to inform and improve EPC ratings would encourage building owners to implement the audit recommendations (thereby raising the impact of the audits), as well as audits to be undertaken voluntarily, i.e., independently of the Article 14/15 requirements, therefore expanding the number of buildings that have such audits and thus again increasing the market transformational effect. The digitalization of the EPC issuance process and the use of data retrieved from BIM literacy, energy audits, and technical inspections have proven to be instrumental in generating smart EPCs. By leveraging digital tools, sensor data, smart meters, and innovations related to the Internet of Things (IoT) and Artificial Intelligence (AI), the SmartLivingEPC project has demonstrated the potential for streamlining the certification procedure and improving the accuracy of assessments.

7 References

[1]. The European Parliament and The Council of the European Union, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, vol. 276 LNCS, no. May 2010. Strasbourg: The European Parliament and the Council of the European Union, 2018, pp. 75–91. Accessed: Jun. 16, 2022. [Online]. Available: http://data.europa.eu/eli/dir/2018/844/oj

[2]. S. Verbeke, D. Aerts, G. Reynders, Y. Ma, and P. Waide, Final report on the technical support to the development of a smart readiness indicator for buildings: final report. Luxembourg: Publications Office, 2020. doi: doi/10.2833/41100.

[3]. European Commission, Commission Delegated Regulation (EU) 2020/2155 of 14 October 2020 supplementing Directive (EU) 2010/31/EU of the European Parliament and of the Council by establishing an optional common European Union scheme for rating the smart readiness of buildings. Brussels: European Commission, 2020, pp. 9–24.

[4]. European Commission, Commission Implementing Regulation (EU) 2020/2156 of 14 October 2020 detailing the technical modalities for the effective implementation of an optional common Union scheme for rating the smart readiness of buildings. Brussels: European Commission, 2020, pp. 25–29.

[5]. European Commission, Commission Delegated Regulation (EU) 2020/2155 of 14 October 2020 supplementing Directive (EU) 2010/31/EU of the European Parliament and of the Council by establishing an optional common European Union scheme for rating the smart readiness of buildings. Brussels: European Commission, 2020, pp. 9–24. Accessed: May 26, 2023. [Online]. Available: http://data.europa.eu/eli/reg_del/2020/2155/oj

[6]. Y. Ma, S. Verbeke, C. Protopapadaki, and S. Dourlens-Quaranta, “Calculation sheet for SRI assessment method A/B.” Apr. 2023.

[7]. European Commission, Commission Delegated Regulation (EU) 2020/2155 of 14 October 2020 supplementing Directive (EU) 2010/31/EU of the European Parliament and of the Council by establishing an optional common European Union scheme for rating the smart readiness of buildings. Brussels: European Commission, 2020, pp. 9–24.

[8]. E. Commission et al., Final report on the technical support to the development of a smart readiness indicator for buildings : final report. Publications Office, 2020. doi: doi/10.2833/41100.

[9]. Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures, ISO 52000-1:2017

[10]. World Health Organization. (2010). Indoor air quality: Guidelines for indoor air quality: selected pollutants. WHO.

[11]. Mendell, M. J., Mirer, A. G., Cheung, K., Tong, M., & Douwes, J. (2011). Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence. Environmental health perspectives, 119(6), 748-756.

[12]. Fisk, W. J. (2000). Health and productivity gains from better indoor environments and their relationship with building energy efficiency. Annual Review of Energy and the Environment, 25(1), 537-566.

[13]. Wargocki, P., & Wyon, D. P. (2011). The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). HVAC&R Research, 17(2), 156-170.

[14]. USEPA. (2009). An introduction to indoor air quality (IAQ). United States Environmental Protection Agency.

[15]. Sundell, J. (2004). On the history of indoor air quality and health. Indoor air, 14(s7), 51-58.

[16]. Veitch, J. A., & Gifford, R. (1996). Lighting quality and office work: two field simulation experiments. Journal of Environmental Psychology, 16(4), 347-363.

[17]. Klatte, M., Bergström, K., & Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. Frontiers in psychology, 4, 578.

[18]. Toftum, J., & Fanger, P. O. (1999). Air movement and perceived air quality. Indoor air, 9(4), 226-246.

[19]. Mudarri, D., & Fisk, W. J. (2007). Public health and economic impact of dampness and mold. Indoor air, 17(3), 226-235.

[20]. Rawal, R., & Chandrasekaran, B. (2020). Thermal comfort in buildings. Handbook of Environmental Materials Management, 1025-1038.

[21]. Yang, B., & Zhang, J. (2020). Thermal Comfort of Human. In Advanced Energy Efficiency Technologies for Solar Heating, Cooling and Power Generation (pp. 41-52). Springer.

[22]. Lan, L., Lian, Z., Pan, L., & Huang, X. (2018). Indoor thermal comfort and its influencing factors in residential buildings in Wuhan, China. Indoor and Built Environment, 27(5), 604-614.

[23]. Park, J., Seo, J., Jeong, J., & Kim, J. (2018). A study on the indoor thermal comfort of elderly people in Korea. International Journal of Environmental Research and Public Health, 15(8), 1672.

[24]. Humphreys, M. A. (2005). Thermal comfort and energy-efficient cooling in buildings. Energy and Buildings, 37(7), 722-731. [6] Choi, J. H., Schiavon, S., & Parkinson, T. (2019). Effects of temperature variability on thermal comfort and satisfaction in a controlled laboratory study. Building and Environment, 155, 64-76.

[25]. World Health Organization. (2018). Thermal comfort in the built environment. WHO Regional Office for Europe.

[26]. Kim, S., Kim, Y., & Kim, J. (2019). Analysis of the indoor thermal environment of an office building using measured data. Applied Sciences, 9(14), 2962.

[27]. Choi, J. H., Park, H., & Park, K. (2019). An investigation on thermal comfort and satisfaction in rooms with different temperature variability. Building and Environment, 147, 56-69.

[28]. Fanger, P. O. (1972). Thermal comfort: Analysis and applications in environmental engineering. Danish Technical Press.

[29]. ISO 7730:2005. (2005). Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[30]. Hoyt, T., Arens, E., & Zhang, H. (2012). Thermal sensation and comfort models for non-uniform and transient environments: Part II–local sensation of individual body parts. Building and Environment, 55, 243-254.

[31]. Nicol, F., & Humphreys, M. A. (1973). Thermal comfort in buildings. Building Research Establishment Current Paper, 33(1), 1-30.

[32]. Ali-Toudert, F., & Mayer, H. (2007). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. Building and Environment, 42(2), 1095-1104.

[33]. D'Ambrosio Alfano, F. R., Palella, B. I., Riccio, G., & Verde, P. (2013). Comparison between adaptive models and PMV index in predicting thermal sensation vote of occupants

[34]. ASHRAE. (2017). Thermal environmental conditions for human occupancy. ANSI/ASHRAE Standard 55-2017.

[35]. Danca P., Vartires A., Dogeanu A. (2016). An overview of current methods for thermal comfort assessment in vehicle cabin, Energy Procedia 85 (2016) 162 – 169

[36]. Altomonte, S., Schiavon, S., & Aoki, T. (2016). Visual comfort metrics for indoor lighting design: A review. Renewable and Sustainable Energy Reviews, 56, 396-411.

[37]. Veitch, J. A., & Newsham, G. R. (2000). Lighting quality and office work: Two field simulation experiments. Lighting Research and Technology, 32(1), 37-47.

[38]. Cheong, K. W. D., & Cheong, L. F. (2013). Glare from windows in high-rise residential buildings in Singapore. Building and Environment, 70, 47-56.

[39]. Heschong, L., Wright, R., & Okura, S. (2002). Daylighting impacts on human performance in schools. Journal of the Illuminating Engineering Society, 31(2), 101-114

[40]. Reinhart, C. F., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings, 33(7), 683-697.

[41]. Mardaljevic, J., & Andersen, M. (2006). Daylight in buildings: a source book on daylighting systems and components. James & James.

[42]. Ruck, N., & Littlefair, P. (2012). Daylighting in architecture: a European reference book. Birkhäuser.

[43]. ISO. (2013). ISO 3382-1:2013 Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces.

[44]. Banbury, S., & Berry, D. C. (2005). Disruption of office-related tasks by speech and office noise. British Journal of Psychology, 96(2), 219-237.

[45]. Gerges, S. N. Y., & Ibrahim, R. A. (2014). Acoustical comfort in sustainable buildings: Impact of building orientation. Renewable and Sustainable Energy Reviews, 34, 384-392.

[46]. Aletta, F., & Kang, J. (2019). Soundscape and sound environment quality evaluation. Environmental Impact Assessment Review, 75, 63-73

[47]. World Health Organization (WHO). (2010). Indoor air quality: Biological contaminants.

[48]. Wargocki, P., & Wyon, D. P. (2018). Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information. HVAC&R Research, 24(3), 267-283.

[49]. Environmental Protection Agency (EPA). (2018). Indoor air quality (IAQ).

[50]. Karr, C. J., et al. (2017). Indoor air quality in green-renovated vs. non-green low-income homes of children living with uncontrolled asthma. Environmental research, 152, 476-484.

[51]. ASHRAE. (2019). ASHRAE Handbook-Fundamentals.

[52]. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2019). ANSI/ASHRAE Standard 52.2-2017: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.

[53]. National Institute for Occupational Safety and Health (NIOSH). (2018). Indoor air quality.

[54]. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2019). ASHRAE Handbook-Fundamentals.

[55]. International Energy Agency (IEA). (2013). Ventilation and air infiltration for low energy cooling and fresh air supply.

[56]. Wargocki, P., et al. (2015). Short-term effects of classroom ventilation rate and temperature on pupils' performance. Building and Environment, 93, 69-76.

[57]. Buonanno, G., et al. (2019). Control of carbon dioxide in hospital patient rooms using mechanical ventilation. Building and Environment, 148, 187-195.

[58]. Ghita S., Catalina T. (2015), Energy efficiency versus indoor environmental quality in different Romanian countryside schools, Energy and Buildings 92 (2015) 140–154

[59]. National Cancer Institute. (2019). Radon and Cancer.

[60]. World Health Organization. (2009). WHO Handbook on Indoor Radon: A Public Health Perspective.

[61]. U.S. Environmental Protection Agency. (2016). A Citizen's Guide to Radon.

[62]. Zhang, H., et al. (2018). An evaluation of radon mitigation systems in a UK school. Journal of Radiological Protection, 38(1), 85-96.

[63]. Macedo, J., Campos-Costa, A., & Pinho, R. (2019). Seismic hazard assessment for the Lisbon region using the stochastic approach. Soil Dynamics and Earthquake Engineering, 121, 1-15.

[64]. Strasser, F. O., & Wiemer, S. (2015). Seismic hazard assessment in Europe: challenges and operational solutions. Earth-Science Reviews, 149, 50-68.

[65]. Akkar, S., & van Eck, T. (2010). A review of the seismic hazard and risk assessment studies in Turkey. Bulletin of Earthquake Engineering, 8(6), 1261-1316.

[66]. J. L. Horsley, Physical security: measures, techniques and strategies," 2nd ed. Butterworth-Heinemann, 2012.

[67]. M. E. Osterling and J. R. Bloom, Crime Prevention Through Environmental Design, 3rd ed. SAGE Publications, 2010.

[68]. D. Stipanovic, Crime prevention through environmental design in public housing: a case study, Journal of Housing and the Built Environment, vol. 28, no. 2, pp. 345-359, Jun. 2013.

[69]. Leontief, W.: Environmental repercussions and economic structure. An input-output approach. Rev. Econ. Stat. 52, 262–271 (1970)

[70]. US EPA: Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives—Final Report. EPA/530/SW-91c. U.S. Environmental Protection Agency (1974)

[71]. Hunt, R. G., Franklin, W. E., & Hunt, R. G. (1996). LCA—How it came about: —Personal reflections on the origin and the development of LCA in the USA. The international journal of life cycle assessment, 1, 4-7. https://doi.org/10.1007/BF02978624

[72]. Baumann, H., & Tillman, A. M. (2004). The hitch hiker's guide to LCA. https://doi.org/10.1065/lca2006.02.008

[73]. Thinkstep: A brief history of Life Cycle Assessment (LCA). http://www.gabi-software.com/news/news-detail/article/a-brief-history-of-life-cycle-assessment-lca/. (2016). Accessed 24 October 2022

[74]. PRé:. Company History. https://www.pre-sustainability.com/company-history. Accessed 24 October 2022

[75]. SETAC: In: Fava, J., Denison, R., Jones, B., Curran, M.A., Vigon, B., Selke, S., Barnum, J. (eds.) SETAC Workshop Report: A Technical Framework for Life-Cycle Assessment. Smugglers Notch, Vermont, August 18–23 1990. SETAC Press (1991)

[76]. Curran, M. A., & Young, S. (1996). Report from the EPA conference on streamlining LCA. The International Journal of Life Cycle Assessment, 1, 57-60. https://doi.org/10.1007/BF02978640

[77]. Vigon, B. W., Vigon, B. W., & Harrison, C. L. (1993). Life-cycle assessment: Inventory guidelines and principles (Vol. 1, No. 1, p. 108). Cincinnati, Ohio: EPA.

[78]. Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., van Duin, R., de Goede, H.P.: Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Science (CML), Leiden University, Leiden (1992)

[79]. SETAC: Guidelines for Life-cycle Assessment: A "code of Practice": from the SETAC Workshop Held at Sesimbra, Portugal, 31 March-3 April 1993. SETAC Brussels and Pensacola (1993b)

[80]. The International Journal of Life Cycle Assessment, Springer-Verlag GmbH Germany, part of Springer Nature, https://www.springer.com/journal/11367, Accessed 24 October 2022

[81]. ISO 14040:1997 Environmental management — Life cycle assessment — Principles and framework, This standard has been revised by ISO 14040:2006 | ISO 14044:2006

[82]. ISO 14041:1998 Environmental management — Life cycle assessment — Goal and scope definition and inventory analysis, This standard has been revised by ISO 14040:2006 | ISO 14044:2006

[83]. Goedkoop, M.J., Spriensma, R.: Eco-indicator 99, a damage oriented method for lifecycle impact assessment, methodology report (update April 2000) (2000)

[84]. UNEP/SETAC Life Cycle Initiative Life Cycle Impact Assessment Programme (2002), Guidance on how to move from current practice to recommended practice in Life Cycle Impact Assessment, https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2008%20-%20Guidance%20to%20move%20to%20LCA.pdf, Accessed 24 October 2022

[85]. Ecoinvent: History. http://www.ecoinvent.org/about/history/history.html. (2016). Accessed 24 October 2022

[86]. Klöpffer, W.: Life cycle sustainability assessment of products. Int. J. Life Cycle 13(2), 89–94 (2008). https://doi.org/10.1065/lca2008.02.376

[87]. European Commission, Joint Research Centre, Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD). (2010). Handbook–General Guide for Life Cycle Assessment: Provisions and Action Steps. https://data.europa.eu/doi/10.2788/94987

[88]. PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services

[89]. ISO 14071:2014 Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

[90]. ISO 14072:2014 Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment

[91]. Level(s) – A common EU framework of core sustainability indicators for office and residential buildings, JRC Science for Policy Report, Parts 1 and 2: Introduction to Level(s) and how it works (Beta v1.0)

[92]. Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall & Rydberg, T. (2011). Life cycle assessment: past, present, and future.

[93]. Life Cycle Assessment, Renuables, https://renuables.co.uk/lca. Accessed 24 October 2022

[94]. Assies, J. A. Introduction paper to SETAC-Europe workshop on environmental life cycle analysis of products. In Life-Cycle Assessment, Proceedings of a SETAC-Europe workshop on Environmental Life Cycle Assessment of Products, December 2- 3 1991, Leiden; SETAC-Europe: Brussels, Belgium, 1992.

[95]. Guine´e, J. B.; Udo de Haes, H. A.; Huppes, G. Quantitative life cycle assessment of products 1: Goal definition and inventory. J. Clean. Prod. 1993, 1 (1), 3–13.

[96]. ISO14044InternationalStandard.Environmentalmanagement- Life cycle assessment - Requirements and guidelines; International Organization for Standardization: Geneva, Switzerland, 2006.

[97]. Hunt, R. G.; Franklin, W. E.; Welch, R. O.; Cross, J. A.; Woodal, A. E. Resourceandenvironmental profile analysis of nine beverage container alternatives; U.S. Environmental Protection Agency: Washington, DC, 1974.

[98]. US EPA: Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives—Final Report. EPA/530/SW-91c. U.S. Environmental Protection Agency (1974)

[99]. Studie Umwelt und Volkswirtschaft, Vergleich der Umweltbelastung von Beha¨ltern aus PVC, Glas, Blech und Karton; Basler & Hofman Ingenieure und Planer; Eidgeno¨ssisches Amt fu¨r Umweltschutz: Bern, Switzerland, 1974.

[100]. O¨ kobilanzen von Packstoffen; Schriftenreihe Umweltschutz no. 24; Bundesamt fu¨ r Umweltschutz: Bern, Switzerland, 1984.

[101]. WCED: Report of the World Commission On Environment And Development: Our Common Future. Oxford University Press, Oxford (1987)

[102]. Moltesen, A., & Bjørn, A. (2018). LCA and Sustainability. In Life cycle assessment (pp. 43-55). Springer, Cham.

[103]. Hunt, R.G., Sellers, J.D., Franklin, W.E.: Resource and environmental profile analysis: a life cycle environmental assessment for products and procedures. Environ. Impact Assess. Rev. 12(12), 245–269 (1992)

[104]. Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2018). LCA history. In Life cycle assessment (pp. 17-30). Springer, Cham.

[105]. Hauschild, M.; Wenzel, H. Environmental Assessment of products. Vol. 1: Methodology, tools and case studies in product development - Vol. 2: Scientific background; Chapman & Hall: London, U.K., 1998.

[106]. Hofstetter, P. Perspectives in life cycle Impact assessment: A structured approach to combine models of the technosphere, ecosphere and valuesphere; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1998.

[107]. Goedkoop, M.; Spriensma, R. The Eco-indicator 99 - A damage oriented method for life cycle Impact assessment; PRe´ Consultants: Amersfoort, The Netherlands, 1999.

[108]. Hauschild, M. Z.;Huijbregts, M.; Jolliet, O.; Macleod,M.; Margni, M.; Meent, D.van de; Rosenbaum, R. K.; McKone, T. E. Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony. Environ. Sci. Technol. 2008, 42 (19), 7032–7037.

[109]. Rosenbaum, R. K.; Bachmann, T. M.; Gold, R. S.; Huijbregts, M. A. J.; Jolliet, O.; Juraske, R.; Ko¨hler, A.; Larsen, H. F.; MacLeod, M.; Margni, M.; McKone, T. E.; Payet, J.; Schuhmacher, M.; Meent, D.; vande; Hauschild, M. Z. USEtoxsthe UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 2008, 13 (7), 532–546.

[110]. Guine´e, J. B.; Heijungs, R. A proposal for the classification of toxic substances within the framework of Life Cycle Assessment of Products. Chemosphere 1993, 26 (10), 1925–1944.

[111]. Guidelines for Life-Cycle Assessment: A ‘Code of Practice’; 1st ed.; Consoli, F., Allen, D., Boustead, I., Oude, N. de Fava, J., Franklin, W., Quay, B., Parrish, R., Perriman, R., Postlethwaite, D., Seguin, J., Vigon, B., Eds.; SETAC-Europe: Brussels, Belgium, 1993.

[112]. Steen, B.: A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000-general system characteristics; CPM report 1999:4, Chalmers University of Technology, Gothenburg, Sweden (1999a)

[113]. Steen, B.: A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000-Models and data of the default method; CPM report 1999:5, Chalmers University of Technology, Gothenburg, Sweden (1999b)

[114]. Hauschild, M.Z., Potting, J.: Spatial Differentiation in LCA Impact Assessment—The EDIP 2003 Methodology, Environmental News No. 80; Danish Environmental Protection Agency, Copenhagen, Denmark (2005)

[115]. ACLAAmerican Center for Life Cycle Assessment Website. http:// www.lcacenter.org/ Accessed 17 October 2022

[116]. ALCAS Australian Life Cycle Assessment Society Website. http:// www.alcas.asn.au/ Accessed 17 October 2022

[117]. Thai LCA Network Website. http://www.thailca.net/ Accessed 17 October 2022

[118]. Energy independence and security act of 2007. Public Law 110-140, 2007. http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname)110_cong_public_law&docid)f:publ140.110.pdf Accessed 17 October 2022

[119]. U.S. Environmental Protection Agency: Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels Website. http://www.epa.gov/otaq/renewablefuels/420f09024.htm Accessed 17 October 2022

[120]. UN Environment Programme Life Cycle Initiative website. http://lcinitiative.unep.fr/ Accessed 17 October 2022

[121]. Pennington D, Wolf M, Bersani R, Pretato U (2007) Overcoming barriers to the broader implementation of life cycle thinking in business and public administration. Int J of Life Cycle Assess 12(7):458–460. https://doi.org/10.1065/lca20 07.07.355

[122]. Sonnemann G, Gemechu ED, Sala S, Schau EM, Allacker K, Pant R, Adibi N, Valdivia S (2018) Life cycle thinking and the use of LCA in policies around the world Life Cycle Assess 429–463 https:// doi. org/ 10. 1007/ 978-3- 319- 56475-3_ 18

[123]. Integrated Product Policy - Building on Environmental Life- Cycle Thinking. Commission of the European Communities, COM(2003) 302 final, Brussels, Belgium, 2003. http://eur-lex. europa.eu/LexUriServ/site/en/com/2003/com2003_0302en01. pdf Accessed 17 October 2022.

[124]. European Commission - Joint Research Centre Life Cycle Thinking and Assessment Website. http://lct.jrc.ec.europa.eu/ Accessed 17 October 2022.

[125]. U.S. Environmental Protection Agency Life-Cycle Assessment Research Website. http://www.epa.gov/nrmrl/lcaccess/ Accessed 17 October 2022.

[126]. Kent, D. C., & Becerik-Gerber, B. (2010). Understanding construction industry experience and attitudes toward integrated project delivery. Journal of construction engineering and management, 136(8), 815-825. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000188

[127]. Díaz, J., & Antön, L. Á. (2014). Sustainable construction approach through integration of LCA and BIM tools. In Computing in civil and building engineering (2014) (pp. 283-290). https://doi.org/10.1061/9780784413616.036

[128]. Jalaei, F., & Jrade, A. (2014). Integrating BIM with green building certification system, energy analysis, and cost estimating tools to conceptually design sustainable buildings. In Construction Research Congress 2014: Construction in a Global Network (pp. 140-149). https://doi.org/10.1061/9780784413517.015

[129]. Bayer, C., Gamble, M., Gentry, R., & Joshi, S. (2010). AIA guide to building life cycle assessment in practice. The American Institute of Architects, Washington DC, 16, 17-60.

[130]. AIA, C. (2014). Integrated project delivery: an updated working definition. Integrated Project Delivery.

[131]. Finnveden, G.; Hauschild, M. Z.; Ekvall, T.; Guine´e, J.; Heijungs, R.; Hellweg,S.; Koehler,A.; Pennington,D.; Suh,S. Recent developments in life cycle assessment. J. Environ. Manage. 2009, 91 (1), 1–21, 2009.

[132]. Assies, J. A. A risk-based approach to life-cycle impact assessment. J. Hazard. Mater. 1998, 61 (1), 23–29.

[133]. Nishioka, Y.; Levy, J. I.; Norris, G. A. Integrating air pollution, climate change,and economics in a risk-based life-cycle analysis: a case study of residential insulation. Hum. Ecol. Risk Assess. 2006, 12 (3), 552–571.

[134]. Saouter,E.; Feijtel, T.C.J.Useof life cycle analysis and environmental risk assessment in an integrated product assessment. Environmental Strategies. In Risk Assessment and Life Cycle Assessment; TemaNord 2000:545; Hauschild, M., Olsen, S. I., Poll, C., Bro-Rasmussen, F., Eds.; Nordic Council of Ministers: Copenhagen, Denmark, 2000.

[135]. Sonnemann, G.; Castells, F.; Schuhmacher, M. Integrated lifecycle and risk assessment for industrial processes; Lewis Publishers: Boca Raton, FL, 2004.

[136]. Pehnt, M. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy 2006, 31 (1), 55–71.

[137]. Bjo¨rk, H.; Rasmuson, A. A method for life cycle assessment environmental optimization of a dynamic process exemplified by an analysis of an energy system with a superheated steam dryer integrated in a local district heat and power plant. Chem. Eng. J. 2002, 87 (3), 381–394.

[138]. Levasseur, A.; Lesage, P.; Margni, M.; Desche^nes, L.; Samson, R. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. Environ. Sci. Technol. 2010, 44 (8), 3169–3174.

[139]. Kendall, A.; Chang, B.; Sharpe, B. Accounting for Time- Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations. Environ. Sci. Technol. 2009, 43 (18), 7142–7147.

[140]. Suh, S.; Lenzen, M.; Treloar, G. J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; Munksgaard, J.; Norris, G. System boundary selection in lifecycle inventories using hybrid approaches. Environ. Sci. Technol. 2004, 38 (3), 657–664.

[141]. Hendrickson, C.; Lave, L. B.; Matthews, H. S. Environmental life cycle assessment of goods and services - An input-output approach; Resources for the Future: Washington, DC, 2006.

[142]. Heijungs, R.; de Koning, A.; Suh, S.; Huppes, G. Toward an information tool for integrated product policy: requirements for data and computation. J. Ind. Ecol. 2006, 10 (3), 147–158.

[143]. Zamagni, A.; Buttol, P.; Porta, P. L.; Buonamici, R.; Masoni, P.; Guine´e, J. B.; Heijungs, R.; Ekvall, T.; Bersani, R.; Bien˜kowska, A.; Pretato, U. Critical review of the current research needs and limitations related to ISO-LCA practice; Deliverable 7 of the CALCAS project, 2008. Available at http://www.estis.net/sites/calcas/ Accessed 17 October 2022

[144]. ISO (International Organization for Standardization) (2017) ISO 15686–5. Buildings and constructed assets – Service life planning – Part 5: life cycle costing. Geneva, Switzerland

[145]. Guidelines for Social Life Cycle Assessment of Products; Benoıˆt, C., Mazijn, B., Eds.; UNEP/SETAC Life Cycle Initiative: Paris, 2009. Available at http://www.estis.net/includes/file.asp?site)lcinit&file)524CEB61-779C-4610-8D5B-8D3B6B336463 Accessed 17 October 2022.

[146]. Environmental Life Cycle Costing; Hunkeler, D., Lichtenvort, K., Rebitzer, G., Eds.; CRC Press: New York, 2008.

[147]. Settanni, E. The need for a computational structure of LCC. Int. J. Life Cycle Assess. 2008, 13 (7), 526–531.

[148]. Huppes, G.; van Rooijen, M.; Kleijn, R.; Heijungs, R.; de Koning, A.; van Oers, L. Life Cycle Costing and the Environment.: Institute of Environmental Sciences (CML), Universiteit Leiden: Leiden, The Netherlands, 2004. Available at http://www.rivm.nl/milieuportaal/images/Report%20LCC%20April%20%202004%20final.pdf Accessed 17 October 2022.

[149]. Campion, N. A. (2015). Advancing life cycle assessment: perspectives from the building and healthcare industries (Doctoral dissertation, University of Pittsburgh).

[150]. CEC: Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan. Communication from the Commission. COM (2008) 397/3 (2008a)

[151]. EC-JRC: International Reference Life Cycle Data System (ILCD) Handbook—General guide for Life Cycle Assessment—Detailed guidance, 1st edn. Publications Office of the European Union, Luxembourg (2010)

[152]. Finkbeiner, M.: Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment? Int. J. Life Cycle Assess. 19, 266–271 (2014). doi:10.1007/s11367-013-0678-x

[153]. EC: Questions about the product environmental footprint (PEF) and organisation environmental footprint (OEF) methods. In: EC-Environment. http://ec.europa.eu/environment/eussd/smgp/pdf/q_a.pdf (2016e). Accessed 17 October 2022

[154]. EU (2020b) European Platform on Life Cycle Assessment (LCA). https:// ec. europa. eu/ envir onment/ ipp/ lca. htm#: ~: text= The%20Eur opean% 20Com missi on's% 20pro ject%2 0The ,under lying%20data% 20and% 20met hodol ogical% 20nee ds. Accessed 17 October 2022

[155]. EU (2020c) Environmental Footprint. https:// eplca. jrc. ec. europa. eu//Envir onmen talFo otpri nt. html. Accessed 17 October 2022

[156]. Benoît, C., Mazijn, B.: Guidelines for Social Life Cycle Assessment of Products. UNEP/SETAC Life Cycle Initiative, Paris (2009)

[157]. Huarachi, D. A. R., Piekarski, C. M., Puglieri, F. N., & de Francisco, A. C. (2020). Past and future of Social Life Cycle Assessment: Historical evolution and research trends. *Journal of Cleaner Production*, *264*, 121506. https://doi.org/10.1016/j.jclepro.2020.121506

[158]. United Nations. The Millennium Development Goals Report. 2015. Available online: https://www.un.org/millenniumgoals/20 15_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf (accessed on).

[159]. Soltanpour, Y., Peri, I., & Temri, L. (2019). Area of protection in S-LCA: human well-being or societal quality. *The International Journal of Life Cycle Assessment*, *24*, 2073-2087. https://doi.org/10.1007/s11367-019-01620-y

[160]. Venkatesh, G. (2019). Critique of selected peer-reviewed publications on applied social life cycle assessment: focus on cases from developing countries. *Clean Technologies and Environmental Policy*, *21*, 413-430. https://doi.org/10.1007/s10098-018-1644-x

[161]. Arcese, G., Lucchetti, M. C., Massa, I., & Valente, C. (2018). State of the art in S-LCA: integrating literature review and automatic text analysis. *The International Journal of Life Cycle Assessment*, *23*, 394-405. https://doi.org/10.1007/s11367-016-1082-0

[162]. Benoît Norris, C.; Norris, G.A. Chapter 8: The Social Hotspots Database Context of the SHDB. In The Sustainability Practitioner's Guide to Social Analysis and Assessment; Murray, J., McBrain, D., Wiedmann, T., Eds.; Common Ground Pub. LLC: Champaign, IL, USA, 2015; pp. 52–73.

[163]. ISO 20400:2017 Sustainable procurement — Guidance

[164]. Dreyer, L., Hauschild, M., Schierbeck, J.: A Framework for social life cycle impact assessment (10 pp). Int. J. Life Cycle Assess. 11, 88–97 (2006). https://doi.org/10.1065/lca2005.08.223

[165]. Weidema, B.P.: The integration of economic and social aspects in life cycle impact assessment. Int. J. Life Cycle Assess. 11, 89–96 (2006). https://doi.org/10.1065/lca2006.04.016

[166]. Jørgensen, A., Lai, L.C.H., Hauschild, M.Z.: Assessing the validity of impact pathways for child labour and well-being in social life cycle assessment. Int. J. Life Cycle Assess. 15, 5–16 (2010b). https://doi.org/10.1007/s11367-009-0131-3

[167]. Moltesen, A., Bonou, A., Wangel, A., & Bozhilova-Kisheva, K. P. (2018). Social life cycle assessment: An introduction. In Life Cycle Assessment (pp. 401-422). Springer, Cham. https://doi.org/10.1007/978-3-319-56475-3_16

[168]. Jørgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M.: Societal LCA methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13, 96–103 (2008) https://doi.org/10.1065/lca2007.11.367

[169]. Pollok, L., Spierling, S., Endres, H. J., & Grote, U. (2021). Social Life Cycle Assessments: a review on past development, advances and methodological challenges. Sustainability, 13(18), 10286. https://doi.org/10.3390/su131810286

[170]. Kloepffer, W.: Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 13, 89–95 (2008). https://doi.org/10.1065/lca2008.02.376

[171]. Zamagni, A.: Life cycle sustainability assessment. Int. J. Life Cycle Assess. 17, 373–376 (2012). https://doi.org/10.1007/s11367-012-0389-8

[172]. lkington, J.: Cannibals with Forks: The Triple Bottom Line of 21st Century Business. Capstone Publ, Oxford (1997)

[173]. Reed DL (2012) Life-cycle Assessment in Government Policy in the United States. PhD diss. University of Tennessee. https:// trace.tenne ssee. edu/ cgi/ viewc ontent. cgi? artic le= 2502& conte xt= utk_ gradd iss Accessed 17 October 2022

[174]. CEN, BS EN ISO 14040, 2006 Environmental Management - Life Cycle Assessment - Principles and Framework, 2006, https://doi.org/10.1016/j.ecolind.2011.01.007

[175]. ISO, BS-EN 15978, 2011 Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method, 2012.

[176]. C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: a critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416, https://doi.org/10.1016/J.RSER.2016.09.058

[177]. T. Jusselme, E. Rey, M. Andersen, An integrative approach for embodied energy: towards an LCA-based data-driven design method, Renew. Sustain. Energy Rev. 88 (2018) 123–132, https://doi.org/10.1016/j.rser.2018.02.036

[178]. J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build. Environ. 60 (2013) 81–92, https://doi.org/10.1016/J.BUILDENV.2012.11.009.

[179]. T. Jusselme, E. Rey, M. Andersen, Surveying the environmental life-cycle performance assessments: practice and context at early building design stages, Sustain. Cities Soc. 52 (2020) 101879, https://doi.org/10.1016/j.scs.2019.101879.

[180]. T. H¨akkinen, M. Kuittinen, A. Ruuska, N. Jung, Reducing embodied carbon during the design process of buildings, J. Build. Eng. 4 (2015) 1–13, https://doi.org/10.1016/J.JOBE.2015.06.005.

[181]. Sala, S., Amadei, A. M., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. The International Journal of Life Cycle Assessment, 1-20. https://doi.org/10.1007/s11367-021-01893-2

[182]. United Nations (UN) (2015) Transforming Our World: the 2030 Agenda for Sustainable Development. https:// sustainable development. un.org/ post2 015/ trans forming our world. Accessed 17 October 2022

[183]. The study was conducted by The Nature Conservancy, The University of Minnesota and 11 other institutions. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_ScienceofSustainability_SDGs.pdf?epik=dj0yJnU9bkdfekRQMnpMMHQ2N1NjNF9Cd2RfbXRVRGxCRUhuY0kmcD0wJm49R0RXMlUzVnVEeDdDOHFOWno1YXI4dyZ0PUFBQUFBR09HZEdn

[184]. Roberts, M., Allen, S., & Coley, D. (2020). Life cycle assessment in the building design process–A systematic literature review. Building and Environment, 185, 107274. https://doi.org/10.1016/j.buildenv.2020.107274

[185]. WorldGBC, Bringing embodied carbon upfront, London; Toronto. https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf, 2019.

[186]. UKGBC, Tackling Embodied Carbon in Buildings, 2015.

[187]. WorldGBC, Advancing net zero: status report may 2019, London; Toronto. https://www.worldgbc.org/news-media/advancing-net-zero-status-report-2019-publication, 2019.

[188]. HM Treasury, Infrastructure carbon review, London. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/260710/infrastructure_carbon_review_251113.pdf, 2013.

[189]. S.R. Allen, G.P. Hammond, H.A. Harajli, C.I. Jones, M.C. McManus, A.B. Winnett, Integrated appraisal of micro-generators: methods and applications, Proc. Inst. Civ. Eng. Energy. 161 (2008) 73–86, https://doi.org/10.1680/ener.2008.161.2.73.

[190]. M.C. McManus, C.M. Taylor, The changing nature of life cycle assessment, Biomass Bioenergy 82 (2015) 13–26, https://doi.org/10.1016/j.biombioe.2015.04.024.

[191]. Youngs, H. L. (2012). The effects of stakeholder values on biofuel feedstock choices. In *Perspectives on biofuels: Potential benefits and possible pitfalls* (pp. 29-67). American Chemical Society. https://doi.org/10.1021/bk-2012-1116.ch003

[192]. Hellweg, S., & Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), 1109-1113. https://doi.org/10.1126/science.1248361

[193]. Menten, F., Tchung-Ming, S., Lorne, D., & Bouvart, F. (2015). Lessons from the use of a long-term energy model for consequential life cycle assessment: the BTL case. *Renewable and Sustainable Energy Reviews*, *43*, 942-960. https://doi.org/10.1016/j.rser.2014.11.072

[194]. van der Sluijs, J. P. Integrated Assessment, Definition of. In Encyclopedia of Global Environmental Change, Vol. 4, Responding to global environmental change; Tolba, M. K., Ed.; John Wiley & Sons, Ltd.: Chichester, 2002.

[195]. F. Pomponi, A. Moncaster, Embodied carbon mitigation and reduction in the built environment – what does the evidence say? J. Environ. Manag. 181 (2016) 687–700, https://doi.org/10.1016/J.JENVMAN.2016.08.036.

[196]. C. De Wolf, F. Yang, D. Cox, A. Charlson, A.S. Hattan, J. Ochsendorf, Material quantities and embodied carbon dioxide in structures, Proc. Inst. Civ. Eng. Eng. Sustain. 169 (2016) 150–161, https://doi.org/10.1680/ensu.15.00033.

[197]. M.K. Dixit, Life cycle recurrent embodied energy calculation of buildings: a review, J. Clean. Prod. 209 (2019) 731–754, https://doi.org/10.1016/J.JCLEPRO.2018.10.230.

[198]. LETI, LETI Embodied Carbon Primer, Supplementary Guidance to the Climate Emergency Design Guide, London, 2020.

[199]. UKGBC, Net Zero Carbon Buildings, A framework definition, London. https://www.ukgbc.org/wp-content/uploads/2019/04/Net-Zero-Carbon-Buildings-A-framework-definition.pdf, 2019.

[200]. A.E. Fenner, C.J. Kibert, J. Woo, S. Morque, M. Razkenari, H. Hakim, X. Lu, The carbon footprint of buildings: a review of methodologies and applications, Renew. Sustain. Energy Rev. 94 (2018) 1142–1152, https://doi.org/10.1016/j.rser.2018.07.012.

[201]. RICS, Whole life carbon assessment for the built environment, London. http://www.rics.org/Global/Whole_life_carbon_assessment_for_the_BE_PG_guidance_2017.pdf, 2017.

[202]. https://carbonleadershipforum.org/wp-content/uploads/2019/05/2019.05.23-LCA-Timeline-Diagram-spread.pdf

[203]. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of bim-Based LCA method to buildings. Energy Build. 2017, 136, 110–120. https://doi.org/10.1016/j.enbuild.2016.12.009

[204]. Antón, L.Á.; Diaz, J. Integration of Life Cycle Assessment in a BIM Environment. Procedia Eng. 2014, 85, 26–32. https://doi.org/10.1016/j.proeng.2014.10.525

[205]. Nizam, R.S.; Zhang, C.; Tian, L. A BIM based tool for assessing embodied energy for buildings. Energy Build. 2018, 170, 1–14. https://doi.org/10.1016/j.enbuild.2018.03.067

[206]. Wastiels, L.; Decuypere, R. Identification and comparison of LCA-BIM integration strategies. In Proceedings of the IOP Conference Series Earth and Environmental Science, Graz, Austria, 11–14 September 2019; Volume 323. https://doi.org/10.1088/1755-1315/323/1/012101

[207]. Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., & Yuan, H. (2018). Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study. Journal of cleaner production, 172, 3154-3166. https://doi.org/10.1016/j.jclepro.2017.11.087

[208]. Feng, H., Liyanage, D. R., Karunathilake, H., Sadiq, R., & Hewage, K. (2020). BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. Journal of Cleaner Production, 250, 119543. https://doi.org/10.1016/j.jclepro.2019.119543

[209]. Soust-Verdaguer, B., Llatas, C., & Moya, L. (2020). Comparative BIM-based Life Cycle Assessment of Uruguayan timber and concrete-masonry single-family houses in design stage. Journal of Cleaner Production, 277, 121958. https://doi.org/10.1016/j.jclepro.2020.121958

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

[211]. Cheng, B., Li, J., Tam, V. W., Yang, M., & Chen, D. (2020). A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: a case study. Sustainability, 12(2), 685. https://doi.org/10.3390/su12020685

[212]. Palumbo, E., Soust-Verdaguer, B., Llatas, C., & Traverso, M. (2020). How to obtain accurate environmental impacts at early design stages in BIM when using environmental product declaration. A method to support decision-making. Sustainability, 12(17), 6927. https://doi.org/10.3390/su12176927

[213]. Jun, H., Lim, N., & Kim, M. (2015). BIM-based carbon dioxide emission quantity assessment method in Korea. Journal of Asian Architecture and Building Engineering, 14(3), 569-576. https://doi.org/10.3130/jaabe.14.569

[214]. Cang, Y., Luo, Z., Yang, L., & Han, B. (2020). A new method for calculating the embodied carbon emissions from buildings in schematic design: Taking "building element" as basic unit. Building and Environment, 185, 107306. https://doi.org/10.1016/j.buildenv.2020.107306

[215]. Theißen, S., Höper, J., Drzymalla, J., Wimmer, R., Markova, S., Meins-Becker, A., & Lambertz, M. (2020). Using open BIM and IFC to enable a comprehensive consideration of building services within a whole-building LCA. Sustainability, 12(14), 5644. https://doi.org/10.3390/su12145644

[216]. Eleftheriadis, S., Duffour, P., & Mumovic, D. (2018). BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives. Energy and Buildings, 173, 587-600. https://doi.org/10.1016/j.enbuild.2018.05.042

[217]. Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. Automation in Construction, 103, 127-149. https://doi.org/10.1016/j.autcon.2019.02.011

[218]. Jalaei, F., Guest, G., Gaur, A., & Zhang, J. (2020). Exploring the effects that a non-stationary climate and dynamic electricity grid mix has on whole building life cycle assessment: A multi-city comparison. Sustainable Cities and Society, 61, 102294. https://doi.org/10.1016/j.scs.2020.102294

[219]. Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. Building and environment, 140, 153-161. https://doi.org/10.1016/j.buildenv.2018.05.006

[220]. Hollberg, A., Genova, G., & Habert, G. (2020). Evaluation of BIM-based LCA results for building design. Automation in Construction, 109, 102972. https://doi.org/10.1016/j.autcon.2019.102972

[221]. Teng, Y., Xu, J., Pan, W., & Zhang, Y. (2022). A systematic review of the integration of building information modeling into life cycle assessment. Building and Environment, 109260. https://doi.org/10.1016/j.buildenv.2022.109260

[222]. Speck, R., Selke, S., Auras, R., & Fitzsimmons, J. (2016). Life cycle assessment software: Selection can impact results. Journal of Industrial Ecology, 20(1), 18-28. https://doi.org/10.1111/jiec.12245

[223]. https://www.oneclicklca.com/

[224]. Xu, J., Teng, Y., Pan, W., & Zhang, Y. (2022). BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings. Journal of Cleaner Production, 374, 133894. https://doi.org/10.1016/j.jclepro.2022.133894

[225]. Pan, W., Li, K., & Teng, Y. (2018, January). Briefing: Life-cycle carbon assessment of prefabricated buildings: challenges and solutions. In Proceedings of the Institution of Civil Engineers-Engineering Sustainability (Vol. 172, No. 1, pp. 3-8). Thomas Telford Ltd. https://doi.org/10.1680/jensu.17.00063

[226]. Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. Building and environment, 140, 153-161. https://doi.org/10.1016/j.buildenv.2018.05.006

[227]. Carvalho, J. P., Bragança, L., & Mateus, R. (2020). A systematic review of the role of BIM in building sustainability assessment methods. Applied Sciences, 10(13), 4444. https://doi.org/10.3390/app10134444

[228]. Zimmermann, R. K., Bruhn, S., & Birgisdóttir, H. (2021). BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs. Sustainability, 13(10), 5455. https://doi.org/10.3390/su13105455

[229]. Onososen, A., & Musonda, I. (2022). Barriers to BIM-based life cycle sustainability assessment for buildings: An interpretive structural modelling approach. Buildings, 12(3), 324. https://doi.org/10.3390/buildings12030324

[230]. Technical assistance for ensuring optimal performance of technical building systems under the new Energy Performance of Buildings Directive (EU) 2018/844, https://op.europa.eu/en/publication-detail/-/publication/9ee3d7e4-e580-11ed-a05c-01aa75ed71a1/language-en

[231]. Energy performance of buildings directive, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

[232]. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Current consolidated version: 01/01/2021, http://data.europa.eu/eli/dir/2010/31/oj

[233]. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, http://data.europa.eu/eli/dir/2018/844/oj

[234]. Renovation wave, Renovating the EU building stock will improve energy efficiency while driving the clean energy transition, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en

[235]. A European Green Deal, Striving to be the first climate-neutral continent, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[236]. Nearly zero-energy buildings, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

[237]. Delivering the European Green Deal, Climate Action, https://climate.ec.europa.eu/news-your-voice/news/delivering-european-green-deal-2021-07-14_en

[238]. Long-term renovation strategies, Energy, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en

[239]. Certificates and inspections, Energy, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/certificates-and-inspections_e

[240]. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, https://eur-lex.europa.eu/eli/dir/2018/844/oj

[241]. Section IT 1.2.4.1.1. General criteria in REGULATION OF THERMAL INSTALLATIONS IN BUILDINGS: CONSOLIDATED VERSION + MODIFICATIONS, MARCH 2021, SECRETARY OF STATE FOR ENERGY, DIRECTORATE-GENERAL FOR ENERGY POLICY AND MINES

[242]. Bijlage XII: Eisen voor technische installaties, Belgian OFFICIAL GAZETTE and monitor 28.10.2020 – and monitor 78086 to 78130.

[243]. https://epb.center/media/filer_public/c0/e8/c0e8da39-5388-482c-9bbb-a55c5c78166e/epbcenter_bldup_webinar6_epbst_heatingsys.pdf

[244]. COMMISSION RECOMMENDATION (EU) 2019/1019 of 7 June 2019 on building modernisation, OJEU L165/70

[245]. Takahiro SATO, Tanabe Lab., Waseda Univ. December 18, 2002

[246]. DG ENERs buildings pages: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

[247]. Energy Performance of Buildings Directive recast: EPBD recast Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, https://eur-lex.europa.eu/eli/dir/2018/844/oj

[248]. Energy Performance in Buildings Center: https://epb.center/

[249]. Technical assistance for ensuring optimal performance of technical building systems under the new Energy Performance of Buildings Directive (EU) 2018/844: Final report with technical guidelines for establishing and enforcing technical building system requirements and system performance assessment and documentation under Article 8 VITO, Waide Strategic Efficiency Ltd, Guidehouse: https://op.europa.eu/en/publication-detail/-/publication/9ee3d7e4-e580-11ed-a05c-01aa75ed71a1/language-en

[250]. EN 15316–1 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 1: General and Energy performance expression, Module M3–1, M3–4, M3–9, M8–1, M8–4

[251]. EN 15316–2 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 2: Space emission systems (heating and cooling), Module M3–5, M4–5

[252]. EN 15316–3 Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 3: Space distribution systems (DHW, heating and cooling), Module M3–6, M4–6, M8–6

[253]. EN 15316–4-1 (heat. & DHW generation, combust. systems) Energy performance of buildings – Method for calculation of systemenergy requirements and system efficiencies – Part 4–1: Space heating and DHW generation systems, combustion systems (boilers, biomass), Module M3–8-1 and M 8–8-1

[254]. EN 15316–4-2 (heat. & DHW generation, heat pump systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–2: Space heating generation systems, heat pump systems, Module M3–8-2, M8–8-2

[255]. EN 15316–4-3 (heat generation, th.solar & PV systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–3: Heat generation systems, thermal solar and photovoltaic systems, Module M3–8-3, M8–8-3, M11–8-3

[256]. EN 15316–4-4 (heating generation, cogen systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–4: Heat generation systems, building-integrated cogeneration systems, Module M8–3-4, M8–8-4, M8–11-4

[257]. EN 15316–4-5 (heating generation, district H&C) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–5: District heating and cooling, Module M3–8-5, M4–8-5, M8–8-5, M11–8-5

[258]. EN 15316–4-8 (heating generation, air heat. & ovhead rad. systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 4–8: Space heating generation systems, air heating and overhead radiant heating systems, including stoves (local), Module M3–8-8

[259]. EN 15316–5 (heating and DHW storage systems) Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies – Part 5: Space heating and DHW storage systems (not cooling), Module M3–7, M8–7

[260]. CEN/TR 15316-6-1 (technical report)

[261]. CEN/TR 15316-6-2 (technical report)

[262]. CEN/TR 15316-6-3 (technical report)

[263]. CEN/TR 15316-6-4 (technical report)

[264]. CEN/TR 15316-6-5 (technical report)

[265]. CEN/TR 15316-6-6 (technical report)

[266]. CEN/TR 15316-6-7 (technical report)

[267]. CEN/TR 15316-6-8 (technical report)

[268]. CEN/TR 15316-6-9 (technical report)

[269]. CEN/TR 15316-6-10 (technical report)

[270]. EN 12831–1 (heat. design load)

[271]. CEN/TR 12831-2 (technical report)

[272]. EN 15316-1: M3 Space heating: general

[273]. EN 15316-1: M8 DHW: general

[274]. EN 12831-3: M8-2 DHW: needs

[275]. EN 12831-1: M3-3 Space heating: needs (sizing)

[276]. EN 12831-3: M8-3 DHW: needs (sizing)

[277]. EN 15316-2: M3-5 Space heating: emission and control

[278]. EN 15316-3: M3-6 Space heating: Distribution and control

[279]. EN 15316-5: M3-7 Space heating: Storage and control

[280]. EN 15316-5: M8-7 DHW: Storage and control

[281]. EN 15316-4-1: M3-8 Space heating: generation

[282]. EN 15316-4-1: M8-8 DHW: generation

[283]. EN 15378-1:Energy performance of buildings - Heating systems and DHW in buildings - Part 1: Inspection of boilers, heating systems and DHW, Module M3-11, M8-11

[284]. EN 15378-3: Energy performance of buildings - Heating and DHW systems in buildings - Part 3: Measured energy performance, Module M3-10, M8-10

[285]. EN 16798-17:Energy performance of buildings. Ventilation for buildings Guidelines for inspection of ventilation and air conditioning systems (Module M4-11, M5-11, M6-11, M7- 11), and

[286]. EN 16798-1:Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6

[287]. EN 16798-1:Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6

[288]. EN 16798-3:Energy performance of buildings. Ventilation for buildings For non-residential buildings. Performance requirements for ventilation and room-conditioning systems (Modules M5-1, M5-4)

[289]. EN 16798-5-1: Energy performance of buildings. Ventilation for buildings Calculation methods for energy requirements of ventilation and air conditioning systems (Modules M5-6, M5-8, M6-5, M6-8, M7-5, M7-8). Method 1: Distribution and generation

[290]. EN 16798-5-2:Energy performance of buildings. Ventilation for buildings Calculation methods for energy requirements of ventilation systems (Modules M5-6, M5-8, M6-5, M6-8, M7-5, M7-8). Method 2: Distribution and generation

[291]. EN 16798-9: Energy performance of buildings. Ventilation for buildings Calculation methods for energy requirements of cooling systems (Modules M4-1, M4-4, M4-9). General

[292]. EN 16798-13: Energy performance of buildings. Ventilation for buildings Calculation of cooling systems (Module M4-8). Generation

[293]. EN 16798-15: Energy performance of buildings. Ventilation for buildings Calculation of cooling systems (Module M4-7). Storage

Annex

A.1 Smart Readiness Indicators

A.1.1 Total SRI readiness indicators

Indicator name	**Total smart readiness**	
	Score	Rating
Description	This indicator displays the overall smart readiness score	This indicator displays the overall smart readiness rating
Input	Refer to input data from Section 2.4.1.2	
Sensors	None	
Algorithm	Refer to calculation from Section 2.4.1.2	
Output	Value in %	Value within 7-step scale
Worked example	Refer to calculation from Section 2.4.1.2	
References	SRI assessment package (v4.5) [6].	

A.1.2 SRI readiness score, per technical functionality

Indicator name	**Smart readiness score**, per technical functionality		
	per Energy performance and operation	per Response to user needs	per Energy flexibility
Description	This indicator displays the smart readiness score for the *technical functionality*		
Input	Refer to input data from Section 2.4.1.2		
Sensors	None		
Algorithm	Refer to calculation from Section 2.4.1.2		
Output	Value in %		
Worked example	Refer to calculation from Section 2.4.1.2		
References	SRI assessment package (v4.5) [6].		

A.1.3 SRI readiness score, per impact criterion

Indicator name	**Smart readiness score**, per impact criterion

	per Energy efficiency	per Maintenance and fault prediction	per Comfort	per Convenience	per Health, well-being, and accessibility	per Information to occupants	per Energy flexibility and storage
Description	This indicator displays the smart readiness score for the *impact criterion*						
Input	Refer to input data from Section 2.4.1.2						
Sensors	None						
Algorithm	Refer to the calculation from Section 2.4.1.2						
Output	Value in %						
Worked example	Refer to the calculation from Section 2.4.1.2						
References	SRI assessment package (v4.5) [6].						

A.1.4 SRI readiness score per technical domain

Indicator name	**Smart readiness score**, per technical domain							
	per Heating	per Domestic Hot Water	per Cooling	per Ventilation	per Lighting	per Dynamic building envelope	per Electricity	per Electric vehicle charging
Description	This indicator displays the smart readiness score for the *technical domain*							
Input	Refer to input data from Section 2.4.1.2							
Sensors	None							
Algorithm	Refer to the calculation from Section 2.4.1.2							
Output	Value in %							
Worked example	Refer to the calculation from Section 2.4.1.2							
References	SRI assessment package (v4.5) [6].							

A.2 Environmental life-cycle Indicators

Indicator Name	Indicator Description	Units
Climate change (global warming potential)	Indicator denoting the potential global warming resulting from the discharge of greenhouse gases into the atmosphere. Climate change is the consequence of human-induced emissions on atmospheric radiative forcing, specifically heat radiation absorption, which has been identified as a subject of paramount concern. Subsequently, this phenomenon may yield adverse ramifications on vital components such as ecosystem health, human well-being, and material welfare. The majority of these emissions have been observed to accentuate radiative forcing, leading to an elevation in surface temperatures on Earth, commonly acknowledged as the greenhouse effect. Consequently, this indicator emphasizes the imperative areas of safeguarding, namely human health, the natural environment, and the built environment.	kg CO_2 equivalents per kg [kg CO_2 eq / kg]
Ozone depletion potential	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer.	kg CFC 11 equivalents [kg CFC 11 eq]
Acidification potential	In the realm of environmental phenomena, a reduction in the pH level of rainwater and fog measurements ensues, subsequently eliciting adverse consequences for ecosystems. Such effects manifest in the leaching of soil nutrients and heightened metal solubility into the soil matrix. The ramifications of acidifying pollutants extend across diverse domains, including soil quality, groundwater, surface waters, living organisms, ecosystems, and even the integrity of constructed materials such as buildings. Among the	mole H+ equivalents [mol H+ eq.] kg SO_2 equivalents per kg [kg CO_2 eq / kg]

	chief contributors to acidification are emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), and ammonia compounds (NHx). Areas warranting particular concern and protection encompass both the natural environment and the constructed urban landscape, as well as human health and the safeguarding of vital natural resources.	
Eutrophication aquatic freshwater	In the realm of freshwater ecosystems, an observable phenomenon emerges in the form of amplified growth measurements of aquatic plants or the proliferation of algal blooms, both of which can be attributed to the elevated presence of nutrients. This influx of nutrients contributes to a state of excessive enrichment, resulting in the exacerbation of aquatic plant growth or the burgeoning of algal populations. Such a scenario warrants scholarly attention, as it pertains to the subject of freshwater ecotoxicity, which delves into the repercussions of toxic substances on the delicate balance and functionality of these vital aquatic environments.	kg P equivalents [kg P eq.]
Eutrophication aquatic marine	Marine ecosystem reaction measurement to excessive availability of a limiting nutrient.	kg N equivalents [kg N eq.]
Eutrophication terrestrial	Enhanced quantification of nutrient accessibility within the soil consequent to the infusion of botanical fertilizers.	mole N equivalents [mol N eq.]
Photochemical ozone formation	Indicator delving into the measurement and subsequent effects of nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOC) on the domains of 'Human Health' and 'Terrestrial Ecosystems' protection. Emphasizing photo-oxidant formation, which engenders the generation of reactive chemical species such as ozone through solar irradiation on specific primary air pollutants, the	kg NMVOC equivalents [kg NMVOC eq.]

	research explores the potential deleterious consequences of these reactive compounds on human health and the environment, including detrimental effects on crops. The pertinent areas of protection under scrutiny encompass human health, the built environment, the natural habitat, and essential natural resources.	
Depletion of abiotic resources - minerals and metals	Indicator delving into the concept of "abiotic resource depletion," an essential metric for measuring the exhaustion of natural non-fossil resources. Abiotic resources encompass diverse natural sources, such as iron ore, crude oil, and wind energy, which are characterized by their non-living origin. This indicator holds significant prominence within sustainability discussions, and consequently, various methodologies have emerged to characterize contributions to this domain. The divergent approaches adopted in these methodologies often stem from disparities in problem definitions. As a result, the scope of this indicator may encompass solely natural resources or extend to encompass human health and the natural environment, thereby warranting comprehensive consideration.	kg Sb equivalents [kg Sb eq.]
Depletion of abiotic resources – fossil fuel	Indicator of the depletion of natural fossil fuel resources.	Mega Joules [MJ]
Water use	Indicator of the amount of water required to dilute toxic elements emitted into water or soil.	Cubic meters [m^3]
Use stage energy performance	“Operational energy consumption”: primary energy demand measurement of a building in the use stage, generation of low carbon or renewable energy.	kilowatt-hours per square meter per year ($kWh/m^2/yr$)
Life cycle Global Warming Potential	“Carbon footprint assessment” or “whole life carbon measurement”: building’s contribution to greenhouse	kg CO_2 equivalents per square meter

	gas (GHG) emissions measurement associated with earth's global warming or climate change.	per year (kg CO_2 eq./m^2/yr
Bill of quantities, materials, and lifespans	The quantities and mass of construction products and materials, as well as estimation of the lifespans measurement necessary to complete defined parts of the building.	Unit quantities, mass, and years
Construction & demolition waste and materials	In the context of construction, renovation, and demolition activities, the aggregate volume of waste and materials produced serves as the basis for computing the diversion rate pertaining to reuse and recycling, adhering to the principles outlined in the waste hierarchy.	kg of waste and materials per m^2 total useful floor area
Design for adaptability and renovation	Building design extent assessment of facilitation future adaptation to changing occupier needs and property market conditions; a building proxy capacity to continue to fulfill its function and for the possibility to extend its useful service life into the future.	Adaptability score
Design for deconstruction, reuse, and recycling	In the realm of architectural design, the evaluation of the potential for future material recovery and reuse, encompassing disassembly considerations to optimize the ease of deconstructing essential building components, is imperative. This entails a comprehensive assessment of the feasibility of reutilizing and recycling said components, along with their associated sub-assemblies and constituent materials.	Deconstruction score
Use stage water consumption	The comprehensive quantification of water utilization for an average building inhabitant, encompassing the ability to distinguish between potable and non-potable water supplies, as well as facilitating the identification of regions facing water scarcity.	m^3/yr of water per occupant

Advanced Energy Performance Assessment towards Smart Living in Building and District Level

https://www.smartlivingepc.eu/en/

https://www.linkedin.com/company/smartlivingepc/

https://twitter.com/SmartLivingEPC

https://www.youtube.com/channel/UC0SKa-20tiSabuwjtYDqRrQ

This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement number 101069639. The European Union is not liable for any use that may be made of the information contained in this document, which is merely representing the authors' view.