ANNEX 72

EBC
Energy in Building and Communities Programme

International Energy Agency

Guidelines for design decision-makers (Annex 72)

Energy in Buildings and Communities Technology Collaboration Programme

February 2023

Technology Collaboration Programme
by iea

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Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO_2eq	CO_2 equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
$LCCO_2$	Life Cycle CO_2 equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO_2 Intensity	The total CO_2 emission embodied, per unit of a product or per consumer price of a product. [kg CO_2eq /unit of product or price]
CO_2eq	CO_2 equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO_2eq]
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO_2, emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO_2 equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO_2eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process
Gross Floor Area (GFA)	Gross Floor Area [m^2]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.

Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO2 data in a model to derive national average embodied energy/CO2 data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analyzed (EN15978:2011)

1. Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of 'low tech', robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems(*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other
Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit
Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)

Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior Simulation
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
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Annex 84: Demand Management of Buildings in Thermal Networks
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Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

2. Summary

The content of the report serves as guidelines for design decision-makers on how to use available information to perform Life cycle assessment (LCA) of buildings during their design process. The building designers and person involved into the planning process are systematically guided through the design steps focusing on the following questions:

– How can the goal and scope of the LCA be linked with the design steps?
– How can the LCA inventory and the data involved in the LCA be organized?
– Which tools can be used?
– Which workflows can be used?
– How can design-related uncertainties be reduced in the workflow?
– How can LCA results be visualized, interpreted and communicated?

These guidelines summarize selected the results and recommendations of several background reports of tasks performed within the IEA-EBC project Annex 72 dealing with the “Assessing Life Cycle Related Environmental Impacts Caused by Buildings”. The overall goal of the project is the harmonization of the methodology and solvation of issues which arise when applying LCA approaches on buildings.

The objectives of the project are:

– To establish a common methodology guideline to assess the life cycle based primary energy demand, greenhouse gas emissions and environmental impacts caused by buildings;
– To establish methods for the development of specific environmental benchmarks for different types of buildings;
– To derive regionally differentiated guidelines and tools for building design and planning such as BIM for architects and planners;
– To establish a number of case studies, focused to allow for answering some of the research issues and for deriving empirical benchmarks;
– To develop national or regional databases with regionally differentiated life cycle assessment data tailored to the construction sector; share experiences with the setup and update of such databases.

Introduction

Life cycle assessment is a complex methodology that requires a lot of input and decisions from the stakeholders involved into the building design process. The decisions have a great impact on the environmental impacts and therefore it is important that they are made at the correct point in the design process. In order to facilitate the decision-making process and to support the design decision-makers, the following report focuses on guiding the design decision makers through the design steps, starting from the early design steps. For each design step, precise instructions are given regarding which tasks and decisions should be made. This ensures that the design follows the overall goal of sustainability. The process may be used for designing new buildings and also for refurbishments since the design process remains very similar.

Objectives and contents of the report

The purpose of this report is to provide support to the design decisions-makers during the design process. For each of the defined design step decision the important topics to consider were identified, the key stakeholders are declared and the purpose of LCA at the selected design step is defined.

The report covers:

– The definition of the design steps, the definition of the tasks in each design step and an overview of the relevant milestones for performing LCA;
– An overview of the systematic building decomposition methods and the appropriate levels at each design step;
– An overview of the tools that can be used for LCA and a selection process for choosing the right LCA tool. A special emphasize is given to the topic of Building Information Modelling (BIM), how the BIM tools can facilitate the LCA assessment and what information should be implemented in the BIM model;
– Strategies on how to reduce the design-related uncertainties;
– An overview of the visualization of the LCA results and which are appropriate in the selected design steps.

The content of the report is resonated in the Design decision table, which offers the overview of all important aspects that are addressed in the report and the supplementary background reports (on which this report builds upon). In this guidelines report, essential results of the Subtask 2 (ST2) of IEA EBC Annex 72 "Assessing life cycle related environmental impacts caused by buildings" are summarized and specific recommendations are presented, accompanied also by supporting information (in which detailed information on basic knowledge and background information are available).

This report and the Design decision table are targeted specifically to design professionals and consultants with the aim of informing them on the subject of assessing life cycle environmental impacts caused by buildings. The goal is to support the integration of life cycle assessment into the design process of new and existing buildings by providing access to the necessary information sources and tools.

Key messages

The following key messages are addressed to the design decision-makers:

1. Encourage the clarification and alignment of national definitions of the design steps and milestones towards the design step definition.
2. Ensure that the necessary input information is provided at each design step to be able to perform the related tasks.
3. Promote in your national country the use of environmental targets along the design process.
4. Use a classification system based on hierarchical grouping principles, to identify the main systems and elements and track materials through the elements and building system that they belong to.
5. Use at the early design steps the IFC building element classification scheme, in case the national systematic building decomposition does not reach the element level.
6. Align structures for systematic building decomposition with environmental, economic, etc. datasets and databases.
7. Promote the development of packages or add-ins or encourage the integration of systematic building decomposition (SBD) in the default configuration of the BIM software.
8. Two approaches are recommended to deal with uncertainties:
   – Approach 1: Optimization strategy: Identify the 5 to 10 key parameters in the building in the early design steps, which allow to remove 80% of the uncertainty, by performing a sensitivity analysis.

   – Approach 2: Project development strategy: Use different data aggregation levels depending on the design steps which are following their logical development: from aggregated data (elements) to disaggregated data (materials).

9. Use LCA tools along all the design steps.
10. Refer to the developed selection process to identify the most appropriate tool for each design step.
11. Encourage interoperability among tools.
12. Collaborate towards the development of a unique model with lifecycle information.
13. Use adequate visualization types from less to more detailed following the selection matrix (different goals and amounts of information).
14. Combine different visualizations in dashboards to be able to display different types of information and support decision making.

3. Building assessment workflows and tools in the design process

3.1 The relevance of the LCA in the design process

The mitigation of the environmental impact of buildings is one of the most important, but at the same time most challenging tasks in the future. To support the reduction of the environmental impacts, specific methodologies and tools have to be used. The most often used is life cycle assessment, which is a systematic methodology that allows for an analysis of the environmental loads related to the material and energy use in buildings over their entire life cycle. It can be integrated into the design process from the very beginning, and evolve along with the project in order to optimize the environmental performance of the design. The need for the integration of the LCA along the entire design stage was already clarified in the Annex 57.

During the building design process, the information about the building are getting more precise. In the early design steps, the available information concerning the building is incomplete but the possibility to influence the environmental impacts and costs that will occur during the building life cycle is at its highest (see Figure 1). In this vein, implementing change in the early design steps will be less costly than at the latest, more detailed design steps. In other words, the sooner we can estimate and implement measures to reduce the environmental impacts, the more effective and the cheaper it will be. There is, therefore, an incredible potential for integrating environmental assessments in the design process, as early as possible.

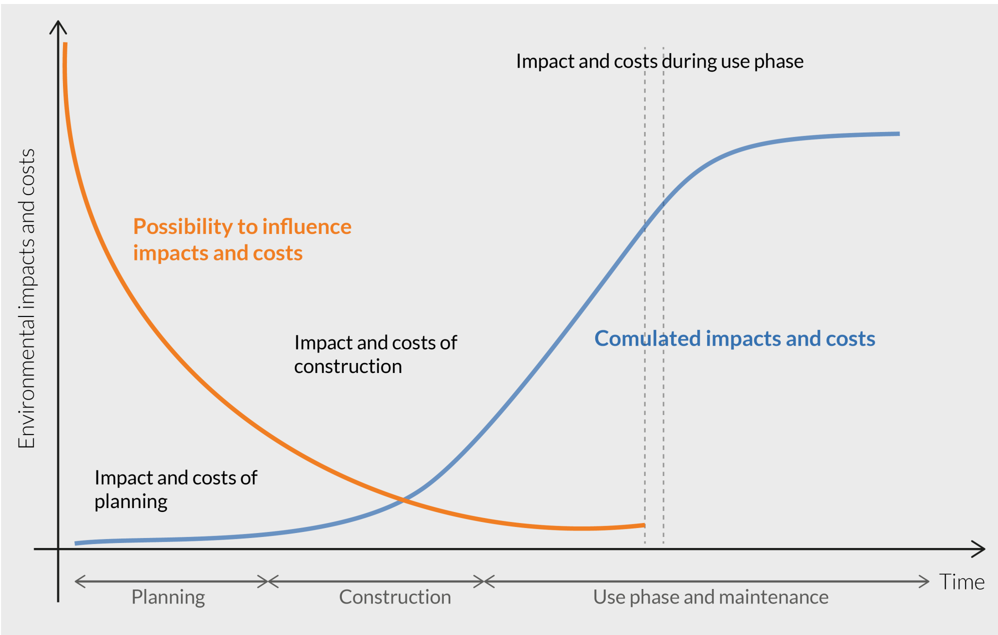

Figure 1: The possibility to influence the environmental impacts and costs during the design process (adapted acc. Kohler and Moffat, 2003)

However, performing an environmental assessment during the design process can be demanding and inaccurate, mostly because of the uncertainties and incomplete information about the building. The integration LCA in the design process is also difficult because of involvement of different stakeholders, such as for designers, BIM specialists, contractors, etc. Other issues which are pointed out are the lack of needed input information, tools suitable for the selected design step and transparent methods to conduct LCA during the design process.

3.2 The practical integration of LCA into the design process

The design process is typically paced by different design steps, in which LCA can be integrated to various extents. In the early design phase, the first steps are the **strategic definition** of the project and the **preliminary studies**, that have to be made in order to get to the **concept design**. In the detailed design phase, the next step is the **developed design**, which is followed by a precise **technical design** step where all the detail technical solutions are developed and the documentation for the procurement is prepared. This documentation is the basis for the next design step, which is the **manufacturing and the construction.** After **the handout and the close up,** the design process is complete and the further steps are connected to the management of the project: the **operation and management** step. Throughout this step, it is important that the performance of the building is evaluated and improved. At the end of life of the building, the final step is the **end of use and recycling.**

Figure 2: Design steps

During the early steps of the design, only limited data is available and a lot of important information for the LCA study are still undefined. The details of the project, and consequently also the information needed for the LCA study, are continuously improving and therefore the LCA should also evolve during the design process. The outcomes of the LCA should be used to optimize the design during the process and should support the designers to make environmentally sound decisions.

During first design steps, LCA can be used to optimize the volume and the shape of the building, as well as the building systems, while in the later steps the LCA can be used to compare different products and further optimize the design. At the beginning of the design, the uncertainties of the result are still high, but it is important to know which decisions have a big influence on the final results. These influential parameters then have to be considered more carefully than the ones which hardly influence the environmental impacts of the building.

Consequently, also the workflows and the tools used to perform the LCA should be accustomed to follow the evolution of the design. Since there are many possibilities and tools which allow to perform an LCA, choosing the most adequate one has become a challenging task for the designers and other stakeholders involved into the design process.

To enable a full integration of the LCA in the design process it is important to know what decision are important to know which options exist at the certain design stage and which are important at the selected point in the design process. Since the designers typically lack the needed background knowledge, it is important to guide them through this process to facilitate their work and to achieve the possible decisions in terms of the environmental emission mitigation.

This report aims to provide a set of guidelines which support the LCA application in the design process, from an international perspective. It includes the most relevant aspects to be considered, the necessary information to conduct an LCA and the key stakeholders during the design process, as well as the related recommendations for a successful integration. With this is should support the reduction of the environmental impacts along the building design process.

Some of the main questions which are answered in this document are:
- How can the goal and scope of the LCA be linked with the design steps?
- How can the LCA inventory and the data involved in the LCA be organized?
- Which tools can be used?
- Which workflows can be used?
- How can design-related uncertainties be reduced in the workflow?
- How can LCA results be visualized, interpreted and communicated?

3.3 To whom are these guidelines focused?

The current environmental crisis is setting expectation in terms of environmental performance which are higher than ever. This increased level of complexity consequently calls for a growing number of skilled stakeholders which are involved in the design process. Due to the complexity of the design process and the additional tasks that are needed to evaluate and optimize the environmental performance of buildings, the stakeholders are facing several challenges. Additionally, each design steps have unique requirements that have to be clarified by the stakeholders. The vast amount decisions and information required from the collaborators involved into the design process may be very challenging if the process in not structured or guided.

Different stakeholders are involved in the design process and each of them has its specific interests. In the guidelines we are differentiating between:

- Clients/Financer/Building owner/Tenant/User: the initiators of the project who should be informed about the environmental impacts of their project, and which consequences the environmental performance can have on other areas (potentially higher expenses, additional taxes, pay-off times for the improvements).

- Designers/Building designers: the designers of the projects, who should be aware how their decisions influence the environmental impacts and act as the link between the client and the other stakeholders. They should be well informed since their decisions and their task to inform stakeholders can have a big impact on the overall environmental performance of the building, especially if no sustainability assessment and certification experts are not involved into the design process. The group of design professionals includes engineering offices, architects, designers and planners, design companies, etc.

- Sustainability assessment and certification experts/Consultants/Auditors: the experts which are involved into the design process to improve the environmental performance of the building. They should have a complete overview how certain decisions influence the environmental performance and the certification results.

- BIM Managers: the experts for the building information modelling, which should be informed or have knowledge about which information should be included in the model to enable the assessment of the environmental impacts. They should know how to create the model in order to enable the interconnection with other tools (LCA, energy demand calculation, etc.).

- Contractors/Service providers: the professionals hired for the realization of the project who should be aware how different construction techniques, material choices, etc. influence the environmental impacts.

- Project commissioners/Authority/Policy makers: the representatives of the authorities, who are responsible that the regulations are followed and who should be aware how important it is that the regulation is aligned with the sustainability goals.

During the evolution of the project, different stakeholders are involved, depending on the design steps. The involvement of different experts is also depending on the size and the complexity of the project, which means that the composition of the different stakeholders is not fixed. It may also be the case that one person has several roles in the same project. However, it is crucial, that the sustainability aspects are followed starting from the early design steps, where the stakeholders have the biggest potential to improve the performance of the building. The client and the designer should have a clear vision on how to archive the desired environmental performance of the building, and this vision should be shared with all the stakeholders that get involved in the design process in the later design steps.

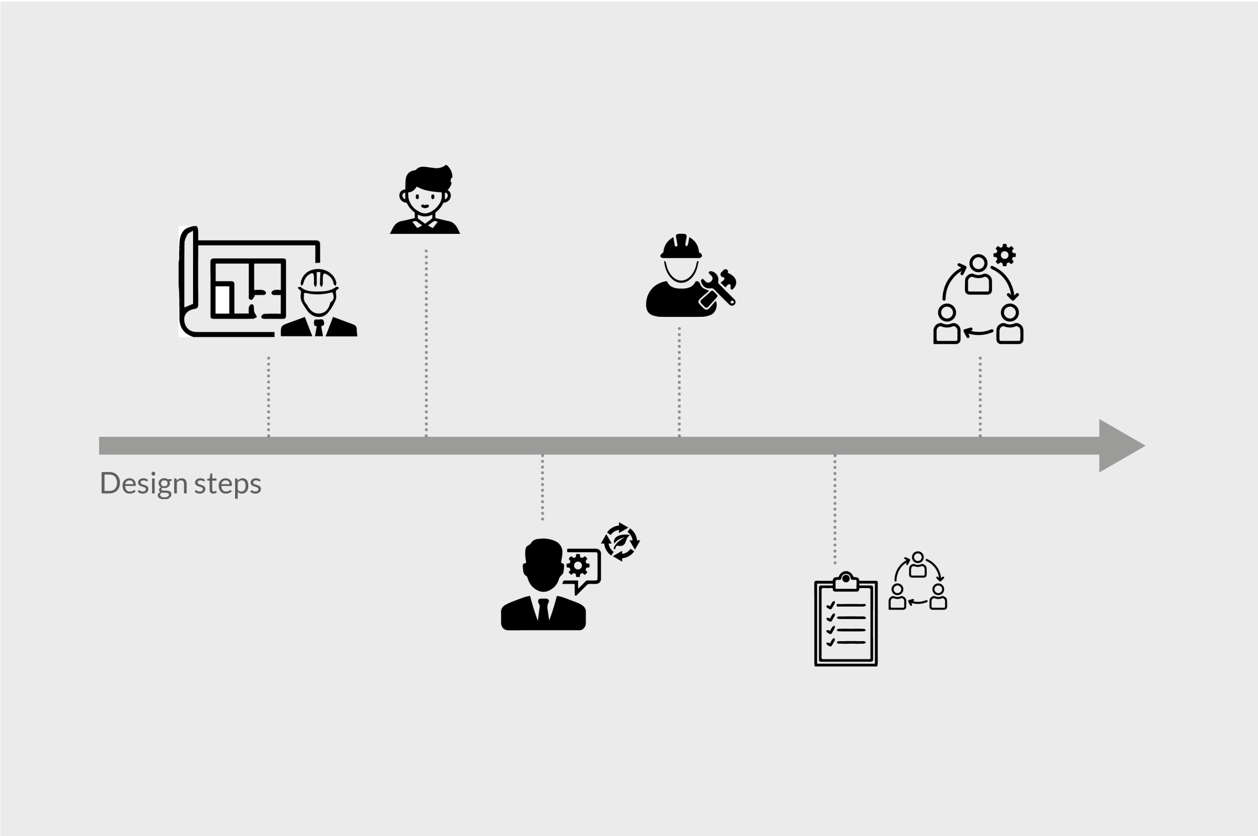

Figure 3: Correlation of the content of these guidelines to the different stakeholders and the design stages

3.4 Organization of the document

These guidelines are organized in different chapters according to the following key questions, which are intended to solve a key topic for the individual design steps defined in 4.1. The questions and are related to the typical LCA stages (see figure 4).

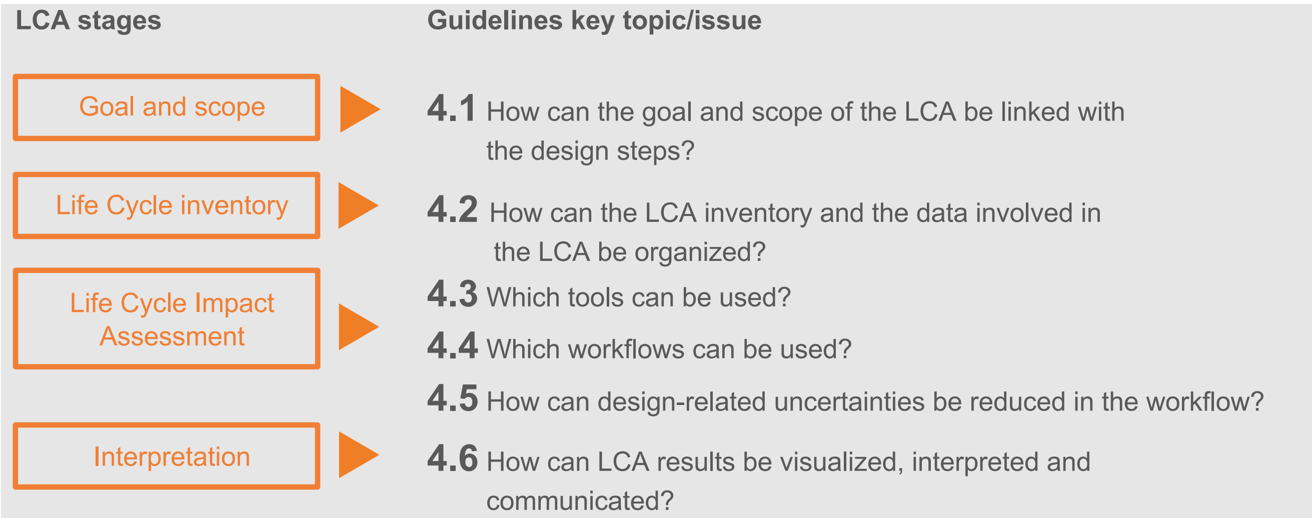

Figure 4: The content of the guidelines

The contents of this report are organized according to the following parts:

– **Part 4.1: How can the goal and scope of the LCA be linked with the design steps?**
  This part is focused on presenting the relevance of establishing a common definition of the design steps when conducting LCA. It contains a proposition for a common definition.

– **Part 4.2: How can the LCA inventory and the data involved in the LCA be organized?**
  This part is focused on presenting the relevance of using a systematic building decomposition to conduct an LCA. It provides recommendations to decide which standard to use.

– **Part 4.3: Which tools can be used?**
  This part presents the existing tools which can be used to conduct LCA during the building design process. It provides a decision-framework to help choose the most suited tool.

– **Part 4.4: Which workflows can be used?**
  This part presents the existing workflows which can be used to conduct LCA during the building design process.

– **Part 4.5: How can design-related uncertainties be reduced in the workflow?**
  This part presents the existing uncertainties during the design process and provides recommendations on how to reduce them.

– **Part 4.6: How can LCA results be visualized, interpreted and communicated?**
  This part presents the visualization possibilities of the LCA results. It includes a decision matrix for choosing the adequate visualization type for the desired purpose.

– **Part 5: Conclusions and final recommendations.**
  This part includes the final conclusions and a matrix summary table for decisions which should help implementing these guidelines in practice.

4. Guidelines and recommendations

4.1 How can the goal and scope of the LCA be linked with the design steps?

The goal and scope definition are the first and crucial step of (building) LCA studies. It is especially relevant, as it determines the context of the analysis, the range of application of the assessment, its interest or purpose, the target group, a clear definition of the system under study and the type of methodology which will be used in the modelling (Klöpffer & Grahl, 2014). In other words, **the goal and scope definition strongly influence the choices and the methods which are necessary in the other stages of the LCA study**. It also determines the limits of the system and the level of detail of the object of study. During the design process, the definition of the building gradually increases and changes.

Thus, it is important to provide a clear and transparent definition of the main design steps of the design process, but also the "milestones", that can be seen as points of the design process which are important or influential for the environmental performance assessment. Such a definition of design steps and milestones enables the assignment of related tasks, the identification of the moment when the LCA can be implemented, which information can be defined, which tools can be used, which information can vary, which are the related uncertainties and which are the deliverables from the perspective of specific professionals.

The starting point of such considerations is the choice of a perspective and system boundaries. When considering the full life cycle of a building from a project-management perspective, then the post-design life cycle stages such as the use phase (building operation, maintenance and replacement), building retrofit or refurbishment, as well as the decommissioning at the end of the service life, have to be addressed. If, on the other hand, the focus is put exclusively on the design and construction process, e.g., from the perspective of architects and engineers as well as construction companies, it may suffice to address exclusively the design steps. The perspective chosen here is a combination of both approaches. It should allow addressing the initial design process as well as design interventions embedded along the life cycle of a building, such as, re-design or extension, refurbishment and, as well as – eventually – the design and management for a controlled decommissioning process towards re-use and recycling.

Error! Reference source not found.5 presents the phase model of a project management process parallel to the physical life cycle of a building, including the design process. It becomes clear that the development of the design task (project identification/clients brief), the building design, and its realization (i.e., construction, use phase) are part of one overall process.

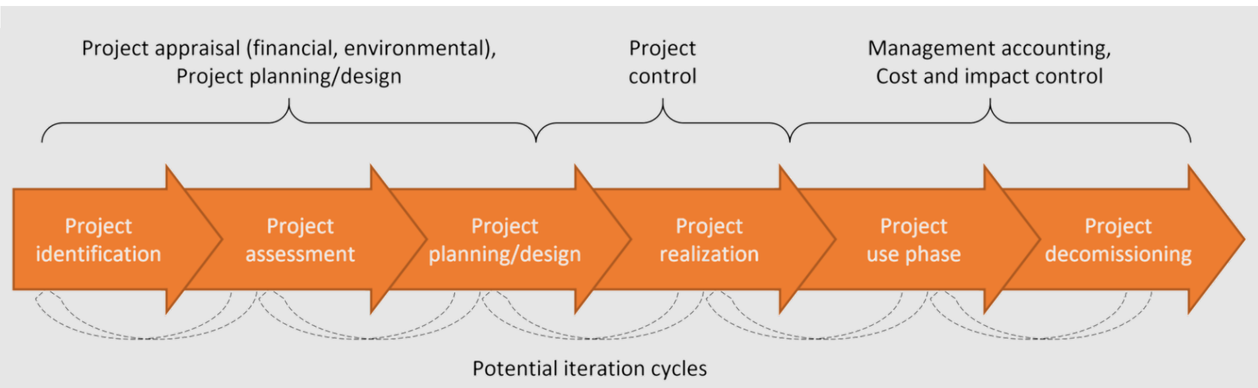

Figure 5: Project planning and management process

4.1.1 What would a common definition of the design steps look like?

The definition of design steps and milestones, as well as related tasks and deliverables, may differ across building design and construction projects as they are subject to agreement amongst the project partners.

Using a spreadsheet-based survey, the design and project step definitions were compiled for 13 countries. Respondents from participating countries were asked to provide the definitions in their respective country, including a detailed description of the tasks and deliverables. Furthermore, participants reported on the presence and timing of relevant milestones, which provide a potential for the implementation of environmental target setting, environmental performance assessment and reporting of environmental performance assessment results. The results of the survey are provided in graphical form in Appendix 1.

The responses from different participants were reviewed in comparison with the well-established building design phase definition of the Royal Institute of British Architects (RIBA). The RIBA Plan of Work (RIBA, 2020) was considered well suited for the purpose of providing a generic definition of the design steps, core objectives and related tasks.

It should be highlighted, as previously mentioned, that the various decisions which are relevant for improving the performance of buildings across their life cycle are not limited to design steps. They include other relevant stages of the building life cycle, such as the construction stage, the use phase – including maintenance and interventions, such as modernizations and refurbishments – as well as, eventually, the decommissioning of the building for recycling and end-of life treatment.

The proposed common definition of the design steps in buildings is presented in Figure 4. The core objectives of each design step are also described, to provide more information about the related tasks. The Levels of Developments (LOD), which would fit the design steps, are also added. The LODs are typically used to qualify the level of details of the BIM models. **The common definition of the design steps, as well as the related core tasks, should serve as a reference for the structure of this report. I**t provides a framework for discussing the available information and appropriate assessment tools and workflows, and how these affect the inherent uncertainty of conducting environmental performance assessments in specific design steps).

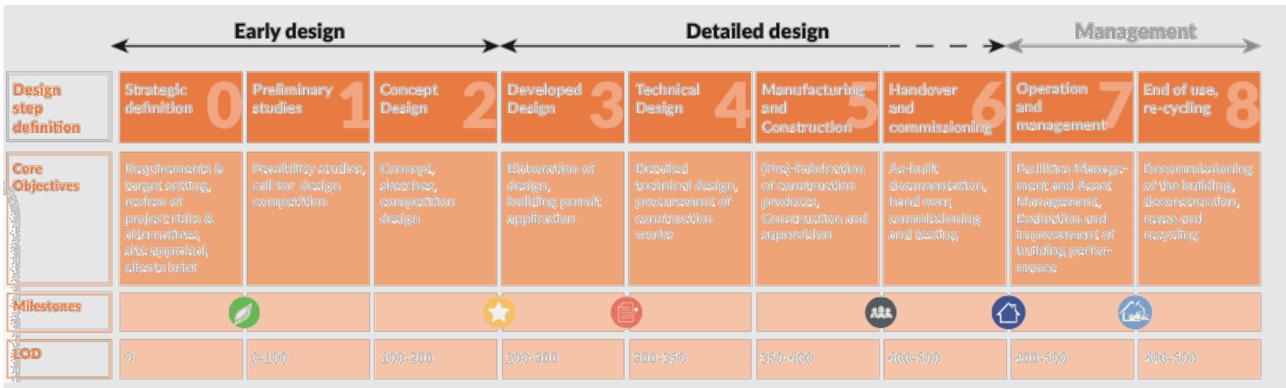

Figure 6: Definition of the design steps for buildings (based on the survey in 13 countries).

Additionally, in order to implement environmental target setting, assessment and reporting (e.g., energy performance, carbon performance) along building design and project phases in the future, a set of milestones and related tasks are proposed in Table 1.

Table 1: Milestones and related tasks for implementing environmental performance assessment into the design-, decision making-, and facility management process.

Milestone	Description of proposed tasks
Environmental performance target definition	Initial definition of the design task, related environmental performance targets by the client, as well as identification of related environmental requirements by laws and standards
Architectural design competition	Definition of environmental targets (e.g., carbon budgets) as part of the call for design proposal Requirement for design competition entries to provide an assessment of environmental impacts (screening assessment) Sustainability assessment “new construction vs. refurbishment”
Building permit application	Environmental assessment (pre check) based on a defined energy and material concept (type of structure, estimation of main construction material quantities and energy consumption for building operation) - based on a design for environment and design for deconstruction approach Evaluation of environmental target fulfilment through public authorities as part of the building permit application process
Procurement of construction works	Tender to include environmental requirements for construction products and building systems in-line with the specified environmental targets
Hand over and commissioning	Commissioning / bringing into service, monitoring and refinement of the building’s environmental performance in use
Decommissioning and deconstruction	Pre-deconstruction audit, plan for deconstruction Decommissioning and deconstruction of the building towards re-use and recycling as well as end-of-lie treatment in-line with life cycle scenarios underlying previous environmental assessments

For the designer it is important that in each step they make the right choices. Therefore, in the Design decision table the important tasks of each deign step are defined (see Figure 7).

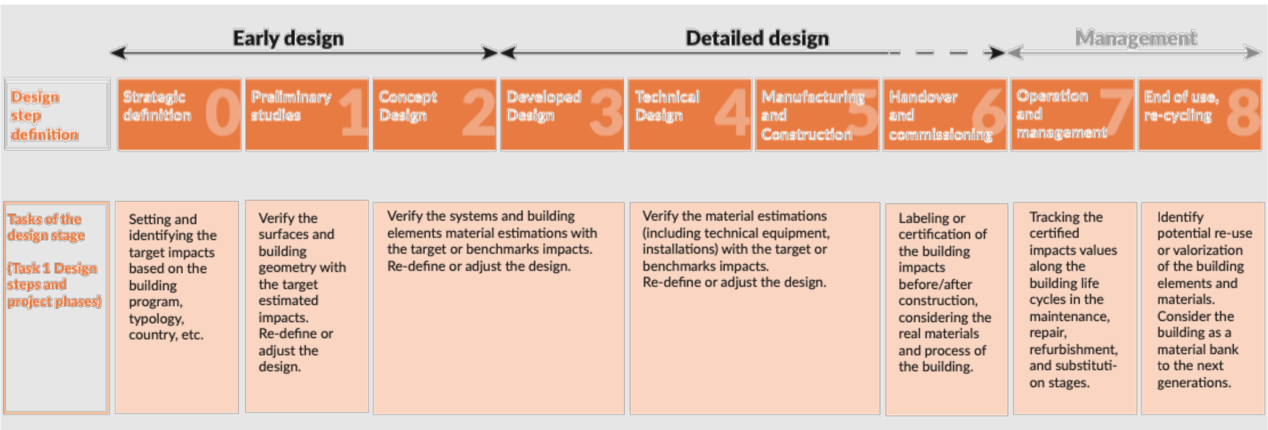

Figure 7: Tasks of the design steps

The presented generic terms and definitions offer a common understanding of the relevant steps, milestones and tasks for fostering implementation of environmental assessment along the building design process and project phases in the participating Annex countries. More information about the study can be found in the related background report.

What can be expected in the background report?

1. Overview and analysis of the design steps and milestones of different countries.
2. A proposal for **a generic definition of design steps** and milestones as a common reference for IEA EBC Annex 72 and beyond.
3. National reports from Annex countries with further details on their definition and implementation of LCA along the design process.

What are the main recommendations/guidelines?

1. Encourage the clarification and alignment of national definitions of the design steps and milestones towards the common model.
2. Ensure that the necessary input information is provided at each design step to be able to perform the related tasks.
3. Promote in your national country the use of environmental targets along the design process, with special attention to the five identified milestones.

4.2 How can the LCA inventory and the data involved in the LCA be organized?

The Life Cycle Inventory (LCI) is one of the most relevant phases in the application of LCA to buildings (EN, 2011). It involves the collection of a large amount of data and comprises, among others, the specification of the physical parts of the building that are included in the assessment. To that end, finding a logical, systematic, clear, transparent, and replicable data structure becomes relevant. This data structure should support the classification of the building parts (such as the structure, the façade, etc.), and the decomposition of the building into different parts, according to different levels of decomposition, such as the group of elements (systems), elements, components, products, materials, typologies and manufacturers (see Figure 8) (Hoxha, 2015), which are crucial for conducting the LCA at different design steps.

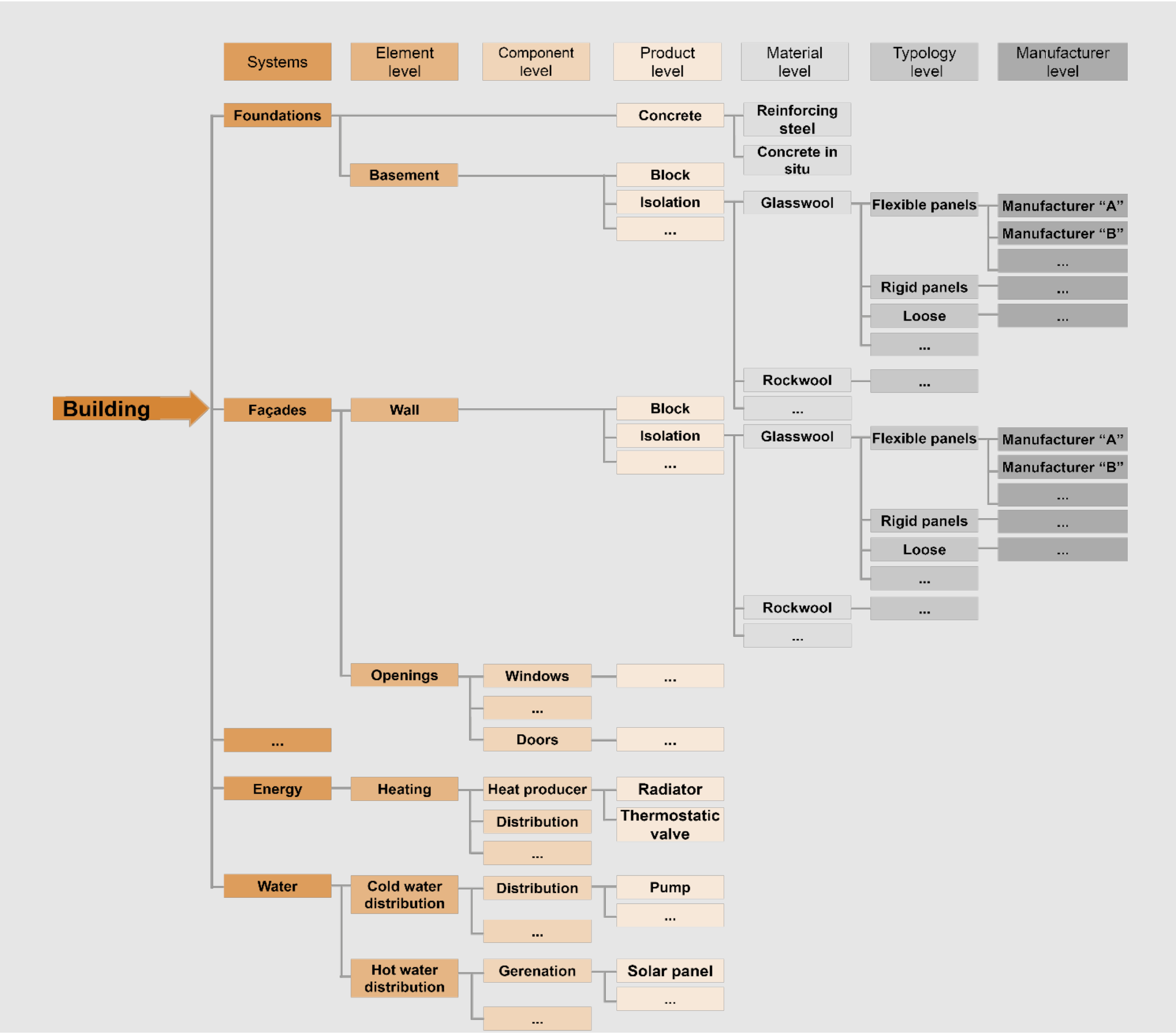

Figure 8: Example of the building decomposition for the building description when conducting LCA. (Source based on: Hoxha, 2015)

4.2.1 Why and how should a systematic building decomposition of the Life Cycle Inventory (LCI) be conducted?

The use of a systematic structure to decompose the building is recommended, especially to reduce efforts in data collection and organization processes (Cheng & Tong, 2017), but also, to help develop a transparent and replicable data and information structure about the building. It allows for the division or decomposition of the building into a number of 'systems', 'elements', components products, materials, typologies, and fabricants (e.g., systems, parts, elements, components, materials or specific manufacturers) and should be performed following specific criteria or structure (Cheng & Tong, 2017; Soust-Verdaguer et al., 2020).

Hence, following a systematic decomposition in a comprehensible and standardized way can improve, among others, **the completeness of the LCI**. Moreover, with regard to the communication of the results, it also improves **the understanding of hot spots for environmental impacts**, when presented at various levels (per life cycle stage, per material, per element, etc.). It means that it can help the designer identify the greatest and lowest contributors to the environmental impacts and decide which strategy can be used to reduce them. To that end, the use of a systematic approach that includes **different levels of hierarchy** (e.g., building, element, material) is recommended (see Figure 9). It can support the assessment at various steps of the building design, e.g., using information about the elements at the beginning of the construction and the level of the material at a later design step. It also supports the consideration of uncertainties occurring at different hierarchical levels and at different steps of the construction. Thus, the process of re-evaluating the assessed components can be facilitated (Shipra Singh Ahluwalia, 2008). Additionally, one of the advantages of using a classification system when conducting LCA is to support results comparability within one country, as well as studies across different countries.

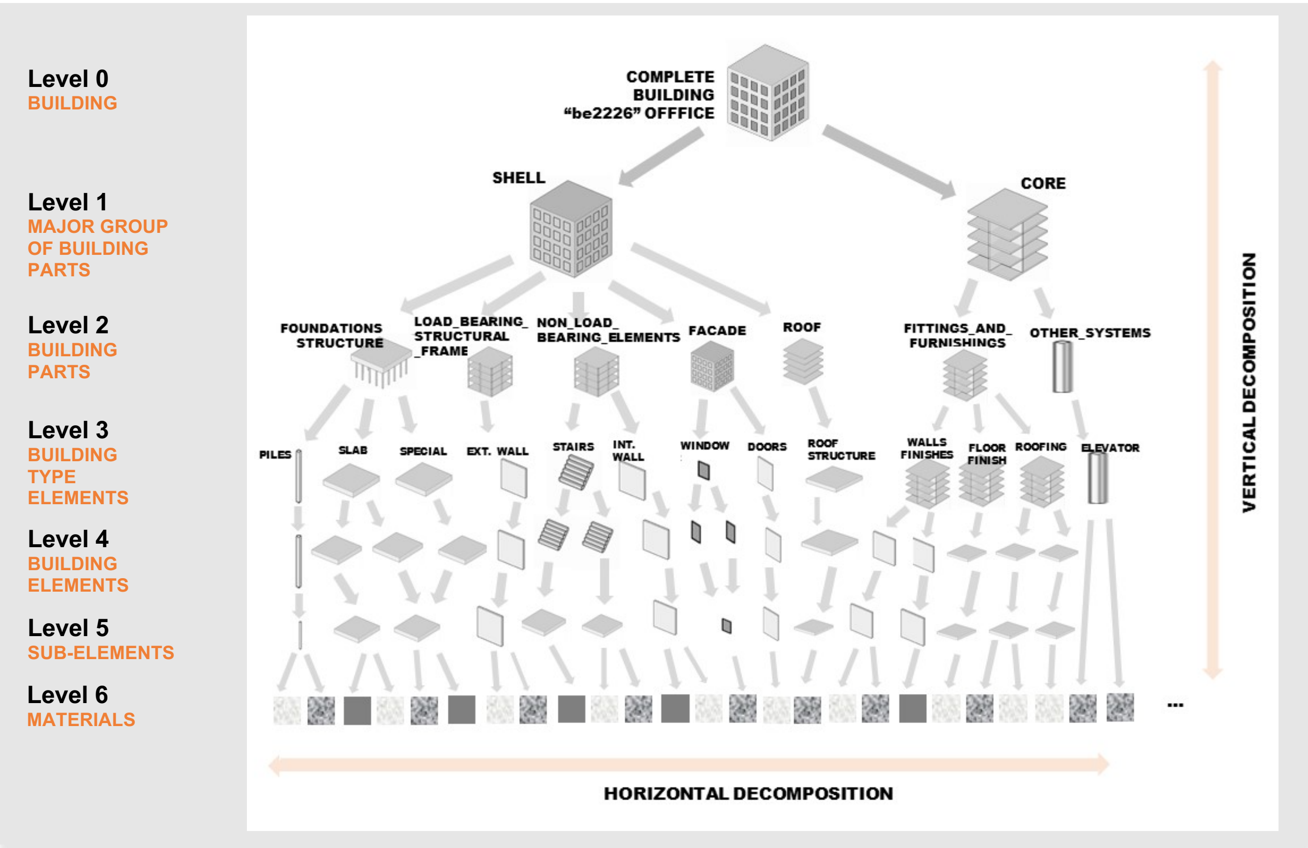

Figure 9: Scheme of the systematic building decomposition of the be2226 reference building following the Austrian ÖNORM B 1801-1 (ÖNORM, 2015). (Source: based on (Soust-Verdaguer et al., 2020) and prepared by authors based on the Austrian standard Austrian ÖNORM B 1801-1 (ÖNORM, 2015)).

The **ISO 12006-2 Building Construction Organization of Information about Construction Works, Part 2: The Classification Framework for Classification** is a global framework for the development of built-environment classification systems and building decomposition (ISO, 2012). This standard is a general framework on which most of the national standards and guidelines for systematic building decomposition data structures used in different countries are based. In the context of the IEA EBC Annex 72 (IEA EBC, 2017), a compilation of different national classification systems applied in different countries to the decomposition of buildings has been carried out (Soust-Verdaguer et al., 2020). The IEA EBC Annex 72 ST2.2 background report presents an overall description of the standards and guidelines used for the systematic decomposition of buildings mainly used in the Annex countries participants, as well as on comparing their main aspects and illustrating the relevance of its consideration when conducting building LCA.

4.2.2 Which standards should be used for a systematic building decomposition?

The standard should help systematize classification and identify the main systems, elements, materials, and products that make up the building. Therefore, it is recommended to follow the standards and guidelines commonly used in the country where the building is designed and constructed. It is also recommended to use the standard which is aligned with existing national databases for environmental data, cost estimations or BIM workflow, to facilitate the integration of LCA calculation into the design process without extra efforts. Moreover, the use of a systematic structure aligned with national standards and classification systems and adapted to the BIM workflow, allows one to obtain a building decomposition followed by the hierarchical structure of the building model (such as the main systems, elements, materials and products). The background report includes a comprehensive list of standards used in different countries.

Table 2: National classification and guidelines for the use of building decomposition to organize LCA information in the Annex countries, including Austria, Belgium, Czech Republic, France, Germany, Netherlands, New Zealand, Spain, Switzerland, and the UK. (Source: Prepared by the authors on the basis of (Afsari & Eastman, 2016) and on national regulation in classification systems).

Country	Standard or guideline based on
Austria	ÖNORM B1801 (ÖNORM, 2015)
Belgium	BB/SfB plus (De Troyer, 2008)
Brazil	ABNT NBR 15575 (NBR 15575-1: Edificações Habitacionais — Desempenho Parte 1: Requisitos Gerais, 2013)
Canada	UNIFORMAT II Elemental Classification (E1557-97) (Charette & Marshall, 1999)
Czech Republic	Not specified – ad-hoc table
France	EQUER model (Polster et al., 1996)
Germany	DIN 276 (DIN, 2008) DIN 18960 (Fröhlich & Fröhlich, 2010)
The Netherlands	NL/SfB
New Zealand	Uniclass 2015 (CPIc, 2015)
Spain	CTE (CTE, 2006) (Spanish Building Technical Code) and BBCA (Andalusian Government, 2017)
Switzerland	SN 506 511 (CRB, 2009)
UK	SFCA (RICS & BCIS, 2012)

4.2.3 How can a systematic building decomposition be integrated in digital tools such as BIM?

In BIM, multiple levels of object definition are needed during the building design steps. At the early design steps, generic objects are used to compose the model. In the detailed design steps, the amount of information about the objects increases, but the object (e.g., a door) will still be the object; changes in the granularity and precision of the object information are detected (International Construction Information Society, 2017).

Taking into account the integration of BIM and LCA in the design steps, two milestones are identified to carry out the LCA: **the early design phase and the detail stage.**

At the early design stage:
– General level of detail (LOD) up to 200.
– Element definition (lower modelling precision, use of generic objects).

At the detail design stage:
– General LOD higher than 300.
– Product/material definition (higher element modelling precision and product/material definition).

In addition to during the modelling process in BIM, in building decomposition, the granularity of the data increases. This means that generally the higher the number of vertical levels, the greater the number of building elements, building sub-elements, products, and materials are identified. However, modelling tools do not always allow for the management of objects/materials/components/products at the same level of decomposition as structures for building decomposition (International Construction Information Society, 2017).

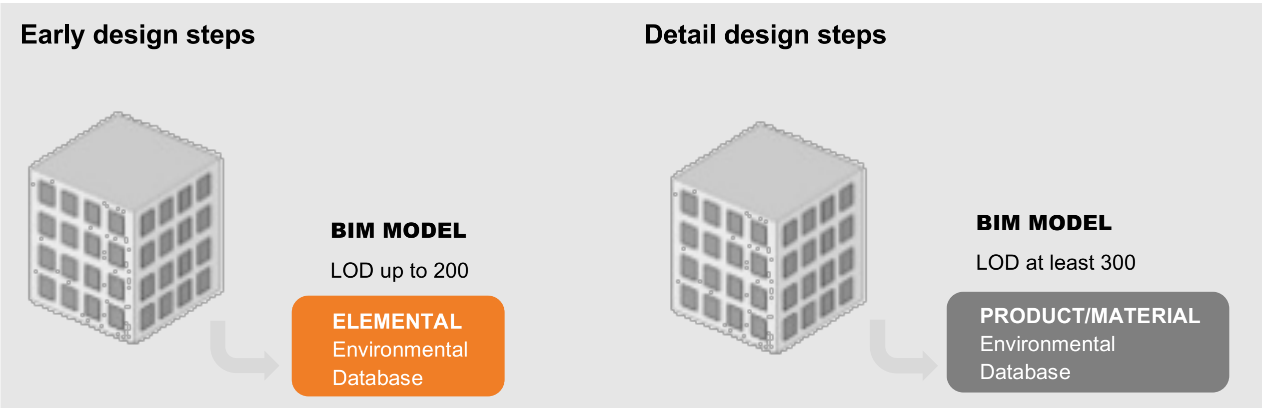

Figure 10: Correlation between the BIM model definition, the design stages, and the environmental databases and environmental information about the building.

A possible path to deal with the information about the building at different design steps is to conduct a systematic building decomposition at different scales. This implies that, to perform a consistent LCA, the granularity of the environmental data should be aligned with the building levels of decomposition: at the early steps of design, the environmental data should be expressed at an element (or component) level, and at the detail steps of design, the data should be expressed at a material level (see Figure 11). In other words, element decomposition should be conducted in the early steps of the design and material decomposition in the detail stages (Soust-Verdaguer et al., 2021). The element level (at early design steps) should include a general classification of the building elements regarding the building main functions. To that end in BIM, this building decomposition at the element level can be organized following a standardized structure such as the IFC (buildingSMART, 2020), and considering its element classification (IfcElement classes), especially including the physical parts of the building (IfcBuildingElement class) (Soust-Verdaguer et al., 2021).

For the designer it is mostly important that they are aware which aggregation on data to use at a certain stage in the project. Therefore, in the Desig decision table there is a proposal for the aggregation of the data at the selected design step (see fig 11).

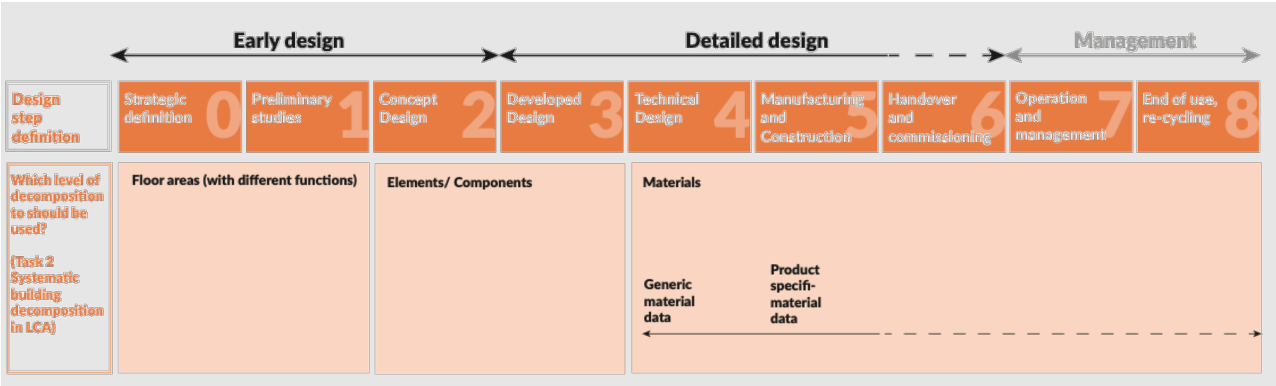

Figure 11: Level of decomposition of the building during the design process

At detailed design steps, the number of building elements can be higher than at the early steps because other secondary elements (e.g. sealing and joining elements) are integrated in the model and LCI. Hence, at the sub-element and material level, the decomposition can include (at least) the main sub-elements and materials that are composing the elements (a consequence of the element classification). More information can be found in the related background report.

What can be expected in the background report Task 2 Systematic Building Decomposition (SBD) to implement LCA?

1. Overview of the existing ISO standards, main concepts and background information regarding SBD.
2. Analysis of the use of standards and guidelines for SBD within the Annex participant countries and application to a case study.
3. Overview of the implementation of SBD in BIM.

What are the main recommendations/guidelines?

1. Use a classification system **based on hierarchical grouping principles,** to identify the main systems and elements and track materials through the elements and building system that they belong.
2. Use at the early design steps the IFC building element classification scheme, in case the national systematic building decomposition does not reach the element level.
3. Align structures for systematic building decomposition with environmental, economic, etc. datasets and databases.
4. Promote the development of packages or add-ins or encourage the integration of SBD in the default configuration of the BIM software.

4.3 Which tools can be used?

Nowadays, design professionals and consultants are not required to aggregate data and perform LCAs manually. There are many web-based and software tools that can be used at different steps of the design process to assist them in this task.

4.3.1 Which types of tools are available?

A diverse range of tools is available:

- Interactive databases or web-based element catalogues:
  They usually contain a database and a simple calculation web-based tool (no software installation is required). For example, 1 m² of a specific element can be calculated just by inputting the thickness of each layer. Different material choices for layers are provided. With very little effort and time, different solutions can be compared with each other. However, note that the background information (data quality) needs to be transparent. Examples of such tools are Bauteilkatalog developed by SIA (Swiss Society of Engineers and Architects) and LEGEP, a tool for integrated LCA developed by Ascona.

- LCA-based design tools
  They measure the environmental performance of products using LCA data and usually allow users to create and model their own custom assemblies and configurations. Note that in many cases they are tied to specific dataset(s) and/or calculation methodologies. The examples of such tools are Gabi, Simapro. Umberto, etc.

- Building information modelling (BIM)
  The software-based BIM organizes and relates physical or financial information to the building. For example, CAD developer like Autodesk included BIM in the software product Revit. LCA data are mass related so BIM software's can also easily include LCA information. The level of support from IFC4 language (Industry Foundation Classes) for different indicators was investigated by the European project SuPerBuildings, where it was found that especially the indicators "consumption of primary energy non-renewable" and "global warming potential" are directly and explicitly supported by the IFC. Although the concept sounds simple, the implementation of LCA data in BIM is not common yet. Lots of new applications are expected to be developed towards this direction over the next years (e.g. plug-in software's that be used for adding embodied impacts data to a 3D model to carry out calculations).

  Note that the selection of calculation tool is less important than the choice of data, standard or methodology, as the latter are more likely to cause variations and lead to inconsistent results. A quick overview of the tools that are currently available can be found in IEA Annex 31.

4.3.2 Which are the existing building LCA tools?

In order to work with a common language, building LCA tools are here distinguished from LCA databases. Building LCA databases represent the foundation for the evaluation of products' environmental impacts. However, they collect lifecycle information and document it, by not allowing an active lifecycle modelling of complex processes and materials. Therefore, they are named **passive aids**.

The actual lifecycle modelling and environmental impact assessment happens in an LCA calculation tool. LCA calculation tools are thus defined as **active tools**, in which users provides entries and derive LCA results as an output. Active tools can be distinguished in 2 main types:

- Pure calculation tools.

– Complex planning tools.

While pure calculation tools aim to provide LCA results in a retrospective way, by not following the whole design process, complex planning tools are specific for the planning process and can be integrated into it. Complex planning tools can be aimed also for a pure calculation. All active tools can be also connected or not to benchmarks and assessments (see Figure 12).

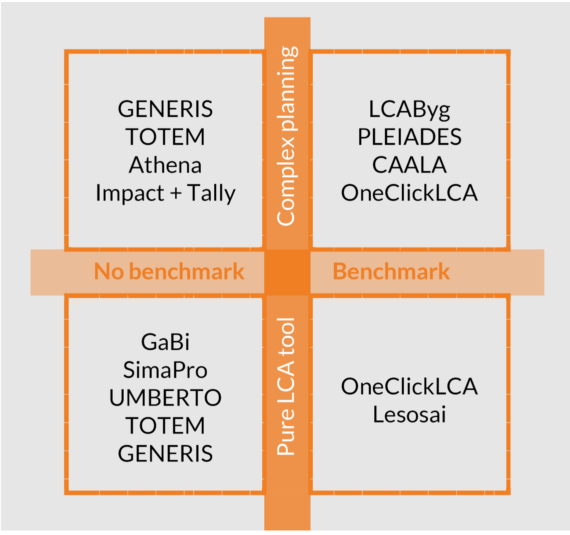

Figure 12: Active tools typology based on survey: examples of “complex planning” and “Pure LCA” tools. Tool provided and not provided with environmental benchmarks.

The survey conducted and presented in the background report showed that most of the tools examined are complex tools for building LCA which work also as pure calculation tools. More than half of them is provided with benchmarks. Pure calculations tool cover totally almost a half of the investigated tools, and the majority of them are not provided with benchmarks. Results show that complex tools with benchmarks are targeted for audiences with basic knowledge in LCA. When a tool is working as a pure calculation tool, sustainability experts and consultants are included as targeted users. Since the most targeted user is the building designer, not surprisingly the main use case of all examined tools is the evaluation and the improvement of the building profile. Due also to the overall lack of benchmarks, a full integration of tools in the design process is not yet achieved. Most of the tools are still to be applied in the latest steps of the design process. As common requirements, building LCA tools provide “cradle-to-grave” analyses, by considering country-specifications, and under consideration of all core environmental indicators (EN 15804).

Input data are often manual. Most of the tools exchange Bill of Quantities and Bill of Materials, which however do not present unique format and therefore data structure and units are case-to-case adapted. This short-coming leads users to re-entering or errors during the compilation of the several documents.

Tool outputs are provided in form of report, pre-formatted templates and with both numerical and graphical options. Results are aggregated in several ways, by considering different level of details or lifecycle stages. Bar charts and/or pie donuts are the most frequent visualization possibilities.

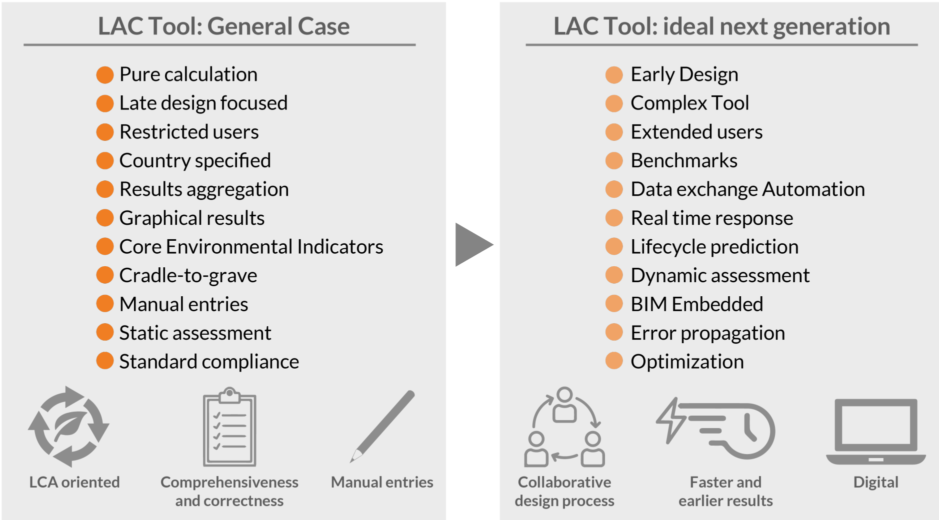

Figure 13: LCA Tools. Synthesis of “general” and “ideal” next generation tools.

Advancements in tools entails the implementation of functions for earlier and faster evaluation of environmental profiles. These requirements are in line with the increasing collaborative design and digitalization in the building sector. Next-generation “ideal” tool should support more the early decision making. Consequently, the intended users should include all stakeholders involved in the building planning, even those who may not have knowledge in the field of LCA to increase all stakeholders’ awareness towards environmental quality. The usability of the LCA tools needs to be increased with consideration of more environmental information, i.e. including transport, construction processes and renovation/end-of-life scenarios. Tools’ databases need to be extended with statistical records, in order to allow for benchmarks derivation. It is important to communicate variations and uncertainties on LCA analysis in a transparent way. This may be feasible with the implementation of results deviation and error propagation. As a next generation tool will be faster, it is also important to implement real time feedback and workflows with higher level of automation, e.g. plug-in or IFC object enrichment and import/export, as for instance presented in Horn et al., 2020 [17]. Concluding, high efforts need to be addressed to BIM portability, which increases collaborations between the different fields.

4.3.3 How can the most appropriate building LCA tool be chosen?

Based on considerations made in the previous section, a procedure to identify a tool, which can satisfy specific designers’ or user needs is here proposed. The procedure consists in a systematic and pyramidal selection (Figure 14).

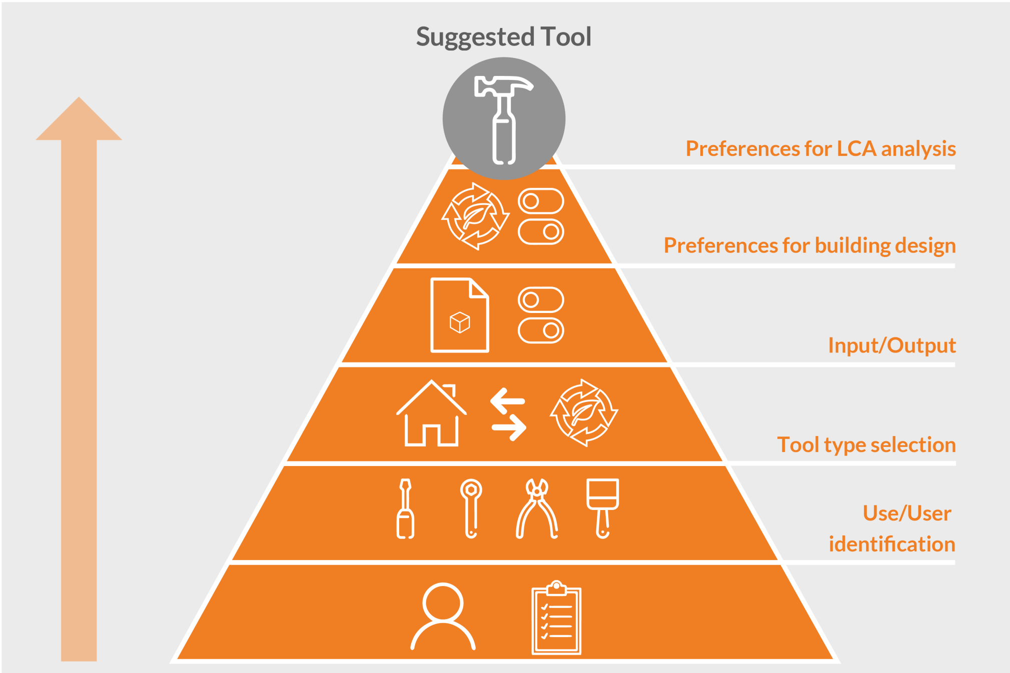

Figure 14: Procedure for tools' identification from toolset.

Requests belonging to the lower part have higher priority for the tool identification process and provide a low filtering. Requests on the higher part select the proper tool with higher level of personalization. Such requests are related to the survey outcomes that show more differences and discrepancies.

a. **Use/User Identification:** the applications and the intended user need to be targeted. A use case is required. The country of application can be declared and this will automatically filter country-specific databases. The identification of user is carried out by investigating audience and its knowledge in field of LCA. Furthermore, a language preference can be provided.
b. **Tool type selection:** pure calculation or complex tools for the building assessment are chosen. The preference regarding the inclusion of benchmarks is provided.
c. **Input/Output:** the lifecycle stages, the system levels to be investigated and, if still necessary, the underlying LCA database are asked (input field). Furthermore, environmental indicators to calculate, preferred template and the data format for results are asked (output field).
d. **Tool features and user's preferences for building design:** this targets more advanced specific users' needs, such as provision of results during the early design stages, optimization algorithms, and interoperability with digital planning or tool coupling possibilities.
e. **Tool feature and user's preferences for LCA analysis:** where deemed useful for the potential user, preferences about, deviation analyses and quality assessment mechanisms are asked.

Within this task a toolset was developed which enables an easier choice of the right LCA tool for the assessment. The toolset is available here in the supplementary materials. Additionally, also general recommendations about the specification that a tool should fulfil at a certain design step is given in Fig. 15.

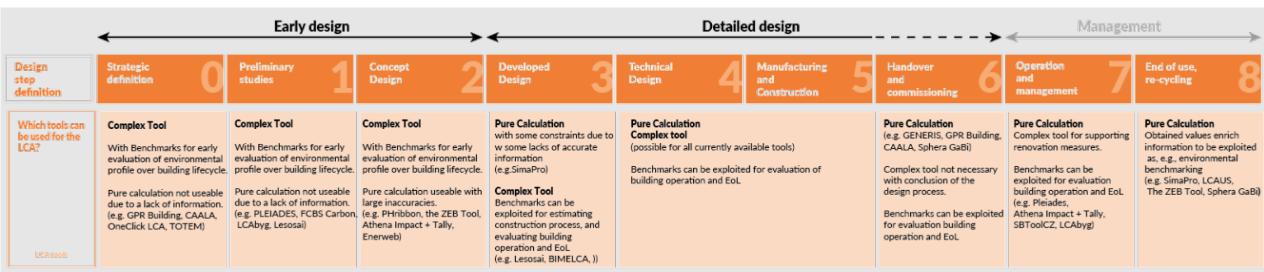

Figure 15: Tools for separate design steps

What can be expected in the background report?

1. Overview of existing LCA tools and information regarding:
   - usability,
   - functionality,
   - interoperability and
   - compliance of currently available LCA tools
2. Development of a process for the selection of a LCA tool
3. Expected improvements of the LCA tools for meeting designers' needs and workflows

What are the main recommendations/guidelines?

1. Use LCA tools along all of the design steps.
2. Refer to the developed selection process to identify the most appropriate tool for each design step.
3. Encourage interoperability among tools.
4. Collaborate towards the development of a unique model with lifecycle information.

4.4 Which workflows are used for LCA (focus on LCA-BIM)?

Based on the literature review, there has been increasing interest in the last few years focusing on the application of LCA in building design practice. However, no common practice or exact specification has been developed yet that facilitates the implementation of different software independent from the used methodology. There is an increasing number of existing software tools, and each of them is based on the own considerations of the developer team.
There are two major different approaches to achieve the integration of LCA into design practice. The first one has evolved from the traditional practice of design that is based on human interaction between stakeholders supported by CAD drawings and text documents (legacy method). Throughout the years, usually import and export possibilities have been developed to speed up manual work, or automation facilitates the fast processing of the input data. This approach has the advantage that full control over the calculations is in hand of the expert. The other approach is the extension of BIM solutions to include LCA in the workflow. This is a more straightforward solution to support information exchange between stakeholders, but on the other hand the exact specification of the calculations is usually out of the hand of the LCA expert if a deep integration is achieved.

The following major requirements can be expressed against a platform for building LCA: *Transparency*, that covers both the background data that the assessment is working with (original source, presumptions, uncertainties) as well as the calculation methodology (bill-of-quantities, replacement, energy demand, etc.). *Interchangeability*, that allows the integration of external solutions such as BIM, and finally *automation*, so that the assessment does not need too much manual work, and as a consequence it might be accessible for a wider audience.

The structure of a building LCA calculation can be generalized to four major modules: background data, modelling, calculation and postprocessing. The main data flow is represented on Figure 1. In the usual case input is provided to the background data and to the modelling module, however, the background data is established prior to and independently from a single calculation (e. g. database), on the other hand the input to the modelling is given specifically for each calculation (usually manually). Output is provided either directly after calculation (e.g. raw data for further use in other systems), or after post-processing (e. g. visualization). The splitting of the latter two modules is necessary because both incorporate various methodological questions that are independent from each other (e. g. how to account for the replacement of the building elements in the calculation component, or how to aggregate the results into a single indicator in the postprocessing component). Each module consists of components that are described in the following.

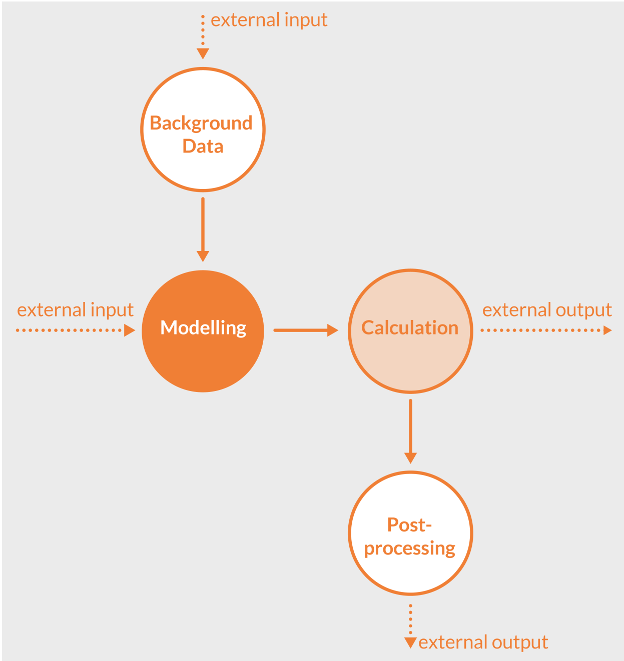

Figure 16: Conceptual representation of the modules and the data flow in the framework

In the framework of this task, we conducted a short survey among the Annex 72 participants to improve our understanding on the calculation procedures and environmental assessment workflows applied in the daily practice. Thirteen partners from 12 countries filled in the survey. The answers are summarized in the following sections. The participating countries were Austria, Canada, China, France, Germany, Hungary, New Zealand, Portugal, Slovenia, Spain, Switzerland and the UK.

The calculation structure is very specific for each country, but there are some similarities. A common solution integrates The *Geometry definition*, *Material definition* and *Bill of materials* in Revit (Spain, New Zealand, France, Canada, Austria, Slovenia). Most of the times, the *LCA calculation* is fulfilled in Excel, in some cases as a dedicated solution including some extra features (*Documentation, Optimization*).
For *Energy calculation* a common solution is to apply EnergyPlus/DesignBuilder when simulation is used. In some cases, optimization is included, but not necessarily with a fully automated, integrated system. In general, all experts use multiple software to do building LCA calculations and there is only one country (France) that applies a full integrated software suite for all the modules.

Finally, the structures can be classified into four categories (Table 2) with decreasing integration/automation in the following order:

– *Specialized standalone software (with BIM integration)*: Externally or internally developed software solutions for multiple modules, including BIM integration (either with a plugin to existing BIM software or standalone BIM module). This is the most advanced solution, but it is usually the result of long-term software-development strategies, which is only feasible with industry participation.
– *Modules based on (visual) scripting*: The automated workflow is enabled through (high-level) visual scripting interfaces of existing software (e.g. Rhino Grasshopper or Revit Dynamo) or other scripting languages (e.g. python, Matlab). This option is more available for a wider community including engineers, designers, and researchers, and therefore it is becoming more and more popular.
– *BIM with further spreadsheet-based calculations:* The workflow is based on existing BIM solutions (e.g. Revit), where the required data can be extracted for further evaluation in a spreadsheet-based system.

This option is the most flexible regarding external models since the required data export does not require any special rules to be applied to the model. Therefore, this method is often used with real design projects.

– *Manual (spreadsheet-based) calculation structure*: In this (legacy) case all input data need to be added manually to a spreadsheet, where all the necessary calculations are done. This requires time-consuming work, but the data is fully controlled and transparent in return.

Furthermore, another exercise was conducted, where the participants (AT, CA, CZ, …) were obtaining the BOQ from the same BIM model using their own workflows. The aim of the exercise was to analyze the advantages and disadvantages of the separate workflows. The results are summed up in the background report.

BIM tools have a lot of different features that can be useful in the BIM-LCA workflow. In the Figure 17 we have defined the most relevant features that a BIM tool should fulfill for an exchange of data between BIM and LCA.

	Early design				Detailed design			Management	
Design step definition	Strategic definition 0	Preliminary studies 1	Concept Design 2	Developed Design 3	Technical Design 4	Manufacturing and Construction 5	Handover and commissioning 6	Operation and management 7	End of use, re-cycling 8
How can BIM help/improve the LCA during the design process? (Task 4 BIM-LCA tools)	Enables to obtain a systematic quantity take-off from the BIM model. -Allows to automatically update of the element extraction, if the design is modified. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during the design process, such as operational energy calculation, optimization, etc.		-Enables to obtain a systematic component quantity take-off for the BIM model. -Allows to automatically update of the component quantities extraction, if the design is modified. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during the design process, such as operational energy calculation, optimization, etc.		-Enables to obtain a systematic material quantity take-off from the BIM model. -Allows to automatically update of the material extraction, if the design is modified. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during the detail design process, such as technical equipments and installations design, building management, etc.		-Enables to obtain a systematic material quantity take-off from the as built BIM model. -Allows to automatically update of the material extraction, if the design is modified before the construction. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during. It can enable the data exchange with the digital permit, digital twins, etc.	-Enables to obtain a systematic material quantity take-off from the as built BIM model. -Allows to automatically update of the material extraction, if the design is modified during the use phase. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during the operational phases (repair, refurbishment, replacement). It can enable the data exchange with the digital logbook, building and material passport, energy performance certificate, digital twins, etc.	-Enables to obtain a systematic material quantity take-off from the as built BIM model. -Allows to automatically update of the material extraction, if the design is modified during the use phase. -Allows to use the same BIM model for different purpose that can facilitate the LCA application during the operational phases (repair, refurbishment, replacement). It can enable the data exchange with the digital logbook, building and material passport, energy performance certificate, digital twins, etc.

Figure 17: The requirements for a BIM toll in separate design steps

What can be expected in the background report?

1. Development of a framework for the overview of the workflows
2. Overview of workflows used for LCA (especially LCA BIM workflows)

What are the main recommendations/guidelines?

1. LCA BIM workflows used in design steps
2. Increased automatization of the workflows
3. Encourage interoperability among tools.

4.5 How can design-related uncertainties be reduced in the workflow?

On the one hand, it is obvious that the designer has major influence on the final environmental impacts of a building. On the other hand, a building project is a long process with multiple actors, and many small influential decisions will be taken during the duration of the project. Therefore, the designer has the difficult task of carrying the long term and overall vision of the project while being able to take the right decisions all along the project. It means that, although a large amount of uncertainty exists in the early phase of the project, some key choices taken in the beginning will in fine highly influence the environmental impacts of the building. How can the right decision be taken? When is it possible to take one decisive choice? This is the complex task of the designer.

Therefore, it is important to know which kind of uncertainties exist in an LCA study, which are the possible pathways to reduce them, and which workflows to reduce the uncertainties have proven to be the most efficient.

4.5.1 Which kind of uncertainties exist in the LCA?

The uncertainties of the LCA can have different sources which can be divided into two great categories (Figure 1)
- Exogenous uncertainty, namely uncertainty that the designer cannot influence;
- Uncertainties during the design steps, namely uncertainties that the designer can influence.

This document focuses on the uncertainties that can be influenced by the designer. The aim is to define a strategy for design decision-makers which would allow them to handle and analyze LCA-related uncertainty in different design steps.

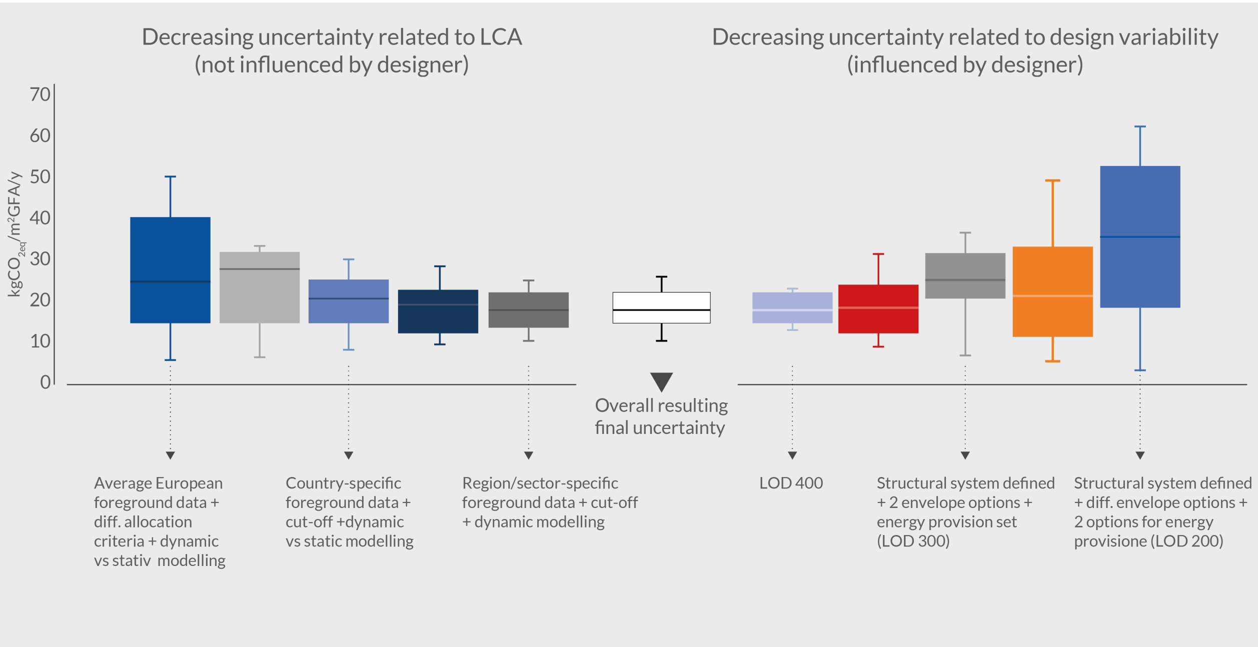

Figure 18: Uncertainty sources in building LCA, divided according to the designer's influence.

4.5.2 What are the possibilities to reduce the uncertainties during the design process?

This part provides guidance on how to reduce the uncertainties through the design process. Two different strategies for the reporting and reduction of uncertainties were identified:
- The project development strategy
- The optimization strategy

A detailed overview of the existing design flows to reduce the uncertainties can be found in the background report.

4.5.3 What are the recommendations to reduce the uncertainties during the design process?

In order to support the designer during the decision process, LCA experts have to adapt their tool to provide the right level of information depending on the available data at each specific design step of the project.

We have identified two fundamentally different strategies to provide decision support through the design process. The first one is to develop LCA that provide reliable results for each step of the design (the project development strategy), the second one is to suggest to the designer to take in the very early steps of the design the key decision that will influence 80% of the uncertainty, even though a classic design process would not put this decision so early in the design (the optimization strategy).

The project development strategy

In the first strategy (see Figure 19), the LCA calculation has to adapt to the level of details available all along the design process. It means that in the early design steps, there is a need for aggregated data which include assumption on typical construction process, even if the designer would not specify them. In the very early design steps, the project is described with simple volume and surface. Although a wall is represented only as a plane in 3d or as a line on plan, for the early design LCA, it already means a given quantity of material assuming a typical construction process. This under-specified LCA method (Tecchio et al., 2019; Cavaliere et al., 2019) is key in order to guide designers towards the lowest possible environmental impact considering their choice. In a later step, once geometry, heating system, material performance are defined, the designer will choose between two producers which will then influence transport distance. However, transport usually has a very minor influence on the environmental impact of a building.

BAUTEILKATALOG			KBOB	LOD			
Construction categories	Building compo-nents	Constructive solutions	Materials	LOD 400	LOD 300	LOD 200	LOD 100
C.Structure	Load-bearing wall	Wooden frame construction	Hardwood	GWP	GWP	GWPaverage GWPmin GWPmax	GWPaverage GWPmin GWPmax
			Wood fibre insulation board	GWP			
			…	GWP			
		Concrete frame construction	Concrete	GWP	GWP		
			Reinforcement steel	GWP			
			…	GWP			
		…	…	GWP	GWP		
E. Envelope	Exterior wall cladding	Wooden cladding	Pine wood	GWP	GWP	GWPaverage GWPmin GWPmax	
			Larch wood	GWP			
			…	GWP			
		Plasterboard plastered, wooden substructure	Plaster	GWP	GWP		
			Hardwood	GWP			
			…	GWP			

		…	…	GWP	GWP		
G. Finishing	Interior wall finishing	Gypsum finishing	Gypsum	GWP	GWP	GWPaverage GWPmin GWPmax	
			Paint	GWP			
			…	GWP			
		Wooden finishing	Wood	GWP	GWP		
			Paint	GWP			
			…	GWP			
		…	…	GWP	GWP		

Figure 19: The illustration of the project workflow that follows the design steps proposed by (Cavalliere et al., 2019).

Following this first workflow, where LCA calculation is adapted to the design process, it is recommended to work with aggregated database, calculating building elements rather than specific material quantities. It is also recommended to work with database showing the worst and best cases for each element, in order to visualize the remaining range of environmental impact that can be achieved depending on the options taken.

The optimization strategy

In the second workflow (see Figure 20), which is focused on the optimization, a parametric LCA calculation is done in the very early design steps, in order to identify the most influential parameters. This simulation will show to the designers the 5 to 10 parameters that they need to fix from the beginning of the design in order to reduce uncertainties to the maximum. The classic rule of 80/20 is valid and usually 80% of the uncertainty are controlled by 20% of the parameters. This decision support approach is very efficient as it allows to fix from the beginning the essential parameters, and afterwards, the designer can make more detailed choices that will not drastically influence the results. It means that decision can still be taken according to LCA results, for instance choosing the material with the lowest environmental impacts according to EPDs (Environmental Product Declarations), but somehow even if the choice is not environmentally driven, but aesthetically or economically driven, it won't have major influences because the type of decision which are taken at that moment have minor environmental consequences. This is of course because the material choices, which have crucial consequences, have been taken in the early design steps and are then not discussed again.

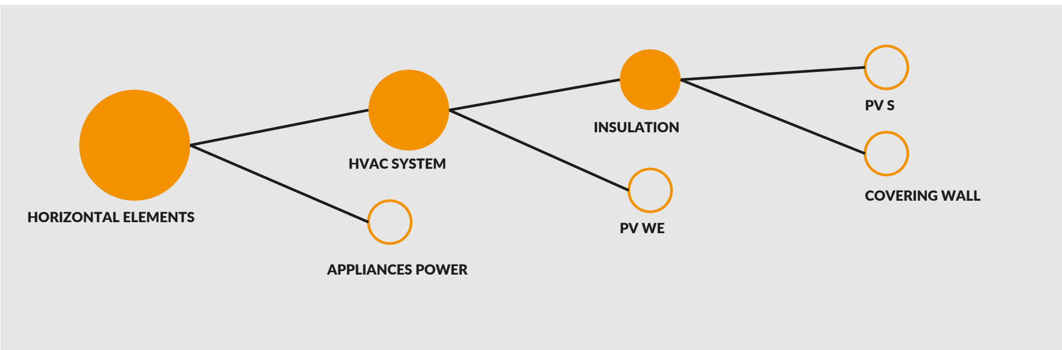

Figure 20: The illustration of the project workflow that follows the optimization strategy proposed by Jusselme et al., 2017

Following this workflow, the LCA expert is providing to designers in the very early stage the 5 to 10 decision they need to take. It requires tough early decision that will then influence most of the design, but the interest is that the environmental impacts of the building are nearly already fixed, which allows the designer to focus again on what they know best, meaning good architecture, which will be within an environmental budget that has been agreed in the beginning.

The important tasks of each of the proposed strategy for the reduction of the uncertainties are summed up in the Fig 21.

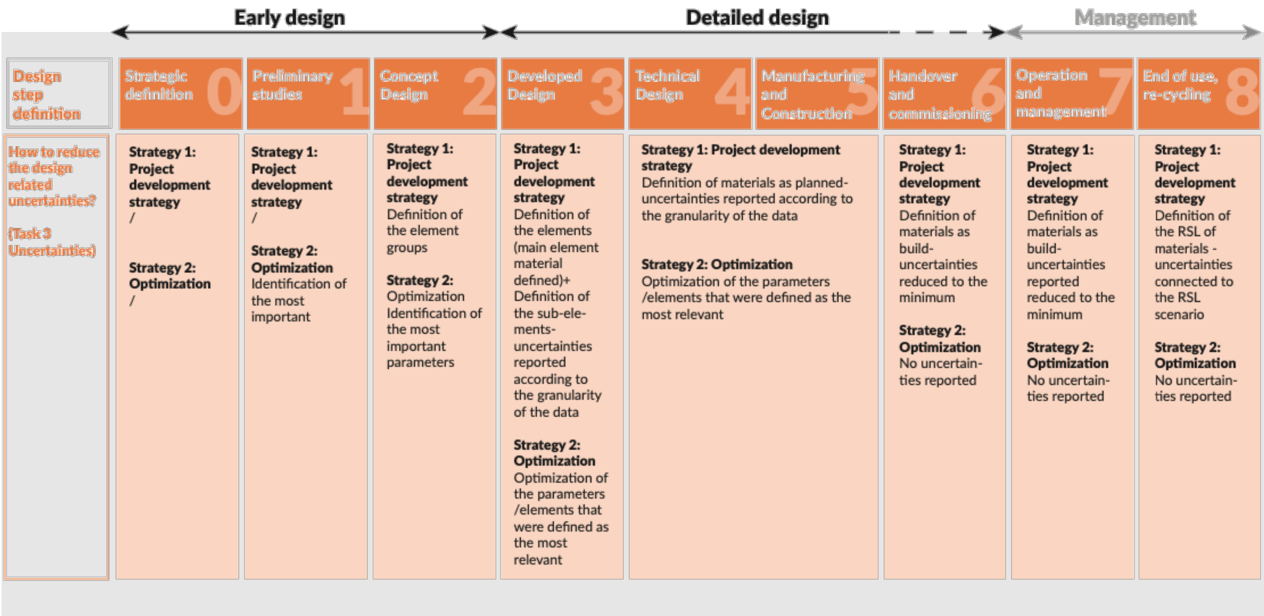

Figure 21: Strategies how to handle the uncertainties in separate design steps

What can be expected in the background report?

1. Description of the two main workflows to handle uncertainties along design process.
2. Overview of different method used to aggregate data all along design process.
3. Example of integration of LCA in BIM and associated risks in term of uncertainties.

What are the main recommendations/guidelines?

Two approaches are recommended to deal with uncertainties:

Approach 1: Project development strategy
- Use different data aggregation levels depending on the design steps which are following their logical development: from aggregated data (elements) to disaggregated data (materials).

Approach 2: Optimization strategy
- Identify the 5 to 10 key parameters in the building in the early design steps, which allow to remove 80% of the uncertainty, by performing a sensitivity analysis.

4.6 How can LCA results be visualized, interpreted and communicated?

The communication and visualization of results to support the interpretation are closely related to the definition of the Goal and Scope (5.1). Depending on the purpose of the study, the intended audience and the design stage, the communication and visualization formats can vary very much. Although the number of building LCA tools has been growing recently, they provide limited visualization options. Currently, there is no harmonization between the ways of visualizing building related LCA results neither in practice nor in academia. This makes it especially difficult for practitioners and non-LCA experts to make use of the LCA results. The interpretation phase is often considered complex by them (Malmqvist et al., 2011; Zanghelini et al., 2018). While the need for visualization is evident and often stated in the literature (Cerdas et al., 2017; Otto et al., 2003; Sala & Andreasson, 2018a), few researchers have focused on developing visualizations for building LCA results. These few studies such as (Basbagill et al., 2017; Kiss & Szalay, 2019; Otto et al., 2003; Röck et al., 2018; Wiberg et al., 2019) propose novel types of visualizations often dedicated to one type of stakeholder involved in the design process of a building. These studies compare a few visualization types, but a comprehensive review of visualization of building LCA results is currently not available.

Visualization techniques are usually used to communicate and analyze data and information for a different purpose. For example, they can make information easy to explore and more usable when the volume of information grows (Shneiderman, 1996). As such, visualization is key for decision support (Sala & Andreasson, 2018b), but also optimization of the design during the design process (Attia et al., 2013). If designers cannot intuitively match the results with the architectural design, then there is a tendency that the analyses performed will not affect the actual design decisions (Jensen et al., 2018). In contrast, if the visualizations are meaningful to designers, significant improvement of the environmental impact can be achieved (Basbagill et al., 2017) and collaboration in interdisciplinary design teams is improved (Landgren et al., 2019).

4.6.1 Definition of goals during the interpretation phase of LCA

Six typical goals during the interpretation phase of LCA results are defined with relation to visualizations.

a. **Identification of hotspots**: Many LCA studies are conducted to identify so-called hotspots that are responsible for a large share of the environmental impact. This hotspot analysis can be conducted at different levels of detail. In the case of buildings, the aim is often to identify building elements (walls, roof, etc.), individual materials, or life cycle phases with a large environmental impact.

b. **Comparison of options for design improvement**: If the aim is to use the LCA results to improve the design or decide between several design alternatives, a comparison becomes crucial. The comparison can be carried out on different levels of detail, for example comparing different buildings, different building elements or building materials.

c. **Correlation, uncertainty, and sensitivity analysis**: The analysis of the correlation of parameters or indicators becomes important when the aim is to optimize a design towards different criteria, see for example (Kiss & Szalay, 2020a). The correlation analysis is often applied to support design guidance to make appropriate choices based on a large set of options instead of only a few. Uncertainty analysis often refers to the uncertainty inherent to the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty, and data variability (ISO 14044, 2006). Furthermore, sensitivity analysis is often carried out in the interpretation phase to test the influence of modelling choices, such as system boundaries, allocation approaches or the choice of specific datasets (Guo & Murphy, 2012), on the overall assessment results.

d. **Benchmarking**: Especially with regards to fulfilling thresholds defined in national building regulations or GBCS, benchmarking becomes very important. Additional benchmarks could include national averages, previous projects or the average within a building portfolio. Furthermore, global targets, such as the 2-degree target or global frameworks, the planetary boundaries (Rockström et al., 2009) or the 2000 Watt society (Jochem et al., 2004) can be used as benchmarks.

e. **Spatial distribution**: This aspect relates to the aim of identifying where environmental impacts are caused. Therefore, maps are often used to highlight the spatial distribution of the impact, e.g. (Houlihan Wiberg, Wiik, et al., 2019).

f. **Temporal distribution**: To identify when environmental impacts are caused, often charts plotting the development of the impact over time are used, e.g. over the lifetime of the building (Eberhardt et al., 2019).

4.6.2 Which types of visualization of LCA results are used and for which stakeholders during the design process of buildings?

To answer this question, three sub-research questions are used for the review of both the building LCA software and the scientific literature.

1. Which design steps is targeted?
2. Which are the intended stakeholders?
3. Which visualization types are used?

We reviewed the currently most commonly used LCA software tools for buildings. The list of tools is based on previous reviews (Cavalliere, 2018; Hollberg, 2016). Detailed information about the methodology can be found in the background report.

The analysis showed that most building LCA tools focus on the detailed design steps (see Figure 22), while there are slightly more scientific papers addressing the early design stages. The results furthermore show that most building LCA tools intend to address building design professionals. No tool tries to specifically address decision-makers. As most tools claim to address several stakeholders, expert judgement was used to classify the tools to simplify the classification and provide clear results. Similar to the building LCA tools, the majority of the visualizations presented in the literature address building design professionals. About one third focusses on LCA experts, while only 12% address decision-makers.

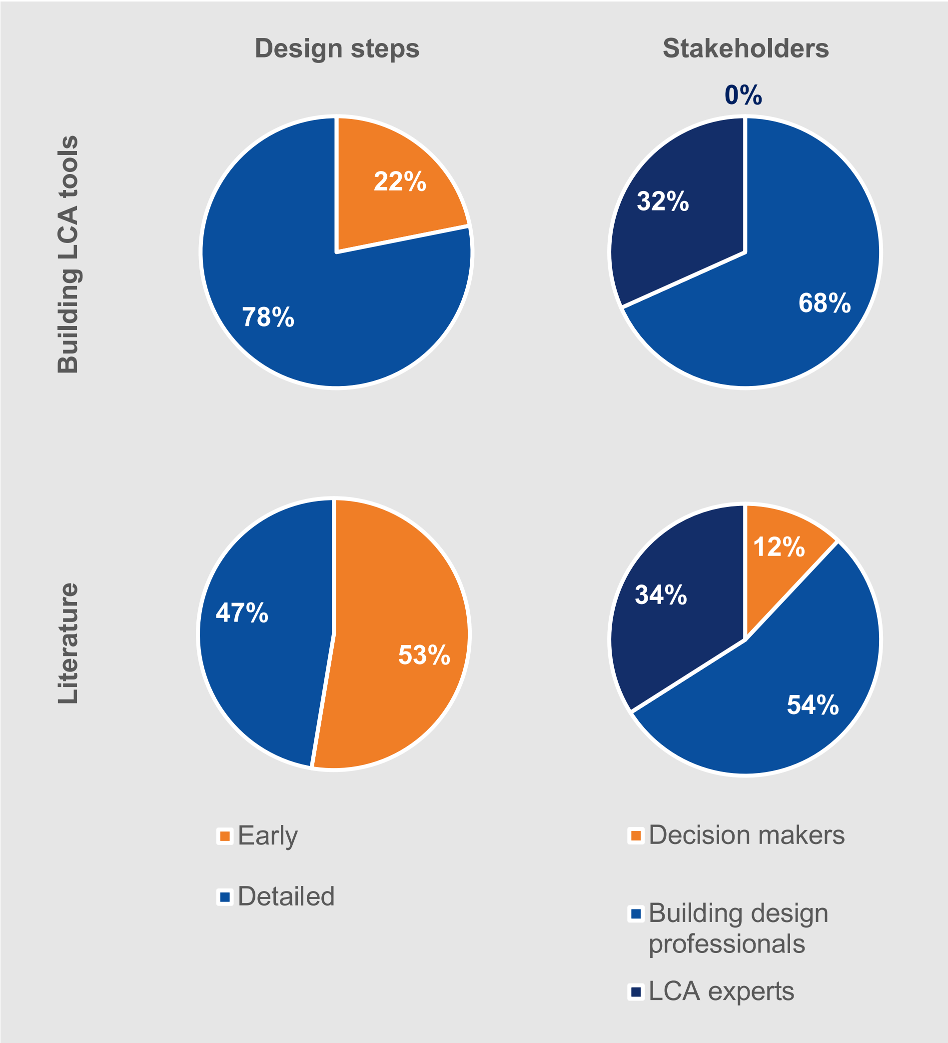

Figure 22: Design steps and stakeholders mainly addressed by building LCA tools and the literature

Most building LCA tools use more than one, but only a few types of visualization, e.g., pie chart and bar chart. Only one of the analyzed tools does not provide any visualization. Bar charts and variations of it such as grouped or stacked bar charts are the clear majority, followed by pie charts. Like the building LCA tools, most published literature use bar charts and variations of it. A major difference to the results of the tools is the increased use of complex visualizations. Scatterplots sometimes including a Pareto front are used 12 times, for example. Table 4 shows that common visualizations (e.g. bar charts) are used as well as more complex visualization options (e.g. scatter plots) for both LCA experts and building design professionals. They are grouped (A, B, C, etc.) based on common characteristics.

Description	
One discrete variable is plotted, and one indicator is expressed	**A**
One discrete variable with single-level hierarchic subdivision is plotted and one indicator is expressed	**B**
One discrete variable with multi-level hierarchic subdivision is plotted and one indicator is expressed	**C**
Two discrete variables are plotted, and one indicator is expressed	**D**
One continuous variable is plotted, and one indicator is expressed	**E**
One continuous variable with a single-level hierarchic subdivision is plotted and one indicator is expressed	**F**
Multiple continuous variables are plotted and one indicator is expressed	**G**
One discrete variable is plotted and multiple indicators (with different units) are expressed	**H**

For decisions-makers, we find that a small variety of visualizations is presented. The literature with a focus on visualization provides more variety including options such as clusters or maps. The literature presenting case studies have a clear majority of common visualizations such as bar charts and variations of it. Scatter plots and Pareto fronts seem to be the only complex visualizations that are used by all types of papers. Although many authors in analyzed literature specifically focus on early design stages, no clear differences of the use of visualizations can be seen with regards to the design stages.

Table 3: Number of visualization types per stakeholder and design phase

		A											B			C				D		E	F	G+H				
		Pie chart / donut chart	Vertical bar chart	Horizontal bar chart	Grouped bar chart	Tornado chart	Pictorial unit chart	Pictorial fraction chart	Scale	3D Colour code	Colour map	Bubble map	Stacked bar chart	Normalised bar chart	Box plot	Multi-level pie chart	Sun burst	Sankey	Tree map	Heat map	Multiple series 3D bar chart	Line chart	Stacked ordered area chart	Radial / spider / polar chart	Parallel coordinates	Scatter plot / pareto front	Cluster	3D Scatter plot
LCA tools	Decision makers	1	4	0	4	0	0	0	1	0	0	0	5	1	0	0	3	0	0	0	0	0	0	0	2	0	0	0
	Building design prof.	13	13	4	14	0	0	0	6	2	1	0	17	4	1	0	3	4	2	1	0	4	1	2	2	1	0	0
	LCA experts	4	11	0	10	0	0	0	3	1	1	0	9	3	0	0	3	2	0	0	0	3	1	2	2	1	0	0
	Early	5	5	3	6	0	0	0	2	1	0	0	7	2	0	0	1	1	2	0	0	1	0	0	0	0	0	0
	Detailed	9	13	1	10	0	0	0	5	1	1	0	13	4	1	0	3	3	0	1	0	3	1	2	2	1	0	0
Literature	Decision makers	0	3	0	1	0	1	0	0	2	0	0	4	1	3	0	0	0	0	2	0	3	0	0	0	3	1	0
	Building design prof.	2	3	0	7	2	0	1	1	6	0	1	7	0	5	1	1	1	0	0	1	2	0	2	3	8	1	1
	LCA experts	0	7	2	6	0	1	0	0	1	1	1	4	2	2	1	1	2	1	5	0	3	1	2	4	4	1	2
	Early	1	7	3	5	2	0	1	1	5	0	1	4	0	5	1	1	2	0	0	1	1	0	0	4	5	0	1
	Detailed	2	4	1	7	0	1	0	0	1	1	0	8	2	3	1	0	0	1	5	0	7	1	2	0	8	2	1

4.6.3 A decision matrix for visualization type in LCA

Eight groups of visualization types are identified within the collected visualizations. The process how to choose the appropriate visualization type is shown in Figure 23.

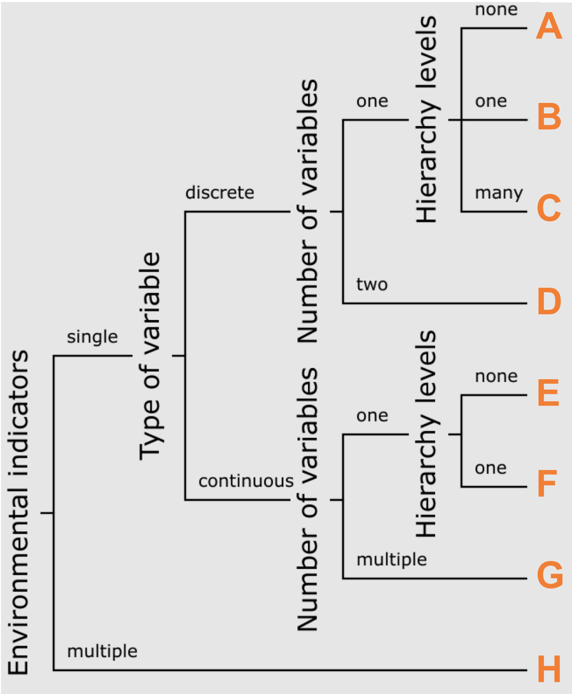

Figure 23: Categorization steps to define groups of visualization types and description of the groups

The synthesis shows that several visualization options exist for all the LCA goals. In the Figure 23 the number of choices made is increasing left to right. Consequently, also the with the visualizations are including more information and are more complex. In addition, the number of objects for the assessment proved to be relevant. Therefore, a differentiation between one, few and many (>100) objects of assessments is introduced and indicated by the type of border around the icons in Figure 24.

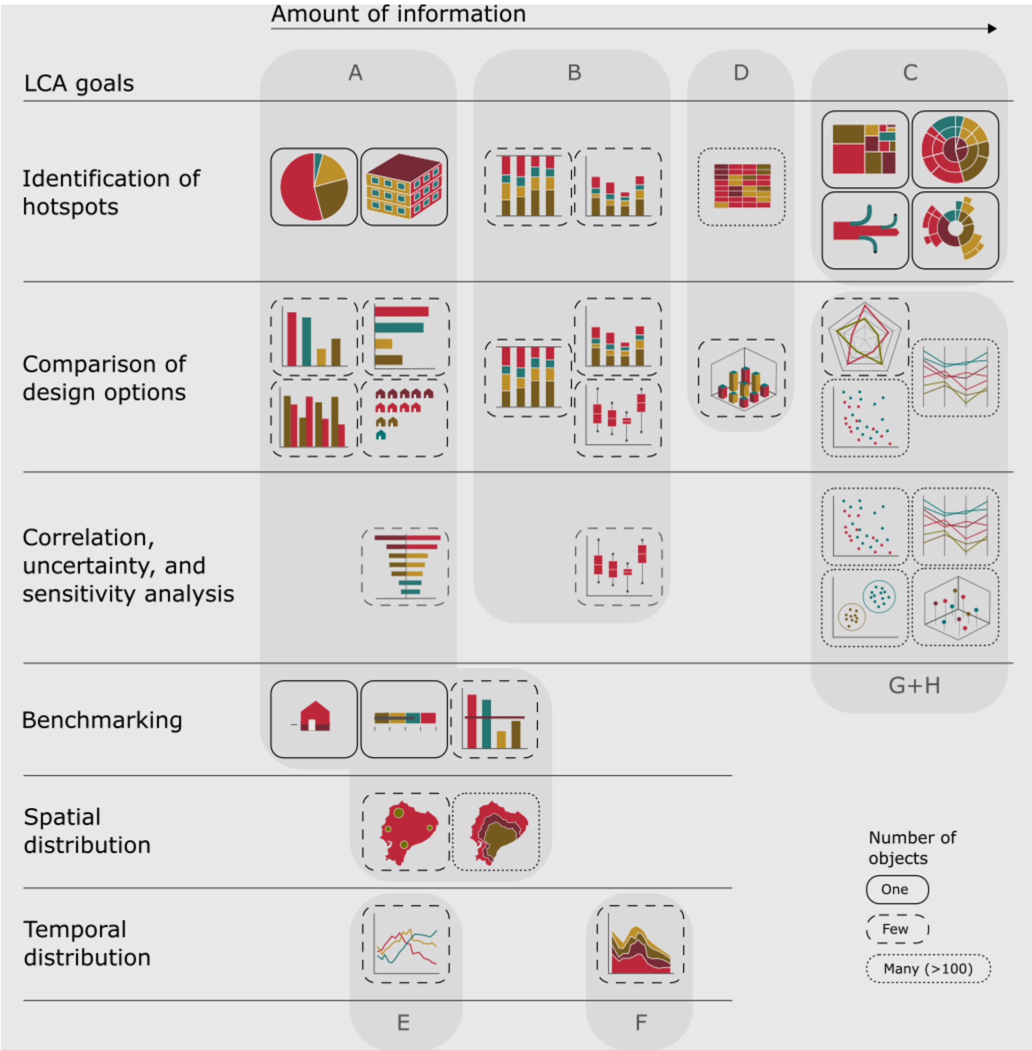

Figure 24: Synthesis of the LCA goals, the group of visualization types, and the amount of information displayed in the visualization

For the LCA goals of temporal distribution, spatial distribution, and benchmarking only two or three options each could be found in the literature. All these options are only suited to communicate one environmental indicator and one design variable. In the case of bar charts with a benchmark threshold, it is possible to show several environmental indicators next to each other, but this requires either normalization or adding an individual axis for each bar, which would correspond to showing several single bar charts next to each other. The visualization options that are part of group A and E have no hierarchy levels, while the stacked ordered area chart as part of group F has one hierarchy level that could be used to plot the evolution of the environmental impact of individual building elements and the sum for the whole building over time, for example.

Identification of hot spots and comparison of design options are the most common LCA goals in the reviewed literature and they show the highest variety of visualization options. For identification of hot spots, only discrete variables are used. The options in group A, B, and C, all visualize one variable with increasing hierarchy levels, for example the embodied impact of building elements. The options in group D allow to visualize two variables, for example heating systems and insulation materials for renovation (Hollberg & Ruth, 2013).

The comparison of design options can be visualized with a limited amount of information, such as a bar chart. If the number of options for comparison reaches a certain point, the type of visualization becomes limited. Then mostly scatter plots are used to identify clusters or a Pareto front (group G). There is a lower limit for the number of objects for these types of charts to become meaningful. Parallel coordinate plots are often used to visualize several parameters and their interdependencies. If few design options are compared regarding multiple indicators, visualization options of group H, such as spider charts, are used.

Uncertainty analysis is often an important part of LCA. A common way to visualize uncertainty is an error bar in bar chart or a box plot providing additional information by showing quantiles. A simple but rarely used approach in the analyzed literature, is to show and rank the sensitivity of design parameter using a tornado chart (Basbagill et al., 2017). The most common way to show correlation is the use of scatter plots and variations of them in 2D and 3D, but also parallel coordinate plots are used, for example (Miyamoto et al., 2019).

While several visualization options exist for all LCA goals, certain types of visualizations are only used for one specific LCA goal in the analyzed literature, e.g., a pie chart is only used for a part-to-whole comparison to identify hotspots, and a scale is only used to show the result in relation to a benchmark.

The narrative of the visualizations is different therefore the Deign decision table proposes which visualization methods are appropriate in the selected design step.

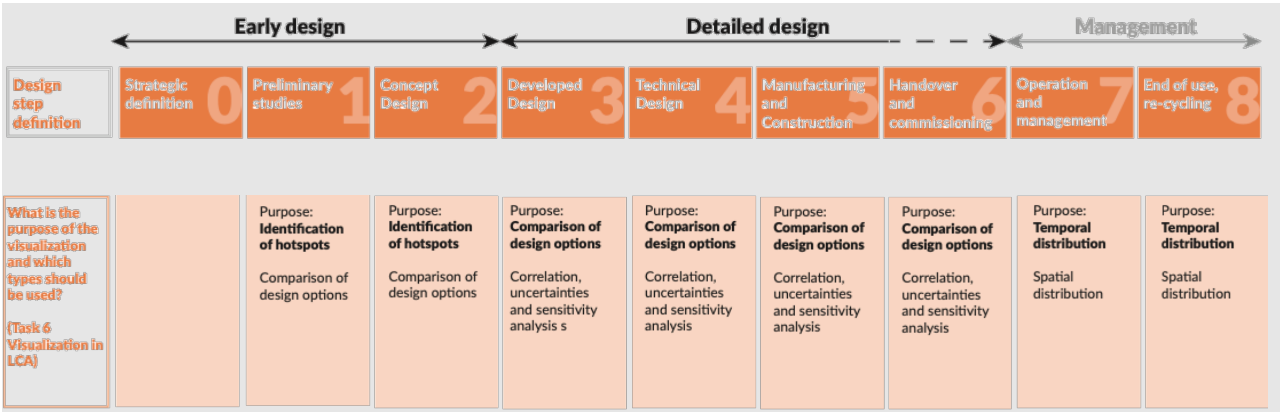

Figure 25: Visualisation types in separate design steps

What can be expected in the background report?

1. Overview of visualization types for LCA results.
2. Development of a selection matrix for choosing the most appropriate visualization types based on:
   - The goal of the LCA.
   - The amount and complexity of the information to be communicated

What are the main recommendations/guidelines?

1. Use adequate visualisations types from less to more detailed following the selection matrix (different goals and amounts of information).
2. Combine different visualisations in dashboards to be able to display different types of information and support decision making.

5. Conclusion and decision table

During the building design process, there is a great potential to implement measures to reduce environmental impacts. However, the application of consistent and standardized methods such as LCA can be complex and lead to contra-productive misuses, if several aspects are not taken into account. Hence, to support the stakeholders involved in the building design process and transfer to them scientifically based findings, this guidelines report provided outlook and recommendations related to the integration of the LCA into design process and design tools. It focused on answering questions such as when and for what purpose will the LCA be conducted, how to prepare the information about the building to be integrated in the tools or workflow, which workflows and tools should be used, which visualization and communication of the results in LCA should be used, for whom and for what is the LCA needed.
It is worthy to mention that the level of implementation of the guideline and recommendations which we have provided depends on the regional or national level of maturity in the LCA (methods, environmental data, classification systems) and BIM implementation in current practice. Despite the heterogeneity among different national LCA methods, existing environmental databases, among others, following the proposed guideline the potential for unpredictable errors and inconsistent results in the LCA calculation along the design steps can be reduced.

To improve the understanding and enable a practical use of the contents of this document to all the stakeholders involved, a summary of these guidelines and recommendations to reduce environmental impacts along the design process have been included in a special practice-oriented document: the **Design Decision Table**.

5.1 The Design Decision Table

The design decision table includes the summary of the main aspects that should be addressed, including relevant outputs from these guidelines and the background reports.

The table aims to provide a practical use of the guidelines and recommendations and orient their major finding to current practice.

To that end, the table should be read in the following order:
– The **Columns** represents the design steps according to the common definition, milestones and general LOD of the elements and objects included in the BIM model (based on the Background Report Task 1);
– The **Rows** includes the main questions that should be addressed in order to encourage the current practice use of the LCA during the design process focused on reducing building environmental impacts and provide a consistent and scientifically-based support to all the stakeholders involved in the design process, especially the designers.

This table provides recommendations to:
– Determine the relevance and main aspects to be considered at the design steps to reduce the environmental impacts (connected and based on Experts interviews and Survey outputs);
– Identify the stakeholder's involvement at each step (connected and based on to Experts interviews and Survey outputs);
– Define the milestones and building information that should be archived to conduct the LCA during the design process, (see background reports);

- Define the goal, purpose of the LCA and the utility of the LCA following an evolutionary sequence of the data aggregation and building definition (see background reports);
- Define the data granularity, systematic building decomposition, level of data disaggregation that should be achieved at each design step (see background reports;
- Determine the potential support and utility of BIM in the LCA implementation during the design process (see background reports);
- Reduce design-related uncertainties in the LCA (see background reports);
- Determine the appropriate visualization type to support de decision making at each design step (see background reports).

	Early design			Detailed design				Management	
Design step definition	**Strategic definition** 0	**Preliminary studies** 1	**Concept Design** 2	**Developed Design** 3	**Technical Design** 4	**Manufacturing and Construction** 5	**Handover and commissioning** 6	**Operation and management** 7	**End of use, re-cycling** 8
Core Objectives	Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre-) Fabrication of construction products, Construction and supervision	As-built documentation, hand over, commissioning and testing	Facilities Management and Asset Management, Evaluation and Improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling
Milestones									
LOD	0	0-100	100-200	200-300	300-350	350-400	400-500	400-500	400-500
Important to consider for reducing the environmental impacts	**Clarify the need for the building** Is a new building needed? Can an existing building be transformed/retrofitted instead?	**Build less: Reduce area built where possible** Reduction or optimization of the built area to the minimum	**Optimize the building shape design to reduce the energy demands as much as possible** Integration of passive and bioclimatic design strategies in the design of the building volumes	**Optimize the design of the building systems, especially structure and envelope** Integration of passive and bioclimatic design strategies in the design of the building envelope Can I reduce or optimize the material quantities in the building?	**Optimize the design of the building services, finishings (and the rest of the building systems)** Can I reduce or optimize the embodied and operational building impacts? Which materials and construction systems enable to minimize transports, waste generation, construction and operational/use emissions?	**Coordinate actions of the stakeholders based on awareness about the environmental impacts**			Can the materials to be demolished be reused/ recycled/upcycled/ downcycled?
Who are the most important stakeholders? Key role at the stage	**Designers (architect and engineer)** **Client**	**Designers (architect and engineer)** **Client**	**Designers (architect and engineer)** **Client** **Sustainability assessment and certification expert**	**Designers (architect and engineer)** **Client** **Sustainability assessment and certification expert** **BIM manager**	**Designers (architect and engineer)** **Client** **Sustainability assessment and certification expert** **BIM manager** **Contractor**	**Designers (architect and engineer)** **Client** **Sustainability assessment and certification expert** **BIM manager** **Contractor**	**Designers (architect and engineer)** **Client** **Sustainability assessment and certification expert** **BIM manager** **Contractor** **Project commissioning**	**Designers (architect and engineer)** **Client** **BIM manager** **Commissioning management systems**	**Designers (architect and engineer)** **Client** **Contractror**
Information needed for conducting the LCA	Definition of the **building program with general areas**		Definition of the **main building elements** (material quantities and BIM model verified) what if scenario assessment comparison	Definition of the **building elements to be included in the building** (estimated material quantities and BIM model verified)					
Purpose of LCA	**Identify the baseline scenario** To optimize the volume/built surface ratio, (especially in residential buildings)		**Improve the design of the building volume** To compare building design alternatives and macro components		**Compare different products and manufactures** and reduce the building's environmental impacts				**Compare/determinate the potential of reuse and recycling of the building**

general information

Figure 26: Design decision table (part 1)

related to background

Task of the design stage Design steps and project phases	Setting and identifying the target impacts based on the building program, typology, country, etc.	Verify the surfaces and building geometry with the target estimated impacts. Re-define or adjust the design.	Verify the systems and building elements material estimations with the target or benchmarks impacts. Re-define or adjust the design.		Verify the material estimations (including technical equipment, installations) with the traget or benchmarks impacts. Re-define or adjust the design.	Labeling or certification of the building impacts befor/after construction, considering the real materials and process of the building.	Tracking the certified impacts values along the building life cycles in the maintenance, repair, refurbishment and substitution stages.	Identify potential re-use or valorization of the building elements and materials. Consider the building as a material bank to the next generations.
Which level of decomposition to should be used? Systematic building decomposition in LCA	**Floor areas (with different functions)**		**Elements/Components**		**Materials** **Generic material data** ← → **Product specific material data**			
How to reduce the design related uncertainties? Uncertainties	**Strategy 1: Project development strategy** /	/	Definition of the element groups	Definition of the elements (main element material defined) + Definition of the sub-elements uncertainties reported according to the granularity of the data	Definition of the materials as planned-uncertainties reported according to the granularity of the data	Definition of materials as build-uncertainties reduced to the minimum	Definition of materials as build-uncertainties reported reduced to the minimum	Definition of the RSL of materialsuncertainties connected to the RSL scenario
	Strategy 2: Optimization /	Identification of the most important	Optimization Identifikation of the most important parameters	Optimization of the parameters/elements that were defined as the most relevant	Optimization of the parameters/elements that were defined as the most relevant	No uncertainties reported	No uncertainties reported	No uncertainties reported
Which tools can be used for the LCA? LCA tools	**Complex Tool** With Benchmarks for early evaluation of environmental profile over building lifecycle. Pure calculation not useable due to a lack of information. (e.g. GPR Building, CAALA, OneClick LCA, TOTEM)	**Complex Tool** With Benchmarks for early evaluation of environmental profile over building lifecycle. Pure calculation not useable due to a lack of information. (e.g. PLEIADES, FCBS Carbon, LCAbyg, Lesosai)	**Complex Tool** With Benchmarks for early evaluation of environmental profile over building lifecycle. Pure calculation useable with large inaccuracies. (e.g. PHribbon, the ZEB Tool, Athena Impact + Tally, Enerweb)	**Pure Calculation** with some constraints due to w some lacks of accurate information (e.g.SimaPro) **Complex Tool** Benchmarks can be exploited for estimating construction process, and evaluating building operation and EoL (e.g. Lesosai, BIMELCA,))	**Pure Calculation** **Complex tool** (possible for all currently available tools) Benchmarks can be exploited for evaluation of building operation and EoL	**Pure Calculation** (e.g. GENERIS, GPR Building, CAALA, Sphera GaBi) Complex tool not necessary with conclusion of the design process. Benchmarks can be exploited for evaluation building operation and EoL	**Pure Calculation** Complex tool for supporting renovation measures. Benchmarks can be exploited for evaluation building operation and EoL (e.g. Pleiades, Athena Impact + Tally, SBToolCZ, LCAbyg)	**Pure Calculation** Obtained values enrich information to be exploited as, e.g., environmental benchmarking (e.g. SimaPro, LCAUS, The ZEB Tool, Sphera GaBi)
How can BIM impove the LCA during the design process? Workflow in LCA	Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization)		Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization)		Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization, technical equipment)	Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization, technical equipment, digital twin)	Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization, technical equipment, digital twin, management)	Possibility of systematic quantity take-off from BIM Automatic update in case of changes The use of BIM models for different purposes (LCA, operational energy, optimization, technical equipment, digital twin,facility management, CE)
What is the purpose of the visualization and which types should be used? Visualization in LCA		Purpose: **Identification of hotspots** Comparison of design options		Purpose: **Comparison of design options** Correlation, uncertainties and sensitivity analysis			Purpose: **Temporal distribution** Spatial distribution	

Figure 27: Design decision table (part 2)

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Appendix

A1 Design steps definition. Results of a survey amongst Annex participants

Using a spreadsheet-based survey, the design and project step definitions were compiled for 13 countries. Respondents from participating countries were asked to provide the definitions in their respective country, including a detailed description of the tasks and deliverables. Furthermore, participants reported on the presence and timing of relevant milestones, which provide a potential for the implementation of environmental target setting, environmental performance assessment and reporting of environmental performance assessment results. Five milestones were suggested for allocation:

(1) Definition of environmental performance targets
(2) Architectural design competition
(3) Building permit application
(4) Procurement of construction works
(5) Hand over and commissioning
(6) Decommissioning and deconstruction

Mapping of design stage and project phase definitions

As highlighted in the initial phase / step model concept (Figure A1-1), the various decisions relevant for improving the performance of buildings across their life cycle are not limited to design steps. They include other relevant stages of the building life cycle, such as the construction stage, the use phase – including maintenance and interventions, such as modernizations and refurbishments – as well as, eventually, the decommissioning of the building for recycling and end-of life treatment.
The survey showed that most countries are structuring design steps and project phases and related tasks based on a more refined structure than initially suggested. Based on the findings of the survey as well as the review of existing definitions from RIBA, this report hence proposes a generic definition of five design steps, including the pre-design (0-5) and three post-design phases / stages (6-8) incl. definition of related key tasks (Figure A1-1).

0	1	2	3	4	5	6	7	8
Strategic definition	Preliminary studies	Concept design	Developed design	Technical design	Manufacturing and construction	Handover and comissioning	Operation and management	End of use, re-cycling
Requirements & target setting, review of project risks & alternatives, site appraisal, clients brief	Feasibility studies, call for design competition	Concept, sketches, competition design	Elaboration of design, building permit application	Detailed technical design, procurement of construction works	(Pre)-Fabrication of construction products, Construction and supervision	As-built documentation, hand over, comissioning and testing	Facilities Management and Asset Management, Evaluation and improvement of building performance	Decommissioning of the building, deconstruction, reuse and recycling

Figure A1-1: Common definition of design steps and project phases with related key tasks.

Based on the responses to the survey amongst Annex participants, a mapping of the generic definition of design steps and project phases with the national definitions was prepared (Figure A1-2). This mapping aims at providing a visual overview for Annex countries to relate their national situation and definitions to the general definitions and recommendations formulated in the works of IEA EBC Annex 72.

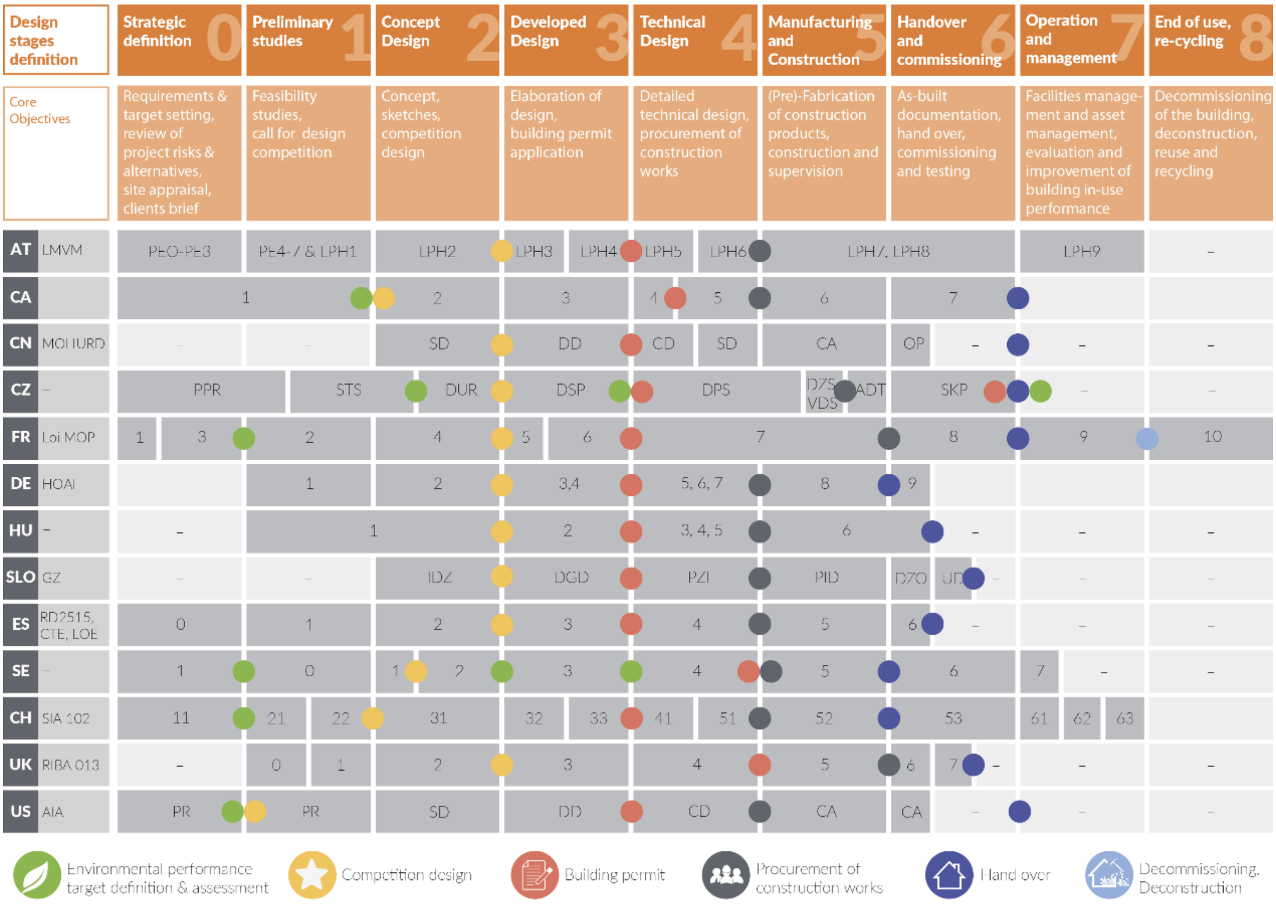

Figure A1-2: Country specific design processes

Overview and mapping of the common definition of design steps and project phases and typical tasks in relation to specific design tasks and milestones in the participating Annex countries.