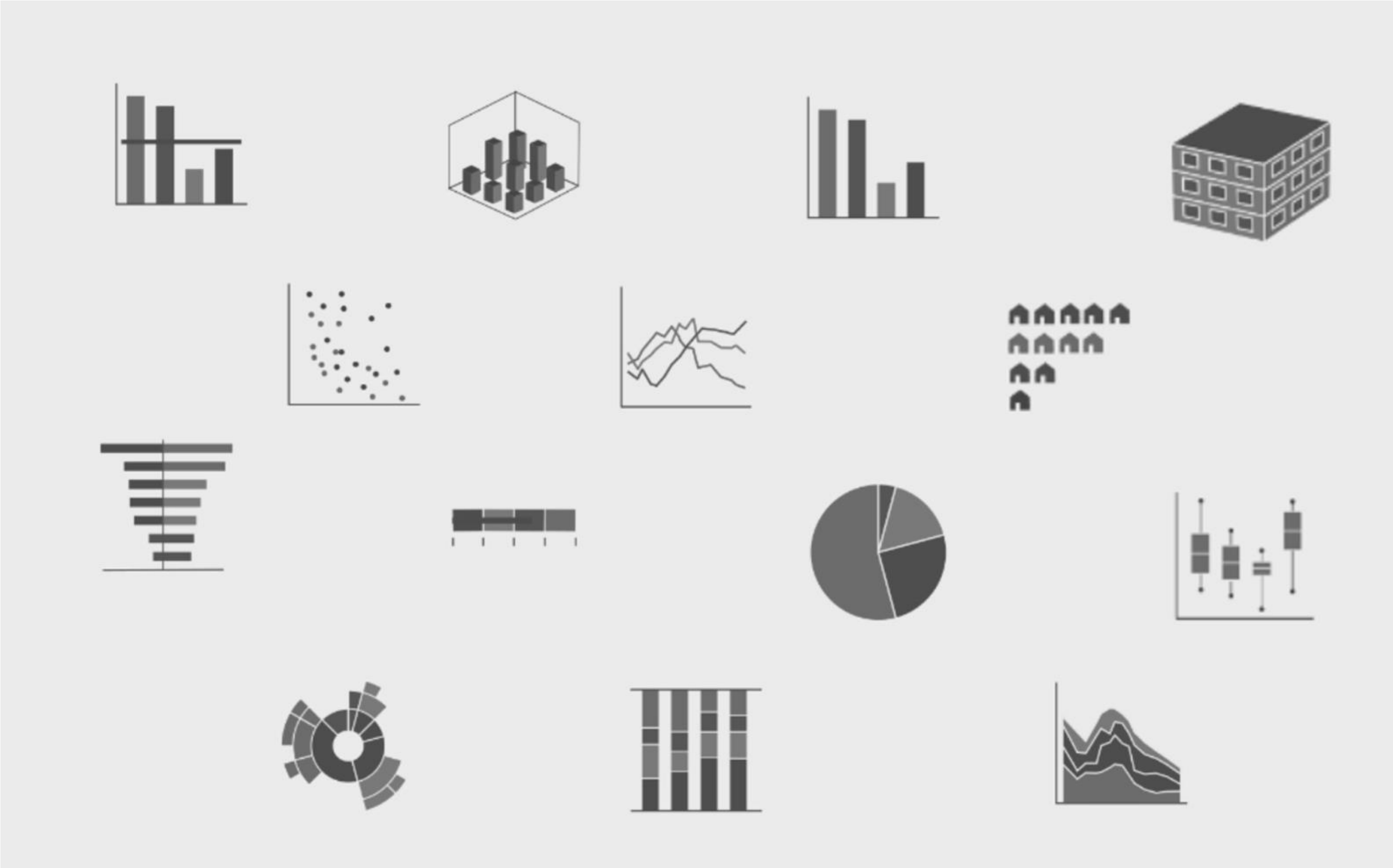
# Visualising LCA results in the design process

## A Contribution to IEA EBC Annex 72

April 2023



International Energy Agency

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# 1. Table of content

# 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 |
| **$CO_2$eq** | $CO_2$ 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 $CO_2$eq /unit of product or price] |
| **$CO_2$eq** | $CO_2$ 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 $CO_2$eq] |
| **Contractor** | Synonym: Service provider |
| **Clients** | Synonyms: financer, building owner, tenant, user |
| **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-$CO_2$eq /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 $CO_2$eq 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. |
| **Project commissioning** | Synonyms: project commissioners, authority, policy makers |
| **RSP** | Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011) |
| **Sustainability and certification expert** | Synonyms: consultant, auditor |

# Summary

Life Cycle Assessment (LCA) is increasingly used for decision-making in the design process of buildings and neighbourhoods. Therefore, visualisation of LCA results to support interpretation and decision-making becomes more important. The number of building LCA tools and the published literature has increased substantially in recent years. Most of them include some type of visualisation. However, there are currently no clear guidelines and no harmonised way of presenting LCA results. In this report, we review the current state of the art in visualising LCA results to provide a structured overview. Furthermore, we discuss recent and potential future developments. The review results show a great variety in visualisation options. By matching them with common applications of LCA we provide a structured basis for future developments. Case studies combining different kinds of visualisations within the design environment, interactive dashboards, and immersive technologies, such as virtual reality, show a big potential for facilitating the interpretation of LCA results and collaborative design processes. The overview and recommendations presented in this report provide a basis for future development of intuitive and design-integrated visualisation of LCA results to support decision-making.

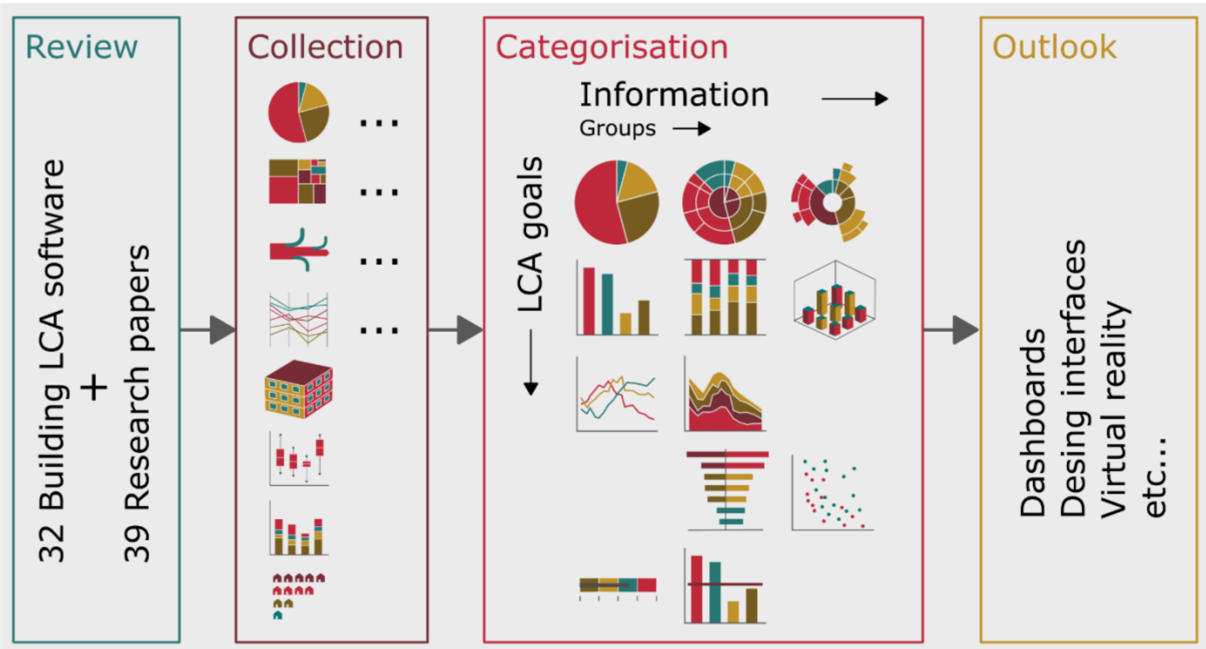



**Figure 1:** Graphical abstract

A publication was created at the same time as this background report. The publication can now be found under: Alexander Hollberg, Benedek Kiss, Martin Röck, Bernardette Soust-Verdaguer, Aoife Houlihan Wiberg, Sebastien Lasvaux, Alina Galimshina, Guillaume Habert. 2021. "Review of visualising LCA results in the design process of buildings" *Building and Environment*, 190, 107530, https://doi.org/10.1016/j.buildenv.2020.107530

# Introduction

## Need for visualisation of LCA results

Many aspects of the goal and scope phase of Life Cycle Assessment (LCA), such as functional unit or reference study period are defined in the national standards or the guidelines for Green Building Certification Systems. Furthermore, it is defined which environmental indicators should be provided as results, e.g., Sweden will only make Global Warming Potential (GWP) mandatory, while Switzerland looks at GWP, the Primary Energy Non-Renewable Total (PENRT) and a single-score indicator called *Umweltbelastungspunkte* (UBP). This indicator is specifically calculated for Switzerland based on the method of ecological scarcity (Frischknecht & Knöpfel, 2013). The DGNB system uses five environmental output indicators, and PENRT and the Primary Energy Renewable Total (PERT) in addition.

However, the form in which the LCA results should be communicated is not clearly defined. The EeBGuide (Wittstock et al., 2012) includes guidelines and templates for reporting of the results, but they aim at LCA experts. Furthermore, the European Joint Research Centre published a guideline for the interpretation of results for LCA experts (Zampori et al., 2016).The American Institute of Architects issued an extensive guide for building LCA, but only mention a benchmark comparison as support for interpretation (Joshi et al., 2010). There are no guidelines for interpretation of LCA results addressing a wider range of stakeholders involved in the building design.

As a result, the interpretation phase of LCA is still considered complex (Malmqvist et al., 2011; Zanghelini et al., 2018). Previous studies in this field (Cerdas et al., 2017; Frankl & Rubik, 2018) provide evidence that one of the obstacles to the broader use of LCA is the difficulties in the understanding and communication of results. Often the LCA results are not comprehensible for stakeholders such as policy and decision makers, although previous research demonstrates that the integration of life cycle aspects in the design process can improve decision-making involving non-experts (Baldassarri et al., 2016). In current practice, LCA results of buildings are used for certification and documentation, but barely to improve the building design or fundamental decisions related to the intended project (J. Basbagill et al., 2013; Wittstock et al., 2009). To use LCA results as basis for decision-making in the design process, the results have to be interpretable. At the same time, the interaction and cooperation between the different stakeholders and the exchange of relevant data and information between them should be promoted (Baldassarri et al., 2016).

Here, a particular emphasis on suitable visualisations can provide the necessary information and decision support. The importance of visualisation of LCA results has been widely discussed in the literature (Cerdas et al., 2017; Otto et al., 2003a; Sala & Andreasson, 2018). Visualisation techniques are usually used to communicate and analyse 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). The field of visualisation is closely related to the visual analytic field, which intends to reduce complex cognitive work and is "required to process large data sets towards enabling an informed decision-making" (Cerdas et al., 2017). The application of visualisation techniques has been expanded to different disciplines and domains, especially to those that involve an extensive use of data such as LCA. Hence, regarding the potential of the visual analytics to improve the understanding of LCA results, visualisation can facilitate efficient human cognitive capabilities by amplifying cognitive sensors, reducing search/lost, enhancing the pattern recognition and supporting easy reasoning, among others (Rio et al., 2019). Considering the different application areas of LCA (e.g. EPDs, design optimisation, or legislative decisions taken by policymakers), each application focuses on different stakeholders, and each one has its information requirement (Cerdas et al., 2017). As such, visualisation is key for decision support (Sala & Andreasson, 2018), but also optimisation of the design during the design process (Attia et al., 2013).

In 1996, Shneiderman defined a type by task taxonomy based on the common visual information seeking mantra “overview, zoom and filter, details on demand” (Shneiderman, 1996). If provide at the right time and in the right form, visualisations can support the information seeking. 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 visualisations are meaningful to designers, significant improvement of the environmental impact can be achieved (John Basbagill et al., 2017) and collaboration in interdisciplinary design teams is improved (Landgren et al., 2019).
While the need for visualisation is evident and often stated in the literature, few researchers have focussed on developing visualisations for building LCA results. These few studies such as (John Basbagill et al., 2017; Houlihan Wiberg, Lovhaug, et al., 2019; Kiss & Szalay, 2019; Otto et al., 2003b; Martin Röck et al., 2018b) propose novel types of visualisation often dedicated to one type of stakeholder involved in the design process of a building. These studies compare a few visualisation types, but a comprehensive review of visualisation of building LCA results is currently not available. Although the number of building LCA tools has been growing recently, they provide limited visualisation options. Currently, there is no harmonisation between the ways of visualising building related LCA results neither in practice nor in academia. This makes it especially difficult for practitioners and non-LCA expert to make use of the LCA results.

### Objectives

This report provides a review the current state of the art in visualising LCA results for buildings. Visualisations used in current building specific LCA software tools and the scientific literature are collected and clustered to provide an overview. This overview should provide a starting point for improved visualisation of LCA results and harmonisation. Furthermore, the potential of using the visualisation of LCA results in design interfaces that support decision-making in the design phase of buildings are discussed.

# 1. Method

The method consists of three parts. In the first part, typical applications for LCA in the design process are defined. In the second part, visualisation options from both building LCA software tool and the scientific literature in the field are collected and analysed. The building LCA tools are used to cover the state of the art in practice while the literature is analysed to review the current research. In the third part, categories to classify the different visualisation options found in the review are defined.

## 1.1 Definition of applications for LCA in the design process

Six typical applications for LCA are defined with relation to visualisations.

1. 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.

2. 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.

3. Correlation, uncertainty, and sensitivity analysis

   The analysis of the correlation of parameters or indicators becomes important when the aim is to optimise a design towards different criteria, see for example (Kiss & Szalay, 2020). 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.

4. 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, such as the planetary boundaries (Rockström et al., 2009) or 2000 Watt society (Jochem et al., 2004) can be used as benchmarks.

5. 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).

6. 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).

## 1.2 Analysis of existing visualisation options

The main research question for the review is "Which types of visualisation of LCA results are used when and for which stakeholders during the design process of buildings?" To answer this main research question, three sub-research questions are used for the review of both the building LCA software and the scientific literature.

1) Which design stage is targeted?
2) Which are the intended stakeholders?
3) Which visualisation types are used?

The currently most commonly used LCA software tools for buildings are reviewed. The list of tools is based on previous reviews (Cavalliere, 2018; Alexander Hollberg, 2016). The list was updated and extended based on input from the IEA EBC Annex 72 researchers. The final list includes 39 LCA software tools dedicated explicitly to buildings or building components. The majority of tools have been developed for whole building LCA, but most of them also allow for the assessment of individual components. It cannot be guaranteed that all building LCA tools are included, but we are sure to have covered the most common ones based on the expert feedback. We therefore assume the analysed tools to be sufficient to provide an overview of the field. The information about the tools was collected based on free demo versions, experts' feedback using the tools and freely available online material such as tutorials, demo videos, and handbooks. Tools that were not published or where there was no information accessible were excluded from the review. Seven of these tools were excluded from the analysis due to lack of information leading to 32 analysed tools.

To identify different visualisation approaches presented in scientific literature, we conducted a systematic literature review, based on the protocol for Systematic Literature Review (SLR) and including additional studies via the 'snowball' approach (Higgins & Green, 2008; Wohlin, 2014). As the aim is to identify studies addressing the visualisation of LCA aspects related to buildings and construction, we conducted the systematic search using the keyword string: "(LCA OR life cycle assessment OR life cycle analysis) AND (building OR construction) AND (visualization OR visualisation)". The search was performed via 'ScienceDirect', searching the selected terms in the papers' “abstract, title or author-specified keywords”. Documents identified through the SLR protocol were screened based on their title and abstract and excluded if out of scope (e.g. if they were not addressing buildings or construction). The database search was conducted in April 2020. The addition of snowball studies continued until submission of the manuscript.

The SLR provided 32 papers. 16 papers were removed from the review as the main focus was not LCA of buildings. 23 papers were added following the snowball approach and using expert knowledge. Primarily, literature focusing on visualisation methods and development of new LCA methods or tools was added. Secondly, case studies were added that provide novel or unique types of visualisations. As there are a large number of building LCA case studies using at least one type of visualisation, it is impossible to include all. Therefore, the snowball approach was stopped when no new types of visualisations could be found. Finally, 39 papers were included. Although we selected literature on visualisation method or tool development first, most of the analysed papers present case studies. Eleven papers aim at providing visualisation methods or examples for building LCA. The majority of analysed papers are scientific journal papers followed by peer-reviewed papers in conference proceedings. One book was added as grey literature, because this type of visualisation could not be found in the peer-reviewed literature.

## 1.3 Definitions for classification

### Definition of design stages

Design stages in the planning process of buildings are usually defined differently by different stakeholders and in different national contexts. Furthermore, no common definition is used in the analysed literature to further specify the intended design stages. Therefore, we only differentiate between an early and a detailed design phase and use the joint model proposed in **Figure 2:** . We define the early design phases as including the strategic definition, preliminary studies and the concept design phase, typically including sketches and the competition design (phases 0 to 2). Often there is a break in the tools and sometimes the design team after this phase. The detailed design phase describes the development of the design until the completion of the building, including the building permit application, tendering, construction drawings and the construction itself (phases 3 to 6). The operational and end-of-life phase are significant considering the life cycle. However, the user influence in the operational phase is very big and often unpredictable. Monitoring completed buildings would allow stakeholders typically involved only in early design phases to learn from previous decisions. Nevertheless, stages 7 and 8 are excluded here.

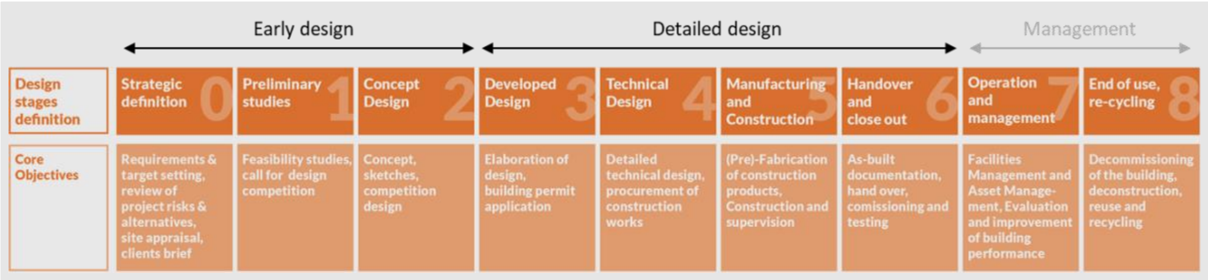



**Figure 2:** Proposal for a joint model of building design and project phases

## Definition of stakeholder groups

Three groups of stakeholders, which can be expected to have an increasing level of expert knowledge regarding LCA are defined based on their role in the design process.

1) *Decision-makers* are defined as the group responsible for the final decision. Often these stakeholders are responsible for the budget or the ones paying for the building. The group includes private and public clients, individual building owners, but also investors, project developers, housing associations, portfolio managers, policymakers, etc. In the case of participatory design processes, citizens can also be included in this group.

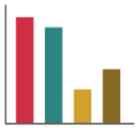
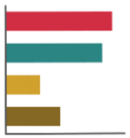
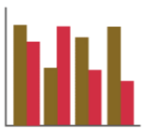
2) *Building design professionals* is used as a term to summarise all building experts without specific LCA training. The group mainly consists of architects and engineers involved in the design process.

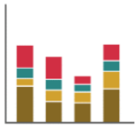
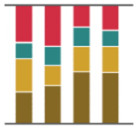
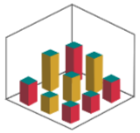
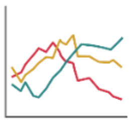
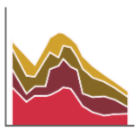
3) *LCA experts* are a group typically consisting of sustainability consultants, auditors for GBCS, and researchers.

## Definition of visualisation types

The different types of visualisation found in the review are sorted and structured. Charts with similar names but referring to the same visualisation type such as radial chart and spider chart are combined. **Error! Not a valid bookmark self-reference.** provides an overview with icons of the 27 visualisation types their advantages and disadvantages and examples for application from the literature.

**Table 1:** Visualisation types found in the review with examples of application, advantages, and disadvantages

| # | Name | Icon | Description | Examples of application | Advantages | Disadvantages |
|---|---|---|---|---|---|---|
| 1 | Pie chart / donut chart |  | A circle divided into sectors which are proportional to the share of the category they represent. The sectors can be labelled with additional textual information. | Share of impact between building elements (Alexander Hollberg et al., 2016) or life cycle stages (Paulsen & Sposto, 2013). | Quick overview, often used, and easy to understand | Only one variable can be displayed at once |
| 2 | Multi-level Pie Chart |  | Same as the pie chart, but each sector can be further divided into subsectors that represent categories within that sector. | Share of impact between materials (first level) and life cycle stages (second level) (Kiss & Szalay, 2019); Share of emissions between building types in a neighbourhood (level 1-2), and life-cycle-stage (level 3) (Resch et al., 2020). | Multi level hierarchy can be displayed, can be enriched and enlarged by integrating interactive elements. | Hierarchy needs to provide same depth for each main category. Same angle (and represented value) in different levels will appear as different plotted area, which can be misleading. |
| 3 | Sunburst |  | Same as the multi-level pie chart with subsectors that do not necessarily fill the parent sector. Usually 2-5 levels are possible to display. Can be increased in interactive plots. | Share of impact within the LCA stages, building components down to materials (Kiss & Szalay, 2020). | Multi level hierarchy can be displayed. With interactive elements, many leaves are possible. | Same angle (and represented value) in different levels will appear as different plotted area, which can be misleading. |
| 4 | Vertical bar chart |  | Rectangular bars in a vertical chart with proportional height/length to the values represented. Expresses relation of categorical value against a numerical on the same scale. | Comparison of building façade composition alternatives for impact (Bernardette Soust-Verdaguer et al., 2018); Comparison of impact in different locations (Oyarzo & Peuportier, 2014). | Quick overview, often used, and easy to understand | One value per variable is possible, and if a large number of bars is included can be more difficult to read the labels/tag of the values in a horizontal position. |
| 5 | Horizontal bar chart |  | Same as the bar chart but horizontal. | Comparison of different materials' performance (Kiss & Szalay, 2020) or embodied impacts (Resch et al., 2020; B Soust-Verdaguer et al., 2020). | Quick overview, often used, and easy to understand, also allows to include a large number of bars. | One value per variable is possible. |
| 6 | Grouped bar chart |  | Same as the bar chart but includes more than one series to horizontally compare different categories. | Comparison of life cycle impacts of different design alternatives (B Soust-Verdaguer et al., 2020); Comparison of life cycle impacts of different materials (thickness, heating system, isolation material and type of glazing) (Alexander | Quick comparison of different series of values. Series can be even plotted with different units by applying a secondary y axis on the right side. | One value per variable and series is possible. The comparison between values with different units is difficult. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | Hollberg & Ruth, 2016; Kiss & Szalay, 2020). | | |
| 7 | Stacked bar chart |  | Same as the bar chart but includes more than one series to vertically compare different categories. | This option allows to compare different categories (as the grouped bar chart) but also the grouped total, for example the comparison of the embodied emissions produced by different materials and the contribution of the different building parts (Lobaccaro et al., 2018). | Possible to compare the relative weight of different series of values. | Only absolute values can be displayed |
| 8 | Normalised bar chart |  | Similar to the stacked bar chart but includes more than one series to vertically compare different categories. | Comparison of the environmental impacts in percentages of different design alternatives, for example, the contribution of life cycle stages' of environmental impacts over the building lifespan (Eberhardt et al., 2019). | Quick comparison of different series of values. Also allows to compare the sum of them (partial and total values per series and bar). | One value per variable and series is possible |
| 9 | Multiple series 3D bar charts |  | Similar to the grouped bar chart but provides three axes to compare different series of values. | Comparison of the environmental impacts of different design alternatives on two axes, for example heating systems and insulation material for renovation measures (Alexander Hollberg & Ruth, 2013). | Extends dimensionality compared to 2D bar charts. | Difficult to overview, the visibility depends on view angle |
| 10 | Line chart |  | Display information as a series of (ordered) data points connected by straight line segments. Can show one or several lines. An error band could be included to visualise the distribution of results similar to the box plot, but continuous. | Change of cumulated emission over years (Eberhardt et al., 2019); Cumulated embodied and operational impact change over years (M. Röck et al., 2020); Monthly energy demand within a year (Tronchin et al., 2019). | Can show how values change over a continuous variable (e.g. time). | Can cause misunderstanding if the cut of y axis is improperly done |
| 11 | Stacked area chart |  | Similar to a line chart but the area below the line is filled. Multiple series of data are plotted on top of each other, resulting the filled area to express the sum of the data. The values could also be normalised to provide a normalised stacked area chart | Change and share of emission factors of grid-electricity over time and within neighbouring countries (Vuarnoz & Jusselme, 2018). | Can shows how different group/series of values change over a continuous variable (e.g. time) | Can cause misunderstanding if the cut of y axis is improperly done |

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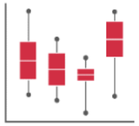
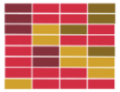
| 12 | Sankey /Alluvial Diagram |  | Flow diagram where the width of the arrows is proportional to the flow quantity they are representing. | Representation of flows, energy distribution(Jusselme et al., 2018); representation of financial and environmental costs during the building life cycle (Miyamoto et al., 2019). | Specific type of flow diagram | Can cause confusion if the organization of the nodes and the connections is not carefully considered |
| 13 | Box plot |  | A representation of groups of numerical data by their quartiles. One box refers to a series of numerical data (usually >1000) | Deviation of the hourly impact of grid electricity within a year (Kiss et al., 2020); Distribution of expected environmental impact within alternative designs (A Hollberg et al., 2019); Distribution of impact within case studies (Martin Röck et al., 2018b). | Possible to compare distributions instead of single values | Statistical sampling may bias the results |
| 14 | Tree map |  | Tree maps display hierarchical (tree-structured) data as a set of nested rectangles. The area of a rectangle is proportional to the data. | Share of energy and associated emissions of grid electricity originating from different countries (Vuarnoz & Jusselme, 2018). | Express the relative weight with different size shapes. | Limited information provided |
| 15 | Heat map |  | Individual data contained in a matrix form is coloured by the third dimension. | Percentage of impact savings within building elements and impact categories (Eberhardt et al., 2019); Variation of the impact of hourly grid electricity within days of a year and hours of day (Kiss et al., 2020; Vuarnoz & Jusselme, 2018). | Useful to categorize or organise a set of variables in a hierarchy. | When a large number of values is included, it can be difficult to understand and identify (rank or visualize) the categories. |
| 16 | Radial chart / spider chart / polar chart |  | Type of diagram that allows to show more than one series of values and related them to multiple categories. | Comparison of different alternatives and environmental impact categories (Oyarzo & Peuportier, 2014). | Possible to visualize multiple indicators. | The order, origin, and scale of the axes heavily influence the appearance and the interpretation of results (Odds, 2011), which can easily lead to bias. |
| 17 | Tornado chart |  | Special type of horizontal bar chart, where the categories are ordered so that the largest is on the top. | Expression of design parameter influence (positive or negative) on performance (John Basbagill et al., 2017). | Quick comparison of a sets of data series where different variables can be displayed | Can display only two sets of data series. |

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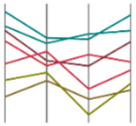
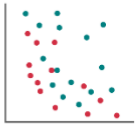
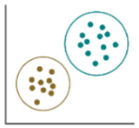
| 18 | Parallel coordinates |  | Allows to represent the relations between multiple features with even different scale. Each vertical bar represents one variable and each line is one observation /individual/case. | Display the different design variants that form the supporting points for the meta-model (Jusselme et al., 2017). Used in multi-objective optimization to show the evolution of the parameters (Kiss & Szalay, 2020). | Useful to visualize many variables and many observations | The appearance depends on the order of variables. |
| 19 | Pictorial unit chart |  | Allows to represent and compare the relation (in magnitude) between different elements by using icons to represent them. | Not an example directly related to building LCA, but could be adapted: Comparison of different dietary patterns related to meat consumption (Goossens et al., 2018). | Useful to graphically express a comparison between more than two values. The use of icons can help to express a message for non-expert audience (such as designers, policy makers, clients) | Limited information about values, only generic comparison of variables. |
| 20 | Pictorial fraction chart |  | Similar to the pictorial unit chart but use one icon to represent and compare the relation (in magnitude) of different aspects of the element (icon). | Visualisation of the environmental impact per resident of a building (Alexander Hollberg & Klüber, 2014). | Useful to graphically express a comparison between two values. The use of icons can help to provide a clear and simple message to non-expert audience | Limited to the comparison of two values. |
| 21 | Scatter plot |  | Numerical two-dimensional data in Cartesian coordinates, where each dot represents a dataset | Solutions in the objective space of a bi-objective optimization (embodied, operational impact) (Kiss & Szalay, 2020) or GWP and investment costs (Klüber et al., 2014). | Multiple categorical dimensions can be expressed with using colour, size, shape, etc. | When a large number of dimensions are displayed it may be difficult to read. Also, there is risk of overplotting. |
| 22 | Cluster |  | Similar to the scatter plot but groups values into clusters. | Comparison and grouping into clusters of values. Clusters representing the energy performance classes (M. Röck et al., 2020). | Multiple categorical variables can be showed and grouped with using colour, size, shape, etc. | When a large number of dimensions are displayed it may be difficult to read. Also, there is risk of overplotting. |
| 23 | 3D Scatter plot |  | Numerical three-dimensional data in Cartesian coordinates, where each dot represents a dataset. | Solutions in the objective space of a three-objective optimization (Klüber et al., 2014); Correlation of energy demand to two building parameters(Jusselme et al., 2018). | Multiple categorical variables can be expressed with using colour, size, shape, etc. | When too many dimensions are included, it may be difficult to understand. Also, the angle may be an issue regarding visibility. |
| 24 | 3D Colour code |  | Parts of the represented item is coloured according to the associated numeric data. | The building can be used to intuitively identify the elements with the highest impact as part of a hot spot analysis, for example: Improvement potential of building elements (Martin Röck et al., 2018b); Share of impact/energy | Useful to visualize the distribution and magnitude (colour code scale) of the variables in the usual design environment (CAD/BIM). This can help to get a closer relation to the object. | The visibility angle may be an issue. |

| | | | | | |
|---|---|---|---|---|---|
| | | | loss of surfaces within the building life cycle (Kiss & Szalay, 2019); Emission factors of building elements projected in VR (Houlihan Wiberg, Lovhaug, et al., 2019) | | |
| 25 Bubble map |  | Combines a map visualisation (2D image) with the bubble chart. The sizes of the bubbles are proportional to the magnitude they represent. | Used for display the location of the manufacturing points of different products (Houlihan Wiberg, Wiik, et al., 2019). | Useful to visualize the variation of a variable in a region (map support). | The scale and visibility may be an issue. |
| 26 Colour map |  | Combines a map visualisation (2D image) and its correlation with other variables and/or magnitudes. | Combines the map visualization with a colour scale in order to assist into intuitive understanding of environment (Samsel et al., 2019). | Useful to georeference the values' distribution, and a size reference of the values magnitude. | The scale and visibility (overlapping) may be an issue. |
| 27 Scale |  | Represents the visualisation of a bar graph indicating the correlation with a benchmark, reference or target value. | Common in different building LCA tools (e.g. Lesosai, CAALA, Bombyx), to show the performance of the building to benchmarks. | Useful to focus on a single variable | Limited information can be shown. |

In the analysed literature, the general goal of the visualizations is to show the relation between design variables or design alternatives and the environmental impact. In most cases, there are multiple options to visualise the relation. Therefore, we introduce several categories. Four aspects are used to categorize the collection of visualizations specifically for the use in a building LCA study:

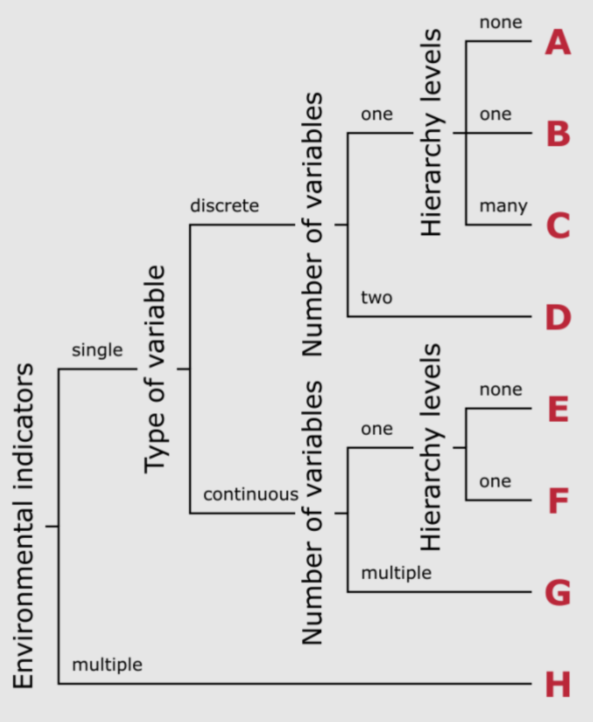
1. Number of environmental indicators
   The representation of the environmental impact as a single-score value or multiple values is often discussed by LCA experts (Kägi et al., 2016). Therefore, the capability of visualising single or multiple indicators with different units in one graph (without aggregation) is used as one differentiation. If the aggregation into a global indicator is possible, it is seen as one indicator from the perspective of visualization, because the values have the same unit and can be plotted on the same axis.

2. Type of variables
   Visualised variables can be either discrete (e.g. construction material options or design alternatives) or continuous (e.g. fenestration ratio or insulation thickness), which is a key aspect in choosing the visualization type. Each variable is plotted on a separate axis.

3. Number of variables
   The number of evaluated variables can range from one (e.g. comparing a few fixed design alternatives will result in one categorical axis) to many (in a complex optimization problem) and the possible number of visualised variables are limited by the dimensionality of the plot. Furthermore, it is important to mention that a colour scale or colour code can be seen as expressing another dimension of information. In general, the sum of indicators and variables gives the dimensionality of the graph.

4. Hierarchy levels
   The hierarchic decomposition of the results plays a key role in finding hotspots. The hierarchy may refer to lifecycle stages, the decomposition of the object (e.g. building components) or even to environmental aspects in case of an aggregated indicator. Different visualisations can be used to express hierarchic data, but the level is limited by the type of visualisation. We differentiate between non-hierarchic charts, visualisations with one level of hierarchy (parent-child), and multiple (deep) levels of hierarchy.

Using these aspects for categorisation, eight groups of visualisation types are identified within the collected visualisations. The categorisation process is shown in Figure 3.




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

**Figure 3:** Categorisation steps to define groups of visualisation types and description of the groups

# 2. Results

## 2.1 General analysis of building LCA tools and the literature

The full table of the review of the building LCA tools and the scientific literature can be found in **Table 2** and **Table 3**.

**Table 2:** Results of review of building LCA tools (If the analysed tool completely matches one of the boxes, it is marked with x, while (x) is used, if it matches partially.)

| | | | Goal | | Design stage | | Stakeholders | | | Visualisation type | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Country of origin | Name | Whole building LCA | Building component LCA | Early | Detailed | Decision makers | Building design professionals | LCA experts | Pie chart / donut chart | Multi-level pie chart | Sun burst | Vertical bar chart | Horizontal bar chart | Grouped bar chart | Stacked bar chart | Normalised bar chart | Multiple series 3D bar chart | Line chart | Stacked ordered area chart | Sankey | Box plot | Tree map | Heat map | Radial / spider / polar chart | Tornado chart | Parallel coordinates | Pictorial unit chart | Pictorial fraction chart | Scatter plot / Pareto front | Cluster | 3D Scatter plot | 3D Colour code | Colour map | Bubble map | Scale | Number of visualisations | Website |
| | | | 27 | 5 | 7 | 25 | 0 | 28 | 13 | 13 | 0 | 3 | 11 | 4 | 14 | 18 | 5 | 0 | 4 | 1 | 4 | 1 | 2 | 0 | 2 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 2 | 1 | 0 | 5 | | |
| 1 | AT | eco2soft | | x | | x | | x | (x) | | | | | | | | | | | | | | | | | | | | | | | | | | | x | 1 | https://www.baubook.info/eco2soft/?SW=27&lng=2 |
| 2 | AU | eTool LCD | x | (x) | | x | | x | | | | | | x | | | | | | | | | | (x) | | | | | | | | | | | | | 1 | https://etoolglobal.com/ |
| 3 | BE | Totem | x | | | x | | x | | x | | | | | | x | x | | | | | | | | | | | | | | | | | | | x | 4 | https://www.totem-building.be/ |
| 4 | CDN | Athena Impact Estimator | x | | x | | | x | | x | | | | x | x | x | | | | | | | | | | | | | | | | | | | | | 4 | http://www.athenasmi.org/our-software-data/impact-estimator/ |
| 5 | CDN | Athena EcoCalculator | | x | x | | | x | | x | | | | x | x | x | | | | | | | | | | | | | | | | | | | | | 4 | http://www.athenasmi.org/our-software-data/ecocalculator/ |
| 6 | CH | Bombyx | x | | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | x | | | x | 2 | https://www.food4rhino.com/app/bombyx |
| 7 | CH | Lesosai | x | (x) | | x | | x | (x) | x | | | x | | x | x | | | | | | | | | x | | | | | | | | | | | | 5 | http://www.lesosai.com/en/ |
| 8 | CH | Eco-Sai | x | (x) | | x | | x | (x) | x | | | x | | x | x | | | | | | | | | | | | | | | | | | | | | 4 | http://www.eco-sai.com |
| 9 | DE | CAALA | x | (x) | x | (x) | | x | | x | | | x | | | | | | | | | | | | | | | | | | | | | | | x | 3 | https://caala.de/ |
| 10 | DE | Legep | x | | | x | | (x) | x | x | | | x | | | x | | | x | | x | | | | | | | | | | | | | | | | 5 | https://legep.de/?lang=en |
| 11 | DE | Generis | x | (x) | | x | | (x) | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | | 1 | www.generis.live |
| 12 | DE | eLCA | x | (x) | | x | | | x | | | | x | | | x | x | | | | | | | | | | | | | | | | | | | | 3 | https://www.bauteileditor.de/ |
| 13 | DK | LCAbyg | x | | | x | | x | (x) | | | | x | | x | | x | | x | | | | | | | | | | | | | | | | | | 4 | https://www.lcabyg.dk/ |
| 14 | ES | TCQM-GMA | x | (x) | | x | | x | x | | | | | | x | | | | x | x | x | | | | | | | | | | | | | x | | | 5 | https://itec.es/programas/tcqi/gestion-ambiental/ |
| 15 | ES | NECADA | x | (x) | | x | | x | x | | | | x | | x | | | | | | | | | | x | | | | | x | | | x | | | | 5 | http://project.necada.com/ |
| 16 | FI | OneClick LCA | x | (x) | x | | | x | | x | | | x | x | x | x | | | x | | x | | x | | | | | | | | | | | | | | 8 | https://www.oneclicklca.com/ |
| 17 | FR | ClimaWin | x | (x) | | x | (x) | x | x | | | | x | | x | x | | | | | | | | | | | | | | | | | | | | | 3 | www.bbs-logiciels.com/clima-win/ |
| 18 | FR | ELODIE | x | (x) | (x) | x | (x) | x | x | | | x | x | | x | x | | | | | | | | | | | | | | | | | | | | | 4 | www.elodie-cstb.fr |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | FR | Pleiades ACV | x | (x) | (x) | x | (x) | x | x | | | | x | | x | x | x | | | | | | | | | | | | | | | | | | | | 4 | www.izuba.fr |
| 20 | FR | ThermACV | x | (x) | | x | (x) | x | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | x | 3 | www.logicielsperrenoud.com |
| 21 | FR | ArchiWIZARD | x | (x) | | x | (x) | x | x | | | x | | | | | | | | | | | | | | | x | | | | | | | | | | 3 | fr.graitec.com/archiwizard/ |
| 22 | FR | Vizcab | x | (x) | | x | (x) | x | x | | | x | | | | | | | | | | | | | | | x | | | | | | | | | | 2 | vizcab.io |
| 23 | FR | COCON-BIM | x | (x) | | x | (x) | x | x | | | | x | | x | x | | | | | | | | | | | | | | | | | | | | | 3 | www.cocon-bim.com |
| 24 | NL | MRPI MPG - software | x | | | x | | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | http://www.mrpi-mpg.nl/Home/Home |
| 25 | NO | ZEB Tool | x | (x) | (x) | x | | x | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | | 1 | Internal use only |
| 26 | SE | BM2 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 | https://www.ivl.se/sidor/vara-omraden/miljodata/ byggsektorns-miljoberakningsverktyg.html |
| 27 | SE | Klimatkalkyl | | x | | x | | x | | x | | | x | | | x | | | | | | | | | | | | | | | | | | | | | 3 | https://www.trafikverket.se/tjanster/system-och-verktyg/Prognos--och-analysverktyg/Klimatkalkyl/ |
| 28 | UK | BRE Lina | | x | | x | | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | https://www.bre.co.uk/lina |
| 29 | US | EC3 tool | x | | | x | | x | | | | | | | | x | | | | | x | x | | | | | | | | | | | | | | | 3 | https://buildingtransparency.org/dashboard |
| 30 | US | Tally | x | | x | | | x | | x | | | | | x | x | x | | | | | | | | | | | | | | | | | | | | 4 | https://choosetally.com/ |
| 31 | US | Bees | | x | | x | | x | | | | | | | | x | | | | | | | | | | | | | | | | | | | | | 1 | https://www.nist.gov/services-resources/software/bees |
| 32 | UK | H\B:ERT | x | | x | | | x | | | | | | | | x | | | | | | | x | | | | | | | | | | | | | | 2 | https://www.hawkinsbrown.com/services/hbert |

**Table 3:** Literature review (If the analysed paper completely matches one of the boxes, it is marked with x, while (x) is used, if it matches partially.)

| | | Type | | | Aim | | | Stake holders | | | Visualisation type | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Reference | Journal | Conference | Grey | Visualisation | Method/tool | Case study | Decision makers | Building design professionals | LCA experts | Pie chart / donut chart | Multi-level Pie Chart | Sun burst | Vertical bar chart | Horizontal bar chart | Grouped bar chart | Stacked bar chart | Normalised bar chart | Multiple Series 3D Bar Charts | Line chart | Stacked ordered area chart | Sankey | Box plot | Tree map | Heat map | Radial / spider / polar chart | Tornado chart | Parallel coordinates | Pictorial unit chart | Pictorial fraction chart | Scatter plot / Pareto front | Cluster | 3D Scatter plot | 3D Colour code on building | Colour map | Bubble map | Scale |
| | | 24 | 14 | 1 | 11 | 12 | 16 | 6 | 28 | 17 | 2 | 2 | 1 | 11 | 4 | 10 | 10 | 2 | 1 | 7 | 1 | 2 | 8 | 1 | 5 | 2 | 2 | 4 | 1 | 1 | 12 | 2 | 2 | 6 | 1 | 1 | 1 |
| 1 | (John Basbagill et al., 2017) | x | | | x | | | | x | | | | | x | | | | | | | | | x | | | | x | | | | x | | | | | | |
| 2 | (Cerdas et al., 2017) | | x | | x | | | | | x | | | | | | | | | | | | | | | x | | | | | | | | | | | | |
| 3 | (Duprez et al., 2019) | x | | | | x | | | x | x | | | | x | | x | | | | | | | | | | | | | | | | | | | | | |
| 4 | (Eberhardt et al., 2019) | x | | | | | x | | | x | | | | | | (x) | x | x | | x | | | | | x | | | | | | | | | | | | |
| 5 | (Gilles et al., 2017) | x | | | | x | | | x | | | | | | | | | | | | | | | | | | | | | | x | | | | | | |
| 6 | (Goossens et al., 2018) | x | | | | x | | x | | x | | | | x | | x | x | | | | | | | | x | | | | x | | | | | | | | |
| 7 | (Hester et al., 2018) | x | | | | x | | | x | | | | | | | | | | | | | | | | | | x | | | | x | | | | | | |
| 8 | (Alexander Hollberg et al., 2016) | | x | | | | x | | x | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | |
| 9 | (Alexander Hollberg et al., 2019) | | x | | | | x | | x | | | | | | | | | | | | | | x | | | | | | | | | | | | | | |
| 10 | (Alexander Hollberg & Ruth, 2016) | | x | | | | x | | x | | | | | | | x | | | x | | | | | | | | | | | | | | | | | | |
| 11 | (Alexander Hollberg & Ruth, 2013) | x | | | | x | | | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | |
| 12 | (Alexander Hollberg & Klüber, 2014) | | | x | | | x | | x | | | | | | | | x | | | | | | | | | | | | | x | | | | | | | |
| 13 | (Jusselme et al., 2017) | | x | | x | | | | x | x | | | | | | | | | | | | | | | | | | x | | | | | | | | | |
| 14 | (Jusselme et al., 2018) | x | | | | | x | | | x | | | | | | | | | | | | x | | | | | | x | | | | | x | | | | |
| 15 | (Kiss & Szalay, 2019) | | x | | x | | | | x | | | x | | | | | | | | | | | | | | | | | | | | | | x | | | |
| 16 | (Kiss & Szalay, 2020) | x | | | | | x | | x | x | | | x | x | x | x | | | | | | | | | | | | x | | | x | | | | | | |
| 17 | (Kiss et al., 2020) | x | | | | | x | x | | x | | | | x | | | x | x | | x | | | x | | x | | | | | | | | | | | | |
| 18 | (Klüber et al., 2014) | | x | | | | x | | x | x | | | | | | | | | | | | | | | | | | | | | x | | x | | | | |
| 19 | (Le et al., 2018) | x | | | | | x | | x | x | | | | | | x | | | | | | | | | | x | | | | | | | | | | | |
| 20 | (Lobaccaro et al., 2018) | x | | | | | x | | | | | | | | | x | x | | | x | | | | | | | | | | | x | | | | | | |
| 21 | (Miyamoto et al., 2019) | | x | | x | | | | x | x | | | | | | | | | | | | x | | | | | | x | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | (Mousa et al., 2016) | | x | | x | | (x) | x | | | | | | | | | | | | | | | | x | | | |
| 23 | (Otto et al., 2003a) | x | | x | | | | | x | | | | | | | | | | | | | | x | | | | |
| 24 | (Oyarzo & Peuportier, 2014) | x | | | | x | | x | x | | | x | | | | | | | | | x | | | | | | |
| 25 | (Paulsen & Sposto, 2013) | x | | | | x | | x | | x | | | | | x | | | | | | | | | | | | |
| 26 | (Resch & Andresen, 2018) | x | | | x | | | | x | | x | x | x | | | | | x | | | | x | | | | | |
| 27 | (Resch et al., 2020) | x | | | x | | | x | | | | x | x | x | x | x | | | | | | x | | | | | |
| 28 | (M. Röck et al., 2020) | x | | | x | | x | x | | | | | | | x | x | | x | | | | x | x | | | | |
| 29 | (Martin Röck et al., 2018b) | x | | x | | | | x | | | | | | | | | | x | | | | | | x | | | |
| 30 | (Martin Röck et al., 2018a) | | x | x | | | | x | | | | | | | | | | x | | | | | | x | | | |
| 31 | (Samsel et al., 2019) | x | | x | | | | | x | | | | | | | | | | | | | | | | x | | |
| 32 | (Scherz et al., 2018) | | x | | x | | | x | | | | | | | | | | | | | | | | | | | x |
| 33 | (Bernardette Soust-Verdaguer et al., 2018) | x | | | | x | | x | | | | x | | | x | | | | | | | | | | | | |
| 34 | (B Soust-Verdaguer et al., 2020) | x | | | | x | | x | | | | x | x | | | | | | | | | | | | | | |
| 35 | (Tronchin et al., 2019) | | x | | x | | x | | | | | | | | | x | | x | | | | x | | | | | |
| 36 | (Houlihan Wiberg, Lovhaug, et al., 2019) | | x | x | | | x | x | | | | | | | | | | | | | | | | x | | | |
| 37 | (Houlihan Wiberg, Wiik, et al., 2019) | | x | x | | | | x | (x) | | | x | | | | | | | | | | | | x | | x | |
| 38 | (Vuarnoz & Jusselme, 2018) | x | | | | x | | | x | | | | | x | | x | x | | x | x | | x | | | | | |
| 39 | (Zea Escamilla & Habert, 2015) | x | | | x | | x | x | | | | x | | | x | | | | | | | x | | | | | |

The analysis showed that most building LCA tools focus on the detailed design stages (see Figure 4) while there are slightly more scientific papers addressing the early design stages. Most tools address several design stages but have a focus either on the early or detailed design stages. If this differentiation was not provided by the tool developers, expert judgement was used for classification.
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 visualisations presented in the literature address building design professionals. About one third focusses on LCA experts, while only 12% address decision-makers.

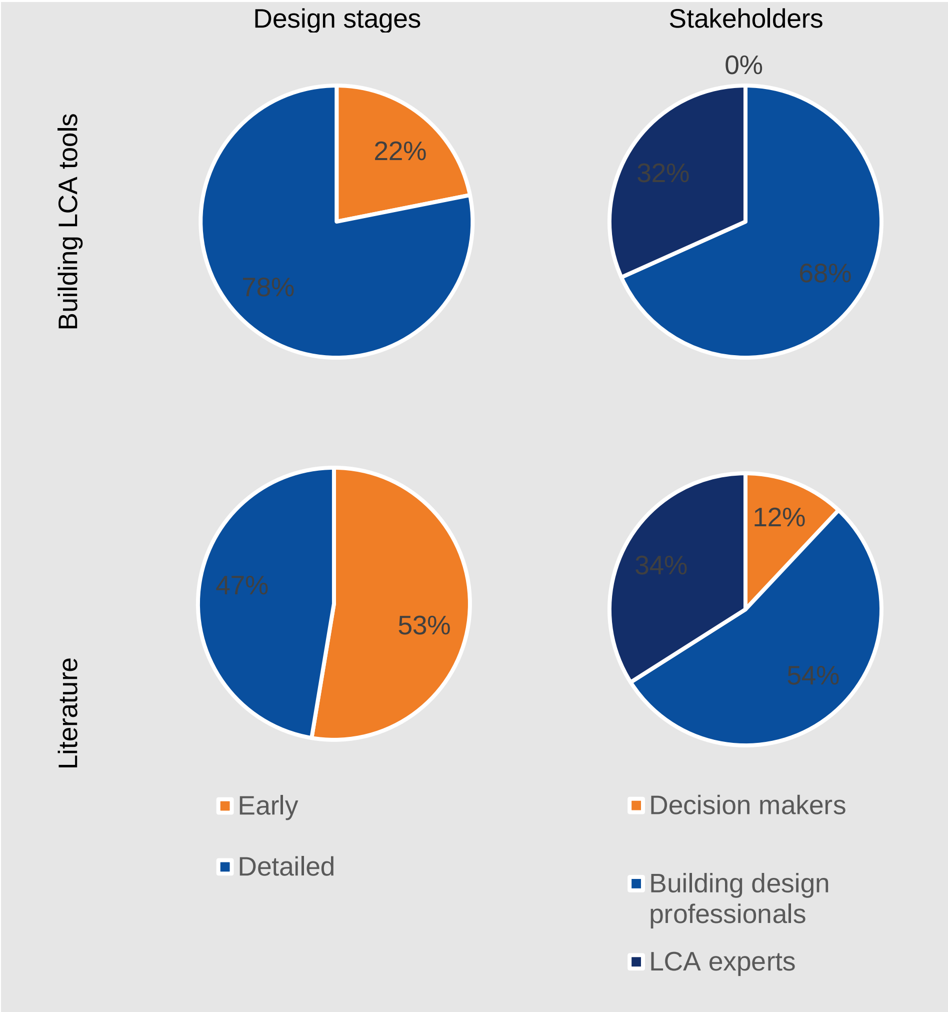



**Figure 4:** Design stages and stakeholders mainly addressed by building LCA tools and the literature

## 2.2 Types of visualisations used

Counting the number of visualisations used by the building LCA tools reveals that most tools use more than one, but only a few types of visualisation, e.g., pie chart and bar chart. Only one of the analysed tools does not provide any visualisation. On average, three types of visualisations are used per tool, while the tool with most different types of visualisations uses eight types.

Bar charts and variations of it such as grouped or stacked bar charts are the clear majority, followed by pie charts (see Figure 3). Those kinds are used by more than ten tools and can therefore be seen as common visualisations. Furthermore, the use of 'complex' visualisations with a large amount of information, such as scatter plots or parallel coordinate plots is very limited. The only tools that make use of a 3D colour code visualisation are developed by researchers. Currently, no commercial tool uses this kind of visualisation.

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 visualisations. Scatterplots sometimes including a Pareto front are used 12 times. Six publications use a representation on a 3D model. Five of them represent the colour code within the 3D design environment, while one uses Virtual Reality (VR) to show the results on the 3D model.

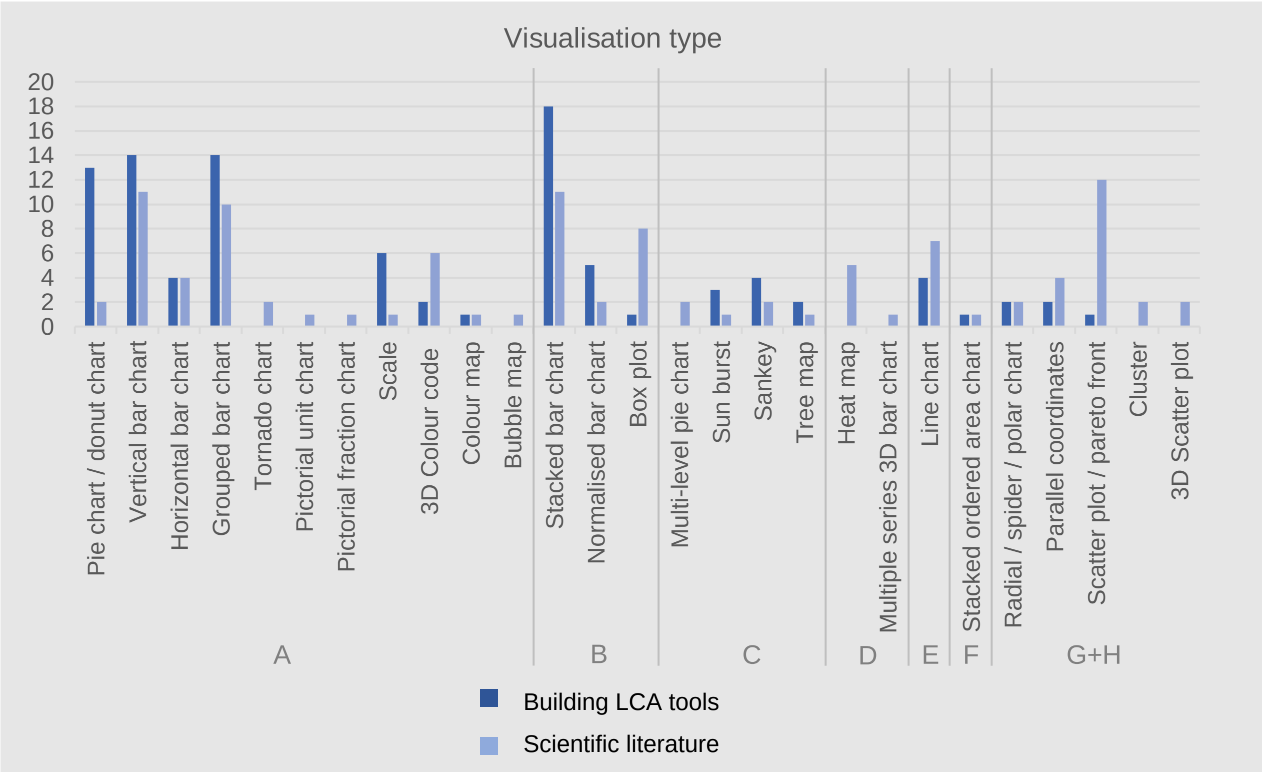



**Figure 5:** Number of visualisation types found in the review of building LCA tools and the literature

Analysing the hotspots regarding the use of visualisation options by building LCA tools for different stakeholders (see Table 2) shows that common visualisations (e.g. bar charts) are used as well as more complex visualisation options (e.g. scatter plots) for both LCA experts and building design professionals. For decisions-makers, we find that a small variety of visualisations is presented. The literature with a focus on visualisation provides more variety including options such as clusters or maps. The literature presenting case studies have a clear majority of common visualisations such as bar charts and variations of it. Scatter plots and Pareto fronts seem to be the only complex visualisations that are used by all types of papers. Although many authors in analysed literature specifically focus on early design stages, no clear differences of the use of visualisations can be seen with regards to the design stages.

**Table 4:** Number of visualisation 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 | Line chart | Stacked ordered area | 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 |

## 2.3 Synthesis of visualisation types and applications for LCA

The results of the analysis of visualisation types are synthesised based on the typical application of LCA and the category of visualisation type in Figure 6. Several visualisation options exist for all the LCA applications. Therefore, they are ordered from left to right with the increasing amount of information transferred in the visualisation. In addition, the number of objects for the assessment proved to be relevant. From the visualization aspect, each design alternative corresponds to a data point. One data point may consists of the hierarchically structured results, but the different data points cannot be aggregated. 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 6.

For the purpose 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 normalisation or adding an individual axis for each bar, which would correspond to showing several single bar charts next to each other. The visualisation 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 applications in the reviewed literature and they show the highest variety of visualisation options. For identification of hot spots, only discrete variables are used. The options in group A, B, and C, all visualise one variable with increasing hierarchy levels, for example the embodied impact of building elements. The options in group D allow to visualise two variables, for example heating systems and insulation materials for renovation (Alexander Hollberg & Ruth, 2013).

The comparison of design options can be visualised 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 visualisation 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 visualise several parameters and their interdependencies. If few design options are compared regarding multiple indicators, visualisation options of group H, such as spider charts, are used.
Uncertainty analysis is often an important part of LCA. A common way to visualise 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 analysed literature, is to show and rank the sensitivity of design parameter using a tornado chart (John 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). Scatter plots are also used to show uncertainties.
While several visualisation options exist for all LCA applications, certain types of visualisations are only used for one specific LCA application in the analysed 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.

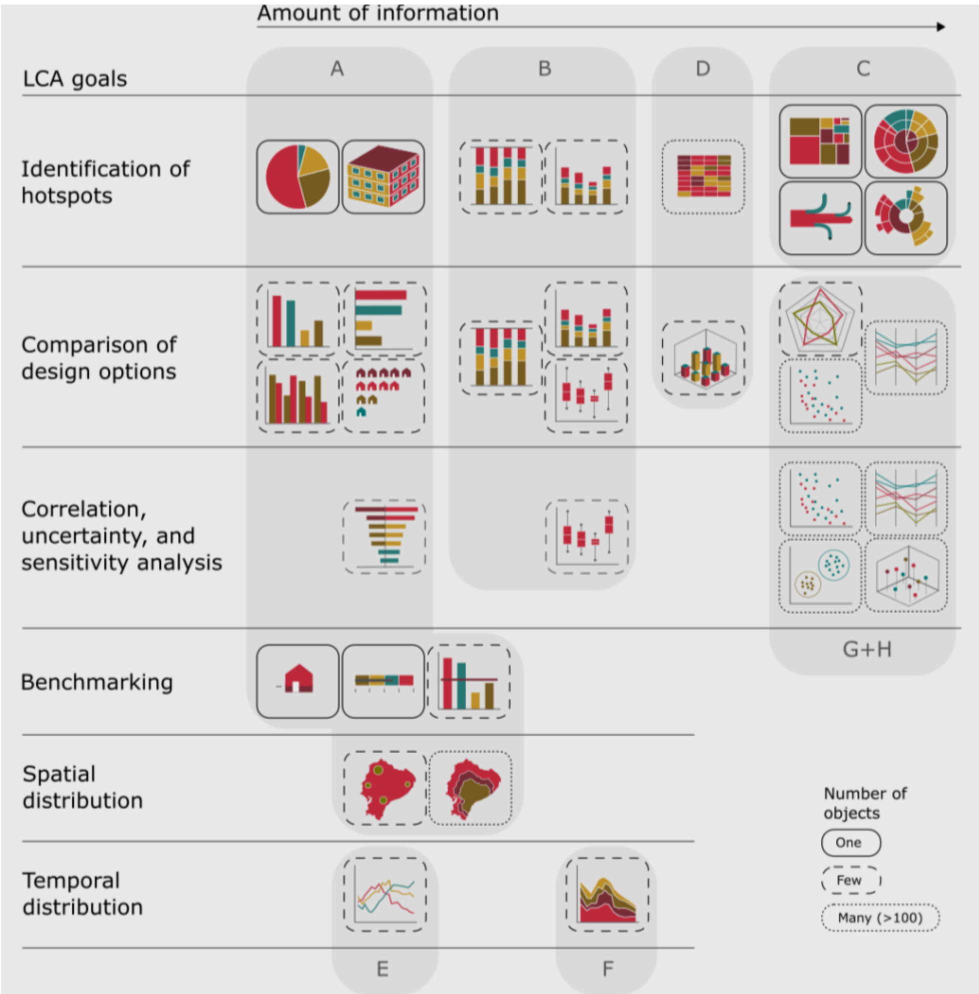



Figure 6: Synthesis of the LCA applications, the group of visualisation types, and the amount of information displayed in the visualisation

# 3. Discussion

## 3.1 Use of visualisations in the design and decision-making process

### Information requirements

In contrast to most industrial design products, most buildings are individual designs. Therefore, each design task is approached differently in a different constellation of stakeholders, leading to different required information for decision-making. Nevertheless, tasks within the design process are repeated, and visual information can support when provided in the right way. It is important to define the visualisation strategy considering which are the decisions that should be taken during the design stages.

In terms of LCA, the *overview* part of the information seeking mantra (Shneiderman, 1996) is often related to identifying hot spots on a low level of detail (e.g. operational vs. embodied impact) or the relation to a threshold in a scale to answer the questions whether a national limit value can be met, for example. The overview could also include the comparison of total results of different building variants (Asdrubali et al., 2013; Pombo et al., 2016).

The *zoom and filter* phase often refers to a hot spot analysis on a more detailed level (e.g. building elements or life cycle phases). This can be implemented using visualisations with a higher level of hierarchy, such as sun burst diagrams (Kiss & Szalay, 2019) or heat maps (Cerdas et al., 2017), amongst others.

The *details on demand* phase can include a very detailed hot spot analysis, e.g. on individual materials or a temporal analysis to identify when impacts are caused. Such information could be confusing in the first interpretation of the LCA results, but very valuable for understanding the background and providing an explanation for results, see (M. Röck et al., 2020) for example.

### Dynamic visualisations

When implemented in a building LCA tool, in theory, all visualisation options can allow for dynamic and interactive elements. The introduction of interactivity by using dynamic visualisations further enhances the possibilities of how information can be extracted from the charts. We identified three types of possible interactivities. *Subselection or filtering of data* allows to elaborate the further information on one or a set of results and can support the zoom and filter phase. *Expanding deep hierarchy levels* that cannot be displayed at the same time, is possible for the visualisation options in group C and can provide the details on demand. Furthermore, *ordering* of the data is possible in different kinds of visualisation, e.g. dynamic bar charts or tornado charts.

### Multi-criteria assessment

Design and decision processes are complex and usually integrate many criteria. These can be multiple indicators for LCA as shown in group H, but also a combination of LCA results with other performance indicators, such as costs (Klüber et al., 2014) or daylight (Carlucci et al., 2015). The most typical example for visualisation of multiple criteria found in the literature are 2D (or 3D) scatterplots. They show a correlation between two (or three) indicators and allow to identify clusters, trade-offs and Pareto fronts of optima, e.g. (Kiss & Szalay, 2020; Płoszaj-Mazurek, 2020). If more than three indicators should be compared spider/radial/polar charts are used, e.g. (Oyarzo & Peuportier, 2014). However, they only work for a few objects of assessment and introduce potential bias when interpreting the results (see Table A1 in the Supplementary Information for the advantages and disadvantages). If many design parameters should be visualised at the same time, a common solution consists of parallel coordinates, e.g. (Kiss & Szalay, 2020; Miyamoto et al., 2019).

## 3.2 From visualisations to design interfaces

### Dashboards as decision support tools

An alternative for multi-criteria assessment is a combination of different graphs in dashboards. Dashboards provide the opportunity to visualise different kinds of visualisation types to present information on many criteria at the same time. Furthermore, they allow using different types of visualisations at different levels of details, either for different stakeholders or to follow the information seeking mantra (Shneiderman, 1996). Adding dynamic visualisations allows for direct interaction and using the visualisations as design tool.
An early example of using a dashboard to visualise LCA results of buildings for decision making is provided by Basbagill et al. (John Basbagill et al., 2017). More recently, Houlihan Wiberg et al. (Houlihan Wiberg, Wiik, et al., 2019) and Cho and Houlihan Wiberg (Cho, 2019) developed dashboards for parametric net zero GHG emission neighbourhood (ZEN) developments. The ZEN key performance indicators (KPIs) as defined in the ZEN Definition report (Wiik et al., 2018), such as embodied GHG emissions and transport-related GHG emissions, are visualised amongst other parameters. Testing such an interactive tool was carried out on one of the proposed ZEN pilot case studies for a new and retrofit school design in Trondheim, Norway and showed how selected ZEN KPIs and interrelationships between different design parameters can be dynamically visualised to support the decision-making process (Cho, 2019).

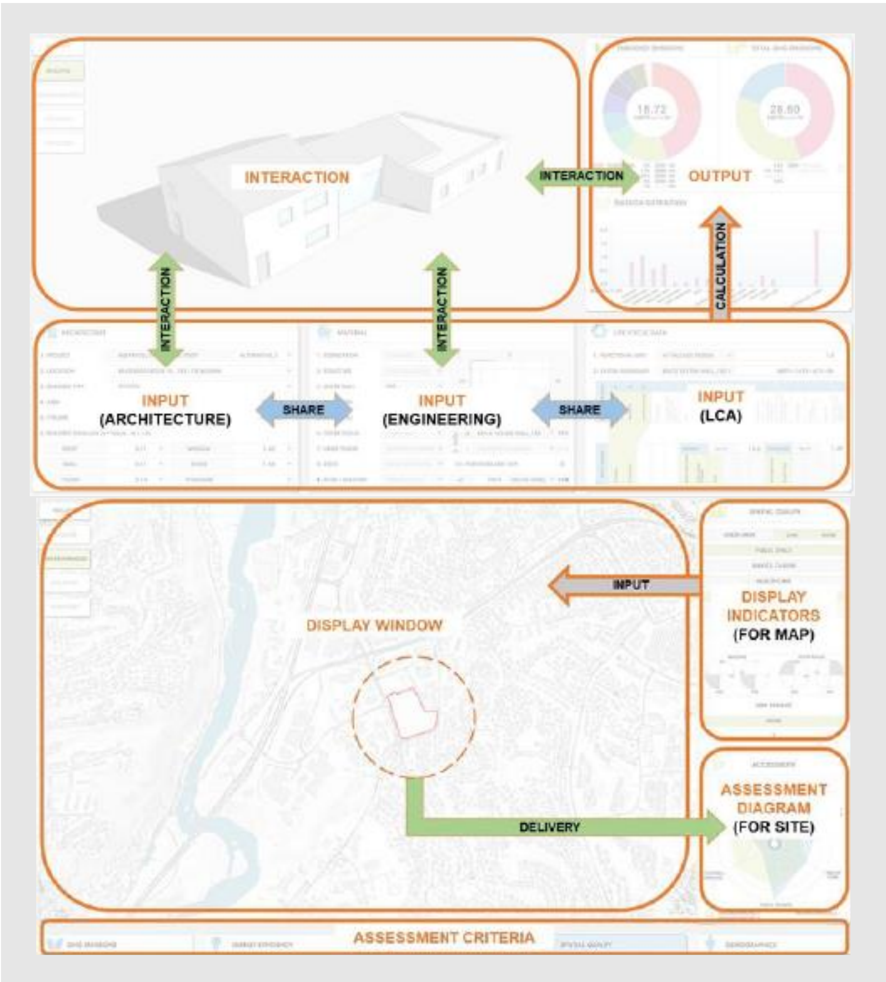



**Figure 7:** Dashboard showing the main structure of small-neighbourhood platform (Cho, 2019)

### Virtual reality to support integrated design processes

Integrated design processes have been proposed to enable the design and implementation of sustainable buildings in practice, supporting communication and the exchange of relevant information amongst the various stakeholders (Leoto & Lizarralde, 2019). This is true for all kinds of building projects, but especially important for the development of net zero emission buildings and neighbourhoods. The complexity rises as ever more stakeholders are involved in handling both 'top down' neighbourhood level data as well as 'bottom up' building and material level information. Considering aspects such as GHG emissions as KPIs is still new and challenging for many policy makers and building design professionals, not to mention citizens, who also need to be included early in participatory, integrated design processes (Baer, 2018). A more recent approach to support these processes is the use of immersive technologies, such as virtual reality (VR). The potential of using VR to enable users to explore and interact with real design projects was investigated by Houlihan Wiberg et al. (Houlihan Wiberg, Lovhaug, et al., 2019). Figure 8 shows examples of visualisations applied in the virtual environment for presenting information such as a) performance in relation to benchmarks, b) airplane icons as a type of pictorial unit chart, and c) a colour code to visualise the impact of building elements. As such, these visualisation types do not differentiate from the visualisations used on screens or paper. According to Houlihan Wiberg et al. (Houlihan Wiberg, Lovhaug, et al., 2019), VR offers a more intuitive means to interpret the performance of a building or neighbourhood design and is an invaluable tool to engage users with no prior scientific knowledge. Furthermore, VR provides a means to overcome traditional interdisciplinary barriers by improving communication. These results are in line with Juraschek et al. (Juraschek et al., 2018) who emphasize the potential of VR in communicating LCA results and bridging the gap between LCA experts and non-experts.


Figure 8: Snapshots using VR to visualise GHG emissions of buildings (Mathisen & Løvhaug, 2019) using a) red and green columns to show being below or above a treshhold, b) airplane icons to relate GHG emissions of a building to flying, c) a colour code to visualise the impact of building elements

## 3.3 Implications and recommendations

The review of the literature emphasised the need for visualisation of LCA results for LCA experts, but especially for stakeholders involved in the design process without detailed LCA knowledge. This need becomes even stronger due to the increased use of LCA results as KPIs in participatory design processes not only on building but also on neighbourhood level.

The analysis of the current building LCA tools showed that most tools use common visualisations such as pie charts or bar charts and variations of them. The review of the literature revealed a variety of more advanced visualisation types. Advanced visualisation types and design interfaces can enable the communication of complex information for LCA experts and building design professionals as well as decision makers concerned with assessing and improving the environmental performance of buildings and neighbourhoods. In general, there is still much room of exploring different visualisation options for presenting LCA-related information and for investigating their suitability for different stakeholder groups. Especially, the use of dynamic visualisations for interactive exploration of the results can support the information seeking during the design process. We would like to propose the synthesis of Figure 6 as starting point for building LCA tool developers to adapt more visualisation types for different purposes and stakeholders.

In relation to the preferences for different visualisations of stakeholders, the review presented here, is limited. We structured the visualisation types according to the LCA applications, the amount of information shown in the visualisation, and the number of objects. It can be assumed that with the increasing level of LCA knowledge stakeholders have an increasing demand for detailed information. However, this assumption should be verified in studies with stakeholders. We therefore recommend to use the results presented here for stakeholder surveys and interviews in the future. In addition, more case studies and application tests are needed to evaluate the support the visualisations provide in the design process for the final objective of planning more sustainable buildings and neighbourhoods.

# 4. Conclusions

The need for visualisations has been widely discussed in the literature. The importance of making LCA results understandable for decision-makers is growing as LCA is increasingly used in the design process The need for visualisations has been widely discussed in the literature. The importance of making LCA results understandable for decision-makers is growing as LCA is increasingly used in the design process as a basis for environmental performance assessment of buildings and neighbourhoods. This report presents a review of the most common building LCA tools, which showed that the majority uses common visualisation options, such as pie charts or bar charts. In addition, we systematically reviewed the scientific literature and found a greater variety of visualisations and more complex visualisation options. Most of the complex visualisation with a larger amount of information communicated in the visualisations are used for correlation analysis, multi-criteria optimisation, or uncertainty quantification. Furthermore, a trend towards visualising the results in a 3D design environment is observed.

The discussion highlighted the importance of providing visualisations adapted to the goal and scope of the LCA study, as well as to provide the right amount of information during the design phase to support the information seeking mantra of overview, zoom and filter, and details on demand. Furthermore, we provided examples of how dynamic visualisations can support this process and showed that there is a big potential of combining different visualisations into dashboards which allow an overview to be provided and answers to several design questions and applications of LCA at the same time. In this report, we provide a synthesis of LCA visualisation options, which, in combination with the common information seeking mantra, can provide a good starting point for building LCA tool developers and researchers to develop stakeholder-specific dashboards and provide relevant information on the environmental performance of buildings and neighbourhoods. There is a big potential to be addressed in the near future by the LCA and building performance community to make the most of the large variety of visualisation options available.

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