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Visualising carbon in the design and delivery of buildings – A review of the evidence

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Abstract

Reducing carbon emissions has become a goal for international climate change and decarbonisation policy initiatives, particularly in the built environment. Setting and addressing these goals and accounting for how targets are being met poses a major challenge for professionals in the UK and internationally. Industry working groups, think-tanks and newly formed organisations are developing new guidance on techniques, tools and approaches. This paper reviews evidence within academic journal articles of visualisation practices associated with carbon reduction in the design and delivery of buildings. The review uses a narrative method to review academic literature published in the last 5 years. Findings show visualization tools can be categorised as supporting the refinement of design solutions with regards to carbon performance, by aiding the understanding of carbon contributions of different building elements, decision making, benchmarking and enhancing interactions with carbon related data. The implications of the review are twofold. First, the evidence collated enables a new understanding of the implications of different ways of conceptualising and visualising carbon on the design and delivery process, by categorising the functions of visuals and their prevalence within the literature. Second there are implications for future research on carbon reduction in the built environment and associated domains.

Keywords – built environment, carbon reduction, design, delivery, visualisation.

1. Introduction

In recent years new policy and industry guidance on decarbonisation in the built environment has proliferated (He and Prasad, 2022; Prasad et al., 2023; Satola, et al., 2022). This includes a significant increase in consultation efforts focused on achieving net-zero building standards and addressing embodied carbon within building regulations, specifically Part Z (Nikologianni et al., 2022). Furthermore, there is a substantial amount of policy involvement, target setting, and the utilization of environmental assessment models aimed at promoting a comprehensive approach towards achieving net-zero goals. This multifaceted movement towards carbon reduction affects a broad range of professionals within the built environment, including architects, engineers, quantity surveyors, and other individuals involved in the design and delivery of buildings (Martinez et al. 2023).

Underlying these efforts is the use of visual representations to convey how targets, measures and assessment of carbon reduction may be achieved. While images are an accepted part of communication, there has been little or no discussion of the visual artifacts drawn upon, whether diagrams, charts, graphs, simulation screen shots or similar. An overview and discussion of the visual artifacts used provides a novel review of how what visualisations are being used to represent carbon (Quattrone et al., 2021) as well as how carbon reduction is abstracted within a particular context (Ravasi 2017). As argued by Messaris and Abraham "pictorial framing is worthy of investigation not only because images are capable of conveying unverbalized meanings, but also because awareness of those meanings may be particularly elusive" (2001, p. 225). Design of buildings in particular is characterised by a reflective, tacit and highly visual design practice (Schon 1984), and though emerging work is starting to analyse how design professionals visualise energy in buildings for instance (Oliveira et al., 2023), there have been no analytical accounts or reviews of visual practices for carbon reduction.

We review built environment academic literature that has engaged with carbon reduction issues not just in terms of what authors have written but also how they have visualized carbon.

2. Methods

The paper employs a loose systematic, narrative literature review approach (Eykelbosh and Fong, 2017) to evidence how carbon reduction is approached visually in-built environment literature.

This approach allows for a comprehensive examination by including a wide range of sources that may not fit within a strict systematic review framework. The narrative strategy employed here enables the synthesis and analysis of this diverse body of knowledge (Anthony, 2023; Vågerö and Zeyringer, 2023), allowing for the inclusion of various types of evidence, including empirical studies, case studies, theoretical frameworks, and conceptual discussions. Lastly, visual approaches to carbon reduction in the built environment often involve contextual and conceptual aspects, including design intent, user experience, and socio-cultural considerations. A narrative review approach facilitates the exploration of these contextual and conceptual dimensions, allowing for a deeper understanding of how visual representations are employed to address carbon reduction in real-world settings.

To identify relevant articles, a search was conducted using academic databases and search engines, namely Science Direct, Scopus, and Google Scholar. The search located original articles and reviews written in English within the past five years, ensuring the inclusion of recent research. This time period was selected due to the significant increase in carbon related discussion surrounding construction projects and associated research, driven by research agendas and changes in national policy (SW Energy Hub, 2019). As such a five-year period permits sufficient incorporation of this period.

To construct effective search queries, specific keywords were combined to form customized strings, comprising the terms carbon visualization, carbon representation, net-zero visualization, and net-zero representation. The search criteria were designed to be internationally inclusive with results filtered to prioritise the most relevant evidence. After conducting preliminary searches to assess the effectiveness of different search terms. Criteria to select documents were applied in two screening stages. Stage 1 involved screening based on abstracts, while Stage 2 involved screening full documents. At Stage 1 articles found amounted to 1112; after filtering for relevance and duplication a total of 116 articles were included. The review included using a transparent and reproducible search to identify studies, and explicit and objective methods to select, extract, quality appraise and synthesise the evidence.

Documents that passed the quality assessment were then analysed. Analysis looked for 1) visual signs and narrative on carbon reduction; 2) materialisation of visual themes; 3) conveyed use of visual artifacts (Pradies et al., 2023). The 116 final sample papers (table 1) were then grouped under according to the function of the article (e.g., review article) (table 2), and specifically how carbon is being discussed (e.g., embodied carbon, whole life carbon), along with the build stages (RIBA 0-7) with which they were concerned.

Table 1. Review of built environment literature - key search terms and number of documents.

	Carbon representation	**Carbon visualisation**	**Net zero representation**	**Net zero visualisation**
Scopus	7	26	4	1
Science Direct	10	41	0	2
Google Scholar	6	10	3	6

Table 2. Visual techniques used in sampled literature and its use.

Name and example references	Frequency	Functionality	Type of article
Bar chart	54	- Comparison of embodied carbon across materials and replacements. - Tracking emissions over time. - Representing of total emission of materials or components. - Comparison of embodied carbon calculation with different present or predicted standards.	• Research papers comparing carbon implications of different design options, materials, or technologies (e.g., Rock et al., 2020). • Whole life carbon research presenting the carbon emissions associated with different life cycle stages or building components (e.g., Meneghelli, 2018). • Performance analysis, investigating the carbon performance of existing buildings or building systems use bar charts to visualize energy consumption, greenhouse gas emissions, or carbon intensity over time (e.g., Ji et al., 2019).
Line graph	21	- Comparison of carbon emissions across buildings or projects.	• Time-series analysis papers examining the carbon performance of buildings or building systems over time often use line graphs (e.g., Eberhardt et al., 2019). • Energy modelling and simulation studies, displaying the carbon intensity or emissions profiles of different scenarios or design alternatives, allowing for easy comparison and identification of the most effective strategies (e.g., Rock et al., 2020).
Box plot	9	- Benchmarking building elements. - Representation of how building may meet incoming carbon related standards.	• Sensitivity analysis research, employing box plots to investigate the sensitivity of carbon emissions to different parameters or variables (e.g., Cang et al., 2020). • Performance benchmarking against standards (e.g., Pasanen and Castro, 2019)
Scatter graph	24	- Plotting numerous embodied carbon calculations for different buildings and building configurations/material specification.	• Simulation modelling using scatter graphs to analyse the relationship between input parameters (such as building characteristics, occupancy profiles, or energy systems) and carbon emissions (e.g., Schmidt and Crawford, 2018).

Cascading target chart	5	- Compartmentalisation of building elements based on carbon (e.g., operational or embodied carbon.	• Performance benchmarking: cascading target charts can be utilized in research papers that compare the carbon performance of different buildings, building systems, or design alternatives (e.g., Jusselme et al., 2018).
Pie chart	19	- Division of building carbon origin (e.g., materials, energy consumption, end of life).	• Carbon footprint research: using pie charts to assess the carbon footprint of buildings (e.g., Marsh et al., 2018).
3D colour-coded images	8	- Division of building elements to show magnitude of carbon per element class or area.	• Building energy simulation, using 3D colour images to represent energy performance, including carbon emissions (e.g., Rock et al., 2018). • Embodied carbon assessment using 3D colour images can be used to represent the embodied carbon of different materials, components, or building systems (e.g., Alwan et al., 2021).
Virtual and augmented reality	4	- Overlaying of energy data from energy services with VR.	• Building performance assessment research, using VR/AR to simulate and visualize the carbon performance of buildings (e.g., Kamari et al., 2020). • Energy management and monitoring research, exploring how VR/AR can enhance the visualization of real-time energy consumption and carbon emissions within buildings (e.g., Chen et al., 2020). • Stakeholder engagement and education research, looking at how VR/AR can facilitate stakeholder engagement by providing interactive and engaging experiences to communicate the carbon impact of design choices (Caldas et al., 2022).
Flowchart	23	- Outlining of environment assessment process for determining material choices.	• Carbon management strategies, using flowcharts to outline the various strategies and measures implemented to reduce carbon emissions in buildings (e.g., Li et al., 2021). • Carbon accounting and reporting, using flowcharts to illustrate the process of carbon accounting and reporting, showcasing how carbon emissions are quantified, tracked, and reported for a building (e.g., Li et al., 2022).

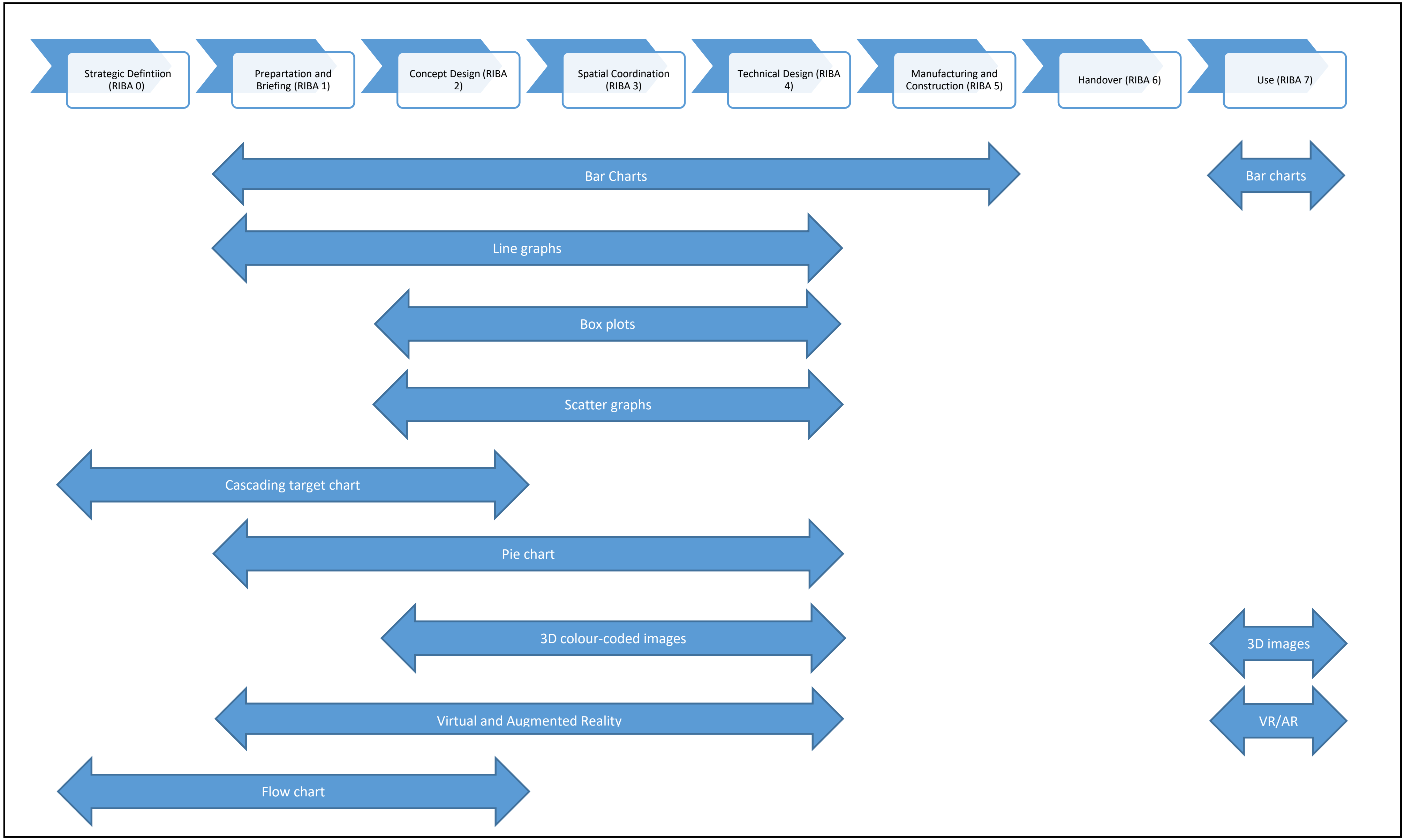


Figure 1: Use of Carbon visualisation techniques across the RIBA stages of a project.

3. Findings

3.1 How is carbon visualised- methods.

Across the 116 number articles and documents reviewed visualisation techniques comprised charts, graphs, and more complex digitised visualisation such as virtual and augmented reality. There was a dominance of certain techniques and methods of visualising, such as pie and bar charts, along with scatter and line graphs, which may be attributed to their simplicity and familiarity with users (Fang et al., 2023). Plus, flowcharts feature in our reviewed articles, highlighting how procedural and process driven carbon research is also present.

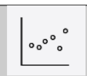
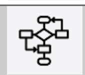
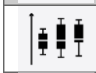
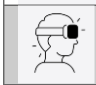
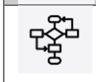
Bar charts, including variations such as grouped or stacked bar charts, are also commonly used as visualizations of carbon information. They are employed in more than 54 articles, making them the prevalent choice for representing carbon-related information. More complex visualizations that involve a large amount of information, such as scatter plots or parallel coordinate plots, are less commonly employed in the analysed research and documents. These types of visualization may offer a more nuanced and detailed representation of carbon data but are currently less prevalent in their use. It is worth noting that the use of 3D colour code visualizations, which provide a three-dimensional representation of carbon-related information, is primarily seen in tools developed by researchers and presented in only a handful of articles (12).

Importantly, in the case of flowchart visualisation, which were identified across 23 articles, the process of understanding carbon in buildings was highlighted. This tool is used to provide a structured representation of the steps involved in assessing and managing carbon-related aspects. They are shown in the literature to indicate the sequence of steps or activities involved in understanding carbon in buildings. This helps stakeholders visualize the logical progression and dependencies between different stages of carbon assessment and management. Plus, flowcharts are seen to incorporate decision points, feedback loops, statements of roles and inputs and outputs associated with each step or activity in the process. This display of carbon therefore differs from other detected here, by assigning actionable points, and processes of delivery of low carbon related activities.

With a significant proportion of authors focusing on the early design stages, many of the visualisation methods were seen to be used across the different design stages (figure 1). For instance, bar charts were used within initial embodied carbon calculations for proposed different materials, and also for post occupancy reviews of monthly energy usage. This suggests that some visualisation techniques are not strongly tied to specific stages of the design process but rather span across multiple stages (figure 1). However, it is noted that although similar visualisation techniques were used to show information from varying build stages, the information within each visualisation did vary due to differing demands at different stages.

Specifically, visuals looked to; compare the potential designs and material choice of a building, specifically their carbon impact, represent the carbon contributions (whether embodied or operational) of specific building elements, aid decision making via the presentation of comparative options, benchmark building options against present and future regulations and legislative standards or targets, communicate carbon related information to audiences such as clients or members of the public, and displaying how the challenge of understanding a building's carbon implications has been approached (table 3).

Table 3: Overview of message of carbon visualisation detected.

Message of visualisation			
Comparing designs of building or material choices			
Understanding carbon contributions from building elements			
Decision making			
Benchmarking			
Communicating carbon information in an interactive manner			
Displaying the process of understanding carbon			

3.1.1 Bar charts

Bar charts were detected regularly across the reviewed literature, for multiple purposes.

Researchers used bar charts to compare carbon emissions across different categories or scenarios. Each bar represents the carbon emissions of a particular category, such as different building elements, materials, or stages of the construction process.

For example, Resch and Andersen (2018) (figure 2) use a bar chart to detail embodied emissions for different materials and replacements for a variety of building case studies.

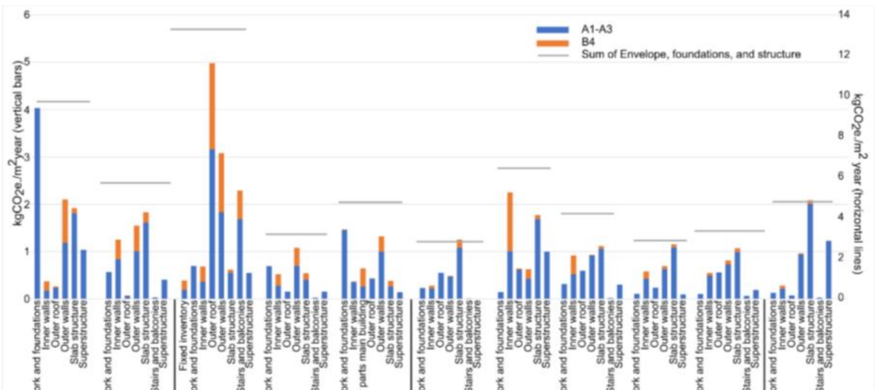


Figure 2: Resch and Andersen (2019); Embodied carbon bar chart.

This visual representation allows for a comparison of the embodied emissions of different building elements across multiple buildings, providing insights into the relative contributions of specific elements to the overall embodied emissions of "Envelope, foundation, and structure" (Resch and Andersen, 2019). By quantifying the emissions in kgCO2e per square meter per year, it allows for a standardized comparison of emissions intensity between different buildings and typologies.

Bar charts can show variations in carbon emissions over time. This allows for tracking changes in emissions over time and identifying trends, seasonal variations, or the impact of interventions (Grant Wilson, 2016). For instance, Ren et al. (2018) utilise bar charts to detail how the carbon footprint of a building element changes over the life cycle of a project (figure 3).

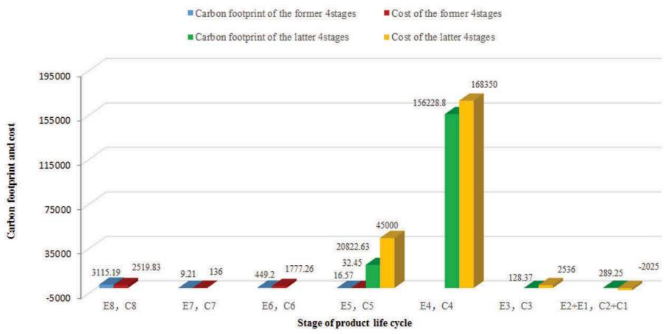


Figure 3: Ren et al., (2018); Carbon footprint of a building component over time

Plus, bar charts used to benchmark carbon emissions against established standards or targets. The bars represent the carbon emissions of different projects, buildings, or components, allowing for easy comparison and assessment of performance against predefined goals. Röck et al., (2020), display this by using bar charts to detail embodied greenhouse gas emissions of buildings against existing and new standards (figure 4).

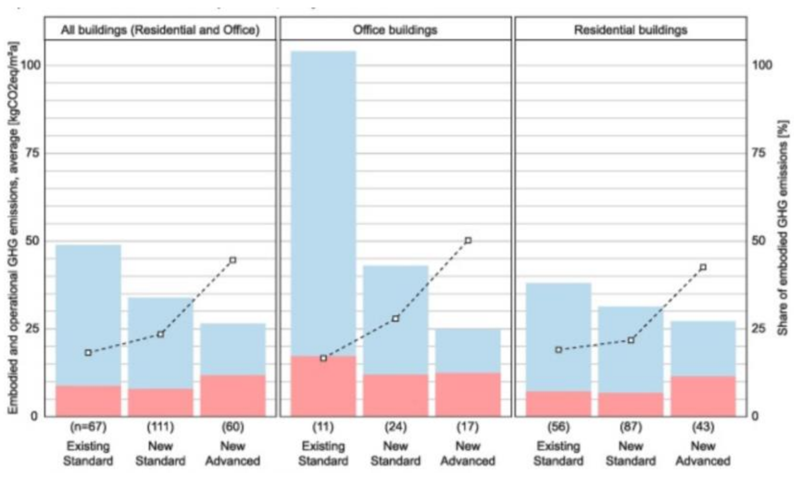


Figure 4: Röck et al., (2020); GHG emission reduction performance against incoming targets

3.1.2 Line graph

Line graphs are utilised to visually represent carbon in buildings by plotting the carbon emissions or carbon-related data over a specific time period. They are used to show the trend of carbon emissions from a building over a specific period, along with being used to compare carbon emissions between different buildings or building projects. For instance, Eberhardt et al., (2019) utilise line graphs to detail the accumulated embodied carbon within a building across its lifespan (in this case 80 years) (figure 5).

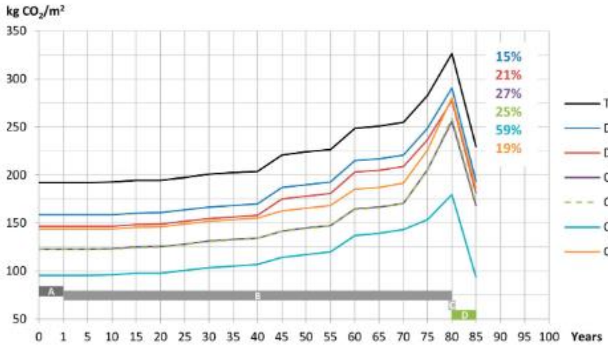


Figure 5: Eberhardt et al., (2019); line graph charting accumulated embodied carbon.

Additionally, line graphs are seen to show how the impact of specific interventions or measures implemented to reduce carbon emissions in a building. By plotting carbon emissions before and after the implementation of a measure, such as energy efficiency upgrades or renewable energy installations, the graph visually demonstrates the effectiveness of the intervention in reducing carbon emissions.

3.1.3 Box plot

Box plots within the literature database are used to provide a concise summary of the distribution and variability of carbon-related data. As such box plots are employed to display the distribution of carbon emissions data within a building or a group of buildings. Plus, they are utilised to help identify outliers, which are data points that significantly deviate from the overall pattern. In this sense box plots provide addition insight that bar charts for instance by highlighting outliers in carbon emissions data and indicating anomalies or areas of concern that require further investigation. By visually identifying these outliers in a box plot, exemplars of box plots are used to aid building professionals in focusing on understanding and addressing the factors contributing to high or low carbon emissions. For instance, Hollberg et al., (2019) use a box plot to benchmark individual elements of a building (figure 6).

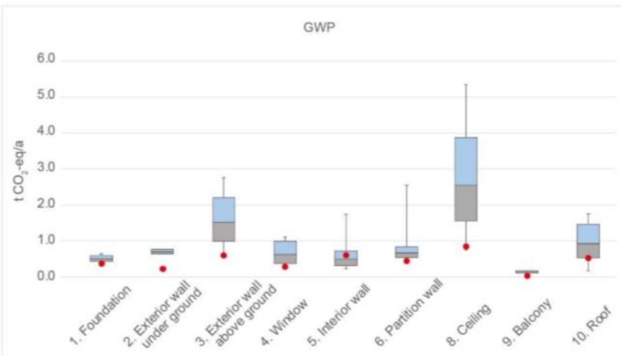


Figure 6: Hollberg et al., (2019); box plot for building component carbon benchmarking.

Box plots can also be used to track changes in carbon emissions over time or assess the impact of interventions. By comparing box plots at different time points or before and after the implementation of measures, one can observe shifts in the central tendency, spread, and presence of outliers, providing insights into the effectiveness of carbon reduction efforts. This is demonstrated by Röck et al., (2020) in their representation of how office and residential buildings may meet new standards (figure 7).

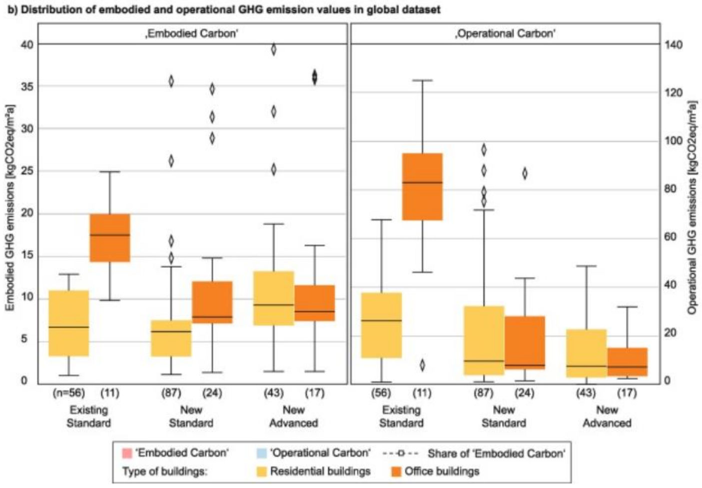


Figure 7: Röck et al., (2020) box plot graph for building performance against future standards.

3.1.4 Scatter graphs

Scatter graphs are identified to visualise carbon by focusing on a relationship between carbon emissions and another variable of interest, such as building area, occupancy, or energy consumption. By plotting these points and examining their patterns, trends, or clusters, one can gain insights into the relationship between carbon emissions and the other variables.

For instance, Płoszaj-Mazurek et al., (2020) utilise scatter plots to detail embodied carbon calculations for different buildings based on height (figure 8).

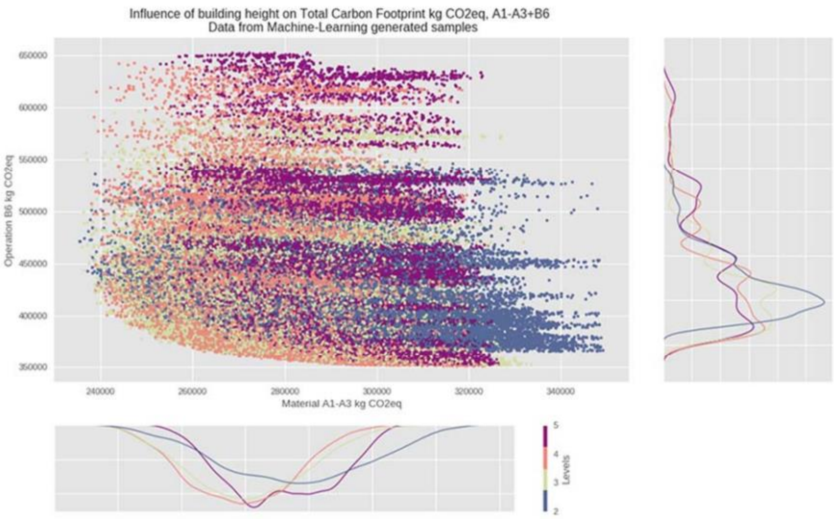


Figure 8: Płoszaj-Mazurek et al., (2020): scatter plot for embodied carbon scenarios.

As such scatter plots permit the identification of outliers or extreme values, along with the indication of how strong a correlation is between variables, or how prevalent groupings are.

3.1.5 Cascading target chart

Cascading target graphs were identified in the literature as a mechanism to visualize carbon in buildings by illustrating the breakdown of carbon emissions into different components or stages. They involve the decomposition of carbon emissions into various contributing factors or stages, permitting the identification of high-impact areas, and the tracking of changes over time. Jusselme et al. (2018) utilise a cascading target chart to compartmentalise the carbon associated with housing, including details of operational carbon, embodied carbon, along with further segmentation into component level figures (figure 9).

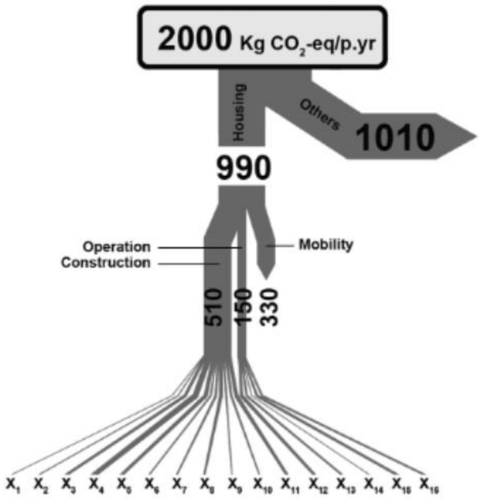


Figure 9: Jusselme et al., (2018); Cascading target chart for carbon emissions.

The layout of cascading target graphs allows for the identification of improvement opportunities. Positive segments represent reductions or improvements in carbon emissions, while negative segments indicate increases or areas of concern. This visual representation helps stakeholders identify areas where efforts should be directed to achieve carbon reduction goals, along with providing a clear and concise visual representation of the carbon emissions breakdown, making it easier to communicate complex information to diverse stakeholders. The visual format allows for a quick understanding of the relative contribution of different components, facilitating discussions and decision-making processes related to carbon reduction strategies.

3.1.6 Pie charts

Pie charts were used by researchers to visualise illustrate the proportion of carbon emissions contributed by various components or sources within the building. For example, slices can represent emissions from energy consumption, transportation, materials, operations, or specific building systems (e.g., Resch, E., & Andresen, I. (2018), figure 10 below).

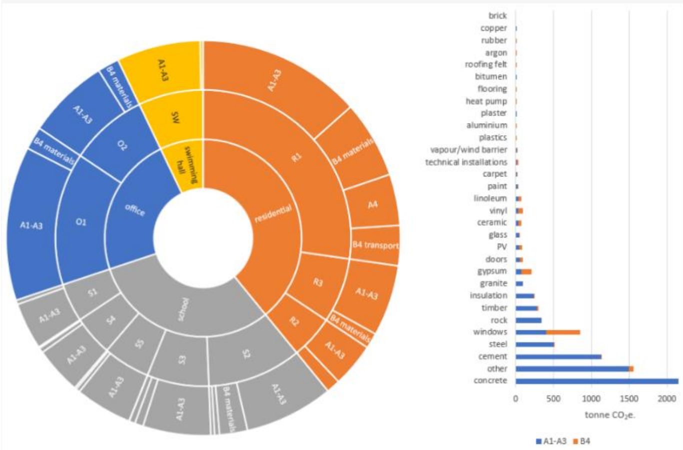


Figure 10: Resch, E., & Andresen, I. (2018); Pie chart displaying carbon emission contributions.

Pie charts such as figure 11 allow for easy visual comparison of the relative contributions of different components to the total carbon emissions. With pie charts providing a clear and intuitive representation of proportions, they make it straightforward to understand the relative contributions of different components and their relationship to total carbon emissions. This makes pie charts effective in communicating carbon-related information to stakeholders, including building owners, designers, and occupants, who may have varying levels of familiarity with carbon footprint analysis.

3.1.7 3D colour-coded images

3D color-coded images can help visualize carbon in buildings by providing a visual representation of carbon emissions of carbon-related data in three-dimensional space. These images allow for the spatial representation of carbon emissions within a building and the intensity or magnitude of emissions in different building areas.

Röck et al. (2018) produced figure 11, detailing a 3D visualization that assigns specific numerical values to indicate the magnitude of the contribution for each building element class. In this case, the values are given in terms of kilograms of CO_2 equivalents per square meter of gross floor area (kgCO2eq/m2GFAa). This provides a precise measurement of the embodied carbon impact associated with each building element class.

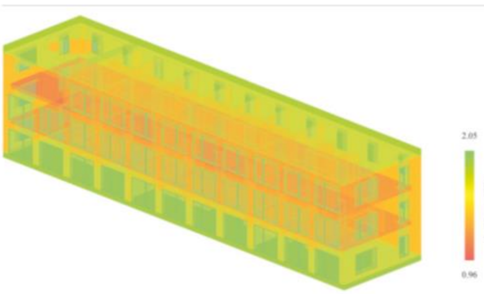


Figure 11: Röck et al., (2018). 3D colour model visualisation (embodied carbon).

Interactive 3D color-coded images enable stakeholders to explore the building and its carbon emissions from different perspectives. Users can manipulate the image, which enhances the understanding of carbon emissions within the building and allows for a more engaging and immersive visualization experience. This interrogation is detailed in work by Mousa et al., (2016), showing in figure 12 how electricity and gas sensors can input data into 3D images to highlight key areas of increased carbon.

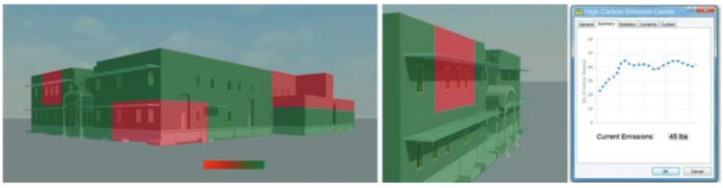


Figure 12: Mousa et al., (2016); interactive 3D image.

3.1.8 Virtual and augmented reality

Virtual reality (VR) and augmented reality (AR) were utilised in the reviewed literature to provide immersive and interactive experiences that help visualize carbon in the built environment by simulating various carbon scenarios in real-time, where users can visualize the carbon footprint of different building designs, materials, and systems by virtually exploring and interacting with 3D models. Suryawinata and Mariana (2022) provide an example of this by using AR to overlay energy information in buildings to aid in decision making (figure 13).

Figure 13: Suryawinata and Mariana (2022); AR energy visualisations.

In the context of carbon reduction VR allows architects and designers to visualize and analyze the energy systems of a building in a virtual environment. By examining the building model and analysing energy data, building professionals can identify opportunities for optimizing the energy system. This includes determining the appropriate equipment and devices needed in the building to minimize energy consumption and maximize energy efficiency. By optimizing the energy system, unnecessary energy use and carbon emissions can be reduced (Suryawinata and Mariana, 2022). Plus, by observing the virtual representation of the building and analysing energy data, architects can identify areas where energy consumption may be excessive or inefficient. This insight enables them to make design modifications, such as optimizing insulation, improving ventilation systems, or incorporating energy-saving technologies, which can lead to reduced energy use and associated carbon emissions (Chudikova and Faltejsek, 2019).

3.1.9. Flowchart

In contrast to the aforementioned visualisation methods, flowcharts were also utilised but I the sense of detailed the process of addressing carbon in buildings. Flowcharts are detected as tools used to visualize carbon in buildings by identifying the key processes or stages within the building's lifecycle that contribute to carbon emissions. We observe literature that uses these to visualise carbon associated with material production, construction, operation, and end-of-life stages. Plus, for each process, they are overserved to aid the determination of the inputs and outputs that contribute to carbon emissions. Inputs which can include raw materials, energy sources, and transportation, while outputs can include emissions such as CO2, CH4, or other greenhouse gases. Consequently, a flowchart is used to visually represent the flow of carbon emissions between the different processes and their corresponding inputs and outputs.

For instance, Gerilla et al., (2007) use a flow chart to detail the environmental assessment of wood and steel reinforced concrete housing construction (figure 14).

Figure 14: Gerilla et al., (2007); flow chart wood and concreate environmental assessment.

3.2 Overview of visualisation techniques

In the selected journal articles, the general goal of the visualizations is to show the relation between design variables or design alternatives and their relative carbon impact. Most building level carbon visualizations focus on the pre-construction stages of a build (figure 1). This suggests that within the research articles reviewed here, much of the temporal context in within earlier project stages. However, there are also papers that address the early design stages, indicating a recognition of the importance of considering carbon impacts at the outset of the design process. Carbon visualizations for early-stage design and detailed design stages differ in both purpose and detail. In the early-stage design, the focus is on exploring and generating design concepts, understanding the overall carbon implications, and identifying potential areas for carbon reduction. The visualizations at this stage are more conceptual and exploratory, aimed at generating ideas and informing design decisions. In contrast, in the detailed design stage, the focus shifts towards refining and implementing the design, optimizing specific components or systems, and ensuring compliance with performance targets. The visualizations at this stage are more detailed and specific, aimed at evaluating and fine-tuning the design for carbon reduction. Additionally, early-stage design visualizations tend to provide a broad understanding of the carbon implications and identifying key design strategies or areas of concern. Detailed design visualizations, on the other hand, require more precise and quantitative information, including specific data on materials, systems, and operational parameters. They may involve detailed calculations, simulations, or parametric models to assess the carbon impact accurately. As such different stakeholders and decision-makers are typically involved in early-stage and detailed design processes.

3.3. Use of visualisations

Overall carbon visualizations are used to help make informed decisions and selecting designs that have lower carbon footprints, by making complex carbon-related information more accessible and understandable, facilitating discussions and raising awareness about carbon reduction strategies. As such they permit the evaluation of different scenarios, trade-offs, and interventions related to carbon reduction in the built environment.

Specifically, the following four areas are detected in the literature as core reasons or uses as to why visualisation are utilised.

3.3.1 Identification of areas of high carbon emission

Carbon visualisations identified are used to detect the areas or activities within a building or construction project that contribute significantly to carbon emissions. This helps in prioritizing efforts for mitigation and improvement. For example, cascading target charts and multi-level pie charts permit the detection of specific building elements which are possibly causing significant impact on carbon projections (possibly in terms of embodied or operational carbon).

3.3.2 Decision making

Visualisations enable the comparison of different design alternatives or strategies in terms of their carbon footprint. This allows decision-makers to assess the environmental impact of various options and make informed choices to reduce carbon emissions. Bar charts offer an example of this, which is well-used within the literature. Numerous research publications utilise bar charts and box plots to compare different options which present themselves in the design process. Plus, carbon visualisations assist decision-makers in evaluating trade-offs between carbon reduction objectives, cost considerations, and other project requirements. By visually representing the carbon impacts of different options, visualisations facilitate informed decision-making and support the identification of optimal solutions. Flowcharts offer a key example of this representation, offering a route to trace how a solution could be optimised and reduced carbon.

3.3.3 Establishing aims and objectives.

Visual representations of carbon performance can be used for benchmarking purposes, comparing the carbon footprint of a building or project against established standards or industry averages. Visualisations facilitate the setting of carbon reduction targets and tracking progress towards achieving those targets. Key visualisations aiding this are line and bar charts expressing explicitly routes of most preferable outcome/performance.

3.3.4 Communicating carbon.

Carbon visualisations aid in effectively communicating carbon-related information to stakeholders, including clients, design teams, and policymakers. They help engage stakeholders in discussions about carbon reduction strategies, foster awareness, and encourage collaborative decision-making. In communicating with stakeholders, visualisations such as 3D colour coding, VR and AR provide increased pathways for interaction with data by stakeholders, providing visuals that are self-explanatory to practitioners and possibly non-practitioners alike.

4. Implications and recommendations

The literature review show evidence of using carbon visualisation for not only building professionals but also for stakeholders involved in the design process who may not have detailed carbon knowledge. Consequently, the role of visualizations is particularly relevant in the context of activities such as participatory design is particularly vital, made even more so by the increased level of carbon related data being used as KPIs in design processes (Wilberg, 2019).

The prevalence of bar and pie charts, along with line graphs, along with their variations, suggests that they are considered effective by their authors in conveying carbon-related data due to their simplicity and ease of interpretation. However, while bar charts are a useful tool for visualizing carbon in architectural design, they have certain limitations and may not offer a complete solution for all aspects of the design process. For instance, they primarily focus on representing quantitative data, such as carbon emissions or energy consumption, but they do not inherently convey spatial information. In building design, spatial considerations are crucial, and it may be necessary to integrate other types of visualizations, such as floor plans, 3D models, or diagrams, to understand the spatial distribution of carbon impacts within a building or across different design options. Plus, bar and line charts provide a high-level overview of carbon data, but they often lack contextual information that is essential for building decision-making. Designers need to consider various factors, such as building function, occupancy patterns, climate conditions, and material properties, which may not be adequately captured in a bar chart or similar. What is more building design involving intricate systems and interdependencies between various elements, such as building envelope, HVAC systems, renewable energy integration, and material selection. As such some simplified visualisations may struggle to represent the complexity of these systems and their interactions. The same can be said for charts and graphs being static representations of data and not offering interactive or dynamic features. In building design, it is often valuable to explore different scenarios, compare design alternatives, and assess the impact of various interventions in real-time, taking into account the experiential knowledge of designers. As such interactive visualizations, such as interactive dashboards or simulation tools, can provide more flexibility and allow designers to manipulate and explore the data in a dynamic and responsive manner. Consequently, we propose a key area of research moving forward is to ascertain the content, role and the extent to which these more interactive visualisation are valuable. Valuable to which stakeholder groups, at which time, and in which research contexts could be add to the visualisation methods such as charts and graphs, and how they may not be appropriate.

5. Conclusion

Visualisations and their need have been widely discussed in the literature. The importance of making carbon understandable for built environment professionals is growing as carbon is increasingly present in the design process. This paper presents a review of carbon visualisation tools, which shows that the majority use common visualisation options (e.g., pie charts or bar charts). In addition, we systematically reviewed the scientific literature and found a variety of visualisations and more complex visualisation options such as 3D imaging and Virtual Reality.

Carbon visualizations are shown to play a crucial role in facilitating informed decision-making and supporting the selection of designs with lower carbon footprints, along with assisting in detail the process of low carbon activities. By making complex carbon-related information more accessible and understandable, visualizations enable the identification of areas of high carbon emission, informed decision making, the establishment of aims and objectives and the communication of carbon to a wide audience. Implications of this research suggest a research agenda is needed, to explore the extent to which visualisations need to take into account the need for design to be responsive and take into account the experiential nature of construction and tackling carbon in buildings.

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