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Analysis and Visualisation of Large Scale Life Cycle Assessment Results: A Case Study on an Adaptive, Multilayer Membrane Façade

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Abstract: The importance of visualisations in context of life cycle assessment has been widely discussed and acknowledged in the literature. Especially with the increasing ability to process and create large-scale LCA results, visualisations are vital tools to not only analyse and interpret but also check and validate underlying datasets. Based on a dataset containing 1.25 million LCA results for all potential configurations within a defined parameter space, different visualisations and analysis methods were applied to identify hotspots, assess parameter sensitivity, gain insights to optimise environmental sustainability, and provide benchmarks for an adaptive, multilayer membrane façade. Box plots for the identification of hotspots, parameter sensitivity, and benchmarking, as well as colour-coded scatter plots, have proven to be incredibly versatile and effective for understanding the results and providing multiple perspectives to gain further insight. The ability to interact directly with interactive visualisation in order to identify and isolate specific areas of interest allows for a very efficient analysis of the relevant aspects of data. However, the usefulness of the proposed visualisations is not only dependant on the quality and characteristic of the underlying data but also on the objectives and scope of the study, as well as the intended medium illustrating the results.

Keywords: life cycle assessment; adaptive façades; LCA visualisation; sustainable product development; environmental sustainability

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1. Introduction and Research Motivation

According to the Emissions Gap Report 2023, greenhouse gas emissions reached a new high in 2022, and the "failure to bring global GHG emissions in 2030 below the levels implied by current NDCs [Nationally Determined Contributions] will make it impossible to limit warming to 1.5 °C with no or limited overshoot and strongly increase the challenge of limiting warming to 2 °C" [1]. Despite a reduction in CO_2 emissions (−5.3%), the buildings sector in Germany still exceeded the permissible annual budgets [2,3] set by the Federal Climate Change Act (Bundes-Klimaschutzgesetz) [4], emphasising the importance of further reductions in buildings and building products. The use of adaptive façades is an approach to reduce the resource and energy consumption of buildings, leading to reduced environmental impact, as they can adapt their properties to changing external conditions or user requirements [5]. However, the involvement of additional engineering disciplines with their respective simulation tools and the incorporation of adaptive components into construction leads to an increased number of possible design configurations, as well as stronger interdependencies between the design and the use phase, all of which have an impact on the environmental performance of a building. For the assessment of potential environmental impact, the life cycle assessment (LCA) method is commonly used. The relevance and usefulness of life cycle assessment (LCA) to optimise the environmental impact within product development and the built environment is indisputable and has been utilised in multiple studies [6–11]. It is acknowledged by lawmakers through regulations like the European Green Deal [12] and the EU Taxonomy [13], as well as green building certification systems such as the DGNB [14] and BREEAM [15].

Combining the LCA framework according to DIN EN ISO 14040 [16] and DIN EN ISO 14044 [17] with methods from the field of data science and accessing the increasingly available data allows practitioners of life cycle assessment (LCA) to automate the process of creating the life cycle inventory (LCI), as well as impact assessment (LCIA), and efficiently create large-scale LCA results for specific products or product portfolios. The reduced effort and increased output enable LCA to be used earlier in product development, where design decisions are still open and being explored.

However, this creates new challenges for LCA practitioners. Because of the increased level of automation, validation of the generated datasets is becoming more important and, due to the vast number of results, more difficult at the same time. For the same reason, the analysis, visualisation, and interpretation of the generated results is more complex as well. Therefore, processes and methods to ensure the gaining of useful insights and avoid misinterpretation need to be established.

Based on large-scale LCA results for an adaptive, multilayer membrane façade, this article demonstrates how various visualisation methods can be employed for analysis, interpretation, and communication, as well as what insights can be derived to optimise the potential environmental impact of the product (Note: The intended medium to work with the visualisations illustrated in this paper is a digital screen with at least 24″ diagonals. While the authors did their best to provide good readability and consistency between the different visualisations, compromises had to be made in order to transport the learnings and insights gained).

2. State of the Art

The automation and aggregation of an LCA in general and the creation of the life cycle inventory (LCI) in particular are two of the five approaches used to simplify LCA for industrial applications and make the results more usable within product development, as identified by Kiemel et al. [18]. Both approaches can enhance practicability when dealing with complex products and high variance because they significantly reduce the effort required for data collection and structuring [18]. Advancements in common computer hard- and software, as well as the availability of data resulting from increased digitalisation, enable LCA practitioners to extract and use this data to model, calculate, and assess millions of product configurations in an automated or partly automated fashion [19–22]. However, commonly used methods for the visualisation of LCA results might not be suitable to analyse and interpret vast amounts of data points, potentially increasing the risk of misinterpretation [23,24]. If the results are created with fully or partly automated workflows, the importance of validation and detection of mistakes in the workflow is further highlighted. While the automated creation of LCI and LCIA results addresses the complexity when performing an LCA and enables the upscaling of assessments, the interpretation becomes even more complex due to the sheer number of results. Even for conventional life cycle assessments considering only one specific product system, the importance of result visualisation to improve decision making has been emphasised in multiple studies [24–27]. While it can prove helpful to derive statistical parameters (such as mean, median, minimum, maximum, variance, etc.) from large sets of LCA results as an initial step, only relying on these causes the loss of valuable information, such as clusters, trends, and dependencies. This information can be captured much better by means of visual exploration to gain customised insights and derive a detailed basis for decision making regarding the product systems investigated.

The Sustainability Data Science Life Cycle (S-DSLC), proposed by Wehner et al. [21], is a concept for automating LCA workflows and providing LCA-derived insights for large-scale product portfolios. It consists of seven phases, encompassing the understanding and preparation, processing, and analysis of LCA data, as well as the application and monitoring of LCA-derived insights to drive sustainability in businesses. The idea behind the S-DSLC concept is to couple the LCA framework according to DIN EN ISO 14040 [16] and DIN EN ISO 14044 [17] with methods and tools from the field of data science [28,29] in order to automate the LCA process, using available data from the manufacturer of a product portfolio to be assessed. This allows for upscaling the—otherwise very labour- and time-consuming—data structuring, modelling, and analysis of LCA. However, the S-DSLC concept only briefly describes the steps to actually "Explore & Analyse" and "Customise & Capture" large-scale datasets. Very few examples of suitable visualisations and specific analysis methods are given.

Based on the S-DSLC concept, Borschewski et al. [22] developed a workflow (CLASS), to create, analyse, and assess the LCA results of all potential configurations within a defined parameter space, specifically for (building) products. This workflow shifts the focus towards the optimisation of a singular product, rather than the higher-level optimisation of a product portfolio, and takes construction-specific sources of data and reporting structures into account. Other than basic analysis and visualisation, it provides a database with "real world" product configurations of an adaptive, multilayer membrane façade for further exploration.

Figure 1 illustrates both the S-DSLC concept and for which phases the CLASS workflow provides detailed methods to generate large-scale LCA results. Additionally, this work specifically focuses on a more systematic approach to the visual analysis of large-scale LCA results in order to provide detailed visualisation and analysis related steps for the phases "Explore & Analyse" and "Customise & Capture". To identify and assess potentially suitable visualisation methods, the goals of interpretation and analysis procedures need to be defined. Hollberg et al. [30] identified six typical goals of the interpretation of LCA results, based on a systematic literature review. These are as follows:

1. Identification of hotspots;
2. Comparison of options for design improvement;
3. Correlation, uncertainty, and sensitivity analysis;
4. Benchmarking;
5. Spatial distribution;
6. Temporal distribution.

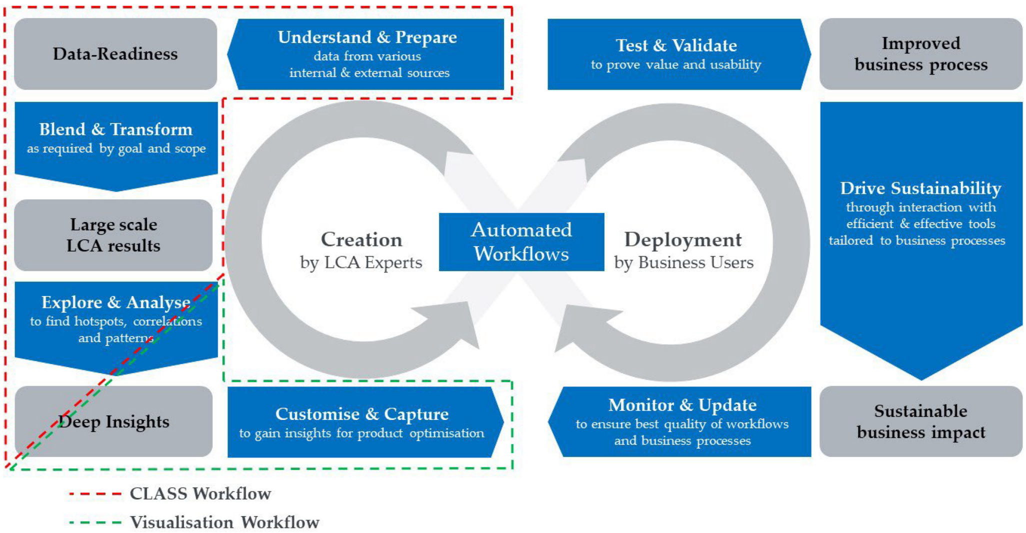


Figure 1. S-DSLC concept according to Wehner et al. [21], with the goal and scope of the CLASS workflow [22] and the visualisation from this manuscript.

Furthermore, Hollberg et al. [30] presented different types of visualisations to specifically visualise LCA results. Depending on the number of objects (denoted here as product configurations—the number of LCA results, respectively) and the interpretation goal. Both the goals of the interpretation and the proposed visualisation methods serve as the basis for this work.

3. Research Approach

3.1. Theoretical Framework

The analysis of the state of the art (Section 2) shows a need for suitable visualisation methods, especially for large-scale LCA results, with the goal of optimising the environmental impact of complex building products with great variance and high numbers of possible configurations. Both Hollberg et al. [30] and Wehner et al. [21] explicitly encourage conducting further research on this topic and highlight "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" [30]. While the literature provides a general framework for creating large-scale LCA results and visualisation methods for few to many objects, it does not provide specific analysis and visualisation methods for complex building products with extensive possible configurations like adaptive façades. Therefore, this article aims to answer the following research questions:

> *Which visualisation methods are suitable for analysing the environmental impact over the life cycle of complex adaptive façades, considering extensive configurations and parameter dependencies to gain insights for design improvements in the development process?*

To answer this question, the S-DSLC phase "Explore & Analyse" is enhanced with additional steps in order to identify and test suitable visualisation and analysis methods (see Figure 2). As a precondition, the underlying dataset needs to be validated. This is particularly important when dealing with automatically created datasets that contain extensive amounts of datapoints, as they cannot all be checked and validated manually with reasonable effort. Then, the goals of LCA interpretation need to be defined. Based on the goals defined, questions and objectives can be derived that need to be answered with suitable visualisation and analysis methods. Potentially viable visualisation and analysis methods are identified in the literature, tested and assessed against the questions and objectives derived. As a result of this process, insightful visualisations are provided for the defined goals of LCA interpretation, which allows LCA experts to answer the questions posed and provide decision support during the development of the product analysed.

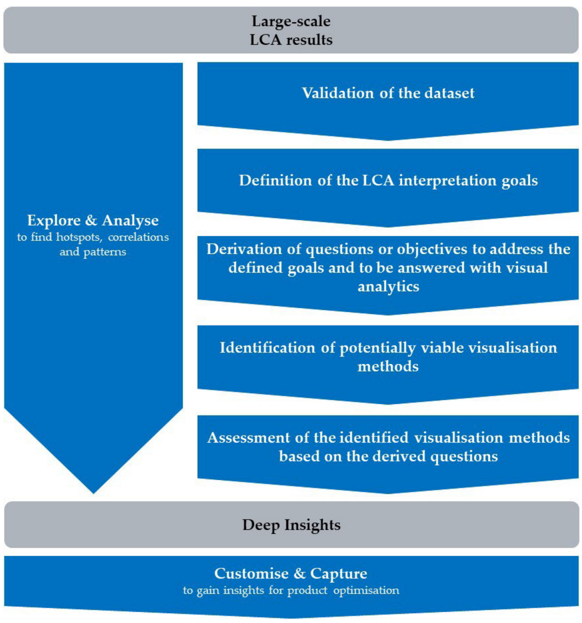


Figure 2. Additional steps within the S-DSLC phase "Explore & Analyse" to identify and provide suitable visualisation methods.

In previous work, a database containing >1 million LCA results for all potential configurations within a defined parameter space of an adaptive, multilayer membrane façade was created [22]. This database serves as a case study to test and identify suitable visualisation methods for large-scale LCA results. More details are presented with the other materials and methods used in Section 4. The primary beneficiaries of the visualisations presented in Section 5 are LCA practitioners and experts having the goal of optimising a product's environmental footprint (identify hotspots, compare options for design improvement, find correlations, and create benchmarks). Section 6 discusses the results, followed by the conclusions and outlook in Section 7.

3.2. Application

To ensure that the created and used database only contains valid options and that the parameter space is represented correctly, a validation of the workflow needs to be performed. First, the parameter space itself needs to be checked to match the goal and scope of the study. If the goal is to assess different possible technical options or a more specific set, this must be represented in the defined parameter values. Then, the following steps can be performed to validate the workflow:

- **Validate workflow results with external calculations:** a comparison of selected configurations (data filtered to specific configurations) with external calculated results must be performed to validate the computational results.
- **Validate the total number of configurations:** the total number of configurations must match the expected one, considering parameter dependencies (not all parameter values are combined with each other, e.g., different materials and their respective end of life).
- **Validate the correct application of parameter dependencies:** this can be automatically checked with if/then mechanisms for each configuration that report true or false values.
- **Validate expected patterns in the data by sorting the results by total impact:** if exact duplicates are possible, they must follow a specific pattern. Identical values may only occur if the parameter space allows for it (e.g., if there are values with identical impact).
- **Validate the correct applications of filters:** the elimination of duplicates with a duplicate row filter provides the ability to check, e.g., which parameter values are included. This is especially useful when dealing with filtered data.
- **Validate the plausibility of the results:** comparing the results with reference scenarios and empirical data allows for assessing the plausibility of the results.
- **Identify and validate outliers:** the visualisation of results allows for identifying outliers and implausible outcomes.

This research is based on the typical goals that Hollberg et al. [30] identified (see Section 2) and is adapted to accommodate large-scale LCA results. A goal of contextualising the results is added in order to obtain an overview of the calculated results and place them into context with a known and established reference system. Goal 3 (comparison) and 4 (correlation) are summarised as "exploration and understanding". Spatial distribution is not part of the scope because the underlying data are not differentiated between different material origins or manufacturing locations. While the data incorporate different electricity scenarios for Germany (consumption in the use phase, scenarios for 2020, 2030, 2040, and 2050) that would allow for the analysis of temporal distribution, this analysis focuses on optimising the environmental impact of the product during development rather than potential impacts in the future. The defined goals of the LCA interpretation are therefore defined as follows:

1. Contextualisation;
2. Identification of hotspots and parameter sensitivity;
3. Exploring and understanding;
4. Benchmarking.

Several questions can be derived based on defined goals that need to be answered by the LCA practitioner through analysis and visualisation.

How can the overall range of the results be gauged and contextualised?
Which parameters have a major influence on the overall environmental impact of the product?
Which options should be preferred, and which should be avoided?
How do interactions between the parameters affect the overall environmental impact?
Which parameters have widespread environmental impacts depending on their value?
Which benchmarks can be derived for an initial assessment of the environmental impacts?

Analysis and visualisation in this case study is therefore performed by starting with a contextual and overarching view and then narrowing the data down to specific areas of interest before allowing for the exploration and understanding of the data, completed by the derivation of benchmarks. The focus hereby is the use of visual analytics to answer the above-mentioned questions in an efficient and appropriate way. Visual analytics combines computational processing and human reasoning to visualise and interpret results [23]. Different types of potentially viable visualisations were collected from the literature and applied to analyse the data and identify useful insights. For better readability, this article only includes the ones that yielded useful insights. Often, the same type of visualisation can be applied to highlight different aspects of the dataset, e.g., by varying the parameter that is displayed on the axes. These are also only included in this article if it helped to transfer the insights gained.

4. Materials and Methods

4.1. Underlying Dataset and Description of the Adaptive, Multilayer Membrane Façade

To test and demonstrate different visualisations for large-scale LCA results, a previously generated dataset was used. The data were created using the CLASS workflow [22] and comprise the results for the impact of 1.25 million different configurations of a 3.6 m by 2.8 m (10 m^2) adaptive, multilayer membrane façade (see Figure 3) on climate change. The façade is intended for use in residential and office buildings with requirements regarding energy demand and user comfort. Its key property is its adaptive nature, realised through complementary printed patterns to manipulate heat and light transmission by inflating and deflating the space between the individual layers (ranging from two to six) of the façade. Depending on the external conditions (temperature and solar radiation), as well as indoor requirements (temperature and glare protection), the cushions are inflated or deflated based on a predefined control strategy.

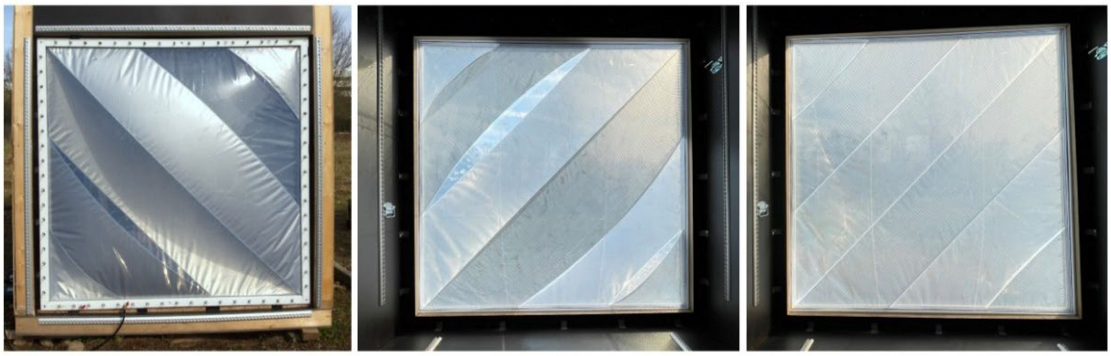


Figure 3. Adaptive, multilayer membrane façade prototype installed in a test bench at the University of Stuttgart. **Left**: outside view (inflated), **middle**: inside view (inflated), **right**: inside view (deflated) [IABP/Weber].

The environmental impact for all potential configurations within the parameter space shown in Table 1 was calculated while considering known parameter dependencies, according to the Environmental Footprint 3.0 [31]. Although an updated version of the Environmental Footprint was published (EF3.1 [32]) very recently, EF3.0 was used in order to remain consistent with previous results. No major changes regarding climate change were expected. For an in-depth description of the LCA modelling, the applied system's boundaries, assumptions, and data sources, please refer to the description of the CLASS workflow in the original publication [22].

Table 1. Parameters and the corresponding values of the underlying dataset [22].

Parameters	Values
Foil material	ETFE; PTFE; PP; PE (0.42 kg/m^2)
Foil end of life	Incineration; Recycling
Number of foil layers	1 to 6
Printing material	Aluminium, Titanium dioxide; Silver; Gold;
Printed area	25 to 100% for two layers (Interval: 25%)
Contact welding length	1 to 4 m/m^2 (Interval: 1 m)
Filling substance	Argon; Air
Frame material	POM; Al 0% s., Al 80% s., Al 100% s.
Frame weight	POM: 13.6 kg/m^2; Aluminium: 4 kg/m^2
Frame end of life	Incineration (POM); Recycling (POM, Al)
Operational strategy	Conductive; Insulating; Adaptive 1; Adaptive 2
Energy consumption (room + actuation)	120 to 595 kWh/a electricity (simulation results)
Electricity mix (room + actuation)	2020; 2030; 2040; 2050
Transport (by truck)	300; 1000; 2500 km

For each parameter value, a stand-alone LCA model was created in LCA for Experts (Version 10.7.1.28; Content version 2023.2) [33], which were modularly combined using the CLASS workflow. Each resulting façade configuration considered the modules A1, A2, A3, A4, B6, C2, C3, C4, and D according to DIN EN 15804 [34] and DIN EN 15978 [35].

To ensure a holistic view, the energy demand for heating and cooling over a 20-year use phase (B6), as well as inflating and deflating, was modelled and simulated by Weber et al. [36] for a shoe box room (width = 3.6 m, height = 2.8 m, and depth = 8.2 m) in Modelica [37] using the Modelica Buildings library [38]. This simulation takes the number of layers, gas filling, and different operational strategies, as well as consistent parameters like efficiency of the heat pump and weather, into account. This additional modelling ensures that for each configuration, the expected energy demand can be included in the LCA model, and the use phase of each configuration is depicted as accurately as possible. The impact on climate change for each electricity scenario is presented in Table 2. The models are based on the EU Reference Scenario [39] and represent the average electricity supply for final consumers in Germany.

Table 2. Impact of 1 kWh from different electricity grid mix scenarios on climate change in Germany.

Electricity Mix Scenario	Impact on Climate Change
2020	0.50 kg CO_2-equiv/kWh
2030	0.39 kg CO_2-equiv/kWh
2040	0.28 kg CO_2-equiv/kWh
2050	0.23 kg CO_2-equiv/kWh

Both the simulation and LCIA results were processed and combined to a complete dataset in tabular form with KNIME Analytics Platform (Version 4.7.7, Build 23 August 2023) [40]. While all impact categories can be implemented in the workflow, only the impact on climate change was analysed in this case. Because large-scale LCA data are already complex to process and interpret, visualising and balancing multiple impact categories is not the goal and scope of this study. The focus on climate change was based on its relevance for decision makers [41] and its importance within the recommended weighting factors for the environmental footprint [42]. However, the visualisation strategy presented is expected to be transferrable to other impact categories accordingly.

For better comprehensibility, one typical 3-layer configuration is depicted in Table 3. For each parameter value, a process-based model was created in LCA for Experts. The LCA results for this specific configuration are depicted in Figure 4.

Table 3. Parameter values and LCI of a typical configuration of the adaptive, multilayer membrane façade.

Parameters	Values
Foil material	ETFE (4.2 kg/m^2)
Foil end of life	Recycling
Number of foil layers	3
Printing material	Silver
Printed area	50% for two layers
Contact welding length	20 m
Filling substance	Air
Frame material	Aluminium with 80% secondary material
Frame weight	40 kg
Frame end of life	Recycling
Operational strategy	Adaptive 1
Energy consumption (room + actuation)	239 kWh/a electricity (simulation result based on the selected parameter values above)
Electricity mix (room + actuation)	2030 scenario
Transport (by truck)	1000 km

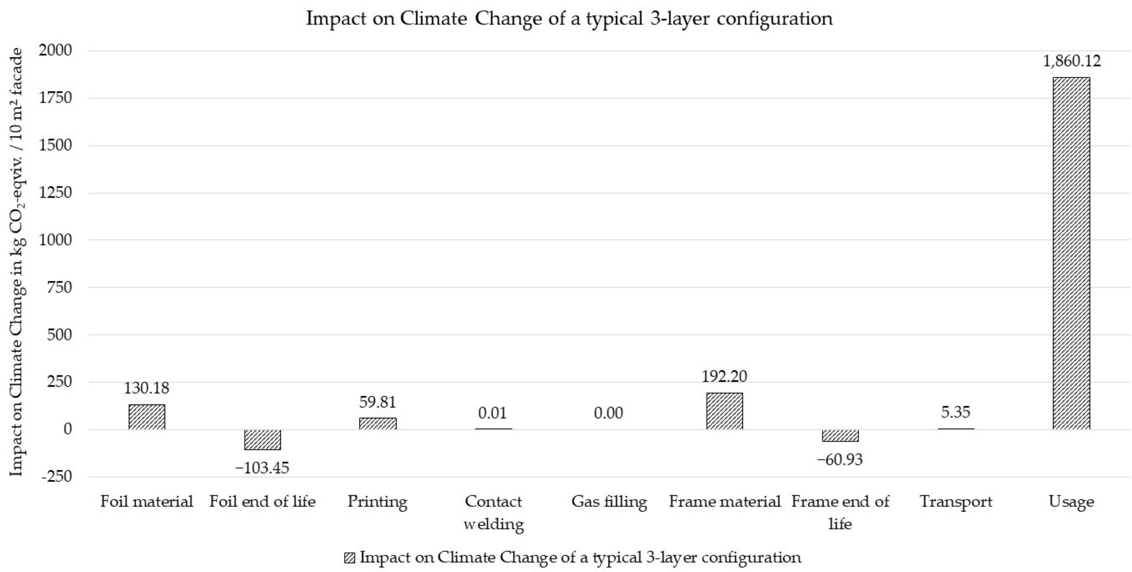


Figure 4. Impact of a typical 3-layer configuration on climate change, differentiated by parameter.

In addition to the impact of each parameter shown in Figure 4, the results were aggregated to life cycle modules from A to D, as well as the total embodied and usage impact.

4.2. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used OpenAI ChatGPT in order to improve the readability and language of individual sentences. Neither was additional information created by the AI tool nor was it used in a systematic way. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of this publication.

5. Results

This chapter provides different visualisations for the defined goals of contextualisation, identification of hotspots and parameter sensitivity, exploration and understanding, and benchmarking, as introduced in Section 3. During the analysis, three different levels of filtering emerged.

- **Unfiltered dataset:** containing all configurations and electricity scenarios for contextualisation, hotspots, and parameter sensitivity.
- **2030 electricity scenario:** containing all configurations utilising the 2030 electricity scenario for the exploration, understanding, and comparison of different design options.
- **2030 electricity scenario and operational strategy ADA2:** containing all configurations utilising the 2030 electricity mix and the OPS ADA2; focusing on only the best performing operational strategy reduces redundancies within the configurations and allows for easier visualisation and analysis.

5.1. Contextualisation

While analysing the adaptive, multilayer membrane façade, it was helpful to first contextualise the results. This provided an overview and could be first undertaken with a comparison to a known reference in order to gauge the overall range of the results and place them into context with a reference.

As reference, a conventional post and beam façade with an aluminium frame and triple thermal glazing with argon filling was considered. The life cycle (production, use phase, end of life) of the reference was individually modelled and assessed in LCA for Experts to ensure maximum comparability. The model was validated by using an environmental product declaration (EPD) for a similar product [43]. The energy demand in the use phase of the reference was simulated with the same boundary conditions (see Section 4.2). Because the adaptive façade was in development and not yet marked as ready, the environmental impact of the use phase was based on the 2030 electricity scenario.

Figure 5 shows a box plot of the total impact on climate change (all considered life cycle phases) of all 1.25 million calculated configurations, together with the impact of the reference system. For the electricity consumption of the use phase, four different scenarios were considered, ranging from 0.5 kg CO_2-equviv/kWh for 2020 to 0.23 kg CO_2-equviv/kWh for 2050.

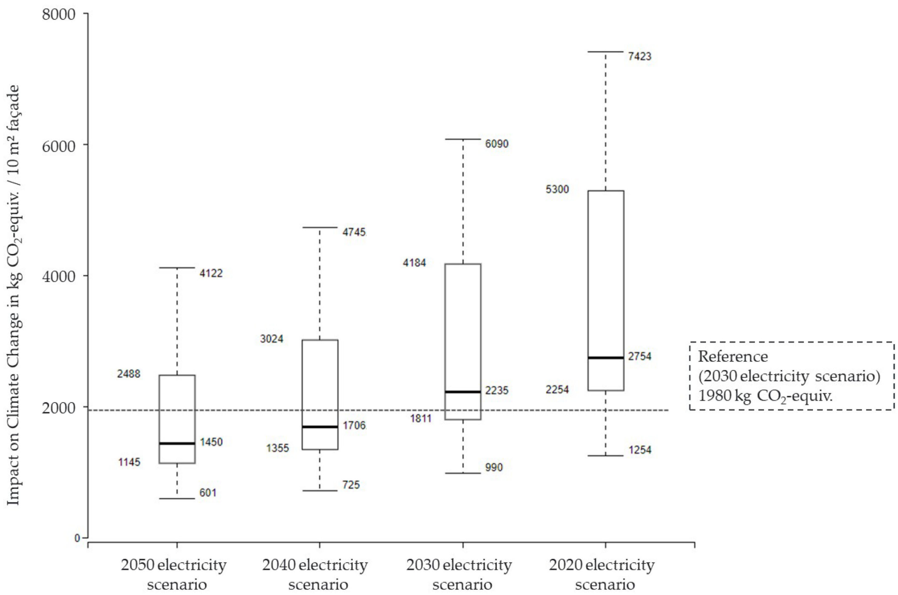


Figure 5. Contextualisation of all calculated LCIA results (impact on climate change) in a box plot, sorted according to the scenarios for electricity provision in Germany for the years 2020, 2030, 2040, and 2050 against a reference façade with triple thermal glazing and argon filling.

The diagram shows that many of the 2030 electricity scenario configurations are considerably worse, compared to the reference system (1980 kg CO_2-equviv). However, there are also promising configurations that inherit only half of the reference impact. To obtain additional context and the first interpretation, colour-coded scatter plots can be used.

Because of the long service life of building products (up to >50 years [44]), the total environmental impact of the life cycle is often dominated by the impact resulting from the use phase. Although the box plot indicates the distribution of the variants with the median, detailed distribution cannot be read from the graph. The simulation results show that the number of layers and the operational strategy used are two of the main influences on energy demand during use. Figure 6 therefore illustrates the total impact on climate change throughout the life cycle for all configurations that utilise the 2030 electricity scenario for the use phase, differentiated by the operational strategy (OPS) of the façade and the number of layers. In the scope of this study, four OPS were investigated: ADA1 and ADA2—two adaptive strategies with different control heuristics, CON—a static conductive strategy (deflated membranes), and INS—a static insulating strategy (inflated membranes). The strategies are described in more detail in [36]. In the graph, a vertical jittering effect is applied. Jittering slightly disperses the data points, aiding in enhancing the visual depiction of data, particularly in scenarios where pinpoint accuracy of data points is less crucial compared to understanding the overall distribution and density of the data. Increased jittering (greater deviation from the centre of each plot) indicates a larger quantity of configurations at that particular value on the x-axis. The diagram shows that the total impact on climate change is in fact strongly interrelated with the operational strategy and the number of layers. With a well-performing OPS, even configurations with less layers become viable, compared to the reference.

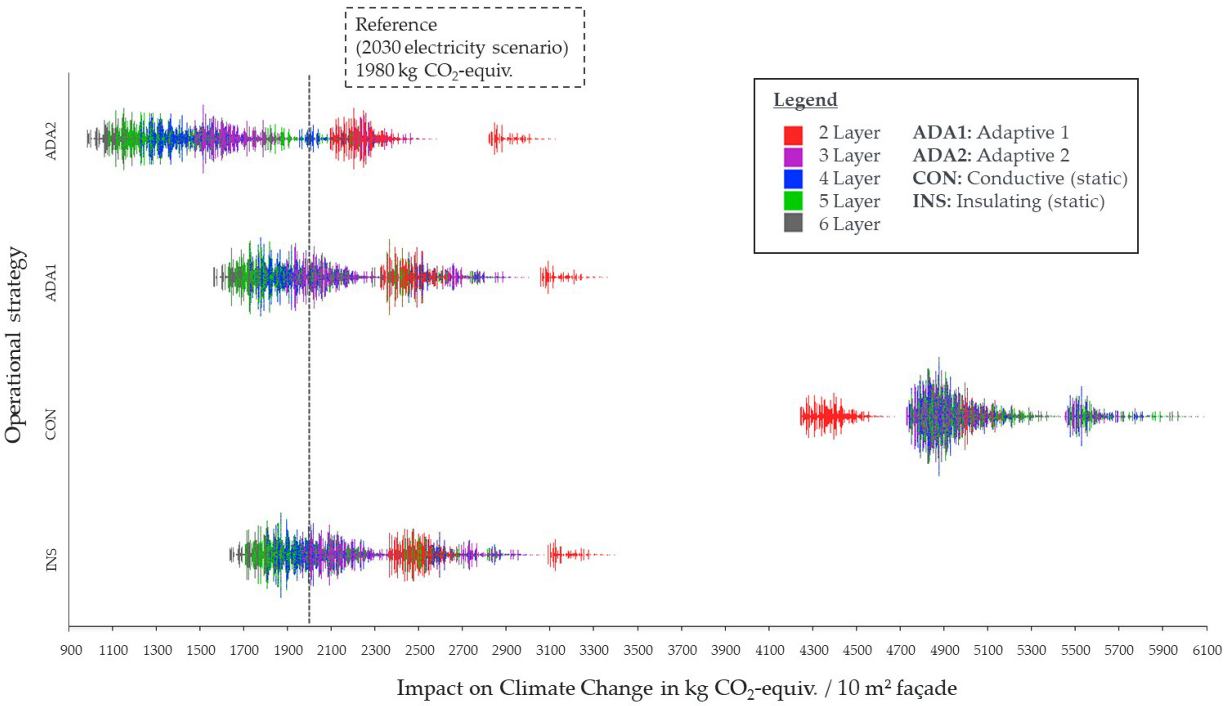


Figure 6. Contextualisation and first interpretation of the results in a jittered scatter plot (data filtered to the 2030 electricity scenario for the use phase).

Another way of contextualising different dimensions of the data is presented in Figure 7. The graph depicts an interactive, colour-coded scatter plot of the embodied and usage impact in relation to the reference system. In addition to the 2030 electricity scenario, the data are filtered to only the best-performing operational strategy, ADA2. Positive values represent configurations with a higher impact; negative values represent those with a lower impact compared to the reference.

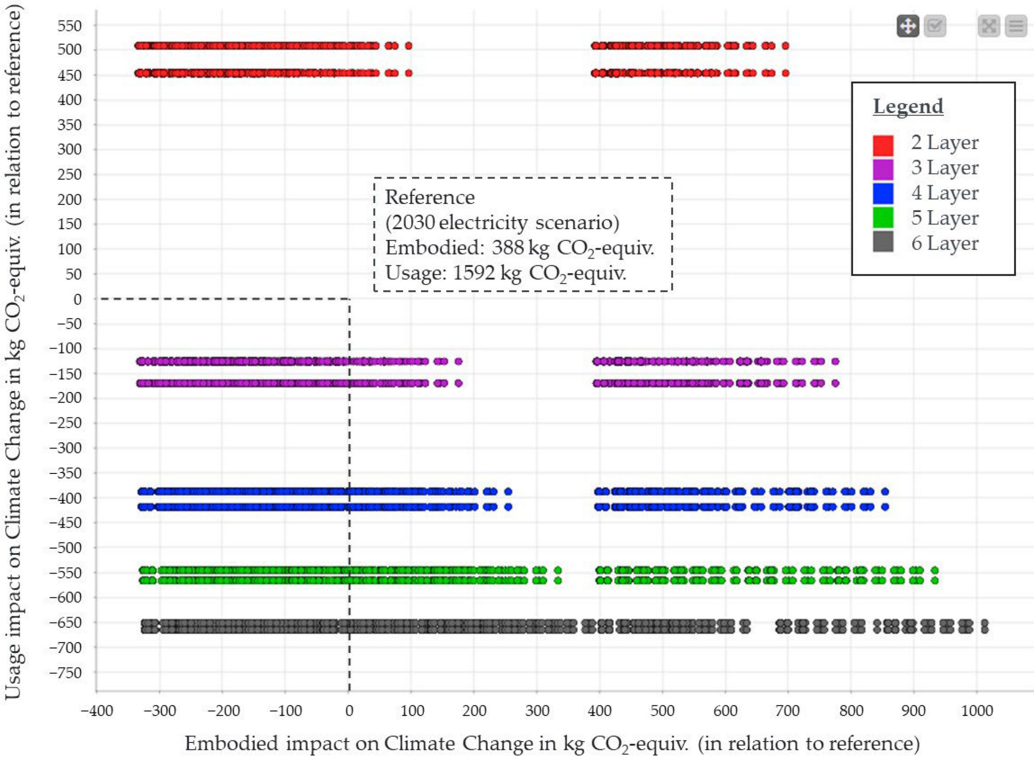


Figure 7. Scatter plot with results in relation to the reference system (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2).

The differentiation between embodied and usage impact also reveals a clear pattern of the usage impact. The higher the number of layers, the lower the impact resulting from the use phase. Within each layer, there are two distinct levels with a decreasing gap between them as the number of layers increases. Further analysis of the data reveals that this pattern results from the use of argon or air as potential gas fillings between the layers. While argon improves insulating properties and therefore reduces the energy demand and the resulting impact during use, the embodied impact is slightly higher due to additional manufacturing and impact at the end-of-life (not visible at this scaling of the axis).

Through contextualisation with a reference, a very specific area of interest could be visually identified (everything below the reference lines). Interactive implementation of this visualisation in data-wrangling software then allowed for easily marking this area in the diagram and filtering the data table behind it accordingly. Based on the filtered data, further conclusions with regard to specific parameter values and beneficial configurations could be drawn. Additionally, the configurations to be avoided (everything above the reference) could be marked and analysed. Both diagrams enabled an assessment of the results in the context of a reference while illustrating the range of the results overall.

5.2. Identification of Hotspots and Parameter Sensitivity

If the main contributors are less obvious or the parameter dependencies are more complex, the identification of hotspots and assessing of parameter sensitivity can also be conducted by visualising the data before contextualisation. This can help to identify which parameters have a major influence on the overall environmental impact of a product and mark parameters that may have a high potential for optimisation and should be analysed in more depth.

As the underlying dataset not only contains the total impact per configuration but also each parameter's impact individually, this allows for calculating and visualising parameter sensitivity. To do this, individual parameter impacts are calculated as a percentage of the total impact for the respective configuration for the unfiltered data (0.00 = 0%, 1.00 = 100%).

To allow for better readability, interdepending parameters were combined, e.g., foil material and foil end of life, as well as frame material and frame end of life. This table could then be visualised as a heat map (Figure 8). The graphic illustrates the value of each cell in the data table, shaded according to the scale that represents the share of the parameter value relative to the total impact of the configuration. Each horizontal line on the y-axis therefore represents one configuration. Darker shading represents a higher share of the total impact. Parameters that appear darker across all configurations can be quickly identified as relevant (here, Usage), whereas mostly white rows within a parameter indicate less relevance (here, Transport, Gas filling, and Contact welding). Parameters with mixed shading can have a high or low relevance depending on the specific configuration and need to be analysed further.

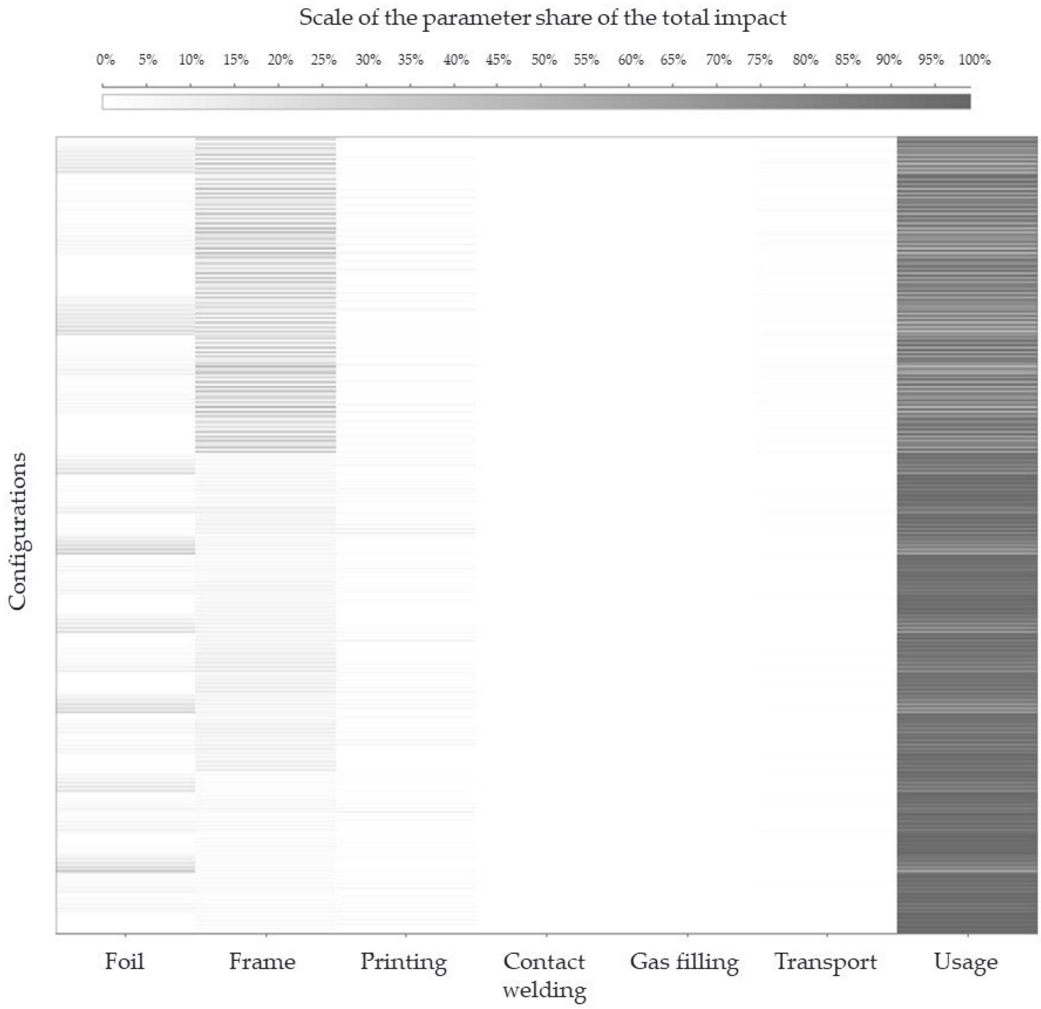


Figure 8. Parameter sensitivity visualised as heatmap for all investigated parameters; production and end of life are aggregated for foil and frame due to the dependency of these two parameters.

While the heatmap can provide fast visual feedback on parameter sensitivity (e.g., the use phase), no additional information regarding hotspots or statistical numbers are given, and the actual numbers are difficult to read, even when colouring the scale. Additionally, the analysis of particular configurations is not possible with this visualisation.

Visualising the table as a box plot can provide this additional information. The box plot in Figure 9 provides the minimum and maximum share of the parameters' impact as boxes of varying sizes with minimum, maximum, and median values. The location of the box in relation to the y-axis additionally provides visual clues about the absolute impact that the parameter has. The diagram therefore provides both parameter sensitivity (box size) and hotspots (position of the box on the y-axis in relation to other boxes).

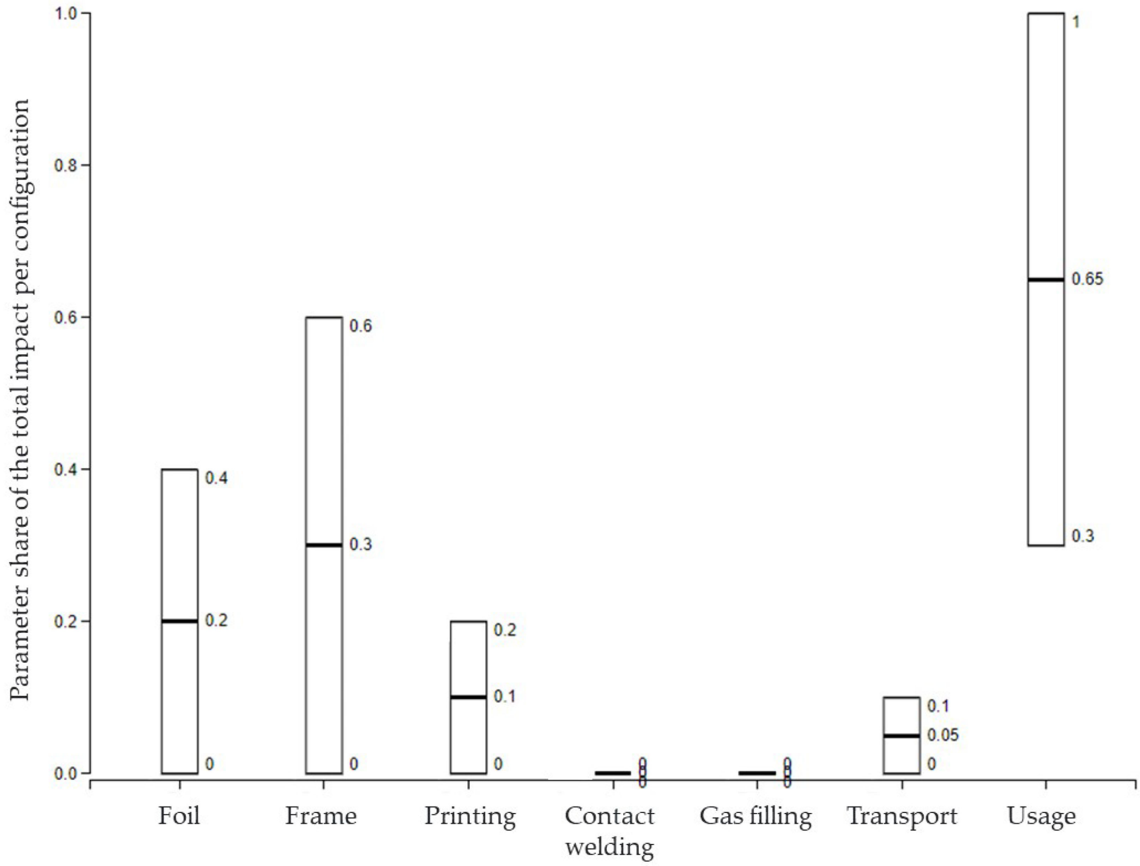


Figure 9. Parameter sensitivity and hotspots visualised in a box plot for all investigated parameters; production and end of life are aggregated for foil and frame due to the dependency of these two parameters.

Both visualisations confirm the previously stated assumption that the use phase is of particular relevance for a product. Additionally, the used foil, as well as the frame, are the most important for the embodied impact, whereas transport, contact welding, and gas filling are less important. Printing seems to be of secondary importance, but considering that only very little mass is used in the printing process, the material and thickness should be chosen with care. Based on the underlying data, it makes more sense to use the box plot for the additional information it can provide; depending on the parameter, however, the heatmap may provide more usable or indicative results.

To assess the range of impact each parameter has in absolute values, a parallel coordinate plot can be used. Each parameter is represented by a vertical axis, and multiple axes (parameters) are drawn parallel to each other. The corresponding parameter values are then plotted as connected line segments across these axes. Each line represents one of the configurations. Figure 10 depicts all configurations within the 2030 electricity scenario, as well as the operational strategy ADA2. The graph illustrates the impact each parameter value incorporates and how these values are combined. Additionally, the number of layers is colour-coded.

Notably, the total impact is clearly differentiated by the number of layers, although large overlapping can be observed. The largely symmetrical appearance hints at the combinatory character of the underlying dataset and may reveal different patterns with other data. The downside of this type of visualisation is that the parameter impact is normalised; therefore, comparing the impact between the parameters is not as efficient in comparison to, e.g., the box plot (see Figure 9).

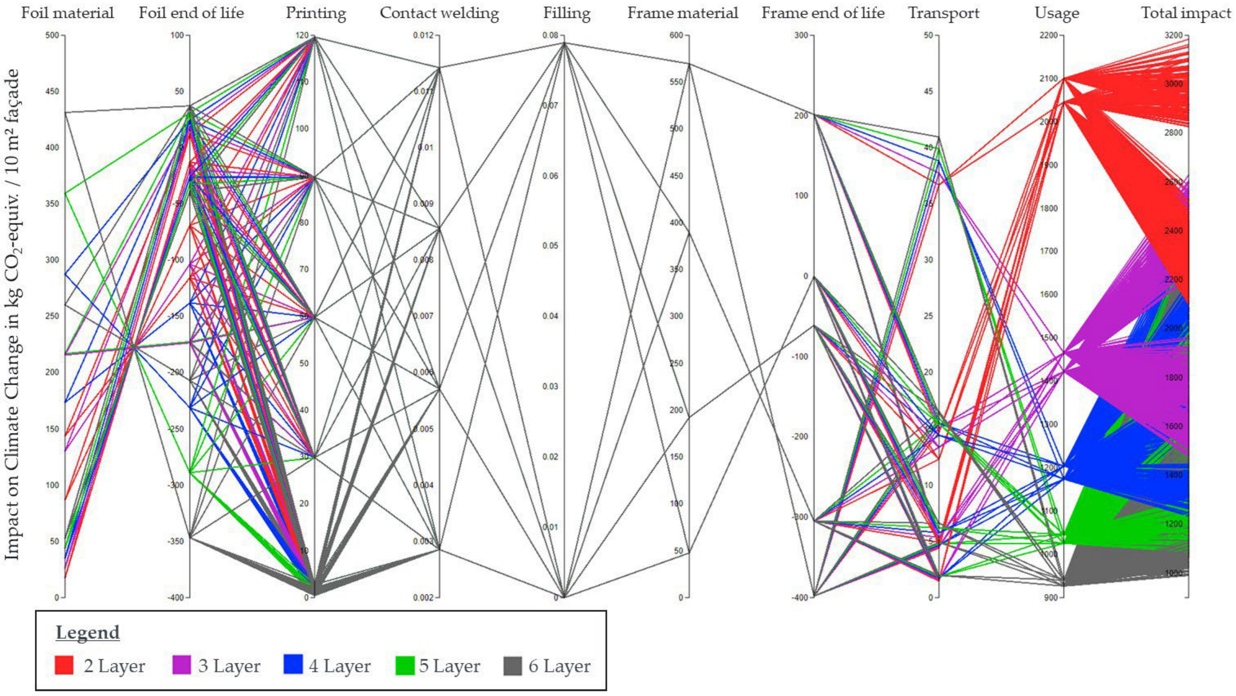


Figure 10. Colour-coded parallel coordinate plot (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2).

5.3. Exploration and Understanding

The goal of exploration and understanding the data is focused on identifying configurations to be preferred or avoided, as well as interactions between the parameters that affect the overall environmental impact. In the case of the adaptive membrane façade, a line plot of each parameters' impact on climate change yields interesting first results. In Figure 11, each line represents the impact of the respective parameter within each configuration of the filtered dataset (2030 electricity scenario, ADA2). Since the line plot depicts the results as they are sorted in the data table, this provides an additional way to explore data and find patterns. Here, the table is sorted by total impact (ascending). Two distinct groups of parameters can be noticed within the graph. The lower part contains the parameters that represent the embodied impact. The top part depicts the impact, resulting from the 20-year use phase. There are five clear steps within the usage impact, which indicate the five different configurations of layers (two layers to six layers). It is also shown that the configurations with lower total impact (towards the left side of the diagram) are the ones with lower usage impact. There are overlaps visible (e.g., around configuration 15,000), but the overarching pattern (clear steps of usage impact related to the number of layers) is clearly noticeable. The implementation of this visualisation in the data-wrangling software is also interactive and allows for zooming in within a selected area. Because the number of the configuration in the graph matches the line in the data table, specific configurations of interest can be identified and further analysed. Figure 12 visualises the same set of data, but these are sorted by usage impact. This diagram clearly shows the combinatory technique with which the dataset was created. Distinct patterns, representing the discrete impact of each parameter value, are visible.

When dealing with multicriteria data, as is often the case in LCA, it may be useful to display additional dimensions in the visualisations. Other than colour-coding, additional dimensions can be added by coupling the size of the data points to one of the parameters of interest within a bubble chart. Figure 13 illustrates the total impact on climate change for the different foil materials, ETFE, PP, PTFE, and PE. The number of layers is colour-coded, and the size of the data points is determined by the usage impact for the respective configuration. Again, it can be seen that configurations with fewer layers result in a higher impact during the use phase. In addition, the diagram shows that there are slight (but no major) differences among the materials used for the foil. This indicates a potential area of compromise, when the product developer must balance technical, financial, and environmental criteria.

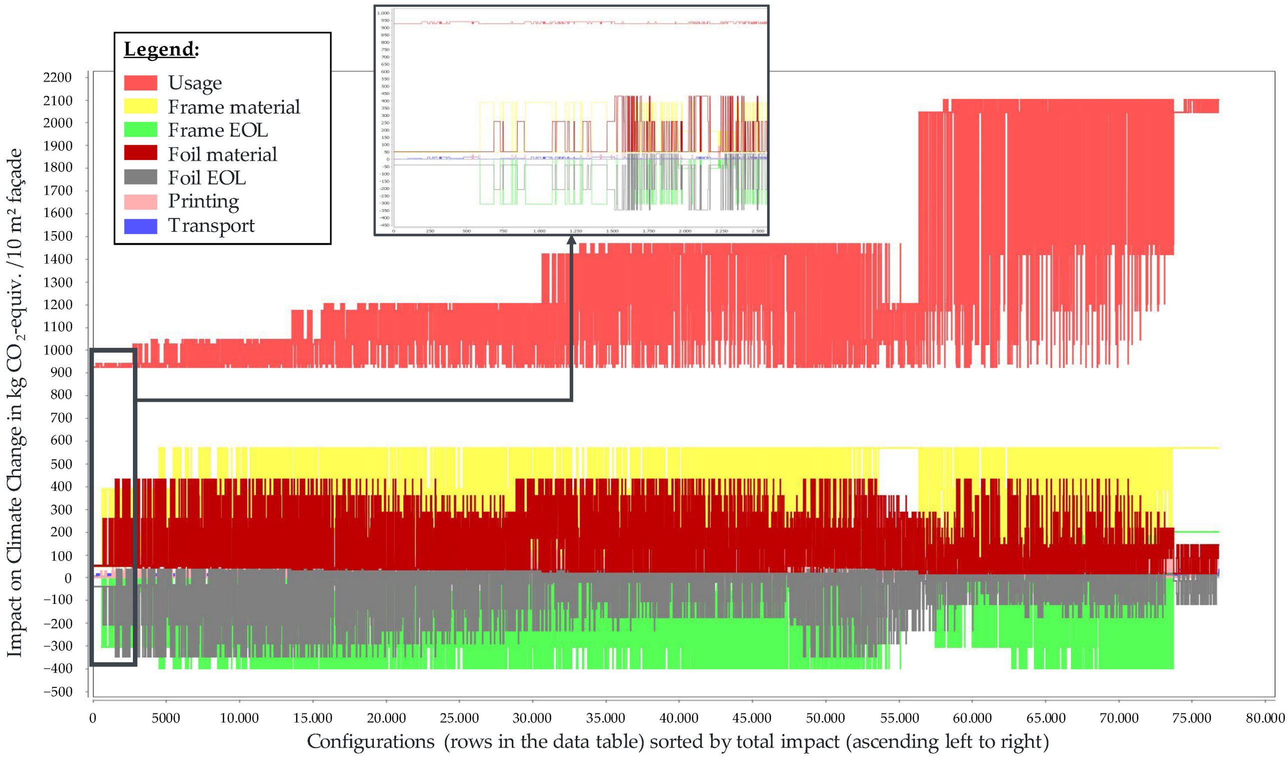


Figure 11. Line plot to find patterns (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2, sorted by total impact), with a zoomed-in window.

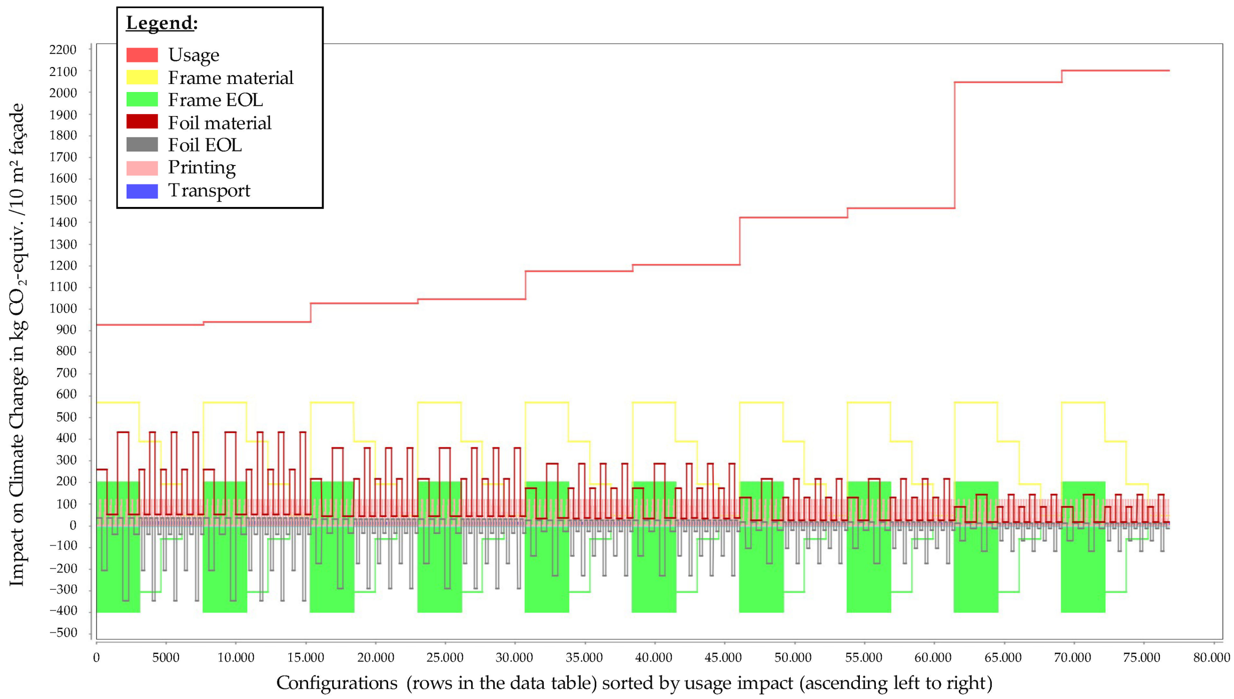


Figure 12. Line plot to identify potential patterns (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2, sorted by usage impact).

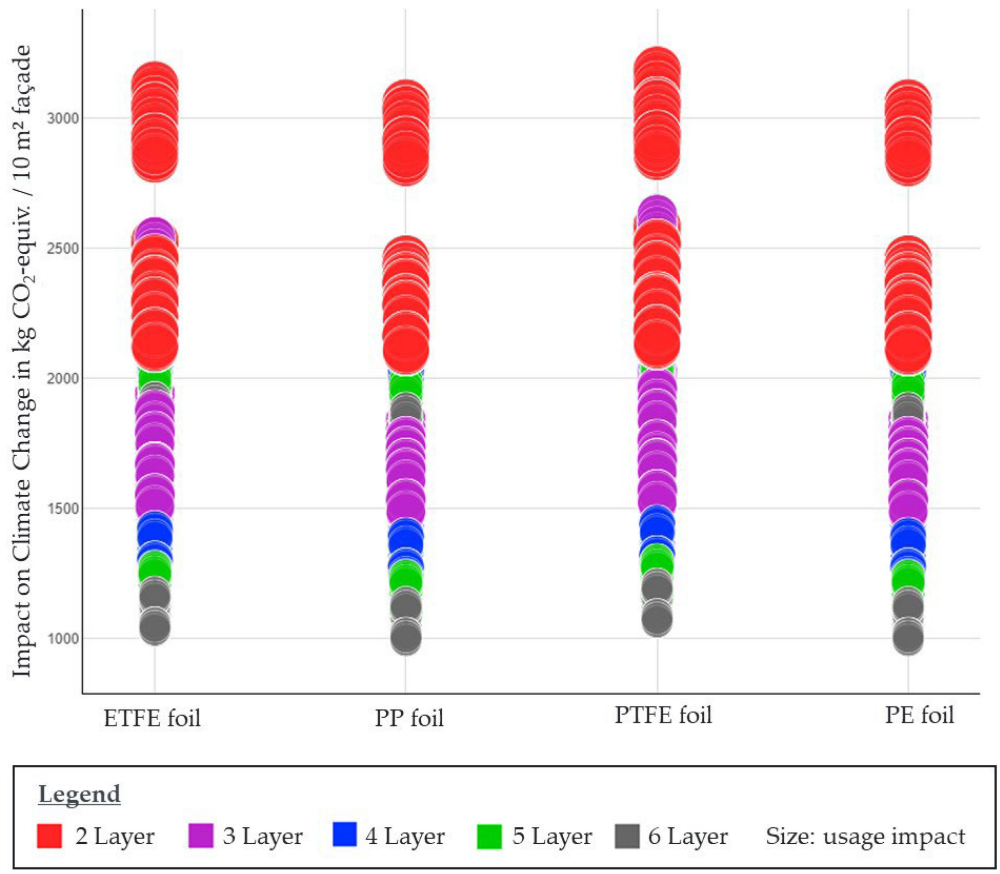


Figure 13. Colour-coded bubble chart for the impacts regarding climate change with four dimensions: material (*X*-axis), total impact (*Y*-axis), number of layers (colour-code), usage impact (bubble size); data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2.

As already shown in Section 5.1, colour-coded scatter plots have emerged as useful tools to analyse and understand data. Both Figures 6 and 7 provide multiple dimensions (*x*-axis, *y*-axis, color-coding, jittering) that help to analyse and understand the data and reveal interdependencies among different parameters. Interactive versions of these plots allow for the live filtering of data and display changes in real time, making them incredibly versatile for exploring and understanding data.

While Figures 6 and 7 focus on the overview and comparison of different operational strategies and layers, both of the following graphs delve deeper into the main contributing factors regarding the embodied impact. Figure 14 illustrates the impact of the filtered dataset on climate change, differentiated by the material of the frame. While both aluminium frames show very similar patterns, the polyoxymethylene (POM) frame displays a different pattern. Colour-coding the end-of-life scenario reveals that this is due to an additional incineration scenario calculated for the POM frame. The graph shows that the incineration scenario has a 50% higher impact on climate change compared to the recycling one and should be avoided. The same can be accomplished with foil materials. Figure 15 depicts the impact on climate change differentiated by different foil materials, with the end-of-life scenario colour-coded analogously to Figure 14. The data show large overlaps and underline the importance of recycling, especially for materials with a higher impact (ETFE and PTFE, in this case). Both of these diagrams showcase the benefits of colour-coding specific parameters to better understand the data and the results, as it can clarify overlapping data.

The presented visualisation in Figures 6 and 7 showcase the influences and differences between the operational strategies, highlight recognisable patterns according to the number of layers, and visualise overlaps among the configurations with different numbers of layers. Figures 11 and 12 indicate a clear relation between the use phase and the total impact, as well as the use phase, number of layers, and gas filling. Figure 13 shows a clear relation between the use phase and number of layers, and it presents results differentiated by an additional dimension (in this case, foil material). Figures 14 and 15 allow for the differentiation of end-of-life scenarios, clearly highlighting the benefits of recycling at the end of life. Therefore, all the presented visualisations enable the exploration and understanding of the dataset, as well as the generation of insights to improve the design of the adaptive, multilayer membrane façade.

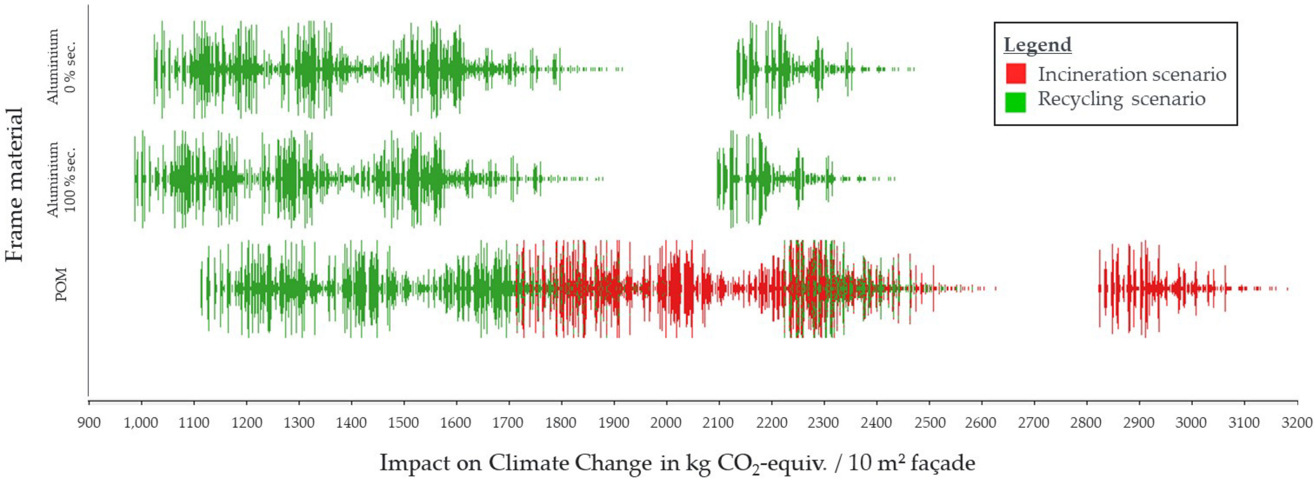


Figure 14. Scatter plot frame materials, colour-coded end of life (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2).

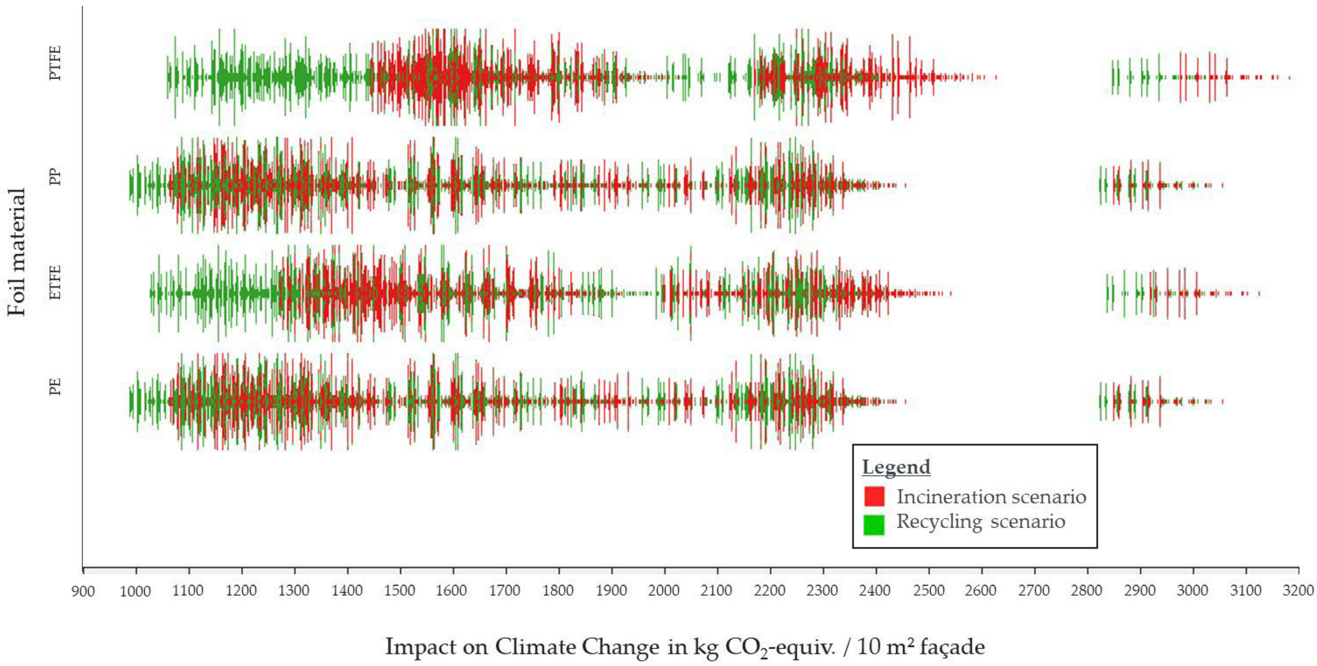


Figure 15. Scatter plot foil materials, colour-coded end of life (data filtered to the 2030 electricity scenario for the use phase and operational strategy ADA2).

5.4. Benchmarking

Assessing all potential configurations within the defined parameter space allows for an efficient calculation of robust, usable, and dynamic benchmarks for the initial assessment of environmental impacts.

The type and amount of information within box plots makes them predestined for the visualisation of benchmarks. Because analysis and calculations are automatically performed by the software applied in the background, this process is very time efficient. Furthermore, filtering the dataset allows for the creation of benchmarks only containing a selected area of interest, enabling dynamic benchmarking tailored to user and use-case-specific queries.

For each number of layers, the minimum, maximum, and median of the impact on climate change over the 20-year life cycle per m^2 room area are given in Figure 16. The boxes represent the interquartile range (IQR) of the dataset. The IQR is the middle 50% of the data and contains the values between the first quartile and the third quartile. Because the results include impact during the use phase, this benchmark is related to the corresponding room area of 29.5 m^2 with the 10 m^2 exterior façade and adiabatic interior walls, which are not part of the LCA.

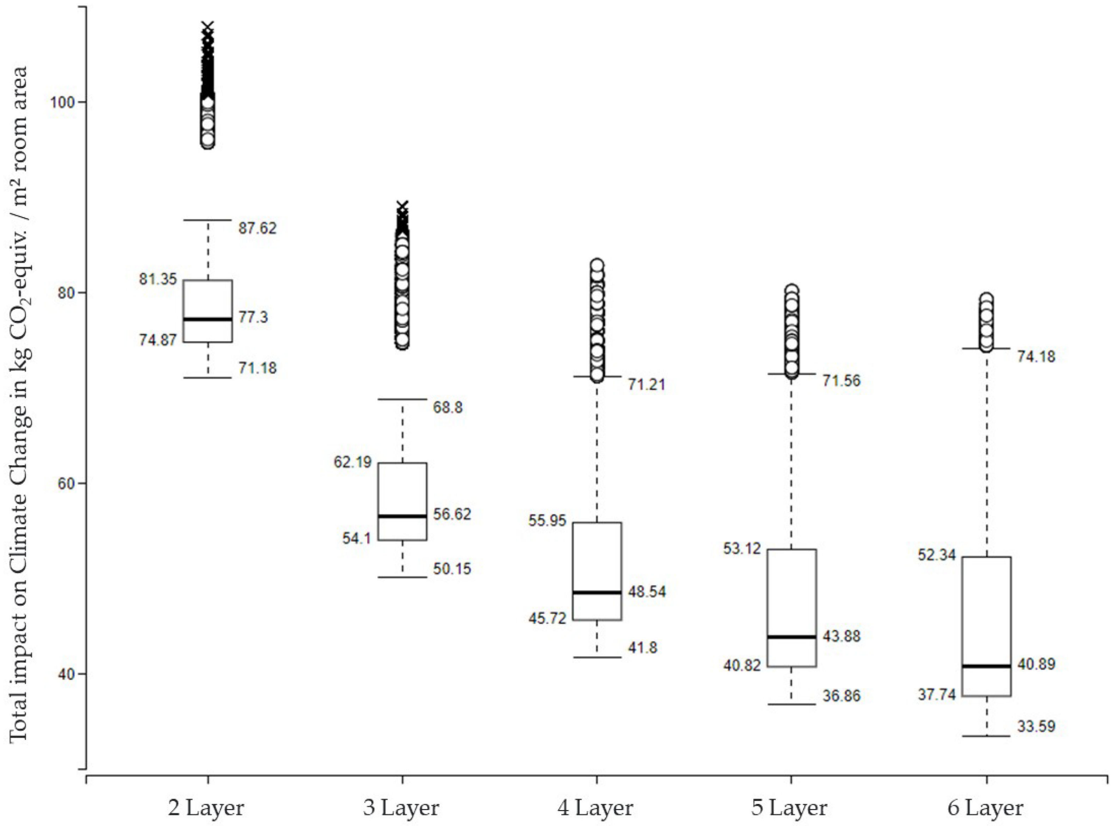


Figure 16. Total impact on climate change per m^2 room area and number of layers.

Figure 17 features the same visualisation as Figure 16, excluding the use phase, and therefore depicts the embodied impact from the manufacturing and end-of-life phases related to one m^2 façade area. The data are filtered to the 2030 electricity scenario, as well as the best performing operational strategy, ADA2. Outliers in both diagrams mainly mark the configurations where an end-of-life scenario is considered incineration. Both benchmarks are based on nearly 80,000 configurations.

Both benchmarks illustrate opposing trends in relation to the number of layers. While the embodied impact increases with more layers, the reduced impact during the use phase offsets and reverses this trend. However, this effect decreases again with the increase in number of layers. Additional layers increase the embodied impact while the usage impact converges against a lower limit and does not decrease enough to fully offset the additional embodied impact. This emphasises and underlines the necessity of a holistic assessment considering all phases of the life cycle.

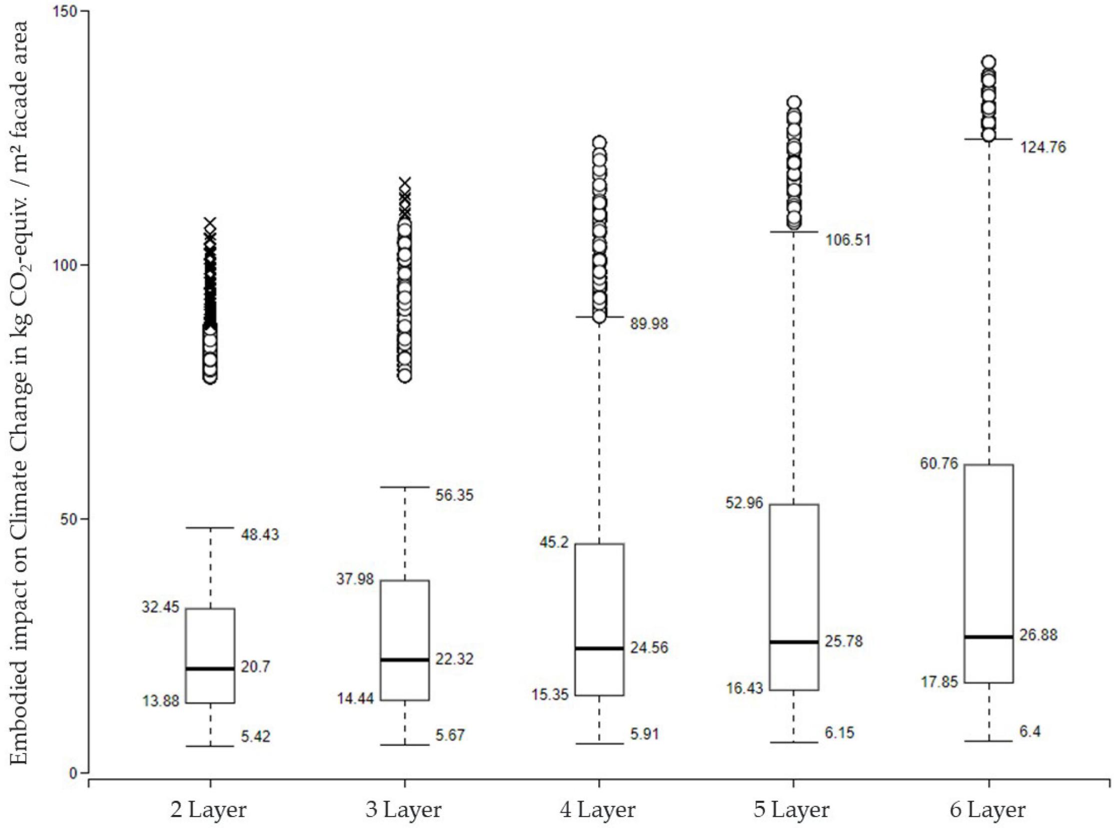


Figure 17. Embodied impact on climate change per m^2 façade area and number of layers (production and end of life; excluding use phase).

6. Summary and Discussion

From an exclusively environmental perspective, the optimal configuration of an adaptive membrane façade within a defined parameter space would be a 6-layer, argon-filled PP foil construction with an aluminium frame constructed from 100% recycling material and printed with titanium dioxide. In combination with recycling at the end of life of the frame and foil, as well as the lowest possible transport distance, these configurations would have the smallest impact on climate change. Figure 18 compares the optimised 6-layer configuration to the typical 3-layer configuration, as described in Section 3.2. However, the analysis of the life cycle reveals that the fifth and sixth layer reduce the impact less than the addition of a third or fourth one. The results are even closer when the 2040 or 2050 electricity scenario for the use phase is considered. Taking technical and economic constraints into account as well, this might be an area for compromise. Subsequent analysis steps could be to limit the configurations to a specific foil material and re-evaluate the influence of additional layers.

In the beginning, the typical goals for the interpretation of LCA results were slightly adapted to accommodate for large-scale LCA results, and several questions were derived that need to be addressed by the LCA practitioner, with suitable visualisations. Based on a dataset containing 1.25 million LCA results for all potential configurations within a defined parameter space, different visualisations and analysis methods were applied to identify hotspots, assess parameter sensitivity, gain insights to optimise the environmental footprint, and provide benchmarks for an adaptive, multilayer membrane façade, as well as answer the questions derived for each of those goals. The underlying dataset, as well as the workflow, were validated using the steps described in Section 4.1. Especially when dealing with automatically generated data and complex workflows, the results must be ensured to be correct and plausible.

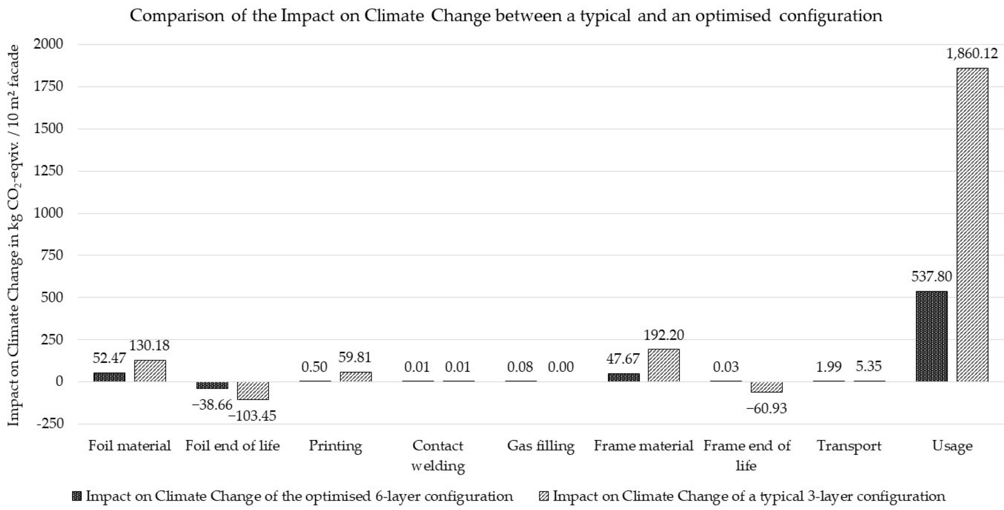


Figure 18. Comparison of the impact of a typical 3-layer configuration on climate change with an optimized 6-layer construction, differentiated by parameter.

Different levels of filtering were explored, and different insights regarding the contextualisation and identification of hotspots and parameter sensitivity were provided, as well as data exploration and understanding. Within the analysis of this case study, box plots emerged as a versatile tool, offering multifaceted insights into parameter sensitivity, hotspot identification, and benchmarking. Scatter plots, especially when enhanced with colour-coding for specific parameters, have proven to be a powerful medium for contextualizing results against a reference, providing detailed insights, and fostering a deeper understanding of a product's environmental impact. The interactive nature of these plots in data-wrangling software allowed for the identification and isolation of specific areas of interest, amplifying their utility even further. Although initially promising, heatmaps were found to be less impactful within the context of this study, offering limited value in terms of parameter sensitivity. The colour-coded parallel line plot provided an understanding of parameter sensitivity and enhanced comprehension of the dataset, but due to the normalisation of the parameters, it needs to be analysed with care. Line plots, particularly in combination with different data sorting, materialised as a useful tool in uncovering underlying patterns within the results. In this case, visualisation enabled easy distinction between embodied and usage impacts. Bubble charts, when complemented with colour-coding, proved to be an effective way of incorporating additional dimensions. This enhanced the understanding of the multidimensional data and enabled the identification and interpretation of interrelated parameters. Moreover, the charts facilitate interactive analysis by enabling the isolation of specific areas of interest.

All visualisation methods applied in this study are summarised with their respective potentials and limitations in Table 4. They enable the comprehensive understanding of large-scale LCA results, extending beyond mere numerical data. Being able to add additional dimensions with colour-coding and filter the data based on interactive plots proved to be instrumental in understanding the data and identifying potential for optimising the lessening of the environmental impact. While the way of visualising and analysing the dataset is transferable to other products, relevant parameters will change and must be identified individually. Depending on the product, some visualisations (e.g., heatmaps like Figure 8 or line plots like Figure 11) may or may not provide useful information. Furthermore, the robustness of the results is strongly linked to the underlying dataset and the area of data that is displayed. Special attention and understanding of the parameter space is needed to avoid bias in the results. An example of this are the different electricity scenarios investigated in this study. Since only the scaling of the usage impact is affected by this, analysing should be limited to only one specific scenario in most cases (assessing parameter sensitivity is an exception to this recommendation).

Table 4. Potentials and limitations of the applied visualisations according to the goal of interpretation.

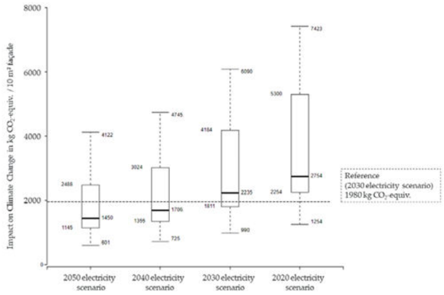
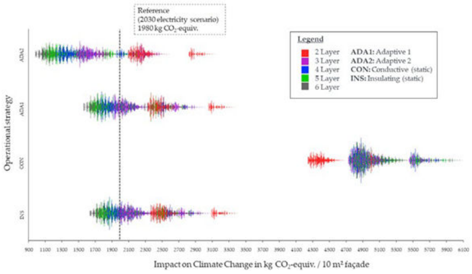
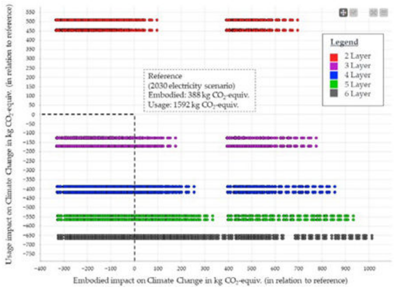
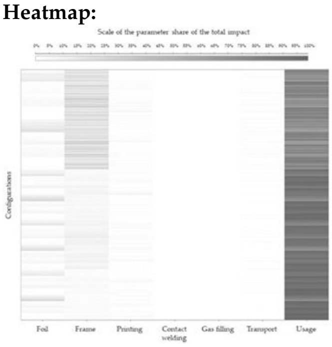
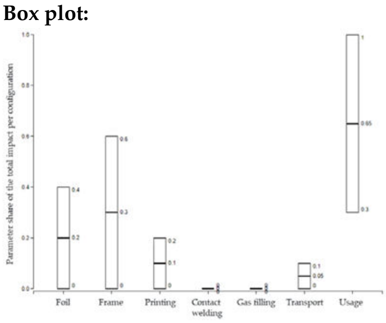
Goal of Interpretation	Visualisation	Potential	Limitations
Contextualisation	**Box plot with reference:** 	Provides a statistical overview of the results and can reveal general trends. Allows for classification with a reference.	No conclusions can be drawn about individual configurations.
Contextualisation	**Scatter plot with reference:** 	Powerful for gauging the results compared to a reference and interpretation. Jittering highlights the frequency of occurrence.	May need additional knowledge or trial and error when deciding which parameter to analyse.
Contextualisation	**Scatter plot with reference:** 	Powerful for gauging the results compared to a reference and interpretation. Interactive versions enable the isolation of data for further analysis.	May need additional knowledge or trial and error when deciding which parameter to analyse.
Hotspots and sensitivity	**Heatmap:** 	May reveal general trends in the data and provides strong visual clues on high-impact parameters.	Moderately dominant parameters and relative impacts are harder to identify. No additional information regarding hotspots or statistical numbers are given.
Hotspots and sensitivity	**Box plot:** 	Provides hotspots (location of the box) and parameter sensitivity (size of the box) and is easy to read.	The absolute impacts of the parameters are not included.

Table 4. *Cont.*

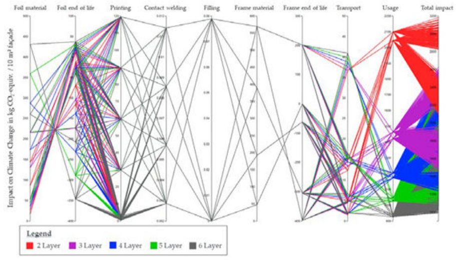
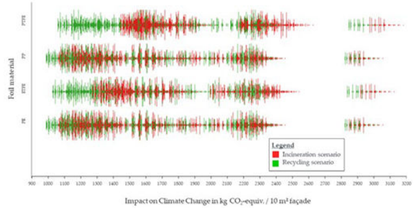
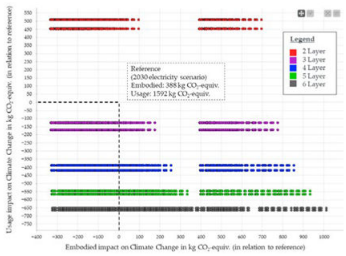
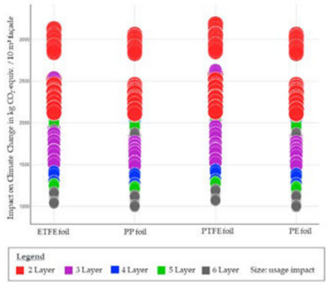
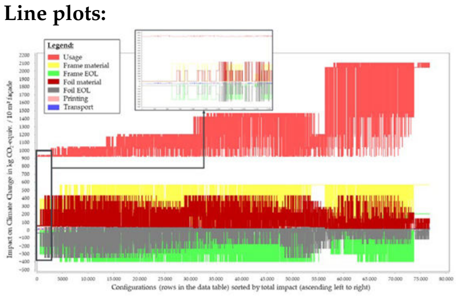
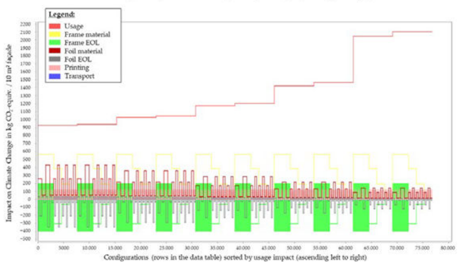
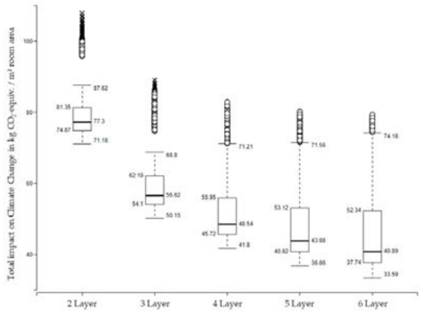
Goal of Interpretation	Visualisation	Potential	Limitations
Hotspots and sensitivity	**Parallel coordinates:** 	Absolute values of the parameters are included and can be compared. Color-coding can reveal distinct patterns and interdependencies.	Parameter impact is normalised. Overlay of data can make the visualisation hard to comprehend.
Exploration and understanding	**Scatter plots:**  	Extremely versatile for exploration and interpretation of the dataset. Color-coding adds an additional dimension to reveal interdependencies. Interactive versions allow realtime filtering (disable or enable parameters or specific values).	May need additional knowledge or trial and error when deciding which parameter to analyse.
Exploration and understanding	**Bubble chart:** 	Useful to explore and understand interdependencies because of the additional dimension compared to scatter plots.	May need additional knowledge or trial and error when deciding which parameter to analyse.
Exploration and understanding	**Line plots:**  	May reveal distinct patterns in the data in combination with the sorting of the table and allows for assignment to configurations.	Potential insights may be strongly dependent on the underlying data.

Table 4. *Cont.*

Goal of Interpretation	Visualisation	Potential	Limitations
Benchmarking	**Box plot:** 	Allows for the efficient visualisation of statistical evaluations that can be used as benchmarks.	Can be difficult to read if the absolute values of the parameters are too far apart.

In contrast to static visualisations, interactive visualisations provide the ability to mark and filter areas of interest, highlight clusters, and provide instantaneous feedback when changing or filtering parameters, making them a vital tool in exploring and understanding underlying data. The downside is that they lose their main benefit completely when printed, shown in a presentation, or included in a manuscript. However, static visualisations are essential to communicate the results of detailed exploration and to illustrate dependencies, correlations, and sensitivities, as well as underline recommendations derived from the insights gained. The intended use of the visualisations also creates different requirements (colours, font sizes, readability of the data) and therefore co-defines their actual usefulness. As touched upon earlier, the size of the medium on which the visualisations are shown may vary from part of a DIN A4 page in a report to a 55″ digital screen in a meeting room, not to mention multiple monitor setups. This highlights the importance of defining a proper goal and scope, and it is at least advisable (if not necessary) to keep this in mind when starting an analysis.

7. Conclusions and Outlook

The importance of visualisations in context of life cycle assessment has been widely discussed and acknowledged in the literature. Especially with the increasing ability of processing and creating large-scale LCA results, visualisations are vital tools to not only analyse and interpret results but also check and validate underlying datasets. This article provides multiple visualisations for different goals of LCA interpretation and illustrates what insights can be gained, using the example of a multilayer, adaptive membrane façade. Box plots for the identification of hotspots, parameter sensitivity and benchmarking, and colour-coded scatter plots have proven to be incredibly versatile and effective for understanding the results and providing multiple perspectives to gain further insight. The ability to interact directly with the visualisation to identify and isolate specific areas of interest allows for a very efficient analysis of the relevant aspects of data. This might be particularly relevant when resources and time are limited.

However, not all visualisations are useful for all levels of filtering or individual stages of the analysis. Visualising all configurations in a scatter plot without colour-coding right at the beginning will likely just overwhelm the analyst, not yield any useful results, and even cause basic findings to be missed. Based on gained insights of parameter sensitivity and a step-by-step understanding of both the product and the data helps to identify the relevant areas and guide the practitioner towards the target-oriented use of the visualisations.

Future work should apply the presented visualisations to different products to assess their transferability. Questions that emerged during this case study are as follows: Do all visualisations yield similar and useful insights when assessing different products? Which ones may be building-product-specific (high impact of the use phase compared to the embodied impact)? Which ones can be applied universally? Answering these questions would help to develop (product-specific or universal) standards and a framework for the efficient analysis and visualisation of large-scale LCA results.

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