Sustainability Data Analytics

an Integrated Data-Informed Approach for Assessing the Sustainability of Design Alternatives

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This study presents an interactive visualization strategy for evaluating design alternatives' sustainability, driven by data from building information modelling (BIM) and life cycle assessment (LCA). After outlining a workflow, we identified the key interaction features of sustainability data to evaluate and improve LCA performance. The low-fidelity prototype, called Green Plans, is presented as a design analytics system aiming to describe these key features. The prototype uses parallel coordinates and Sankey diagrams to examine how form, material, and envelope affect sustainability, and the analytic hierarchy process (AHP) is used to inform the conceptual design. Sustainability is evaluated using key metrics such as global warming potential (GWP), energy consumption, and greenhouse gas (GHG) emissions. The study proposes design data visualization and suggests improvements in simulation, comparative analysis, and integration with design tools.

Keywords: sustainability assessment, comparative analytics, Life Cycle Assessment, interactive design data visualization, design analytics

INTRODUCTION

Architects often find it challenging to make sense of sustainability data (Jusselme et al., 2018), particularly during generative design phases where numerous options are explored. The complexity of interpreting such data and assessing sustainability (Cook et al., 2017) can lead to uncertainty about the results of the design decisions and further improving design solutions. Architects can benefit from new design aid systems that enable interactive investigation of design alternatives considering their potential sustainability performances.

The design process involves trade-offs between different factors influencing the outcome, and identifying these factors to balance sustainability with other design goals can become cognitively demanding. Analyzing multiple factors, such as form, energy consumption, and material type, depends on system features that can reveal the sensitivity of a design's sustainability when exploring trade-offs. The lack of tool features for sustainable life cycle assessment and design to compare different design alternatives is one of the shortcomings of the available sustainability assessment tools (Ness et al., 2007; Zamagni, 2012), such as Tally, One Click LCA, and Athena (Banani et al., 2016; Mateus & Bragança, 2011; Miyamoto et al., 2022a; Ness et al., 2007). There are several other challenges of such tools discussed in the literature. For example, Hollberg et al. (2021) discussed that the lack of clear guidelines and unified visualization methods makes it challenging to communicate complex SLD data.

This paper explores use cases and system features that can support architects' design decision-making process by demonstrating them on a low-fidelity prototype system called Green Plans. Through "Green Plans," we aim to investigate how these shortcomings and challenges can be addressed. The prototype retrieves design data of alternative solutions from Building Information Modelling (BIM) and Life Cycle Assessment (LCA) systems. It presents the design data through interactive visual interfaces for streamlining sustainable life cycle assessment and design (SLD).

RESEARCH QUESTIONS

Our main research goal is to question how design-decision support systems focusing on sustainability data visualizations can assist designers in identifying areas for design improvement and their LCA performance by offering data-informed insight during the various design phases. Concerning this question, we are particularly interested in exploring design analytics interface and their potential for acceptance (Nielsen, 1993) in designing built environments.

- RQ1. How can BIM data be used for sustainable decision-making in the early conceptual design phases?
- RQ2. What are the novel system features that can improve the seamless integration of sustainability evaluation systems into the decision-making workflows of architects and other designers while encouraging sustainable practices?
- RQ3. Which data visualizations have the potential to facilitate the integration of sustainability data assessment in the design process while revealing complex life-cycle data?

RELATED WORK

The pressing need to address the environmental impact of human-related activities on the built environment, which accounts for more than one-third of global greenhouse gas emissions, has prompted research into sustainable architectural practices (Wang et al., 2017; Liu et al., 2022). we investigate the existing studies and tools that combine Building Information Modelling (BIM) and Life Cycle Assessment (LCA) data, particularly emphasizing visual methods for sustainability assessments in architectural design.

Munzner's QuestVis tool stands out as a valuable prototype for environmental sustainability assessment (Munzner et al., 2011). Designed for large-group workshops, it integrates policy decisions, model computations, and scenario analysis. The tool's structured approach aids in understanding complex trade-offs, making it particularly useful for public engagement. With linked views and a multilevel browser, QuestVis enables a comprehensive exploration of the relationship between input choices and environmental indicators. Its iterative design ensures accessibility for laypeople unfamiliar with data analysis while providing deep insights into the implications of policy decisions on sustainability.

Ramanujan et al. (2015, 2017a) highlight the importance of incorporating sustainability-related product metadata into design exploration tools. The framework presented enables sustainability-aware exploration and reuse of previous design knowledge. It utilizes taxonomy-based representations for design metadata, allowing for automated estimation of environmental indicators and part similarities.

Miyamoto et al. (2022b) present a comprehensive visual approach to help architects integrate life cycle assessment (LCA) and life cycle cost (LCC) into their design processes. The authors argue that data visualization techniques can facilitate this integration and provide a comprehensive view of different design alternatives' environmental impact and cost implications (Miyamoto et al., 2019). They suggest a visual method of converting environmental effects into costs to include them with monetary expenses in a life cycle costing methodology. The life-cycle environmental impact and cost of design decisions are analyzed graphically and interactively using various data visualization tools, including Sankey diagrams, radar charts, and bubble charts. Architects can make more environmentally and financially responsible decisions using such visual tools.

Radar charts (Cook et al., 2017; Saunders et al., 2013a) and bubble charts (Gerrish et al., 2017; Saunders et al., 2013b; Zhou et al., 2019) are among the visualizations used in sustainable design to compare design alternatives based on sustainability criteria.

We highlight the adaptability of our system features to dynamic considerations within our prototype's framework. The prototype is designed to flexibly accommodate shifting project priorities, allowing architects to assign variable weights to factors such as form, geometry, material types, compactness of the building, envelope, insulation types, and more, tailored to the unique requirements of each project. This adaptability ensures that sustainability assessments remain aligned with the current project context, facilitating informed design decisions that consider specific trade-offs essential for a project's success (Figures 1-3).

SUSTAINABILITY ASSESSMENT TOOLS

Although certain tools for assessing building sustainability exist, such as LEED, BREEAM, WELL, Green Star, Energy Plus, IES EV, and Ecotec, the integration of BIM and LCA is not frequently used due to their complexity (Röck, Hollberg, et al., 2018a; Röck, Passer, et al., 2018). The BIM-LEED is among the current sustainability assessment tools, which provides an example of BIM and green building assessment integration. Leadership in Energy and Environmental Design (LEED) is a popular sustainable building certification program. The BIM-LEED tool helps designers assess design solutions' sustainability when the design is completed (Cavalliere et al., 2019). However, it does not work for the Low Level of Detail design.

Five LCA tools specifically designed for use with buildings include eToolLCD, OneClick LCA, Athena impact estimator, Tally, and Caala (Sartori et al., 2021, 2022). Table 1 lists the strengths and weaknesses of each tool. LCAs are done manually or semi-automatically within these tools by importing BIM model data. LCA can be carried out at different levels of detail (LOD) for the design options. A higher LOD leads to precise calculations and high accuracy. However, achieving this higher LOD is not always feasible during the design process, especially when designers need a rough estimate of their design's impact on cost, emissions, energy performance, and other sustainability metrics such as GWP and ozone depletion. Therefore, in the early conceptual stages of design with lower LOD, conducting a life cycle assessment with lower accuracy can significantly impact design sustainability, especially when crucial decisions are being made. Lifecycle assessment (LCA) is a complex process involving multiple stages: extraction, manufacturing, transportation, construction, operation, and end-of-life. Quantifying and comparing environmental consequences are challenging, especially for designers dealing with multiple variables. Current LCA tools have complex methodologies, making it difficult for architects and professionals without LCA backgrounds to integrate environmental factors during the initial design phase.

Tools	Strengths	Weaknesses
eTool LCD	Considers cradle-to-cradle life cycle definition and operational energy use. Considers substructure, superstructure, internal finishes, and fittings of the building. Provides various functional units to choose from.	Does not have a material focus.
OneClick LCA	Considers cradle-to-cradle life cycle definition and operational energy use. Considers various building types including commercial, industrial, institutional, residential, and historic or protected monuments. Provides absolute values and project baselines for functional units.	Does not have a material focus. Does not consider the substructure, superstructure, internal finishes, and fittings of the building.
Athena impact estimator	Considers cradle-to-cradle life cycle definition. Provides various functional units to choose from. Has a material focus.	Excludes operational energy use. Does not consider the substructure, superstructure, internal finishes, and fittings of the building.
Tally	Considers cradle-to-cradle life cycle definition. Considers various parts of the building including foundation, substructure, structure, enclosure, finishing and other materials, and external areas and services. Has a material focus.	Excludes operational energy use. Does not provide various functional units to choose from.
CAALA	Considers cradle-to-cradle life cycle definition. Provides various functional units to choose from. Considers German standards, permits, and certifications.	Excludes operational energy use. Does not consider the substructure, superstructure, internal finishes, and fittings of the building. Does not have a material focus.

Table 1 Comparison of LCA tools for Sustainable Building Design

This study aims to present system features on a low-fidelity prototype called Green Plans, which employs Building information modelling (BIM) and life cycle assessment (LCA) data to comparative analytics of the environmental sustainability of multiple design alternatives (Figure 1,2). The prototype includes interactive data visualizations built following Sedlmair's design study methodology (Sedlmair et al., 2012).

As a creativity support tool (Shneiderman et al., 2016), Green Plans proposes an iterative design-develop-evaluate cycle and formative qualitative evaluations (Poth, 2018) to improve the environmental impact of design alternatives in the early stages. Based on the existing literature, we identified an eight-phase design decision-making workflow for building sustainable environments and situated Green Plans as part of its data analytics tasks (Figure 1, indicated by red). The eight phases are covered in the literature in detail, due to the page limitation, we present the data analytics phases or tasks as we discuss the Green Plan’s key system features below.

KEY SYSTEM FEATURES

An effective interface should include grouping and filtering capabilities for organizing and analyzing LCA data based on user preferences. The inclusion of sensitivity analysis allows users to understand the impact of diverse design parameter changes on sustainability metrics, while real-time feedback ensures immediate insights into environmental consequences.

Green Plans is distinguished by its visual sustainability assessment visualization features (Figure 2). It employs visualizations like the Sankey diagram to illustrate the energy flow associated with various design alternatives, in contrast to tools that present data in tabular format. Using a visual approach (Ramanujan et al., 2017b) streamlines the assessment process and facilitates the comparison of various design alternatives, simplifying the process of making sustainable design decisions.

Figure 1 Eight-Phase LCA integrates material databases and builds 3D models consistent with current practices. Phase 6 introduces LCA visualizations in the workflow for detailed or comparative analytics of design alternatives' sustainability data. (created by the author)

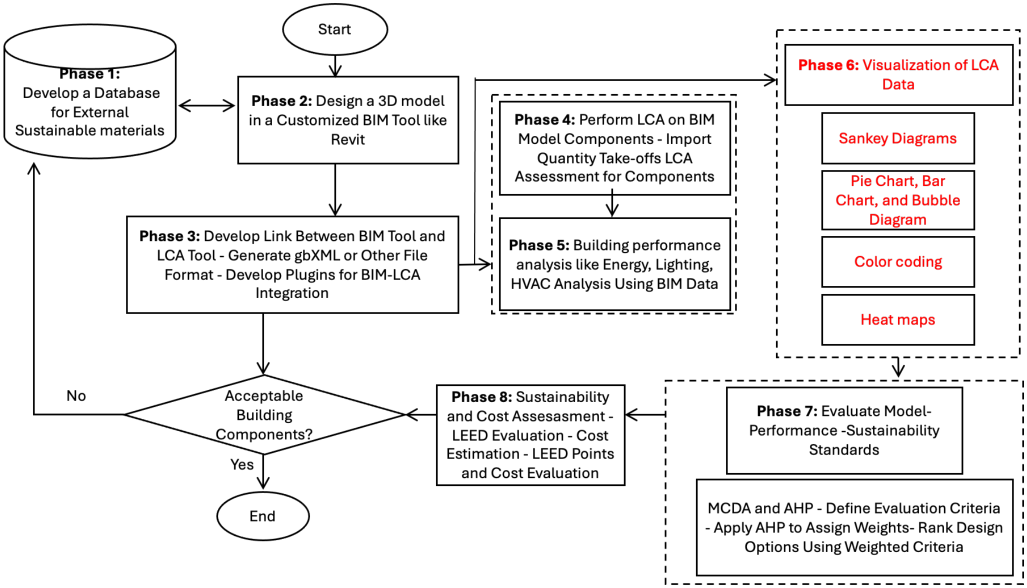
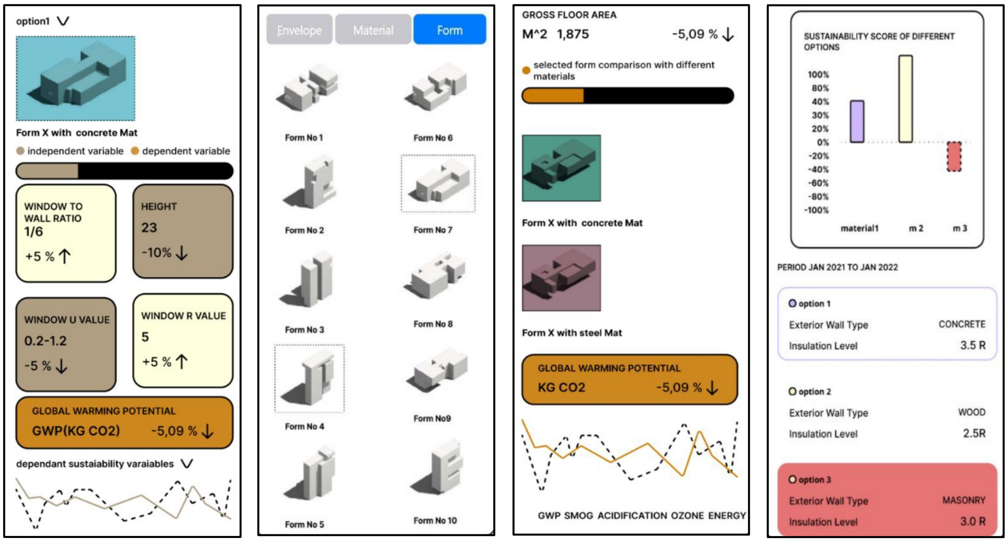


Figure 2 Selection of design alternatives with distinct forms to assess the sustainability of alternatives. Visualizing the sustainability of various design solutions by utilizing dependent variables such as the design option's form, materials, and compactness. (created by the author in Figma)



In developing the Green Plans, the user-centred design principles are used to create an interface tailored to the needs of architects and sustainability consultants. The interface has been developed for desktop and mobile applications to enhance usability and facilitate improved collaboration among design teams. Several mobile interface examples highlight clear navigation, logical organization, and integrated interactive and consistent data visualizations for presenting complex data.

Alternatives comparison

Life Cycle Assessment is a crucial tool for assessing a product's environmental impact throughout its life cycle (Kanafani et al., 2019; Wastiels & Decuypere, 2019). It accounts for all inputs and outputs, quantifies environmental impacts, and identifies inefficiencies. LCA requires overcoming challenges like defining scope, data availability, quantifying impact, and stakeholder evaluation (Anand & Amor, 2017; Röck, Hollberg, et al., 2018b). The Sankey diagram illustrates the contribution of various construction materials to global warming potential and other sustainability assessment metrics, such as emissions and ozone depletion, across different stages of a product's lifecycle (Figure 3). These stages include production, use, construction, end-of-life, and beyond the building's life.

Green Plans aids in design comparison by visualizing form, material, and envelope data and comparing it to the ideal net zero energy building model. Users can customize visualizations and toggle performance parameters.

Parallel coordinate plots

Parallel coordinate plots (PCPs) are useful for sustainability assessments in Green Plans. They represent input and output parameters on parallel axes, providing architects with an overview of the design space. This allows them to quickly understand each parameter's impact, observe relationships, and perform rearrangement operations. The Green Plans prototype can compare selected and non-selected design options, highlight connections, and display exact values per axis. PCPs also enable architects to visually represent numerical data, aiding in exploring design alternatives and meeting sustainability targets.

Multi-criteria decision analysis

Multi-criteria decision Analysis (MCDA) is a formal framework used in sustainability assessments to evaluate complex options involving numerous criteria (Minkov et al., 2016). It involves ranking each criterion for each possible solution, and the best options are determined based on all evaluations. MCDA methods, such as the Analytic Hierarchy Process (AHP), are commonly used in sustainability assessments. MCDM is beneficial for considering interconnected aspects and incorporating uncertainty and subjectivity in decision-making.

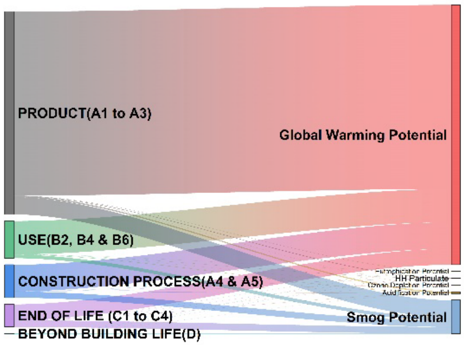


Figure 3: Sankey diagram of construction stages: contribution to global warming potential and greenhouse gas emissions (created by the author in Origin Lab)

ANALYTIC HIERARCHY PROCESS (AHP)

Integrating AHP with visual tools enables designers to methodically evaluate and rank design solutions based on various sustainability criteria, facilitating trade-offs between multiple factors. AHP provides pairwise comparative analysis (Table 4), aiding informed decision-making by quantifying each design's specific needs. Zarghami et al. (2018) discuss the need for a customized sustainability assessment tool for residential buildings. The AHP method is a framework for evaluating design options based on sustainability criteria. It involves defining

Table 2
Matrix for pairwise importance scoring of independent sustainability criteria.

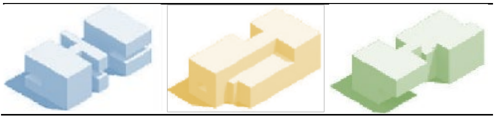
Criteria	Form	Material	Energy	Direction	Compactness	Climate	Building Type
Form	1	3	2	3	2	4	3
Material	1/3	1	1/2	1/2	1/3	2	1
Energy	1/2	2	1	2	1	3	2
Direction	1/3	2	1/2	1	1/2	2	1
Compactness	1/2	3	1/2	2	1	4	2
Climate	1/4	1/2	1/3	1/4	1/4	1	1/2
Building Type	1/3	1	1/2	1	1/2	2	1

decision criteria, assigning relative importance values, and performing mathematical calculations to derive weights or priorities for each criterion.

In this analysis, we examine three distinct designs (Alternative 1, 2, and 3) (Table 3) and assess their performance on a scale of 1 to 5 for each indicator using the weights from Table 4. The alternatives are compared based on the trade-offs indicated by weights based on preferences such as form, material, energy, direction, compactness, climate, and building type.

Table 3
Three design alternatives were evaluated.

Alternative 1 Alternative 2 Alternative 3



Designers and specialists work together to balance design factors like shape, material, envelope, and energy efficiency. To evaluate sustainability, proper weights must be assigned to these parameters (Tarne et al., 2019). Conversations and consultations involve the Analytic Hierarchy Process (AHP) to assess the importance of each criterion. This process creates a priority scale, assigning weights for each criterion, such as energy efficiency being more important than material sustainability. Table 2 presents a matrix for pairwise comparisons of independent sustainability criteria for our design options. Based on the overall scores, Alt. 3 has the highest score (4.204), indicating that it is the most sustainable design option among the three assessed options. Designers calculate weights for sustainability criteria and use visualization tools like Sankey diagrams, radar charts, and bubble charts to analyze design alternatives, providing clear trade-offs and strengths and enabling stakeholders to make informed decisions.

Sensitivity analysis ensures consistency and reliability of decisions, resulting in prioritized weights for each design option. Tools like Sankey diagrams, radar, and bubble charts can represent each design's impact and cost life cycle. This approach provides a systematic consideration of multiple criteria, fostering the development of sustainable solutions.

Table 4
Calculation of Weight for Each metric based on its priority in the project.
Three design alternatives used for demonstration

Criteria	Weight	Alt. 1	Alt. 2	Alt. 3
Form	1.660	4	3	5
Material	0.087	4	3	4
Energy	0.128	3	2	5
Direction	1.660	3	4	4
Compactness	1.128	4	3	4
Climate	0.550	3	2	5
Building Type	2.700	4	4	5
Overall Score	--	3.228	2.884	4.204

CHALLENGES OF INTEGRATING BIM AND LCA

Although there is potential for combining BIM and green building evaluation, challenges must also be addressed. Standardized formats and protocols are required for seamless information exchange, as data interoperability between various software systems continues to be an issue. Furthermore, protecting data privacy and security when implementing cloud-based technology is essential to protecting critical project information.

CONCLUSION AND FUTURE WORK

A significant challenge is the lack of tools for promoting sustainable design in Architecture, Engineering, and Construction (AEC) services. To address this, a comprehensive prototype called the Green Plan prototype has been developed using data-driven approaches from BIM and LCA to visualize sustainability data. This approach simplifies the assessment of design options, allowing architects, designers, and stakeholders to make informed decisions. Future efforts should focus on simulations, tool comparisons, maintenance manual integration, and cloud-based technology.

Advancements in Visual Analytics tools for Sustainable Lifecycle Design (SLD) are crucial for enhancing sustainable design. The Analytic Hierarchy Process (AHP) and visual tools systematically evaluate, and rank design solutions based on sustainability criteria. This method helps decision-makers understand the significance of each design option concerning overall sustainability objectives. Visual tools like Sankey diagrams, radar charts, and bubble charts enhance the interpretation and communication of results, providing a holistic understanding of trade-offs and implications. In developing solutions, collaborating with domain experts (Remy et al., 2020), particularly in specialized fields like the AEC industry, can enhance the validity of sustainability assessments and lead to more efficient and ecologically conscious designs. We will rely on their insights to improve the Green Plan's functionality, ensuring it meets designer demands and creates more effective solutions.

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