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RESEARCH ARTICLE

Designing for Circularity: User Study of CirQA, a Circularity Quick Assessment Tool for Early-Stage Building Design

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Abstract

The construction sector, which is responsible for nearly 40% of emissions and almost third of all waste generated, is under increasing pressure to integrate sustainability principles, particularly in the early design stage, where key decisions influencing a building's lifecycle are made. This paper presents a user study on a Circularity Quick Assessment (CirQA) tool, aiming at accessibility to a broad range of users, including those with varying levels of expertise. CirQA employs parametric design methods and data repositories to generate digital building models in the early design stage with the corresponding environmental impact. A user study was conducted with 16 professionals from various backgrounds to assess the tool's usability, design, relevance and decision-making impact. Both quantitative and qualitative data were collected, with qualitative data analyzed through thematic coding and SWOT analysis. Results indicated that CirQA was generally perceived as user-friendly and effective for early-stage sustainability assessments. Also, areas for refinement were identified, including improving the clarity of data presentation, enhancing the interface, and providing more detailed guidance on circularity metrics. The SWOT analysis identified strengths in the tool's ease of use and comprehensive functionality, weaknesses in its interface usability and data interpretation, opportunities for broader integration and customization, and threats related to increasing complexity. The study concludes that CirQA holds significant potential to advance circular and life cycle-oriented building design, with future efforts focused on optimizing user experience, expanding lifecycle metrics, and ensuring regulatory adaptability to enhance informed decision-making.

Keywords Circular Economy · Parametric Design · Quick Assessment · Lifecycle Impact Assessment · Early-Stage Building Design

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List of Abbreviations

Abbreviation	Full Form / Description
AEC	Architecture, Engineering and Construction
AA	Algorithm-Aided
AD	Algorithmic Design
AP	Acidification Potential
BIM	Building Information Modeling
CAD	Computer-Aided Design
CE	Circular Economy
CirQA	Circularity Quick Assessment
CFA	Construction Floor Area
CO_2	Carbon Dioxide
DfD	Design for Disassembly
DPP	Digital Product Passport
EDS	Early Design Stage
EI10	Environmental Indicator 10 (specific disposal indicator)
EPD	Environmental Product Declarations
EoL	End-of-Life
EU	European Union
FA	Functional Area
GA	Ground Area
GD	Generative Design
GHG	Greenhouse Gas
GFA	Gross Floor Area
GWP	Global Warming Potential
IT	Information Technology
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LC	Life Cycle
MFA	Material Flow Analysis
MP	Material Passport

MS Excel	Microsoft Excel
NFA	Net Floor Area
ÖNORM	Austrian Standards (Österreichisches Normungsinstitut)
PENRT	Primary Energy Non-Renewable Total
PD	Parametric Design
SWOT	Strengths, Weaknesses, Opportunities, Threats
TA	Traffic Area
UI	User Interface
VPL	Visual Programming Language
3D	Three-Dimensional

Introduction and Literature Review

Background on Life Cycle Assessment and Circularity in Early Design

As the world confronts the realities of global warming, rising sea levels, and more frequent extreme weather events, it becomes increasingly critical to address the environmental impacts of construction activities. To make informed decisions for truly environmentally friendly construction, life cycle assessment (LCA), circularity and circular economy (CE) are instrumental in providing a holistic view of environmental impacts throughout all stages of a building's life, from material sourcing to construction, operation, and eventual end-of-life (EoL). LCA is defined as the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (LC) (ISO 14040:2006, n.d.). Circular construction entails the creation, utilisation, and repurposing of buildings, construction elements, products, materials, spaces, and infrastructure, all while minimising the depletion of natural resources, environmental pollution, and negative impacts on ecosystems. Specifically, regarding buildings, a circular structure maximises resource utilisation and minimises waste across its entire lifespan.

The European Union (EU) has been at the forefront, with initiatives such as the circular economy action plan and the european green deal, which aim to decouple economic growth from resource use and environmental degradation (Circular Economy Action Plan - European Commission, n.d.; European Commission, n.d.). Specific guidelines, like the principles for buildings design and the construction and demolition waste management protocol, provide frameworks for reducing the environmental impact of construction activities (Study on Circular Economy Principles for Buildings' Design: Final Report | European Circular Economy Stakeholder Platform, n.d.; European Union, 2024). Additionally, the EU's efforts to promote climate neutrality and manage waste effectively highlight the need for comprehensive strategies that encompass the entire lifecycle of buildings, from design to demolition. The importance of these measures is further underscored by reports on the total impact of the construction sector on emissions and resource consumption, which stress the urgency of transitioning to more circular and sustainable building practices (European Union, 2022). Findings shows that the sector was responsible for 37 percent of global operational energy and process-related CO_2 emissions in 2022, rising to just under 10 Gt CO_2 and energy consumption reached 132 exajoules, more than a third of global demand (Programme & Construction, 2024). At the same time, as a further challenge, the construction sector is one of the least digitized, resulting in fragmented data and inefficient processes (European Commission, n.d.). Recent studies have explored the use of digital tools such as material passports (MP), artificial intelligence (AI) and blockchain technology to support the circular reuse of building materials, especially during the dismantling and deconstruction phases (De Wolf et al., 2024).

But current approaches often fail to provide sufficient data on circularity and environmental performance in the very early design stage (EDS), where key decisions that shape a building's lifecycle are made. One of the key challenges is to create tools that offer quick, accurate assessments while remaining intuitive and accessible to users with varying expertise in sustainability, LCA, and CE principles in the architecture, engineering and construction industry (AEC). This supports compliance with standards like ISO 14044 (provides guidelines for conducting LCA, focusing on quantifying environmental impacts from a product's creation to disposal), EN 15978 (targets the environmental performance of entire buildings, encompassing their construction, operation, and end-of-life stages), EN 15804 (sets out core rules for environmental product declarations (EPD), detailing emissions, resource use, and waste generation during the production of building materials and EU Level(s) Framework as a set of guidelines for assessing and enhancing the sustainability performance and cost of buildings throughout their lifecycle (Level(s) - European Commission, n.d.; ÖNORM EN 15804:2022 02 15, n.d.; ÖNORM EN 15978:2012 10 01, n.d.; ÖNORM EN ISO 14044:2021 03 01, n.d.).

This study investigates the integration of LCA and circularity principles into an algorithm-aided (AA) - parametric design (PD) quick assessment tool - tailored for the EDS of building design. PD operates independently of whether a design is algorithm-aided (AD) or generative (GD) and focuses on the use of parameters and rules to define and manipulate design geometry. The parametric model allows designers to adjust inputs (parameters) and see corresponding changes in real-time (Caetano et al., 2020). This study examines how professionals from diverse backgrounds perceive the usability, interface, and overall effectiveness of such tool. The research explores the perceived strengths, weaknesses, opportunities, and threats associated with the tool's implementation. The objective is to develop a technically robust and user-friendly parametric tool that supports informed decision-making. The tool is based mainly on the simplified input, which opens the opportunity for the mentioned involved parties with different backgrounds to engage in the LCA process without previous knowledge of AD, PD, building information modeling (BIM), or complex database structures. The tool builds upon the framework developed in previous research, which integrated life cycle data to perform comprehensive life cycle, cost and circularity assessments (Pibal et al., 2025).

Digital Integration for Circular Construction: Material Passports, BIM, and Parametric Tools

The integration of digital technologies such as BIM and MP is crucial for assessing resource availability and optimizing waste reduction, providing a strategic approach to smart disassembly (Trubina et al., 2024). MP, serving as digital repositories play a pivotal role in enabling the implementation of sustainability and CE practices within the industry (Hoosain et al., 2020). While there exists no universally agreed-upon definition for MPs, alternative terms like digital product passports (DPP) are prevalent, as discussed in existing literature (Çetin et al., 2023; Plociennik et al., 2022). A MP serves as a detailed data repository that contains information about the materials used in a building, such as their composition, origin, quality, and location, which can be crucial for EoL recovery and reuse. The potential of material inventories to inform planning through comprehensive inventory models highlights the importance of understanding the materiality of built environments for the management of circular cities (Schiller & Gruhler, 2024). However, challenges such as lack of standardization and high costs associated with the digitization of existing structures remain hurdles to widespread adoption (Banihashemi et al., 2024). Further, the key inputs for conducting LCA include quantities and environmental indicators, which are crucial for evaluating the environmental impacts of products and services (Grimal et al., 2019).

To establish a CE within the construction sector, a comprehensive strategy is imperative, involving diverse measures such as advocating for policies favoring dismantling and reuse over demolition, employing assessment methodologies like LCA, and ensuring accessible digital repositories like MPs to facilitate the reuse of building materials (Freek van Eijk et al., 2021). Çetin et al. (2023) conducted interviews indicating that 83% of respondents believe that LCA information should be integrated into digital documentation. However, all respondents expressed concerns regarding its limited availability (Çetin et al., 2023). Corona et al. (2019) underscore the limitations of existing circularity indicators, advocating for future developments grounded in methodologies like LCA or material flow analysis (MFA)(Corona et al., 2019; Khadim et al., 2022). Moreover, researchers emphasize the distinction between 'CE' and 'sustainable development,' urging for a holistic consideration of economic, social, and environmental factors alongside circularity evaluations (Blum et al., 2020; Corona et al., 2019; Saidani & Kim, 2022). CE presents new avenues for exploration beyond LCA (Dervishaj & Gudmundsson, 2024). Specifically, the study highlights the potential for leveraging design algorithms for structures and establishing connections between digital twins (DT) and MPs to enable digital collaboration. A systematic review examining the intersection of digital transformation and CE principles within the AEC critically evaluates the role of digital technologies in fostering circularity in construction projects (Banihashemi et al., 2024). The significance of BIM-based EoL decision-making and digital transformation in the built environment emphasizes the importance of integrating LCA data into digital processes for informed decision-making (Akbarieh et al., 2020).

A study reviewing digital tools supporting the CE in the built environment focuses on providing an analysis and exploring the role of digital tools in facilitating circular design, concluding for example that computational tools provide greater flexibility, more varied workflows and metrics, and the capability for parametric optimization (Dervishaj & Gudmundsson, 2024). They propose to explore how tools such as computer-aided design (CAD) and BIM, alongside computational methods, can aid practitioners in evaluating circular design strategies. Further studies present on the other hand parametric design tools for LCA, offering innovative solutions for estimating environmental impacts during the design phase. There is also a growing recognition of the need for more user-friendly assessment tools that can be easily adopted by professionals in the early and advanced design stages (Apellániz et al., 2024; Basic et al., 2019; Płoszaj-Mazurek et al., 2020). The landscape of LCA tools varies widely, offering different features and limitations. A review of building LCA tools and related literature shows that most tools are geared toward the detailed design stage, while the scientific literature places slightly more emphasis on the early design stage. Additionally, most tools and visualizations are targeted at building design professionals, with very few addressing decision-makers, revealing a critical gap in supporting strategic-level users (Hollberg et al., 2021). A tool comparison, appendix A, shows that LCA tools differ notably in their functional scope, integration capabilities, assessment outputs, underlying material databases, user accessibility, and applicability across building design phases.

Usability Challenges and Climate Impact: LCA Tools, Recommendations and Potential for Climate Mitigation

Soust-Verdaguer et al. (2017) discuss the challenges faced by end users, particularly designers and engineers, in using building model based LCA tools effectively (Soust-Verdaguer et al., 2017). They emphasize the need for users to understand the LC processes of buildings to obtain reliable environmental performance results. The paper also identifies the significant effort required by end users due to the complexities involved in these processes. Recommendations for improving such tools include the development of more user-friendly platforms that can provide quick, representative, and comparable results with minimal user effort. Gantner et al. (2018) point out that, in practice, simplified methods for calculating these assessments are often not employed until the very end of the building's planning and construction phases. And that even for relatively simple projects, like residential buildings, completing a LCA can be a time-consuming task (Gantner et al., 2018). This underscores the complexity and labor-intensive nature of LCA and existing assessment tools. Caldas et al. (2022) provides an in-depth analysis of how various tools within the AEC can contribute to climate change mitigation through the implementation of CE strategies. The study systematically reviews literature to evaluate tools such as LCA, BIM, and MP, among others. It focuses on how these tools can be applied across different stages of a building's life cycle and their effectiveness in reducing greenhouse gas (GHG) emissions (Caldas et al., 2022). The paper highlights the integration of tools, particularly LCA, BIM, and MP, as critical for enhancing CE strategies aimed at mitigating climate change and concludes by proposing future research directions and improvements such as utilize LCA in the EDS; ensure LCA addresses all aspects of sustainability—environmental, economic, and social; waste recovery or closed-loop scenarios (reuse, recycling, or energy recovery), and to quantify biogenic CO_2 for bio-based materials. LCA and building models should therefore be used in EDS, linked with other tools; with a developed materials library that includes information on product circularity, such as recyclable content and potential for reuse or recycling; incorporate waste management, circular product evaluation, design for disassembly (DfD), and building materials passports (Caldas et al., 2022). These recommendations highlight the need for continued innovation and integration of LCA and CE within the AEC industry to maximize their contribution to climate change mitigation.

User-Centered Design and Prototyping for LCA Tools: Usability and Integration

When conceptualizing novel tools, user studies and prototyping are critical components of the design and development process. User studies, when conducted early in the development process, lead to better design decisions and prevent costly revisions later (Kujala, 2008). Studies explore the role of environmental experts in promoting sustainable development in AEC through institutional work, showcasing the complexities of expertise in influencing organizational change (Gluch & Bosch-Sijtsema, 2016). By conducting user studies early in the development cycle, designers can gather valuable insights that inform the creation of prototypes. From presentation prototypes, functional prototypes, breadboards, and pilot systems, each serve distinct purposes in the iterative design process. The importance of selecting the appropriate type of prototype to match the development stage and the specific goal of the project is to be underscored (Baeumer et al., 1995). The concept of "pretotyping" takes this a step further by advocating for even earlier testing of ideas. This pretotyping focuses on validating whether an idea is worth pursuing before significant resources are invested in developing prototypes (Savoia, 2011). Aligning prototyping with further research needs, scholars suggest exploring ways to simplify the use of LCA tools, especially through better integration into design workflows like BIM (De Wolf et al., 2023). Research is needed to ensure that tools are more cost-effective and user-friendly, with a focus on increasing their applicability for mainstream professionals. Research should focus on validating these tools from an end-user perspective, emphasizing their practical utility and ensuring that resources are widely available to support broader adoption (De Wolf et al., 2023). Supporting the broader usability discourse, Nielsen and Landauer (1993) introduced a mathematical model to predict the discovery of usability problems through user testing or heuristic evaluation. Their model demonstrated that a single evaluator typically uncovers about 31% of total problems. Notably, they estimated that approximately 16 evaluations are needed to uncover nearly all usability issues in a system. This emphasizes the value of iterative, resource-conscious testing in design workflows—an insight that directly informs the development of more accessible, scalable evaluation tools.

Research Gap, Questions and Research Design: Quick Assessment Tool

The integration of digital tools and methodologies into a CE framework for LCA is essential for advancing sustainable practices in the AEC industry. We thus hypothesize that the challenge lies in creating tools that not only provide quick and accurate assessment but are also intuitive and accessible to a broad range of users, including those with varying levels of expertise in sustainability, LCA and CE principles in AEC. Hence, this research seeks to explore how these principles can be effectively integrated into a quick assessment PD tool for the EDS. Moreover, the study explores the potential improvements suggested by users and providing insights for future research. The research design (Figure 1) employs a systematic approach to develop and evaluate the prototype. While the circularity quick assessment tool architecture is foundational, the focus of this study is on evaluating the user study and insights for future tool optimization. Conducting the user studies, qualitative data analysis and SWOT analysis, this article addresses the following research questions:

- **RQ1:** How can sustainability and circularity principles be effectively integrated into a quick assessment tool for EDS?

- **RQ2:** How do professionals from various backgrounds perceive such tool, and what is its impact on their decision-making processes regarding building LC and CE principles?
- **RQ3:** What are the perceived strengths, weaknesses, opportunities, and threats of the proposed CirQA tool?

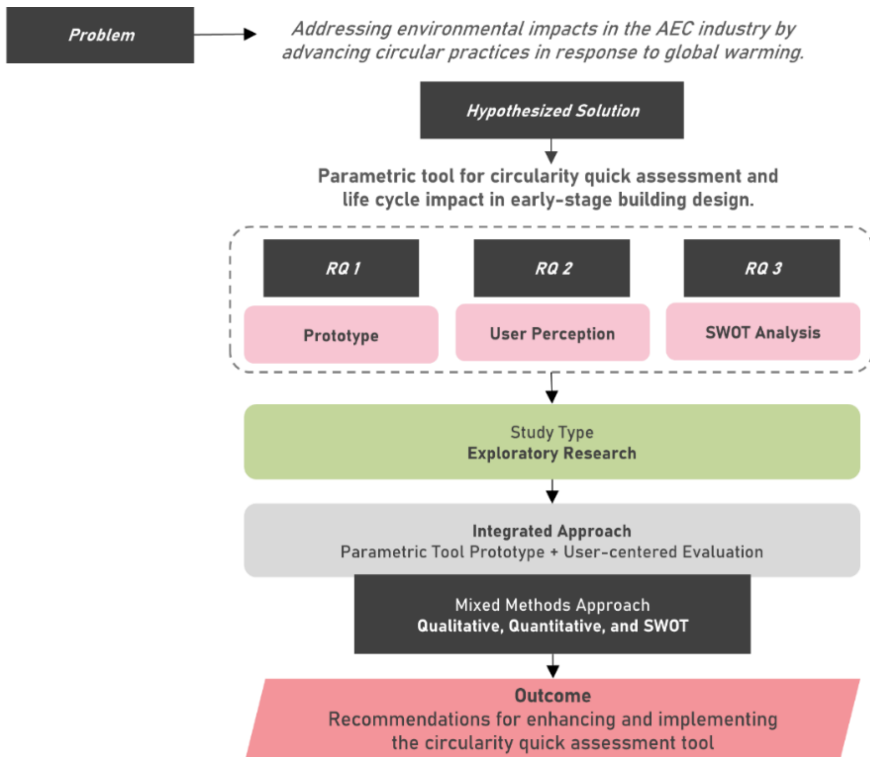

Figure 1 Research Design: Systematic Approach to Develop and Evaluate a Circularity Quick Assessment Tool

Methodology

This study employed a three-stage methodological framework encompassing prototype, user study, and data analysis to evaluate the prototype of CirQA (Figure 2).

The initial phase focuses on rapid prototyping through visual programming using Rhino3D and Grasshopper and HumanUI plug-in, enabling quick edits and iterative testing of core design logics. Building upon frameworks and data from previous studies, particularly regarding LCA and circularity (Pibal et al., 2025), component-level data was integrated via spreadsheet and connected directly to the algorithm. The resulting output was a basic but functional prototype, allowing for early-stage validation. The second phase involved a user study aimed at identifying challenges and assessing the tool's effectiveness. A total of 16 participants were recruited, representing a mix of expert users and potential adopters, aligned with the Nielsen & Landauer (1993) model for estimating usability problem discovery. Participants engaged in hands-on interaction with the CirQA prototype, and their experiences were observed and documented. A questionnaire-based assessment was conducted both before and after the testing session. Field notes taken during the session provided additional qualitative insights. The final phase comprised a multi-faceted data analysis approach. Qualitative data was examined using the grounded theory method, extracting core statements, categories, and labels relevant to user interaction. Quantitative analysis focused on ease of use, interface clarity, data input/output quality, decision support, and overall satisfaction. Finally, a SWOT analysis was conducted to identify the tool's strengths, weaknesses, opportunities, and threats, contributing to the roadmap for future tool optimization.

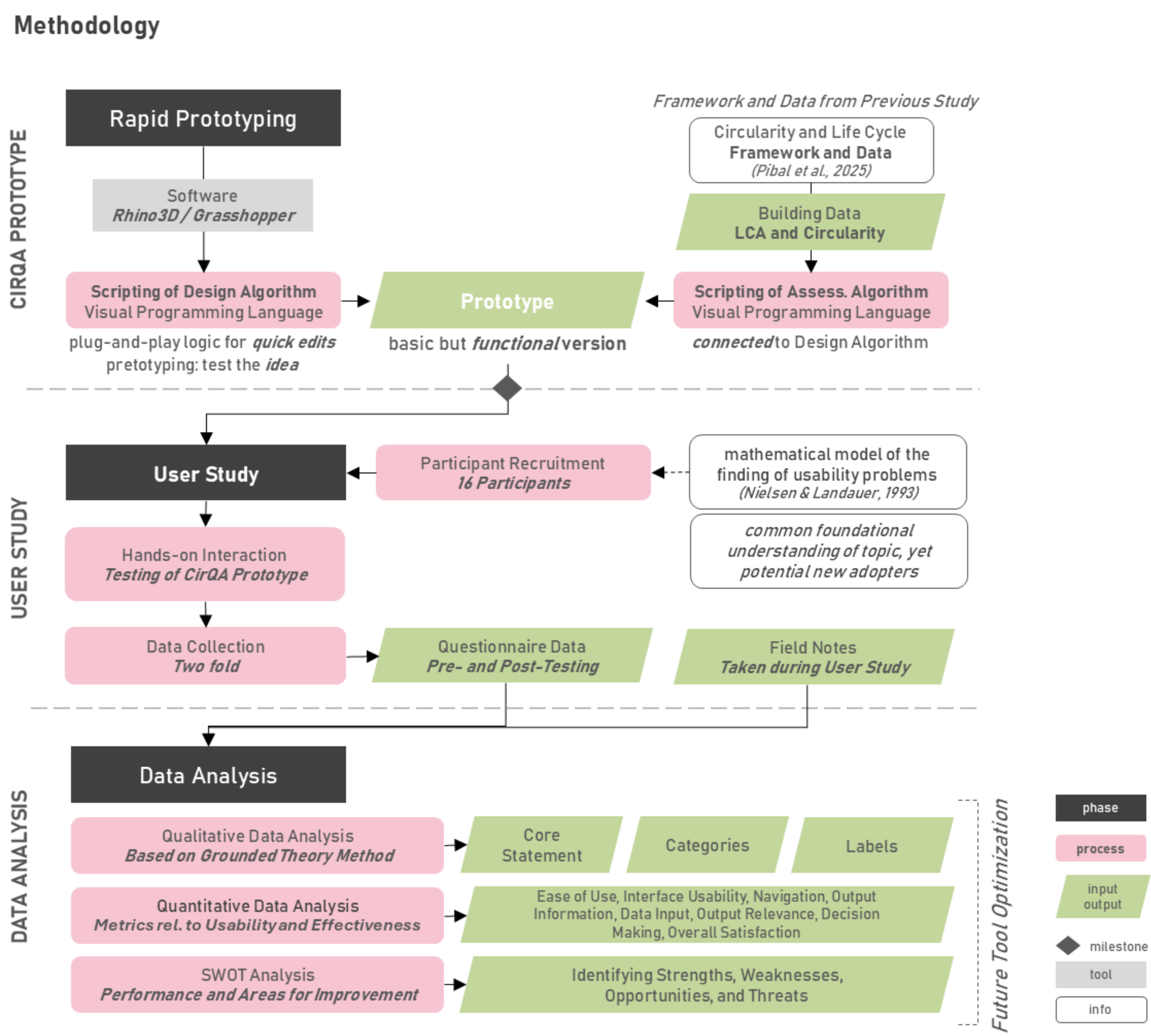

Figure 2 Methodology - Three Phases: CirQA Prototype, User Study and Data Analysis

CirQA Prototype

The prototype represents the initial implementation and integration of the design and assessment algorithms. It serves as a basic but functional version of the tool that can be tested and refined based on user feedback. Inspired by the concept of "The Right It" (Savoia, 2011), we developed a prototype, which emphasizes the importance of ensuring that a product, service, or tool is the right solution before investing significant resources in its development. The CirQA architecture leverages a combination of parametric design approaches and structured data to create adaptable building models. The prototyping leverages Rhino-Grasshopper, providing a CAD geometry creation platform and a versatile, node-based visual programming interface. CirQA offers an embedded generative algorithm that automates the design creation process, eliminating the need for manual 3D modeling. Users can define key design parameters such as plot coverage, building height, and orientation. The resulting massing model is then divided into floors and assigned materials to building elements. This functionality allows users - both experts and non-experts-to generate a preliminary building design while simultaneously conducting a real-time assessment. Additionally, integration with MS-Excel facilitates flexible data interaction. This architecture ensures robust model creation, quick plug and play and data input. The design and assessment algorithms automate the processes of model creation, LCA and circularity assessment.

Tool Components and Functionalities

The components and functionalities of the input panel, Table 1, allows users to define crucial parameters. These inputs enable users to create tailored building models that meet specific design and sustainability requirements. The output panel - LCA CE, Table 2, provides vital insights into the environmental impact of the building design. The output panel – mass and spatial, offers analysis of the building's spatial and material properties through metrics like total mass of the building, component masses, and various calculated areas and volume breakdowns.

Table 1 Overview of CirQA Components with Details and Functionalities

Panel	Component	Details	Functionality
CirQA Input	Building class I-VI	Selection for building classes ranging from 1 to 6. (derived from Viennese Building Code)	Allows users to classify the building according to predefined categories, influencing subsequent parameter settings and assessments.
	Building height (m)	Slider to adjust the building height within the range of Building Class in meters.	Enables users to define the overall height of the building, a critical parameter in design and assessment.
	Building orientation (Design)	Slider to adjust the building shape.	Allows for customization of the building's shape.
	Floor height	Input for floor height in meters.	Determines the height of individual floors, influencing the building's overall dimensions and volume.
	Number of floors	Dropdown to select the number of floors.	Allows users to set the total number of floors, affecting the building's vertical profile and spatial organization.
	Base area	Input fields for the base area dimensions (length x width).	Defines the building's footprint, crucial for space planning and material estimation.
	Building components	Dropdowns to select different building components such as outer walls, inner walls (load-bearing and non-load-bearing), ceilings, and roof.	Facilitates detailed specification of building materials and components and component layers, critical for accurate assessment.
	Apartment mix	Slider to adjust the mix of apartment types.	Allows for customization of the apartment mix (range of apartment sizes / number of rooms) within the building, impacting design and functionality.
CirQA Output – LCA and CE	Recycling	Pie chart showing the percentage of materials that can be recycled.	Provides insights into the building's material lifecycle, emphasizing recycling potential.
	Disposal	Pie chart showing the percentage of materials that will be disposed of.	Highlights the proportion of materials destined for disposal, crucial for waste management planning.
	GWP-storage	Bar indicating the amount of CO_2 equivalent stored in biogenic materials.	Quantifies the global warming potential (GWP) stored in building materials,

			important for environmental impact assessments.
	Environmental indicators	Bar chart displaying various environmental impact indicators (GWP, PENRT, AP).	Provides detailed information on environmental impacts, aiding in sustainability evaluations.
	Disposal indicator EI10	Bar indicating the disposal efficiency, with lower values representing optimal disposal.	Assesses the efficiency of material disposal processes, informing waste reduction strategies.
CirQA Output – Mass and Spatial	Total mass of the building	Bar chart showing the total mass of the building in kilograms.	Gives an overview of the building's total mass, important for material assessments.
	Component masses	Breakdown of the mass of different building components such as foundation, inner and outer walls, ceilings, and roof.	Details the distribution of material mass across various components, aiding in material optimization.
	Areas	Bar chart summarizing the calculated areas, including Ground Area (GA), Gross Floor Area (GFA), Net Floor Area (NFA), Construction Floor Area (CFA), Traffic Area (TA), Functional Area (FA).	Provides a comprehensive breakdown of the building's spatial organization, essential for space planning and functional analysis.
	Apartment mix	Bar chart displaying the number of different types of apartments (e.g., 2 rooms, 3 rooms, 4 rooms).	Visualizes the distribution of apartment types, aiding in design decisions related to functionality and user needs.
	Volume	Bar chart showing the types of volume within the building design.	Quantifies the volumetric aspects of the building, crucial for spatial planning.

Interface and Visualisation

The CirQA interface, displayed in Figure 3, is designed using the HumanUI plug-in inside Grasshopper, which is limited to certain visuals but still offers a solid range. The primary aim is to provide the right amount of information and visualization during the EDS and align with the goals of LCA (Hollberg et al., 2021). Exemplary results and design variants are shown in Figure 4 and 5. Bar charts and stacked bar charts are used for identifying environmental and material hotspots, as well as comparing design alternatives. Pie charts communicate proportional metrics such as recycling and disposal shares. Indicator bars support benchmarking against performance thresholds, while spatial distribution is visualized through categorized area and volume charts.

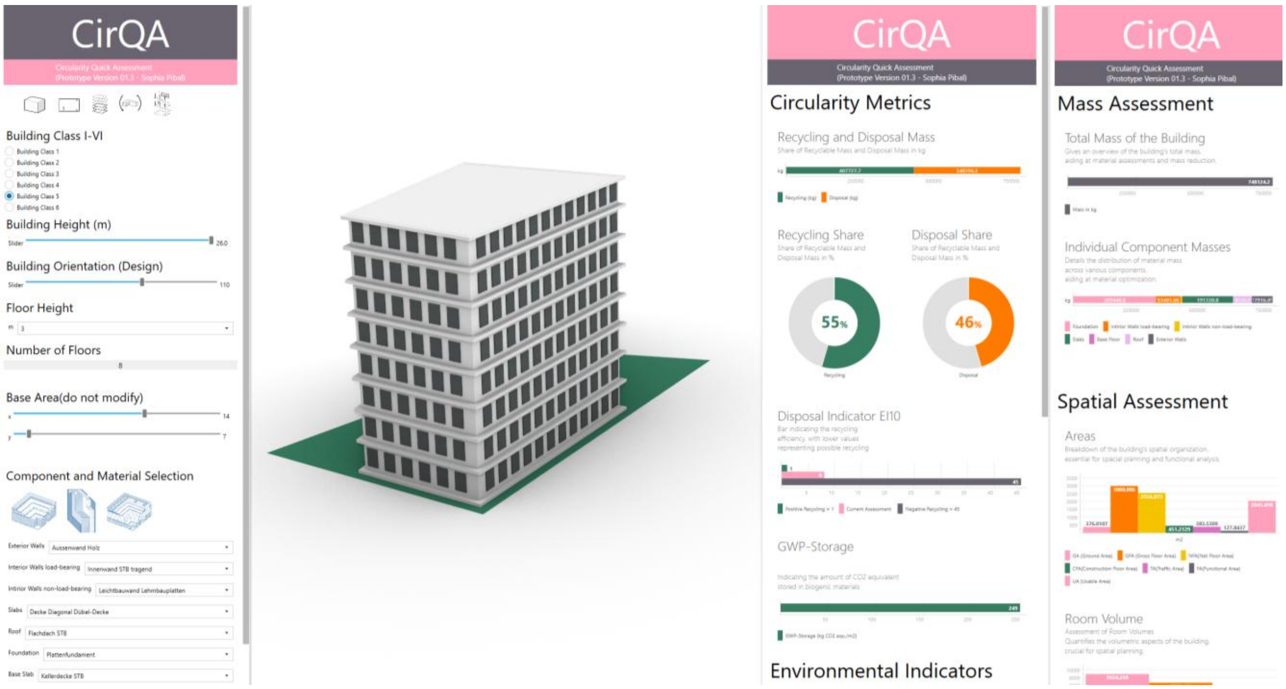

Figure 3. Interface of CirQA Prototype Tool Inside Grasshopper/Rhino 3D/HumanUI

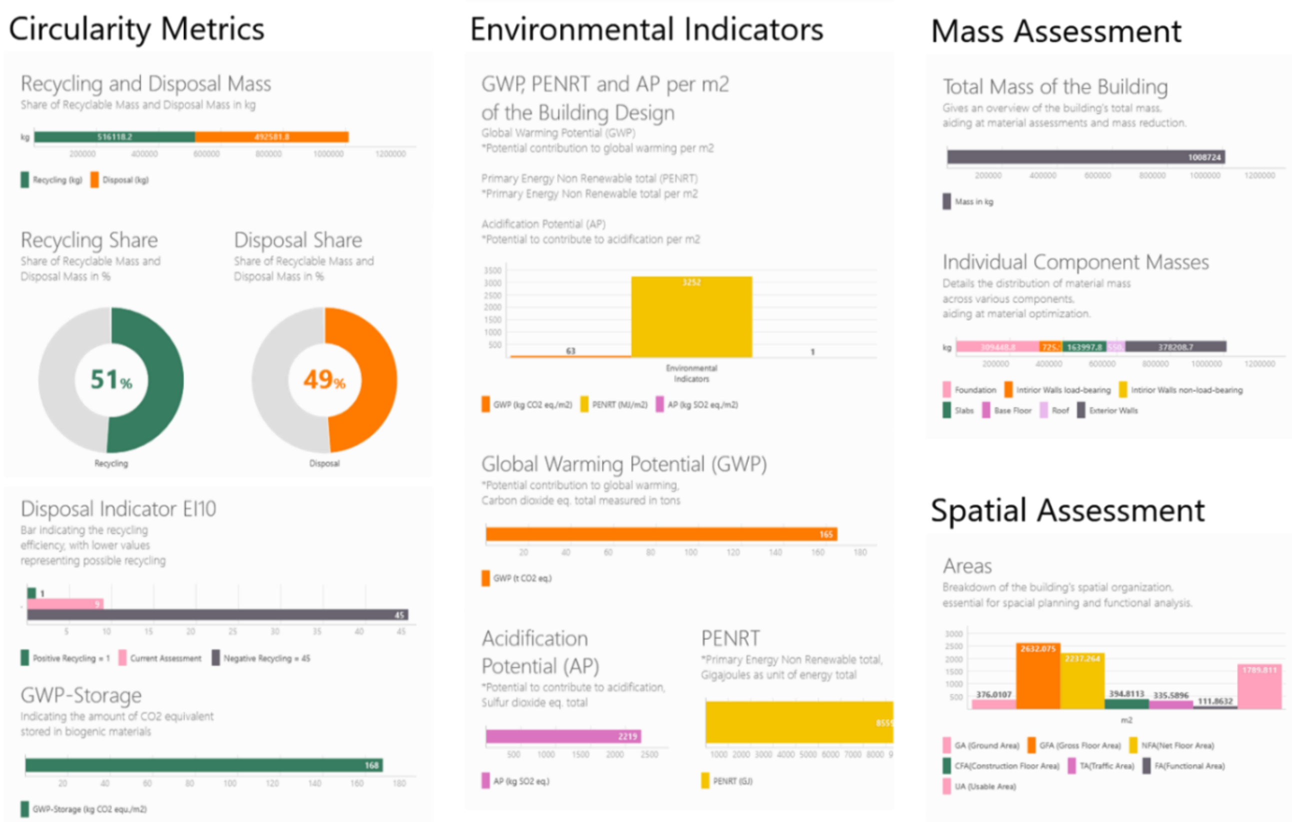

Figure 4 Exemplary Results of Assessment Algorithm (VPL Script) Inside Grasshopper/Rhino 3D/HumanUI

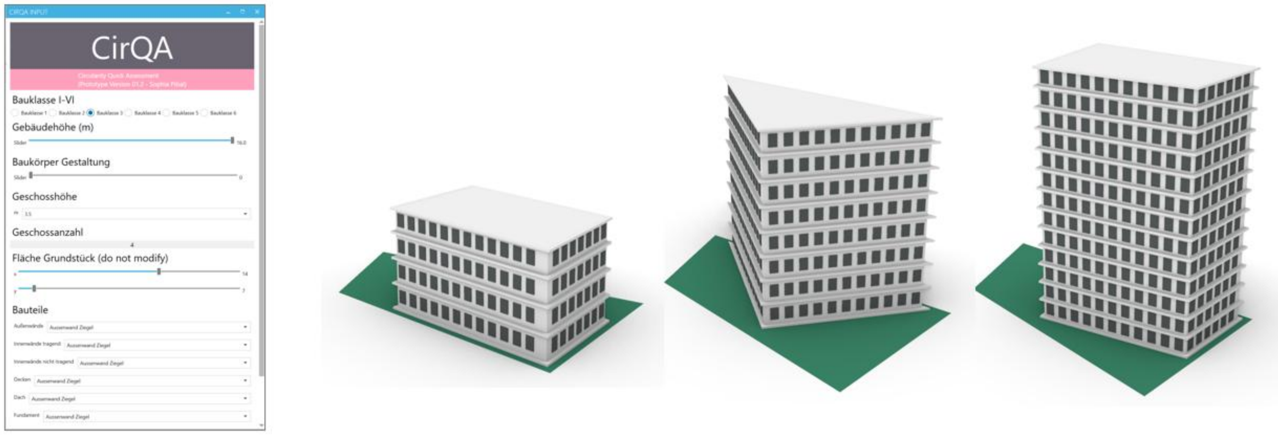

Figure 5 Exemplary Results of Design Variants from Different Input Parameters via Design Algorithm (VPL Script)

User Study

The study aimed to gather detailed insights from a diverse group of participants, all with a common background in research on digital resilient cities but varying in professional expertise across technology, renewable energy, urban planning, architecture, and geosciences. According to established usability research small participant groups of 5–10 users are sufficient to identify up to 80–90% of usability issues in prototype testing and that you need to test with at least 15 users to discover all the usability problems in the design (Nielsen & Landauer, 1993). Given that our study engaged 16 participants from varied backgrounds, this sample size is considered robust for qualitative feedback and aligns with early-stage design validation.

Participants

The study involved 16 participants recruited due to a common background in research on digital resilient cities, whilst reflecting a diverse range of professional and industry experiences, Figure 6. Thus, ensuring a common foundational understanding relevant to sustainability, design, and technology. Their professional backgrounds spanned Architecture (5), Urban Planning (3), and Renewable Energy Planning (2), among other fields like Software Engineering and Data Science as well as Geology. In terms of industry backgrounds, 6 participants came from AEC, while 4 were from Technology/IT sectors, 3 from Urban Planning, 2 Renewable Energy and 1 participant from Geosciences. By including participants with and without prior experience in parametric design, LCA, or circular economy, the study ensured that the tool was evaluated by both advanced and potential new adopters, reflecting real-world variability in end-user profiles within the AEC sector (Figure 7).

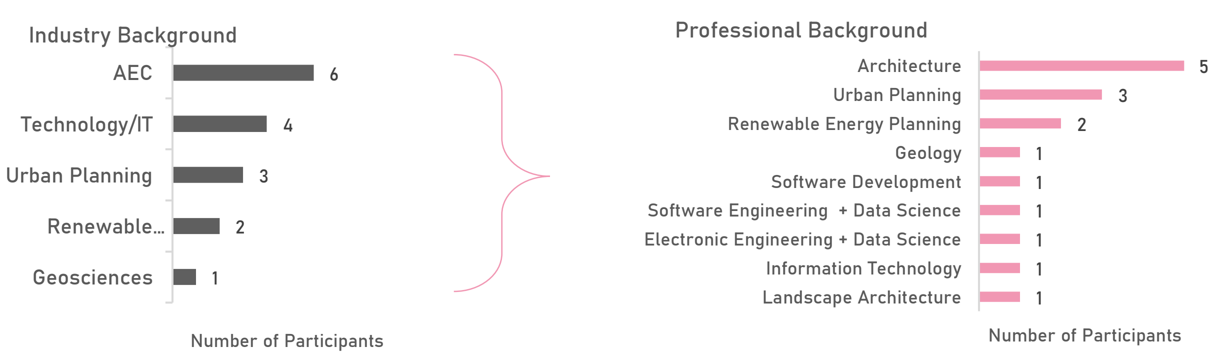

Figure 6 Industry and Professional Background and Number of Participants

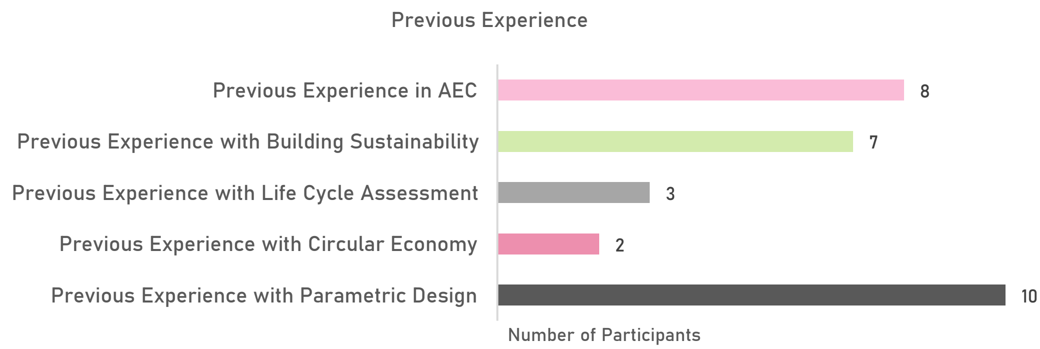

Figure 7 Previous Experience and Number of Participants

Study Design

The materials used during the user study have been a room equipped with laptop and wall-mounted screen displaying the CirQA tool. Used software has been Rhino 3D, Grasshopper, Excel Spreadsheet. Further, the pre-study and post-study questionnaires as well as note-taking materials for researchers. Participants were briefed on the prototype objectives and procedures and provided consent to participate. Participants filled out the first part of a questionnaire, pre-testing information, to gather baseline data on their backgrounds and familiarity with the AEC industry, sustainability assessment and parametric tools. Participants interacted with CirQA, either following a guided session or exploring independently. Researchers took notes and engaged in conversations with participants to gather immediate feedback and observations. Participants completed the second section of the qualitative and quantitative questionnaire to provide detailed feedback on their experiences.

Data and SWOT Analysis

The systematic collection and data analysis process is based on a Grounded Theory Method to evaluate the user studies, Figure 2. Data Collection has been conducted two-fold via notes as well as questionnaires. Researchers documented observations and conversations during the hands-on session. Data from pre-study and post-study questionnaires provide quantitative and qualitative insights into the user experience, shown in appendix B. Initially, the data is subjected to open coding to generate preliminary codes. These codes are refined through a detailed data coding process, resulting in more structured coded data. Further revision and reduction of statements distill the data into essential revised codes. These codes are then organized into categories and labels, each with core statements that capture the main ideas. These categories are assigned levels based on strengths, weaknesses, opportunities, and threats (SWOT), providing a comprehensive understanding of user feedback. The quantitative component of the study was based on structured user feedback collected via a post-interaction questionnaire. Participants evaluated the CirQA tool across key metrics related to usability and effectiveness: Ease of Use, Interface Usability, Navigation, Data Input, Output Information, Output Relevance, Decision-Making Support, and Overall Satisfaction. Each metric was assessed using a 5-point scale (1 = "not at all", 5 = "very").

Results

This section presents the results from the user study of CirQA. Quantitative data provides an overview of user satisfaction and tool effectiveness. Qualitative data identifies common themes, usability issues, and areas for improvement via categories, labels and levels. A SWOT analysis assesses the strengths, weaknesses, opportunities, and threats associated with the CirQA. This multifaceted approach aims to deliver a comprehensive understanding of user experiences and insights for future development.

Quantitative Data Analysis

We evaluated several metrics related to the usability and effectiveness of the tool. Each metric was rated on a scale from 1 to 5, with 1 indicating "not at all" and 5 indicating "very easy/useful/satisfied/relevant". Table 2 and Figure 8 summarize the mean, standard deviation, and median for each metric.

Table 2. Metrics Related to the Usability and Effectiveness of the Tool, Mean and Median

Metric	Mean	Std Dev	Median
from 1 as not at all, to 5 as very easy/useful/satisfied/relevant			
Ease of Use	3,94	0,85	4
Interface Usability	3,88	0,86	4
Navigation	4,38	0,77	4
Output Information	3,56	0,83	4
Data Input	3,88	1,08	4
Output Relevance	4,56	0,74	5
Decision Making	3,44	0,90	3
Overall Satisfaction	4,25	0,61	4

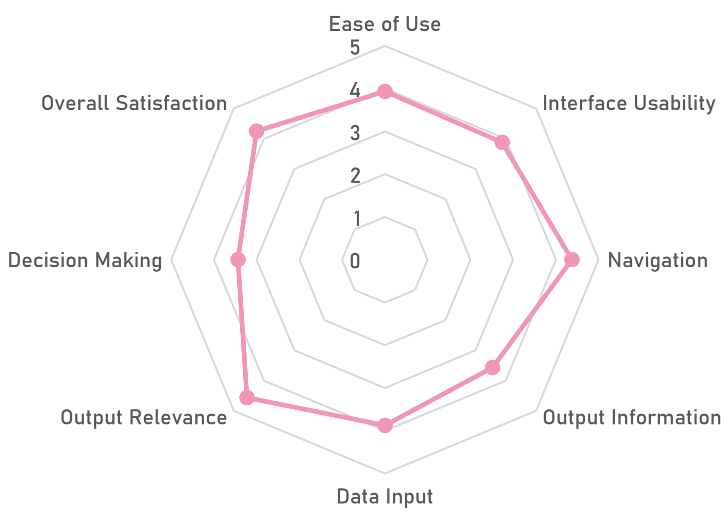

Figure 8 Metrics Related to the Usability and Effectiveness of the Tool, Mean Values

Professionals in software engineering, data science, and renewable energy planning gave consistently high ratings across all categories. This suggests the system aligns well with their expectations for usability, data handling, and decision-making support. In contrast, experts from geology and information technology rated the system much lower, especially in ease of use, output information, and overall satisfaction. These results point to a mismatch between the system's design and the needs or workflows typical of those fields.

Interestingly, while software development is closely related to software engineering, it received more critical feedback, particularly about the clarity and usefulness of outputs. This may reflect a difference in practical needs—developers might expect more flexibility or deeper customization. Fields like architecture and landscape architecture showed moderate satisfaction, with relatively better scores in interface usability than ease of use, indicating that while the interface was navigable, it may not feel intuitive or efficient without additional learning. Ultimately, the process aims at validation focused on aligning the prototype with real user needs and expectations, forming a basis for future tool optimization.

Qualitative Data Analysis: Categories, Labels and Level

The qualitative data analysis is structured to systematically explore user feedback. Each feedback is grouped into broad categories of data input, decision making, ease of use, and output information, relevance and satisfaction, Table 3. Within these categories, specific labels highlight key issues, and user comments are distilled into statements. Feedback is further analyzed using a SWOT framework.

Table 3 Excerpt of Qualitative Data Analysis, Category and Label, Reduced Statements and SWOT Description, and Level

Category	Label	Reduced statements	Swot description	Level
Data input	Components	Include interior walls made of bricks (expand the general material database).	Enhance material options.	Opportunity
Data input	Building design	Define and input the plot as a polyline via rhino.	Simplify input.	Opportunity
Data input	Navigation complexity	Some drop-down lists are not easy to comprehend without knowledge of the right measures and guidelines	Required prior knowledge.	Weakness
Decision making	Goal	Is the goal obvious? Raise awareness for laypeople; material changes should be immediately visible.	Enhance goal clarity.	Opportunity
Decision making	Structural planning	Early structural planning available?	Consider early planning.	Opportunity
Decision making	Variants	The short testing showed me the obvious results. The more wood, the more sustainable and better. However, I'd like to see how the outputs change for small adaptations in design using different materials	Provide detailed analysis.	Opportunity
Decision making	Sustainability	Sustainability is unfortunately only a niche which few people would pay for	Limited market appeal.	Threat
Decision making	Additional information	Without any info, if choosing more sustainable material is not much more expensive, I would not make my decisions	Lack of financial guidance.	Weakness
Ease of use	Explanation	With a short explanation, the user is capable to use this tool by themselves	User-friendly with guidance.	Strength
Ease of use	Additional information	Missing explanations of abbreviations and KPI	Lack of clarity.	Weakness
Interface usability	Environmental indicators	Units: indicate units for environmental indicators.	Missing detail in measurement.	Weakness

Interface usability	Additional information	As mentioned, additional information would still be useful	Improve user guidance.	Opportunity
Navigation	Additional information	Even though not implemented now, the use of icons along with quick info when passing over to jump to delineated input parameters would be quite helpful	Enhance user experience.	Opportunity
Output information	KPI	Provide descriptions for each KPI, e.g., "the building weight translates to ..."; explain its importance and relevance to the user, including the motivation and background.	Enhances understanding and context.	Opportunity
Output information	Recycling and disposal	Make the disposal indicator more understandable; show values defining it (0, 20, 45).	Improve data clarity.	Opportunity
Output information	Additional information	For some, it was easy and logical; for others, it was not clear due to general unfamiliarity with the domain	Domain knowledge is needed.	Weakness
Output information	Material	Missing information if, for example, recyclable means that the input or the output material is recyclable, so if it is primary or secondary material, and if it is recycled or only can be recycled	Lack of clarity.	Weakness
Output information	Values	The range and legend (what's good or bad) would be great to add. Otherwise, it's not easy to understand	Improve data interpretation.	Opportunity
Output relevance	Output export	It would be nice to have the possibility to export the output to a text or document or excel file	Enable documentation.	Opportunity
Output relevance	Variants	During the tool testing, we talked about adding or displaying some options for better comparison of the results, so the user can better understand how their decisions impact the design	Provide comparative analysis.	Opportunity
Output relevance	Design stage	Quick assessment in an eds in planning is a perfect match	Effective early-stage tool.	Strength
Overall satisfaction	Design stage	It gives a first idea of the topic	Effective introductory tool.	Strength
Overall satisfaction	Bim integration	Something like this tool must be built into a BIM software directly to be easily available and easy to use	Integrate with BIM.	Opportunity
Overall satisfaction	Interface	Open-end integration for other assessment tools	Broaden integration options.	Opportunity

Figure 9 illustrates the distribution of categories, and the number of labels assigned to each category based on user feedback, with a total of 351 individual label mentions spread across nine categories and 49 labels. The categories are ranked by the number of labels. Interface usability is the most frequently mentioned category, with 140 label mentions, that users had numerous comments or concerns about how the interface functions and their experience with it. Decision making follows with 65 mentions, suggesting that this aspect of the tool is a significant focus for users, in terms of how well the tool supports or influences their decision-making processes. Output information has 51 mentions, showing that the information generated by the tool is also a critical area of feedback, relating to clarity, relevance, or usefulness of the output data. Ease of use and data input each have 20 mentions, indicating moderate attention to these aspects of the tool, focusing on how easy the tool is to use and how straightforward the data input process is. Output relevance is tagged with 19 mentions, suggesting some focus on how relevant the output is to users' needs or expectations. Navigation received 17, highlighting user feedback on how easy it is to move through the tool's features or sections. Technical issues and overall satisfaction are the least mentioned categories, with 10 and 9 label mentions respectively, indicating that while these areas were noted by some users, they were not the primary focus of feedback.

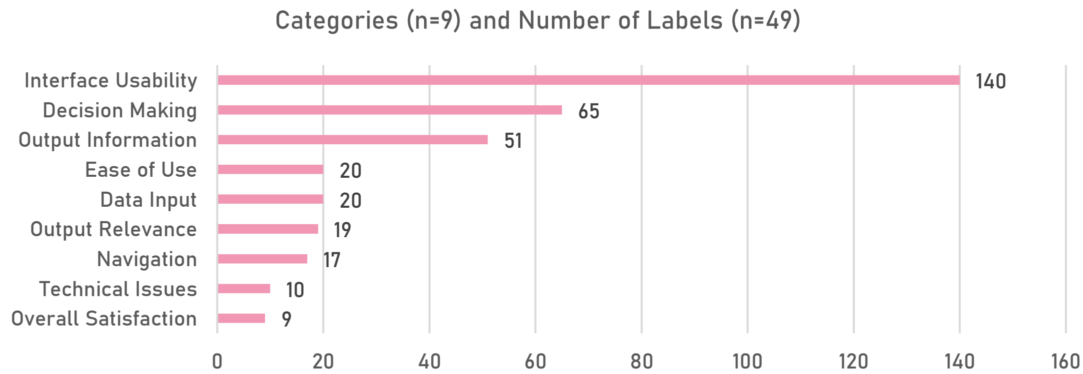

Figure 9 Distribution of Categories and Number of Labels

The granular breakdown of the 351 individual mentions of labels (appendix C) provides a view of user feedback, pinpointing specific areas where the CirQA excels or requires significant improvement. The focus on building design, additional information, and environmental indicators suggests that future development efforts should prioritize these areas to enhance the tool.

SWOT Analysis

In addressing weaknesses and threats and capitalizing on opportunities, the tool can be further refined and established as a resource for promoting circularity in building design. The SWOT analysis highlights that the tool is user-friendly, efficient, and effective for early-stage decision-making, Table 4, with strengths organised into five focus areas: focus area 1 - interface usability and user experience, area 2 -functional depth and data clarity, focus area 3 - visual integration and interactivity, focus area 4 -performance efficiency and accessibility, and focus area 5 - strategic utility and future potential—each highlighting distinct aspects of the tool. Strengths include ease of use, comprehensiveness and functionality, visual and interactive appeal, speed and efficiency and decision-making support. However, it faces weaknesses related to lack of clarity, interface and usability issues, missing details and guidance, documentation and interpretation issues, and missing functionality and features. There are also opportunities to enhance the tool, such as further improving visualization, customization, and broader integration, and data presentation, customization and flexibility, broader scope and integration, user experience, general optimization and future development. Potential threats include increasing complexity, competition from other software, and the risk of becoming outdated, categorized into complexity vs. ease of use, market and legal risks, potential misuse and misinterpretation, external competition, and tool longevity and relevance.

Table 4 Results of the SWOT Analysis Structured in Levels (S,W,O,T), Focus Areas and Descriptions

SWOT	Strengths	Weaknesses	Opportunities	Threats

Focus Area 1	**Ease of use**	**Interface and usability issues**	**Improve visualization and data presentation**	**Complexity vs. Ease of use**
	User-friendly design	Stability issues	Improve visualization	The more comprehensive it becomes, the more complex it will be
	Simple, straightforward	Complex navigation	Improve data interpretation	Compatibility issue with different tools
	Smooth interface	User-unfriendly navigation due to too many windows	Enhance understanding	Commercial players may create similar, more polished products
	Responsive interface	Cluttered interface	Improve user guidance	Could become a feature within other software
	Easy and quick to use	Overly large elements	Simplify interface and design options	Changes in legal requirements
	Effective early-stage tool	Language barrier	Streamline data presentation	Not developing the tool further
	Clear metric definitions		Provide comparative analysis	Misunderstanding or misuse
SWOT	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Focus Area 2	**Comprehensiveness and functionality**	**Lack of clarity**	**Customization and flexibility**	**Market and legal risks**
	Detailed material-level analysis	Lack of clarity in data	Enhance customization and flexibility	Limited market appeal
	Database of sustainability KPIs	Unclear metrics and purpose	Provide optimization options	Changes in regulations
	Real-time LCA analysis	Missing explanations and guidelines	Broaden material options	Policy on CE and competitors
	Important sustainability metric	Fragmented feedback	Explore alternative materials	Another tool outside the process
	Clear evaluation criteria	Usability issues	Expand LCA scope	
	Lifecycle consideration	Confusing data representation	Tailor analysis to objectives	
		Complexity not needed		
SWOT	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Focus Area 3	**Visual and interactive appeal**	**Missing details and guidance**	**Broader scope and integration**	**Potential misuse and misinterpretation**
	Appealing layout and user-friendly	Missing detail in measurement	Integrate with BIM tools	Misunderstanding the tool
	Graphical interface	Lack of integration	Broaden integration options	Confusing real-time feedback

	Visual rendering is a plus point	Missing material and building construction details	Include financial considerations	One can get lost in numbers
	Clear visual design	Unclear criteria for apartment mix	Upscale KPIs	The clear definition of precision if it's exact or an estimation
	Clear building height metrics	Unclear target audience	Improve onboarding	
SWOT	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Focus Area 4	**Speed and efficiency**	**Documentation and interpretation issues**	**User experience and accessibility**	**External competition**
	Speed and quick assessment	Needed help in understanding content	Improve user experience	Compatibility with other tools
	Quick and effective overview	Lack of interpretation of results	Provide detailed analysis	Competitors creating similar products
	Immediate key information	Lack of context for numbers	Provide key data	Could be built into other software
	Immediate response to changes	Confusing interface elements	Enhance learning experience	
SWOT	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Focus Area 5	**Decision-making support**	**Missing functionality and features**	**Optimization and future development**	**Tool longevity and relevance**
	Focus on ecological components	No integration in BIM tools	Continue development	Tool might not evolve with market needs
	Effective on decision-making	Just a simple geometry	Run on a server and improve UI	
	Prioritize key metrics	No much choice of materials	Provide scenario analysis	
	Consistent measurement	Limited flexibility	Expand application scope	
	Highlight carbon impact	Incomplete analysis	Add contextual data	

Discussion

The CirQA user study presents a comprehensive analysis of both quantitative and qualitative data to evaluate user experiences and the tool's effectiveness. Quantitative results, based on descriptive statistics, showed strong scores (mean of 4 on a 5-point scale) in areas like usability, interface design, navigation, and output relevance. However, aspects such as decision-making support and information clarity varied more, suggesting room for improvement.

Qualitative feedback highlighted similar concerns. Users valued CirQA's potential in early-stage sustainable building design but noted challenges including complex navigation, unclear data presentation, and insufficient guidance. These align with findings from the SWOT analysis, which pointed to opportunities for improvement—such as streamlining inputs, enhancing material options, and integrating with BIM software—and flagged threats like limited market appeal and increasing complexity.

Combining quantitative metrics with user narratives underscores the importance of addressing usability issues to broaden CirQA's accessibility, especially for non-expert users. Suggestions included improving KPI clarity, adding data export features, and enabling comparative analyses to support more informed design decisions. Financial data integration and more detailed variant analyses were also identified as ways to enhance decision-making capabilities.

These user insights reflect broader limitations seen in existing LCA tools, which are often complex, data-heavy, and designed for later-stage assessments requiring expert knowledge (De Wolf et al., 2023; Gantner et al., 2018). Tools like One Click LCA and Tally integrate with BIM platforms but remain difficult for non-experts. BEES and Athena, openLCA remain complex, meanwhile, offer more limited functionality and lack spatial or design-phase support (appendix A). CirQA distinguishes itself by enabling early-stage parametric integration and simplified LCA, supporting rapid iterations while remaining user-friendly.

To maintain its value, CirQA must evolve alongside market and regulatory demands. This includes improving visualization, simplifying data presentation, integrating with digital workflows like BIM, and expanding customization for various user needs. Literature supports this approach, emphasizing the need for early-stage integration of LCA to influence material selection, reuse, and energy efficiency (Caldas et al., 2022; Akbarieh et al., 2020; Banihashemi et al., 2024).

Overall, CirQA's strengths—ease of use, early-stage functionality, and visual design—position it as a promising tool for sustainable decision-making. However, challenges in clarity and usability need to be addressed to fully realize its potential. Future research and development should focus on better support systems, flexible and proper interfaces, and alignment with circular economy strategies (Dervishaj & Gudmundsson, 2024; Schiller & Gruhler, 2024, ; Tsay et al., 2023; Hollberg et al., 2021), ensuring CirQA becomes a valuable asset in circular building design. Based on this SWOT analysis, future research objectives have been identified and summarized as research objective/recommendation, thematic area and rationale, Table 5.

Table 5 Future Research Recommendations Based on the SWOT Analysis, Thematic Area and Rationale

Research recommendation	**Thematic area**	**Rationale**
Enhancing clarity and usability	User interface and data presentation	Simplify the interface and optimize visual elements to improve user experience and data comprehension.
Improving data interpretation and guidance	User support systems	Develop comprehensive guidance features to prevent misinterpretation and enhance usability.
Expanding customization and flexibility	Customization options	Incorporate advanced customization to support diverse project needs and sustainability goals.
Integrating broader life cycle and CE metrics	Life cycle assessment and circular economy	Include comprehensive LCA data that covers entire material lifecycles, supporting circular design.
Adapting to evolving market and regulatory landscapes	Market and legal compliance	Ensure the tool remains relevant by adapting to changes in sustainability regulations and market trends.

Evaluating the tool's impact on sustainable decision-making	Real-world application	Conduct studies to assess the tool's influence on sustainable decision-making in real projects.
Mitigating the risks of misuse and complexity	Balancing complexity and usability	Find a balance between detailed assessments and user-friendliness to prevent the tool from becoming overly complex.
Exploring integration with other industry tools	Software integration (e.g., BIM)	Research integration with industry-standard tools to enhance the tool's utility and market appeal.

Conclusion

CirQA addresses the challenges of integrating circularity principles at the early design stages by offering automated assessment and parametric model adjustments. This process, based on simple input requirements, enables ease of use for participants without specialized expertise, streamlining circular design application in AEC workflows. It aids users in making informed decisions about resource efficiency, recycling potential, and environmental impacts, ensuring alignment with LCA and CE goals. CirQA integrates Rhino3D, Grasshopper, and MS Excel, enabling parametric design and data management. This prototype serves as an initial implementation of design and assessment algorithms, allowing for testing and refinement based on user feedback. The conducted user study offers insights into CirQA's usability, effectiveness, and areas for improvement. While the tool is appreciated for its ease of use and relevance to sustainable building design, issues such as unclear metrics, complex navigation, and the need for more detailed guidance highlight areas for refinement. Enhancing usability, data clarity, and integration with existing design workflows, as indicated both by our study and the literature is the objective of future research. Simplifying the interface, improving data presentation, and offering better support for interpreting sustainability metrics could significantly boost user satisfaction and effectiveness. Integrating features like data export, expanded customization, and improved compatibility will keep the tool relevant in a rapidly evolving market and regulatory landscape. Additionally, adapting the tool to evolving regulatory and market landscapes and exploring integration with other industry tools could enhance its impact across the construction sector. By focusing on these improvements, CirQA can become a more accessible and powerful resource aiming at accessibility to a broad range of users, including those with varying levels of expertise - advancing circular building design practices and support informed decision making towards future-proof building design in the AEC industry.

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Declarations

Competing interests The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process During the preparation of this work, the authors used DeepL and GPT to improve readability, language precision, and consistency in terminology, as the authors are non-native English speakers. This allowed the authors to focus on the scientific rigor and clarity of the content. After using these tools, the authors thoroughly reviewed and edited the manuscript, taking full responsibility for its final content.

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