Holistisk livscykeloptimering i tidiga designfaser av byggnader

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Holistic life cycle optimization in early design stages of buildings

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E2B2

Förord

E2B2s vision är en resurs- och energieffektiv byggd miljö.

Bebyggelsesektorn svarar för cirka en tredjedel av Sveriges totala energianvändning och en effektivare energianvändning är en viktig del av utvecklingen av energisystemet. Hållbarhet, effektivitet och robusthet i bebyggelsen behöver stärkas och utvecklas. Lösningarna behöver samspela för att fungera och utnyttjas. Forskning, utveckling, innovation och kommersialisering spelar en avgörande roll.

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E2B2 är ett forsknings- och innovationsprogram från Energimyndigheten där IQ Samhällsbyggnad är koordinator. Programmet startade 2013 och en andra programperiod pågår mellan 2018 och 2024. Projektet som beskrivs i den här rapporten har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten.

Stockholm, 21 december 2022

Rapporten redovisar projektets resultat och slutsatser. Publicering innebär inte att Energimyndigheten tar ställning till framförda slutsatser, resultat eller eventuella åsikter.

Sammanfattning

Beslut i tidiga designskeden är avgörande för att begränsa byggnaders miljöpåverkan och säkerställa brukarkomfort och funktionalitet. Trots att många digitala verktyg har utvecklats för optimering av byggnadsprestanda i dessa designskeden, är deras användning begränsad i praktiken.

Detta projekt har som syfte att överbrygga detta glapp genom att integrera holistisk livscykelutvärdering av byggnadsprestanda i praktiken. Det har genomgått tre faser: en analys av befintliga tillvägagångssätt och verktyg, utvecklingen av ett nytt prestandaverktyg skräddarsytt för behoven i tidiga designskeden, och dess utvärdering i designprocesser.

Resultaten visar på ett tydligt behov för denna typ av verktyg i praktiken, vilket belyser glapp mellan forskning och praktik, samt mellan olika forskningsområden. Även om tidigare studier har tagit hänsyn till användarbehov har de ofta ignorerat den kontext som användarna verkar i, exempelvis i form av beställarbehov och lagstiftning. Projektet introducerar ett ramverk som tar hänsyn till dessa faktorer och demonstrerar ett praktiskt tillvägagångssätt för mjukvaruutveckling av nya verktyg, vilket har resulterat i publiceringen av två tillgängliga verktyg med öppen källkod.

Detta projekt förbättrar förståelsen av olika intressenters behov och praktiker för datorstödd arkitekturdesign i tidigt designskede, vilket lägger grunden för framtida innovationer. De publicerade verktygen med öppen källkod möjliggör användning i praktiken, direkt i designprocesser för en hållbar byggd miljö.

Nyckelord: Byggnadsprestanda, livscykelanalys, designprocess, praktik, arkitekter, verktygsutveckling

Summary

Early design decisions are crucial for reducing the environmental impact of buildings and ensuring user comfort and functionality. Despite many digital tools being developed for building performance optimisation in these stages, their widespread use in practice is still lacking.

This project aims to bridge that gap by integrating holistic life cycle building performance optimisation into practice. It involved three phases: analysing current practices and tools, developing a new performance tool tailored to the needs of early design stages, and evaluating it in design processes.

Results indicate a significant need for such tools in practice, highlighting gaps between research and practice, as well as between different research communities. While previous studies have addressed user needs, they often ignore the context users operate in, like client demands and regulations. The project introduces a framework considering these factors and demonstrates a practical software development approach for new tools, resulting in two published open-source tools.

This project enhances the understanding of stakeholder needs and early design-stage practices in computational architectural design, laying the groundwork for future innovations. The published open-source tools enable practitioners to directly use them in design processes towards a sustainable built environment.

Keywords: Building performance, Life Cycle Assessment, Design process, Practice, Architects, Tool development

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1 Introduction and background

1.1 Background

Today, most architects and designers rely on digital tools to design buildings. While the concept of digital twins and Building Information modelling (BIM) are increasingly used in the detailed design stages and for the construction phase of buildings, more dynamic and flexible approaches are needed in early design stages. In these early stages, designers want to compare different alternatives quickly [1]. Therefore, the modelling effort has to be low. Furthermore, the early design stages provide the biggest optimisation potential (see Figure 1). This optimisation is done by generating and comparing various alternatives. Next to comparing manually generated design alternatives, the analysis results can be used to control the generation of variants by the computer. This approach is often referred to as generative design.

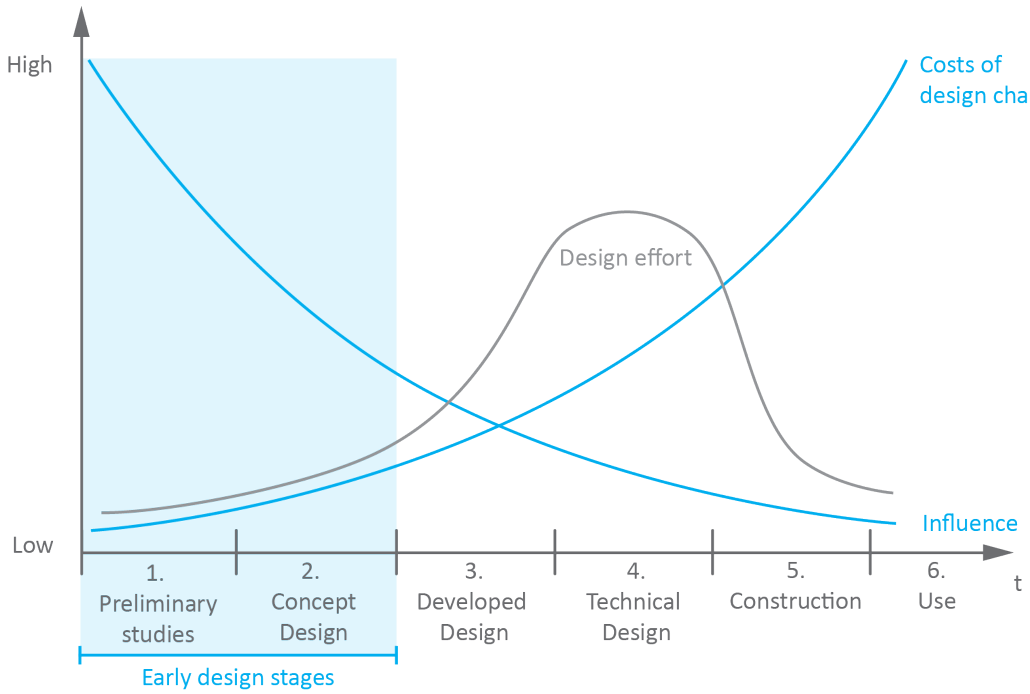

Figure 1: Cost of design change in different design phases (based on [2])

The most common tool in the generative design community is Grasshopper3D [3]. Grasshopper3D provides a whole environment of plugins for all kinds of building performance assessments. Most of them are developed by researchers and open source. They usually focus on very specific aspects, such as daylight and wind simulation. This development is very positive; however, in practice, several challenges arise.

One challenge is that the tools are often free to use but only provide limited user support. As a result, only experts use a few tools in practice. Most of these experts are part of a computational design team in larger architectural offices. While the tools are accessible for everybody in theory, the complexity and barriers to get started are too high for most architects.

Even for expert users, it is challenging to combine different tools for holistic assessment. Different tools often require input data in different formats. Another challenge lies in defining the needed level of accuracy. In most cases, there is a trade-off between accuracy and speed. Speed does not only refer to the calculation time but also the modelling effort and time required for data input. Depending on the design question and the design stage, the calculation algorithms can be simplified.

In summary, it can be stated that there is a big gap between the potential of using computational optimisation for energy-efficient and sustainable design identified by researchers and the application in practice. While a few internationally leading architecture offices and consultancies have started using these approaches, there are many challenges and barriers for architects and designers in general.

1.2 Aim and objectives

This project focuses on integration in practice. The project's main aim of integrating holistic life cycle optimisation in the early design stages of buildings is achieved by following three objectives:

1) Identify the needs of Swedish designers for life cycle building optimisation and analyse current barriers and potentials to provide a foundation for the tool development.
2) Develop a flexible and holistic workflow for life cycle building performance assessment. The workflow is based on existing tools within the parametric design environment Grasshopper3D, and adapts them to the needs in the Swedish context.
3) Evaluate the developed tool workflow and disseminate the gained knowledge to stakeholders. The developed tools are tested with practicing architects and students and published as open source.

1.3 Scope

The project focuses on the Nordic context while taking into account global tool developments and local regulations.

The project focuses on combining embodied carbon, operational energy, operational carbon, and daylight. Potential links to structural analysis are included but are not the focus of the project. Embodied carbon only includes life cycle phases A1- A5, as this is the current practice in Sweden, and data is easily accessible to stakeholders. Additional life cycle phases could be included in the future.

The tool development follows an open-source approach for practice and education. Business models and commercialisation are not part of the project.

2 Method

The project was structured into three main work packages (WPs), each addressing one of the goals:

2.1 WP 1: Analysis of the stakeholder needs and current practice

This WP used a mixed methods approach combining workshops with the reference group or leading computational architects, interviews with designers, observations at architecture offices and a deep review of existing life cycle building performance tools and the literature describing tool evaluation. The interviews with nine architects and sustainability consultants were carried out between February 2022 and May 2023 using the interview to the double method [4]. In this method, the respondent is asked to imagine that their place will be taken by a body double, represented by the interviewer, during their next workday. Then, they are asked to instruct the interviewer on their tasks and behaviours in the workplace during that day. The meta-review included eighty-seven tool reviews and followed a three-step approach shown in Figure 2.

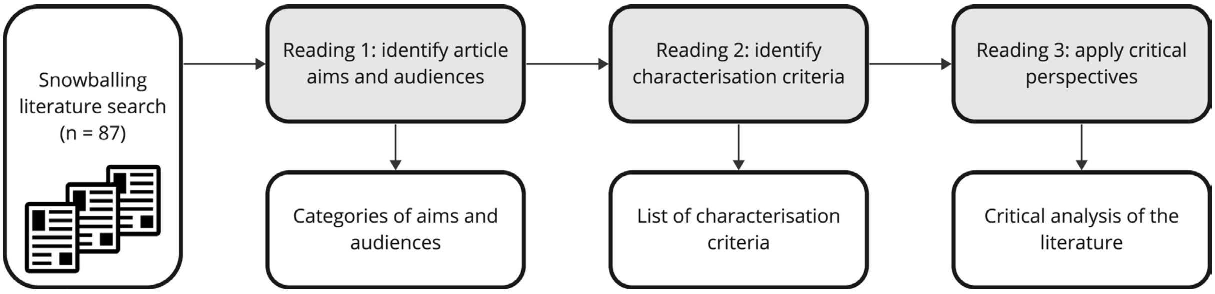

Figure 2: Overview of the meta-review approach

2.2 WP 2: Method and tool development

Using the knowledge gained from WP1, existing tools were analysed towards their potential for developing integrated life cycle building performance analysis workflows. The parametric design environment Grasshopper 3D was used as it provides a flexible basis and is popular among computational designers. A few modules from existing tools, such as BeDOT [5] and Ladybug/Honeybee [6] were used and extended with new modules that were programmed because no existing tool covers embodied and operational carbon, energy demand and daylight in a holistic way. In addition, the potential of using machine learning to replace the time-consuming energy demand simulation was explored. The tool development followed an iterative process with continuous user feedback from the evaluation as part of WP3. After tests with architecture students, a novel panel-based user interface was developed to further simplify the use of the tool in practice.

2.3 WP3: Tool evaluation and dissemination

The developed tool was continuously evaluated through user workshops. In addition, the tool was used in a master course at Chalmers, where 30 students applied it to a design project. In a second iteration of the course, the students used the novel panel-based user interface, which allowed us to compare the user-friendliness and the final performance of the designs with the previous course. Another round of evaluation with architects in their offices using real design projects is planned for autumn 2025.

The dissemination strategy consisted of four parts: Articles in scientific journals and conferences, workshops with the reference group and additional architects, presentations at industry events, and the open-source publication of the developed tools on the popular platform Food4Rhino.

3 Results

The results are presented following the three aims.

3.1 Analysis of the stakeholder needs and current practice

3.1.1 Reference group workshops

At the beginning of the project, a reference group with five representatives of leading architectural offices in the field of computational design was formed. The represented offices included White arkitekter, Fojab, BIG, Kaminsky arkitekter, and Liljewall. The workshop confirmed several assumptions guiding the research design of the project:

1) A clear focus should be on the ”holistic building performance assessment” in the early design stages
2) ”Holistic” is defined as taking a life cycle perspective into account and looking at more than one type of performance indicator, e.g. daylight factor, heating demand and greenhouse gas emissions
3) Costs and qualitative criteria, such as appearance or views, can be left out
4) Workflows to support design improvement for architects are more relevant for practice than computational optimisers
5) A focus on architects' needs is required, but also, clients’ needs should be considered because they ultimately make the decisions

3.1.2 Review of existing tools

The review of the literature revealed that there is a lack of a framework to characterise life cycle assessment and building performance tools. Therefore, a tool characterisation framework was developed by combining previous frameworks for tool reviews.

Most current tools either focus on the performance during the use phase, for example, the energy demand and daylight or the environmental performance related to the choice of materials and components, for example, embodied carbon. Therefore, both domains were reviewed separately.

The developed characterisation framework was first applied to eleven building performance tools available for Grasshopper3D, focusing on the use phase [7]. Four of those tools were analysed in detail. In a second step, the framework was applied to building LCA tools [8]. Thirteen parametric LCA plug-ins for GH were reviewed. Finally, four of these plug-ins were further investigated using the developed evaluation framework, a user persona approach, and a simplified test case.

In both analyses, it was found that the framework was able to successfully differentiate tools based on the level of expertise integrated in the tools and the allocation of responsibility for data entry and interpretation. A contrast was found between easier-to-use, streamlined tools and more complex tools which provide more versatility. The characterisation framework and the resulting overview of approaches can be used to guide the future development of parametric tools.

Finally, a meta-review of eighty-seven tool reviews [9] in the field of life cycle building performance assessment was conducted to identify best practices and remaining gaps. It was found that most previous reviews emphasise technological advancement rather than tool integration in practice by failing to apply the perspective of tool users in design processes. Few tool reviews focus on the tool user, however, they lack the wider perspective of design practice that the user is part of (see Figure 3). It was further found that the reviews mostly lack consistent methodologies. To bridge these gaps, it is proposed that future tool evaluation studies define a clear target user and investigate tools based on how they perform in real-world design processes.

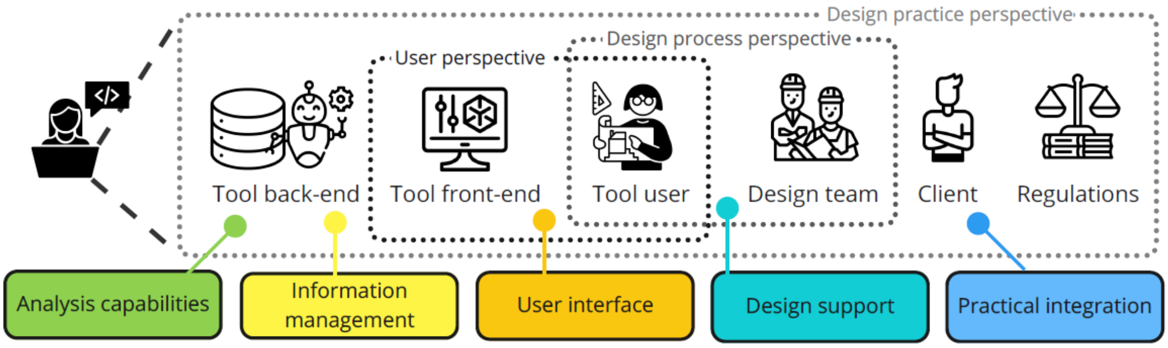

Figure 3: Perspectives applied in the critical meta-review

3.1.3 Interviews and observations

To further collect first-hand information from practice, nine interviews were carried out between February 2022 and May 2023 using the interview to the double method [4]. Analysing the responses from nine architectural practitioners, we identified several design activities, in addition to a previous study by Purup and Petersen [10]. We moulded the responses into two user personas: the *modeller-analyst* and the *educator-strategist*, each representing an architectural practitioner who has the opportunity to transform the architectural design practice toward sustainable solutions. The novel approach allows software developers to collect and convincingly describe design activities and user narratives, helping them to identify and discuss practice needs during participatory software development processes.

To understand how tool learning activities are linked to their perceived usefulness and ease-of-use, we applied interviews and questionnaires during the learning process of a daylight simulation software in a mid-sized architectural office in Sweden [11] . We found that a combination of learning activities is beneficial and that members throughout the organisation hierarchy need to learn about the tool capabilities for integration to be successful. These findings can guide the training approach to focus from ”user” to ”practice”.

3.2 Tool development

The tool development used the insights from the analysis of stakeholder needs and current practise and used an iterative approach. This first step focussed on combining existing tools within the Grasshopper3D environment, linking them and filling gaps. As there was no tool available for embodied carbon in the Swedish context, a novel plugin called *Brimstone* was developed. The plugin retrieves data from Boverket's climate database through API or file access and makes data available in Grasshopper. It is freely available at https://www.food4rhino.com/en/app/brimstone. The second step focused on reducing the effort for data input. A combined database as a single point of contact [12] was developed to avoid the common challenge of needing to input the same information several times, e.g. the material parameters for daylight, energy and embodied carbon analysis. The third step focused on reducing the time to run the simulations. As energy simulations with EnergyPlus are one of the most time-consuming parts, the opportunities to replace this physics-based simulation with a machine-learning-based surrogate model were explored. Different algorithms were tested for heating demand simulation for residential buildings in the Gothenburg climate [13]. The results were promising but need further development before integration into the tool for practitioners. The fourth step focused on the user journey and the user interface. This led to the development of a novel panel-based workflow to guide users and provide visualization options (see Figure 4). This tool called *Heath* is available to download at https://github.com/sawenchalmers/heath.

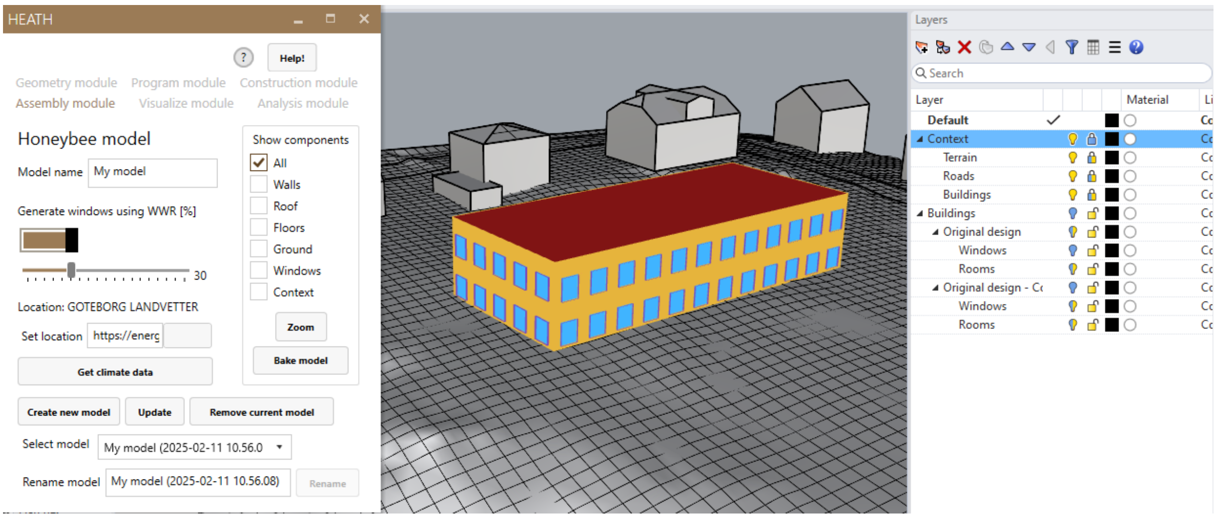

Figure 4: Screenshot of the Heath user interface. The panel-based interface guides the user through a "wizard-like" workflow. The Rhino window is used to visualise geometry and analysis results. Geometry is managed using the built-in Rhino layer functionality.

3.3 Evaluation and Dissemination

3.3.1 Evaluation

The evaluation strategy relies on integrating the tool development into the master program for architecture at Chalmers to be able to observe students using the tools. Furthermore, the evaluation in practice is carried out by collecting feedback from presentations and workshops with the tool.

The project work in the course *ACE405 Design and Performance Optimisation in Architecture* in 2025 showed that the panel-based user interface makes it much easier for students to conduct analyses and interpret the results compared to working with the traditional Grasshopper user interface in 2024. As a result, students had more time to focus on design optimisation and produced better results in the course.

Two workshops with architects in practice have further confirmed that the panel-based user interface and the combined analysis using a single database are of high value. The actual use in a real design project will be evaluated in autumn 2025 and documented in a journal article.

3.3.2 Dissemination

The project's results were shown at several renowned international scientific conferences, including the Sustainable Built Environment Conference Series, the European Conference on Computing in Construction Series and two IBPSA conferences in Denmark and the USA. In addition, one journal article and one licentiate thesis have been published so far, while three additional ones will be submitted soon.

The close contact with the reference group was used as a dissemination channel to practice. Furthermore, the master's students will carry the knowledge and the tools to practice. The Brimstone tool has been downloaded more than 200 times from Food4Rhino up to now and is used by several Swedish architecture offices.

4 Discussion

The interviews confirmed many of the design activities described by Purup and Petersen [10]. In addition, we identified several key design activities which could be added to the framework: activities related to understanding the regulations and client needs, modelling activities producing narratives and graphical material, and analysis activities investigating life cycle impacts. An overview of the revised version of the design process model, including the two user personas, is provided in Figure 5.

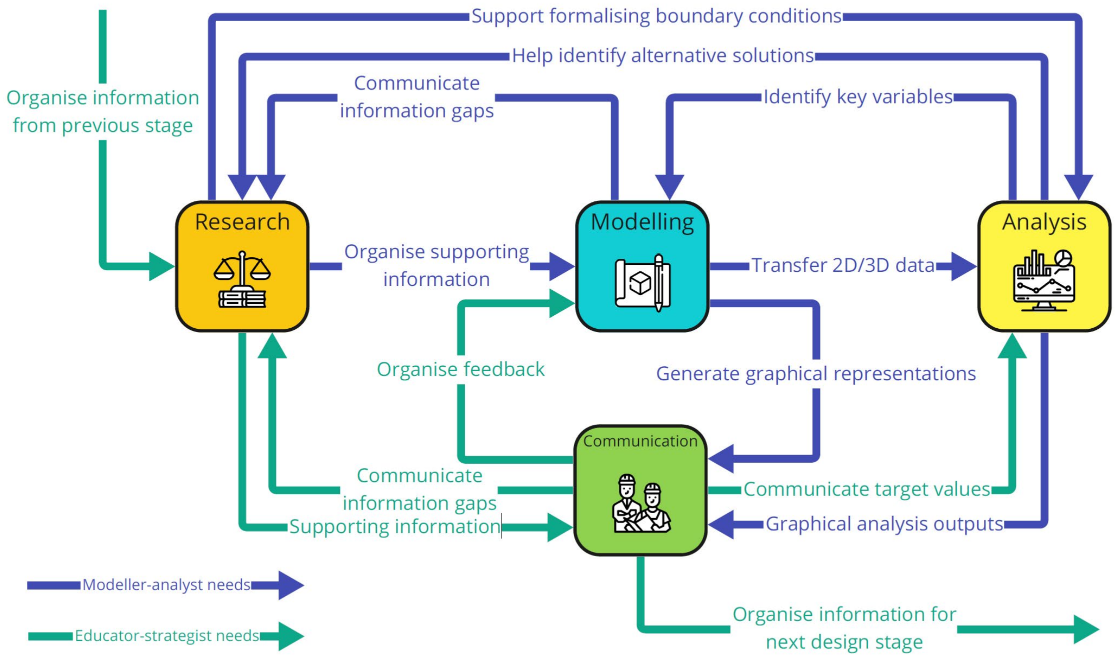

Figure 5: The revised model of the design information is generated through design activities and transferred between them constantly. The arrows represent ways that software solutions can support these transactions of information. The blue and green arrows represent the potential software needs of the Modeller-Analyst and the Educator-Strategist user personas.

The evaluation of the tool with master students showed very successful results, showing the potential the novel approach provides for non-experts. As such, this is promising to achieve the goal of providing easy-to-use tools for a wide range of practitioners. The feedback from practitioners indicates a high potential for taking up such tools, however, the evaluation in the context of a real design process is still ongoing.

The project highlighted the need to go beyond current user need analysis and to include the practice that the user is embedded in, such as the client's needs, regulations and the business model of the office. These have a high impact on the potential uptake of a novel tool in practice. Therefore, we recommend software tool developers and researchers aiming at providing digital tools to practice to take on this practice perspective and use our guidelines.

The project contributed to closing the gap between research and practice and between the currently separated fields of building performance simulation and life cycle assessment of buildings.

The exploration of machine learning to replace time-consuming physics-based simulations proved a high potential but needs further research before being able to be integrated into life cycle building performance tools for practitioners.

5 Conclusions

Decisions in early design stages are key to reducing the environmental impacts of buildings and ensuring high user comfort and functionality. Many digital tools to support environmental and building performance optimisation have been developed in the last years. However, there is still no widespread use of those tools.

This project aims at closing this gap by exploring possibilities of integrating holistic life cycle building performance assessment in practise. The projects consisted of three phases: 1) a thorough analysis of the current practice, stakeholder needs and the available tools and the literature, 2) the development of a novel life cycle building performance assessment tool, and 3) the evaluation of this tool in design and decision-making processes.

The results show that there is a high need in practice for life cycle building performance assessment tools. However, there is a big gap between research and practice. Furthermore, there is a gap between the building performance research community focusing on the use phase and the life cycle assessment community focusing on the environmental impacts related to construction materials. While previous literature has looked at the tool user needs, they lack including the practice that the users are embedded in, such as client needs and regulations. The project proposes a new framework to include such a practice perspective. The project also showed how such a practice-oriented software development approach can be used to develop new life cycle building performance assessment tools. The resulting tool, called Heath, is an open-source tool to allow all stakeholders in Sweden to use it. The project furthermore showed the potential of using machine learning to replace time-consuming simulations, but further research is needed before those approaches are easily applicable in practice.

This report contributes to a deepened understanding of stakeholder needs and the current practice of computational architectural design in early design stages, which provides a valuable foundation for future innovation and tool development far beyond this project. Furthermore, the project's published open-source tools enable practitioners to directly benefit from them in their design projects. As such, this is one step forward towards a sustainable built environment.

6 List of Publications

Scientific articles:

T. Säwén, P. M. Gustafsson, A. Sasic Kalagasidis, and A. Hollberg, 'HOW ARCHITECTS LEARN: TRACING THE INTEGRATION OF A DAYLIGHT SIMULATION TOOL IN ARCHITECTURAL DESIGN PRACTICE, in *Proceedings of the European Conference on Computing in Construction*, Porto, Portugal, 2025, forthcoming.

T. Säwén, A. Sasic Kalagasidis, and A. Hollberg, 'Early Architectural Design Stage User Narratives Applying a Practice Lens to Life Cycle Building Performance Software Needs', submitted to *Engineering, Construction and Architectural Management*

T. Säwén, A. Sasic Kalagasidis, and A. Hollberg, 'Critical perspectives on life cycle building performance assessment tool reviews'*, Renewable and Sustainable Energy Reviews*, vol. 197, no. 7, p. 114407, 2024, doi: 10.1016/j.rser.2024.114407.

T. Säwén, P. Estève-Bourrel, I. Mjörnell, A. Galimshina, G. Habert, and A. Hollberg, 'SINGLE POINT OF CONTACT: DENSITY AS A MAPPING PARAMETER FOR BUILDING MATERIAL DATABASES', in *Proceedings of the European Conference on Computing in Construction*, Chania, Grekland, 2024, vol. 2024, pp. 276–253, doi: 10.35490/EC3.2024.194.

T. Säwén, E. Magnusson, A. Hollberg, and A. Sasic Kalagasidis, 'A Characterisation Framework for Parametric Building Performance Simulation Tools', *in E3S Web of Conferences*, Copenhagen, Danmark, 2022, vol. 362, doi: 10.1051/e3sconf/202236203004.

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Licentiate thesis:

T. Säwén, 'Early Stage Architectural Design Practice Perspectives on Life Cycle Building Performance Assessment', 2023, Chalmers, https://research.chalmers.se/en/publication/538257

7 Open-source software

Brimstone: https://www.food4rhino.com/en/app/brimstone

Heath: https://github.com/sawenchalmers/heath

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