A Designer-Friendly Approach for Performance-Based Design

A User Study and System Proposal

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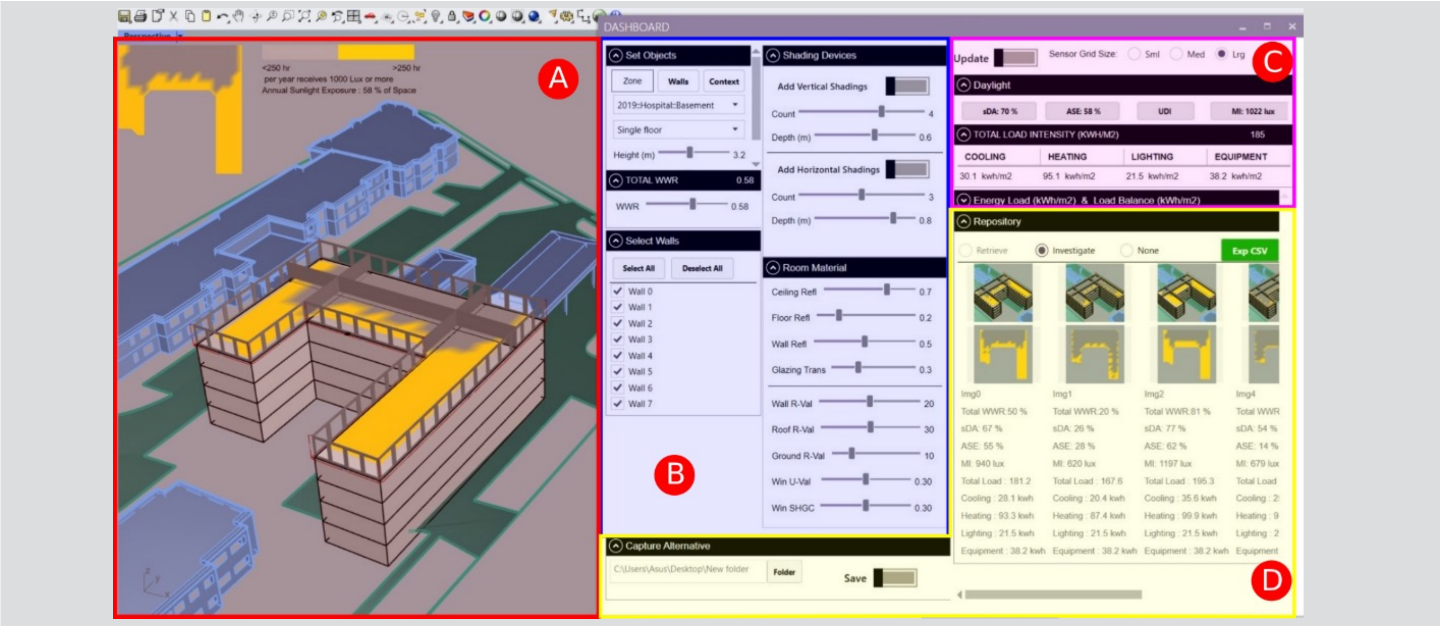

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1 The trial-and-error interface. (A) Rhino3D view with analysis results visualized. (B) Design generation controls. (C) Performance assessment panel. (D) Alternatives management panel.

ABSTRACT

Performance-based design can inform the decisions made during the early stages of design, which can greatly impact the overall sustainability of built environments. However, the tasks related to performance-based design, including generating, exploring, analyzing and visualizing design spaces, face multiple challenges, such as being time-consuming, cognitively demanding, and highly technical and specialized. This paper presents a performance-based design tool that aims to address those challenges by integrating parametric exploration and analysis, surrogate machine learning models of building performance, and data visualization and analysis. We report a formal evaluation of an earlier version of the tool (trial-and-error interface) and use the results to justify and inform the design of the tool we present here (parametric analysis extension). Notably, the formal evaluation highlights the effectiveness of surrogate models in creating fast design tools, as well as the importance of intuitive and explainable interfaces for bringing advanced performance assessment and data analysis techniques into the daily toolkit of designers.

INTRODUCTION

Early-phase design decisions heavily impact the sustainability of built environments, and performance-based design tools and processes can help guide those decisions. However, for performance-based design tools to match the needs of design exploration in early design phases, they need to be sufficiently expressive, minimally imposing on existing workflows, flexible, fast, and user-friendly.

Design space exploration implies the generation of design alternatives (Fang et al. 2021), whether they are a limited number produced by a traditional trial-and-error process or a large population of variations produced by a systematic combinatorial of design inputs. Through parametric analysis and generative design, designers can systematically explore design spaces (Haymaker et al. 2018; Caetano et al. 2020) and understand their input-output relationships aided with performance assessment and comparative studies, which opens possibilities inaccessible through trial-and-error processes. Concretely, parametric workflows can vary design parameters, update the design, trigger dynamic simulations of the different performance aspects, and collect the outputs for visualization and comparison. While performance analysis for a handful of alternatives is affordable computationally, it becomes taxing for large design spaces ranging from hundreds to thousands of alternatives.

In particular, generating, exploring, analyzing and visualizing design spaces face four challenges, namely that they are: (CH-1) cognitively demanding tasks that demand proper tool support, (CH-2) time-consuming tasks due to the computational cost of running performance simulations, especially for large design spaces, (CH-3) highly technical tasks that require expertise in data analytics and building science to interpret results, which designers may not possess, and (CH-4) specialized tasks that require using different tools, leading to frequent context switching.

This paper presents the results of an expert review study conducted to evaluate a performance-based design exploration system (trial-and-error interface) that utilizes parametric exploration, data visualization, and surrogate modelling of building performance. We also use the study's findings to inform the design of an extension to that tool that adds data analytics and generative design capabilities (parametric analysis extension).

PRIOR WORK

In an earlier work (Mottagi et al. 2024a, 2024b), we presented two system prototypes for performance-based design exploration that rely on surrogate performance models to accelerate exploration. The earlier systems relied on a trial-and-error approach. In contrast, designers tweak design parameters (e.g., Window-to-Wall Ratio and shading devices per wall) as they explore different design options, guided by building performance visualizations as predicted by a surrogate model for daylighting prediction and quick annual energy loads calculation. This work and the prior were conducted in collaboration with an industry partner, following a user-centred approach where designers and building scientists are consulted at different project stages. The research project adopts agile system development (Turk, Robert, and Rumpe 2005) and design study (Sedlmair et al. 2012) methodologies. We briefly introduce our prior system next.

Design Model

The parametric design model that can be explored through the trial-and-error interface was developed based on the designer's feedback to have sufficient detail for early phase explorations, e.g., façade studies. In particular, designers start modelling by creating or selecting a (polygon) building footprint in the Rhino3D environment based on which exterior walls are created. Furthermore, designers can define interior walls within the footprint and context elements around the building. Next, designers can generate openings and shading devices by assigning different values of Window-to-Wall (WWR) ratios for each wall and per-wall shading devices, such as vertical or horizontal shading devices, with controllable depths and counts for each.

Trial-and-Error Interface

The trial-and-error interface shown in Figure 1 is built using HumanUI, a Grasshopper plugin for building user interfaces, to enable tight integration with the Rhino3D environment familiar to architects (McNeel 2024). It is composed of four parts:

A. The Rhino3D view, where designers define the building footprint and where the generated geometry and the analysis results are shown.

B. Design generation controls panel, where designers can initiate setting the floor plan outline, the interior walls, and the outside context by choosing them from Rhino's view. Next, they can select individual wall(s) and assign them different shading devices or window-to-wall ratios using sliders. On this panel, designers can also assign different material properties which influence the daylighting and energy analyses, such as surface reflectivity, R-values, and U-values.

C. Performance assessment panel. Summary metrics for daylighting and energy are shown on this panel, and designers can choose whether to run the analysis on demand or automatically after each design change. The daylighting metrics include Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE) or glare, Useful Daylight Illuminance (UDI), and Mean Illuminance (MI). By clicking on any of the daylighting metrics buttons, the system shows its corresponding heatmap on the previously selected footprint (e.g., Figure 1- (A) shows the heatmap for ASE). As for energy, the system calculates different energy loads using Ladybug, which includes cooling, heating, lighting and equipment loads. The energy loads chart, not shown in the figure, presents bar charts with monthly breakdowns of energy loads. Finally, designers can hover over any of the metrics to show a tooltip informing them about its definition and acceptable ranges.

D. The alternatives management panel includes options for saving design options, loading them back, and comparing them side by side.

STUDY GOALS AND PROTOCOL

In this paper, we present the results of an expert review conducted to evaluate the trial-and-error design interface (Figure 1). The study aimed to evaluate the interface's utility, usability, and adoptability. Below is a description of each.

- Utility: whether the interface enables designers to make data-informed decisions in the early design phases, especially regarding daylighting and energy performance.
- Adoptability: whether the interface adds value to designers, fits some need or improves on the current tool(s), and integrates into their current processes.
- Usability: whether the tool is easy to use and learn and whether designers can interpret the results without the assistance of a building scientist.

The study was conducted with seven participants from a collaborating architectural design firm with varying experience levels and familiarity with building science, though all participants were LEED-certified. Table 1 shows a breakdown of the participants' experiences. The study's protocol included first requesting participants to sign consent forms and a survey about their background. Following that, it included a demonstration of the tool, followed by a design task of reducing the Annual Sunlight Exposure (glare) on a building floor while noting the related impact on other daylighting metrics (e.g. daylight autonomy) and energy loads (cooling, heating). Participants were asked to talk aloud as they were performing the design task. Following that, a semi-open-ended interview is conducted, which tackles the evaluation factors listed above. Two researchers recorded, transcribed, and analyzed all the sessions.

Study Findings

The study's results can be categorized into findings that evaluate the interface or findings that suggest future directions. We start with evaluation findings.

Fast and easy to learn. Despite some usability issues, all the participants found the tool easy to use and learn. Many also found it fast. Each design generation during the study took about 30 seconds to 2 minutes.

> *P1:* What I love about this is how fast this generates the information that we are looking for and fast results. *P2*: I appreciate how quickly it was able to generate the simulations. I think it's really fantastic to have all the data comparison and numerous iterations all at once. *P5:* My first impression of the parametric tool is that it's fast.

Granular control. Most participants liked the ability to control the design on a granular level, e.g., applying different window-to-wall ratios for different walls, as it allows them to treat walls based on the direction they face (e.g., southern walls get more light) or the building's interior.

> *P5*: It was good to be able to select specific walls and apply a new ratio to them and apply solar shade in different orientations based on which direction the wall is facing.

Comparative analysis. Most participants agreed that being able to compare alternatives side-by-side was useful or thought it was a promising idea.

> *P6:* Yeah, I think the comparison is really interesting to see. Like, you can see how the numbers change based on what kind of design moves you're making. I think that it's nice.

Visual feedback on building performance. Multiple participants liked the way the performance assessment results were visualized.

> *P2*: I think it was really useful to be able to quickly demonstrate these simple changes and updates to these specific areas...[and] to be able to actually have the data to back these [decisions] up. *PX*: I think it's just being able to see all these different daylighting options right away next to each other. This is really useful to see all in one place.

Years of Experience	Experience with (out of 5):				Frequency of using:	
	Modelling in Rhino	Parametric design, e.g., Grasshopper	Daylight analysis, e.g., ClimateStudio or LadyBug	Energy analysis, e.g., EnergyPlus or OpenStudio	Data visualization	Statistical analysis
2-5	5	3	4	3	Sometimes	Never
2-5	5	4	3	3	Sometimes	Rarely
5-10	5	5	3	1	Rarely	Never
5-10	4	3	2	2	Frequently	Rarely
5-10	2	2	1	1	Sometimes	Rarely
>10	4	2	1	1	Rarely	Never
>10	5	5	5	4	Always	Frequently

Table 1. A breakdown of participants' backgrounds.

Table 1

PX: So having a graphic, this is great for internal comparison, quick internal comparison for graphic presentation.

See, compare, learn, change. The interface supported the performance-based design cycle, including assessing the design and then acting on what is learned.

P7: To see the result and also compare the result and have a mechanism to fine-tune the parameter to change the result accordingly as well. I think that's useful.

How they might have done it otherwise. When asked how they might have done the design task (of reducing ASE/glare) without using our tool, the participants' responses were threefold. The first group said they didn't run such analyses personally and that a separate team of scientists often does it for them; however, it can take days for scientists to get back to them, and this tool can help them test out scenarios before asking the scientists for a thorough analysis. The second group said they would use LadyBug and pre-made scripts that they customize to different projects. But the setup takes time to prepare and run and formatting the results and visualizations won't be available out of the box as on this tool, besides not requiring scripting expertise. The third group said they would use Climate Studio but that this tool would be faster due to the surrogate model used.

Appropriate design resolution. Multiple participants agreed that the level of control and details were sufficient for early design phases.

P5: It's good information to have early on, and I guess the resolution of the information is appropriate for that stage.

Early phase performance-based design. A general consensus was that the tool would be helpful in early design phases, e.g. for very early façade studies, during program placement, or generally during massing or schematic design. Some pointed out that daylighting and energy analyses are skipped at the early phase because they can be complex or designers are unfamiliar with tools that run this kind of analysis. Others thought that the tool would save them time since such concerns (e.g., reducing glare, maximizing useful daylight, balancing energy loads) were common and repeated. In general, they either found the tool useful for (1) getting rapid feedback on ideas before committing to a decision, (2) validating existing ideas they had or flagging problems in them, or (3) pushing forward an idea and showing that due diligence effort was made.

Designer-friendliness. All of our participants had a basic understanding of the physical processes related to energy and daylighting. Still, many were unfamiliar with the specific performance metrics we deploy, such as Daylight Autonomy or Annual Sunlight Exposure. Participants in the study found seeing performance metrics definitions and benchmarking in tooltips beneficial because they allowed them to use the tool without relying on external expertise.

P2: Don't necessarily need a scientist. I think the data was pretty straightforward.

However, some suggested that some coordination with building energy modellers might be necessary to validate the results or have a better understanding of them. Participants also appreciated that they could use the tool without scripting expertise and could see results quickly without much setup.

Adoption. Participants agreed that they could see themselves using the tool or recommending it to others.

P2: Highly recommend it..[to] pretty much anyone else or my team. The efficiency of the software and the amount of data... you can get almost immediately...and that it is easy to use.

The next set of findings is more suggestive and pertain to parametric analysis and design exploration more generally.

Sensitivity analysis. The participants asked if the tool could highlight the parameters with the highest impact on a set of chosen performance metrics. Such analysis is often conducted by building scientists and researchers at the firm using external specialized tools (e.g., JMP, SPSS, Excel), and designers find that it saves them time when they have it. However, conducting such studies takes time on the scientist's part, and there is a small window of opportunity during which they are most beneficial.

Systematic exploration. The trial-and-error interface allows designers to save, retrieve, and compare design variations. However, some participants pointed out that to accurately understand the impact of parameters, they would systematically change one parameter at a time. They also wondered whether the comparison feature (which places a few designs side-by-side) would scale up to comparing more than a few variations.

Performance-based suggestions. Some participants suggested implementing a feature that links walls to their respective impacts on the floor, such as glare. For example, they proposed comparing different design scenarios and identifying the primary causes of glare, enabling designers to prioritize interventions effectively. This would enhance the tool's analytical speed and guide the intervention process for designers.

Performance-based design in the early phases. Finally, many participants agreed that the trial-and-error interface would allow them to consider daylighting and energy earlier than they would typically have. After exploring different scenarios, they can contact the building scientists for deeper and more robust building analysis.

PARAMETRIC ANALYSIS EXTENSION

Based on the study's findings, we propose extending the trial-and-error interface with data visualization and analysis capabilities. With this addition, our approach consists of four major components: (1) parametric exploration and generative design, (2) performance analysis through surrogate models of daylighting and energy loads, (3) data visualization in the form of interactive data visualizations such as parallel coordinates plots and scatterplots and (4) data analysis techniques such as sensitivity analysis, and data clustering.

Through parametric exploration and generative design, designers can systematically sample from the design space and generate new designs on demand (Haymaker et al. 2018; Caetano et al. 2020). Data visualization and analysis techniques can help narrow, organize, and explain the design space to designers (Brown and Mueller 2017) [CH-1]. Surrogate models, as an alternative to dynamic simulations, enable quick generation and analysis of designs (Westermann and Evins 2019; Zorn et al. 2022), which encourages exploration and speeds up the performance assessment of designs [CH-2].

Furthermore, to bridge the expertise gap, we emphasize intuitive interactions and include in-context explanations of performance factors (e.g., daylighting metrics) and analysis results (e.g., parameters' sensitivity) [CH-3]. All the above can be integrated into a single interface implemented into the Rhino3D modelling tool to minimize tool switching and interruptions to designers' workflows [CH-4].

Key System Elements

The following are the key elements of the system we propose.

Combine the trial-and-error with parametric analysis. Both approaches have advantages and can be combined to achieve the best outcomes. Trial-and-error is more familiar to designers and puts them in direct control. However, parametric analysis is more systematic and can unlock efficiencies and opportunities that might be lost through trial and error alone.

Surrogate models. Surrogate models can fit into both approaches to performance-based design, i.e., trial-and-error and systematic exploration, and their approximate but fast results align with the needs of early design phases.

Automated sampling. Automated sampling from the design space is a pre-requirement for systematic exploration, sensitivity analysis, and performance-based suggestions. Sampling becomes faster and more accessible if the generated designs are evaluated through surrogate models of building performance rather than simulations. Furthermore, sampling should happen in the background (whether on the cloud or a separate process) and on demand so as not to interrupt designers' workflows.

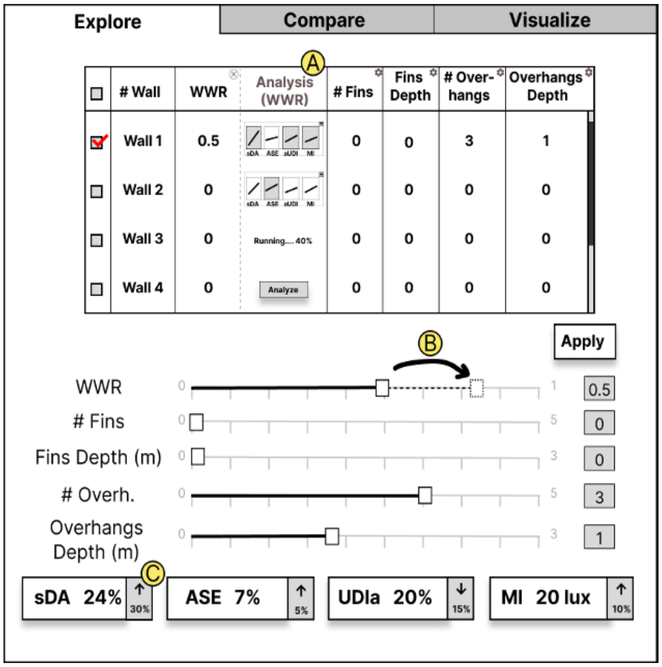
Data visualizations. Data visualizations can be used to quickly compare large numbers of designs and enable designers to systematically narrow and understand the design space and objective space and how they relate. Earlier work on DSE highlighted the need for means of coupling, filtering, grouping, and ranking designs (Chaszar et al. 2016; Matejka et al. 2018; Abu Zuraiq 2020).

Integrated and explainable analysis. Analytical techniques are not commonly part of designers' repertoires, and building analysis may be time-consuming. By relying on surrogate models, parametric analysis techniques such as sensitivity analysis can run quickly in the background. Its results can subsequently be shown to designers in a friendly and contextual manner. For example, correlations between design parameters and performance metrics can be shown on the interface as scented widgets (Willett, Heer, and Agrawala 2007). Finally, the integration of features into one environment keeps designers within their familiar tool ecosystem, whether for design modelling or data analysis.

Give directions. Finally, designers often ask what they could do with the data presented to them when using a performance-based design tool. Providing concrete suggestions, e.g., highlighting walls of highest impact based on the results of sensitivity analysis and contrasting them with benchmarks or building codes, can give them a sense of direction.

Proposed System Design

In this section, we present a few sketches of a proposed parametric analysis extension based on the key system elements we outlined earlier. In the proposed design, designers now choose the walls they wish to change by selecting their respective checkboxes in the top table or directly selecting the walls in the Rhino interface, both of which are synced. After that, designers can adjust the design parameters' sliders and apply the changes once done.



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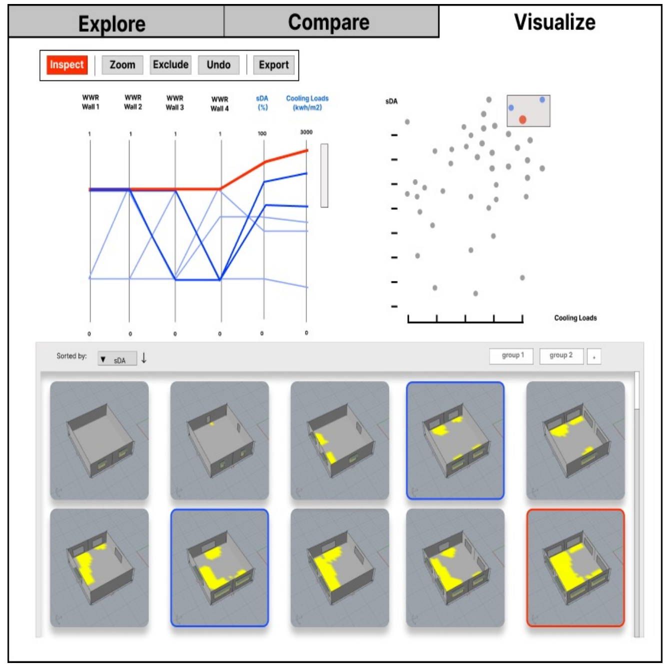

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2 Proposed system for integrated and designer-friendly sensitivity analysis into performance-based design exploration.

3 Data visualizations are provided to help sift through large collections of designs.

The design parameters include WWR values and shading devices' parameters (depth and number of overhangs and fins) for each wall.

Attempting to understand the impact of all design parameters for each wall on each of the metrics requires constructing a massive design space, many parts of which may not be of value to designers. The context surrounding a building, as well as its orientation and geographical location contribute to making certain walls more impactful on the building's performance than others. Designers can utilize this knowledge to ask targeted and contextual questions about the design space and then rely on surrogate models to quickly obtain answers to their questions. In this way, we move from global to local sensitivity analysis (Sedlmair et al. 2014)

To integrate local sensitivity analysis in a lightweight and designer-friendly manner, we propose analysis of specific parameters per wall on demand by opening the analysis panel (Figure 2A) by selecting the clog icon. When analysis is requested, the system samples the minimum, maximum and median values for the chosen design parameter and computes each performance metric. Sampling runs in the background and designers can continue to explore through the trial-and-error approach. When sampling is completed, each sample is evaluated using surrogate models, and a regression analysis of the results is then conducted. The resulting regression line is plotted to indicate how each metric's value changes along with changes to the parameter.

When multiple walls are analyzed - for the same parameter - the wall with the highest slope change for each metric is highlighted (e.g., changing the WWR on Wall 1 results in the highest change to sDA).

Furthermore, when designers attempt to change the value of a design parameter by moving the slider (Figure 2B), the expected change in metrics is computed presented (Figure 2C) using the previously computed regression lines. If multiple walls are selected, the regression lines of the analyzed walls are aggregated. To simplify interactions, only the minimum, maximum and median are computed, but computing more points in between will result in a more accurate regression model. Furthermore, since we rely on fast surrogate models for performance assessment, all the metrics are computed each time a new design is sampled.

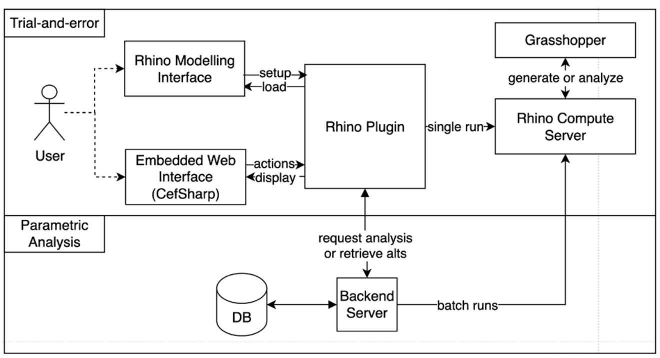
In addition to sensitivity analysis, designers can choose to visualize the already sampled designs by selecting the Visualize option. This allows them to gain an overview of the generated design space through interactive data visualizations, as shown in Figure 3. Furthermore, images of designs are linked to their representations on the charts. Designers can also create groups from designs, zoom on areas of the design space or inspect a specific design of interest, which brings it to the Rhino view, where it could be refined through the trial-and-error interface.

System Architecture

The parametric analysis system we proposed was implemented as a web interface embedded into a Rhino3D plugin, utilizing cloud computation through Rhino Compute and Grasshopper. The trial-and-error interface, initially built as a HumanUI interface, is ported into the same embedded web interface.

DISCUSSION AND CONCLUSIONS

The user study showed rapid and intuitive design capabilities. Participants praised the tool's ease of use and ability to quickly generate and compare design iterations. They appreciated the granular control over specific design elements, such as window-to-wall ratios, which allowed for tailored environmental adaptations. The tool's strength in visualizing performance metrics and facilitating a performance-based design approach was highlighted, making it particularly valuable in early design phases where rapid feedback is crucial. Despite a range of expertise among participants, the tool's user-friendly interface and helpful tooltips made complex performance assessments accessible, suggesting their potential to streamline and enhance

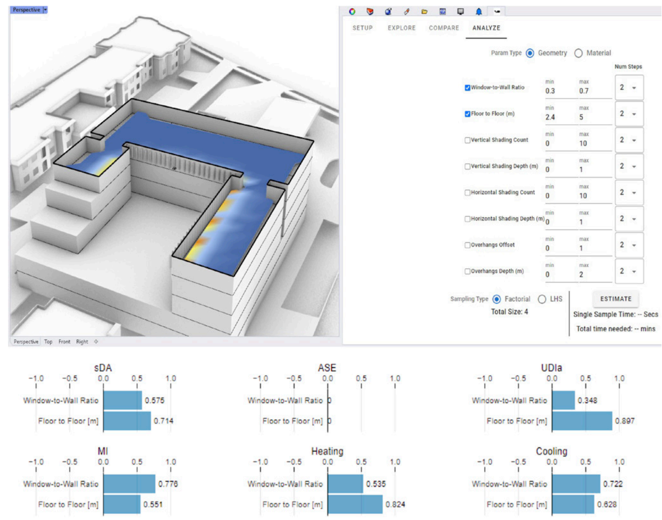


4 The system architecture for a trial-error analysis system. The geometric modelling and Design Analytics interfaces (embedded) provide access to the parametric computation through a Rhino plug-in that communicates with Grasshopper definition (design agnostic) in a Rhino Compute server.

the design process without extensive technical knowledge.

The proposed system capitalizes on surrogate models to enhance the speed at which designs are generated and evaluated. The functional prototype of the interface enables designers to sample designs using Latin Square or factorial generation. By combining fast surrogate models and user-friendly interface design, we proposed an extension to our prior system (Mottaghi 2024b) that makes advanced on-demand parametric analysis accessible to designers (Figure 5). The selected parameter ranges, steps, or sampling choices can be identified before generating design alternatives. Making accelerated evaluation of potential designs possible even before the computationally intense design generation and sensitivity analysis.

In this article, we presented a formal study of a performance-based design tool and proposed a parametric analysis extension informed by the results of that study. In the future, we will continue to develop this tool and conduct a second study to assess whether parametric analysis enhanced the tool's utility for designers without being too complex or overwhelming for them.



5 Design space sampling using various methods to ensure uniqueness of designs generated, prediction of generation time, and sensitivity analysis of design parameters.

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