A User Study on Task-Tool Matching for Simplifying Design Space Exploration in Generative Design

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Abstract. Designers create and evaluate a large set of design alternatives in generative design. Navigating large design spaces presents considerable cognitive and practical challenges, necessitating a new class of tools to manage these alternatives. Interactive data visualizations are integrated into design environments to augment or complement existing tools for applying segmentation strategies, such as simplification. Despite their benefits in filtering and sorting, designers often face difficulties making sense of alternatives due to complex workflows and limited designer-friendly features. This paper identifies opportunities for 'simplification' of design space navigation tasks through task-tool matching by conducting an expert user study using a Design Space Exploration (DSE) tool, DesignSense, which offers advanced features, such as clustering, coordinated views and set operations. We analyzed the data in two levels: task-based and feature (tool)-based. The study's qualitative analysis revealed different flow patterns of interactions with the tool. Based on our findings, we demonstrated enhanced set-based operations extending D-Sense, showing how such patterns of flows can be supported in DSE.

Keywords: Design analytics, data visualization, design space exploration, generative design, simplification through segmentation.

1 Introduction

In architectural design, designers increasingly adopt generative design processes to structure a parametric design space and explore alternatives that may be inaccessible through conventional methods [1]. Navigating design spaces requires systematically assessing each alternative's potential by sorting and filtering spatial and non-spatial data. This cognitively intense task demands a new class of tools: Design Space Exploration (DSE) systems integrating interactive data visualization interfaces. However, a large set of alternatives introduces challenges, as designers must evaluate and organize them based on emerging or predefined criteria such as performance, sustainability, and cost. This task can lead to challenges, even with DSE tools offering advanced filtering, sorting, and selection features by data visualizations.

In this paper, as part of ongoing research, we focused on enhancing DSE interfaces to address this challenge by integrating segmentation features like clustering, coordinated views, and set-based operations. We conducted an expert-user study using DesignSense [2], a DSE tool that offers clustering, set operations, and coordinated visualizations. In this expert user study, we aim to derive the designers' feature use patterns while working with data and form in DSE tools and design guidelines for creating interactive visualizations that support two key concerns: simplification through segmentation (task focus) and segmentation through simplification (tool focus) within the context of DSE interfaces. The goal is to simplify interactions and reduce task complexity—enabling a seamless flow in exploring and evaluating alternatives. We question how DSE tools can better align with designers' workflows. Based on our observations, we compiled a set of tool enhancements and demonstrated them on the extended version of DesignSense [3].

2 Background: A Brief Review of DSE Tools

Scheibehenne et al. [4] emphasize the negative effects of cognitive (choice) overload, where a large set of alternatives can lead to bottlenecks in decision-making. Woods et al. [5] argue that data overload impedes our ability to concentrate on relevant information due to cognitive limitations. Cognitive overload, whether in terms of choice or data, underscores the difficulty of extracting meaningful insights from extensive datasets. In generative design, data overload results in cognitive overload.

The human information processing theory can help reduce the effort required to manage cognitive overload [6]. It explains how cognitive systems handle complex information by 'chunking' [7]. From a tool development perspective, chunking can be understood as 'segmentation,' which divides large amounts of data into meaningful segments (groups or sets) for the designers. At the task level, segmentation involves *abstraction*, *generalization*, and *classification* strategies focusing on relevant information. This process enables individuals to offload cognition to external representations manipulated by multimedia tools, aiding learning and problem-solving [6]. *Abstraction* involves identifying and concentrating on relevant information to simplify tasks and information. *Generalization* facilitates the connection of new information to retrievable knowledge by recognizing patterns and making inferences when encountering new situations. Information is organized into smaller groups through *classification*, which reduces complexity and recall-time in problem-solving and decision-making. These cognitive strategies—*abstraction*, *generalization*, and *classification*—can be supported in new design exploration tools aimed at creating engaging systems as external aids. We contend that such tools might enhance decision-making capabilities when navigating complex data alternatives, preventing feeling overwhelmed by abstraction, integrating new insights with existing ones, and categorizing designs into well-defined groups.

Over the past decade, several Design Space Exploration (DSE) tools have been proposed to support generative design, including Cupid [8], ParaGen [9], Fuchkina et al. [10], D.Star [11], Refinery [12], Design Explorer [13], and DesignSense [2]. Most of these systems merge interactive visualizations of design data with 2D representations or 3D models to varying extents, revealing and filtering the design space, which may aid designers in assessing alternatives both qualitatively and quantitatively. These tools offer data visualizations that may implicitly assist with segmentation. Despite the effectiveness of data visualization, designers frequently encounter cognitive overload due to large sets of alternatives along with their corresponding performance and form data [14,15,16]. Consequently, the question arises: is this overload a result of a mismatch between the task and the provided visualization?

Research has proposed segmentation as a strategy for addressing this challenge, but it has not been widely adopted [2,17]. Proposed approaches include functions like clustering or dimensionality reduction, followed by presenting the results to designers. In this context, segmentation refers to dividing design alternatives into groups of potential solutions with similar characteristics and behaviours determined by data or designers' preferences [16]. Therefore, it involves simplification of the visualizations and functions of the corresponding interfaces supporting the DSE tasks.

The characteristics of systems that support design space exploration through segmentation features can simplify tasks such as selection, clustering, and interaction with design alternatives in sets. Selections and clusters are transient: selections are groups created through interactive visualizations, while clusters are defined algorithmically. Sets are groups stored in a repository for reuse, deferral or backtracking [18]. As a first step, we analyzed eight DSE tools that incorporate clustering and grouping, showcasing results through various visualizations and interactions [19]. This analysis included a systematic review of these tools, drawing information directly from research papers or theses. Guided by two prior studies [15,16], we applied two lenses to define the evaluation criteria for these tools: cognitive-focused (functional category) and interface design-focused (visualization category). These categories served two purposes: first, to identify the most suitable and feasible tool (DesignSense) for our user study, and second, to establish criteria for its evaluation [19].

2.1 Introduction of DesignSense

DesignSense [2] is a visual analytics and DSE tool for navigating design spaces through coordinated views with synchronized selections (Fig. 1). Key features include:

Selection Actions enable users to choose, replace, add interactively, and access alternatives across coordinated views.

2D Scatter Plot displays relationships between two dimensions, with points representing individual designs. Users can select designs by drawing on the plot and adjusting the axes to identify patterns, such as correlations.

Parallel Coordinates Plot (PCP) supports high-dimensional exploration by visualizing parameters along vertical axes. Users can reorder, flip, filter, and select dimensions for varied perspectives.

Augmented Gallery presents thumbnails sorted and resized, filtering to showcase selected alternatives for detailed comparisons across data ranges.

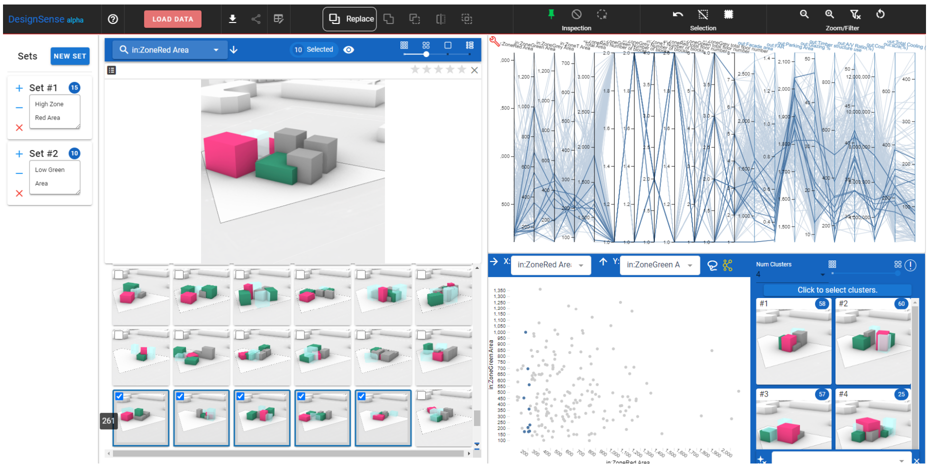

Fig. 1. DesignSense includes coordinated views of design spatial and non-spatial data, offering functions such as set-based operations, Preto Frontier, k-means clustering, and storage and retrieval. The primary visualizations include a scatter plot, a parallel coordinates plot (PCP), and a graphical gallery of design alternatives.

Inspecting Alternatives: Individual alternatives can be examined across views. Enabling “hover mode” provides detailed information of each alternative without clicks, with tooltips on PCP showing precise values.

Overview, Zoom, and Filter: Users can zoom into selections, exclude designs, reset views, or invert selections for focused navigation.

Sets and Operations: Selections are saved as "sets" with optional notes, enabling revisiting or combining them through operations like intersection and addition. Based on criteria, sets can be further intersected, combined, or analyzed.

Sets can also be intersected, combined, or analyzed further based on criteria.

Clustering: Groups similar alternatives based on selected dimensions, providing a structured overview of the design space. Clicking highlights alternatives and operations like intersection or addition, focusing on exploring specific clusters.

3 Methodology

The expert study aimed to evaluate DesignSense and examine user behaviour while exploring large design spaces. We investigated how design space exploration—specifically narrowing and understanding design alternatives—could be enhanced through interactive data visualizations and set-based operations.

The research followed a structured process by the design study methodology [20]. This methodology originated in information visualization and is framed by the "nested model" [21]. It helps researchers identify the types of contributions their research makes. The following describes how our work aligns with this model (Fig. 2).

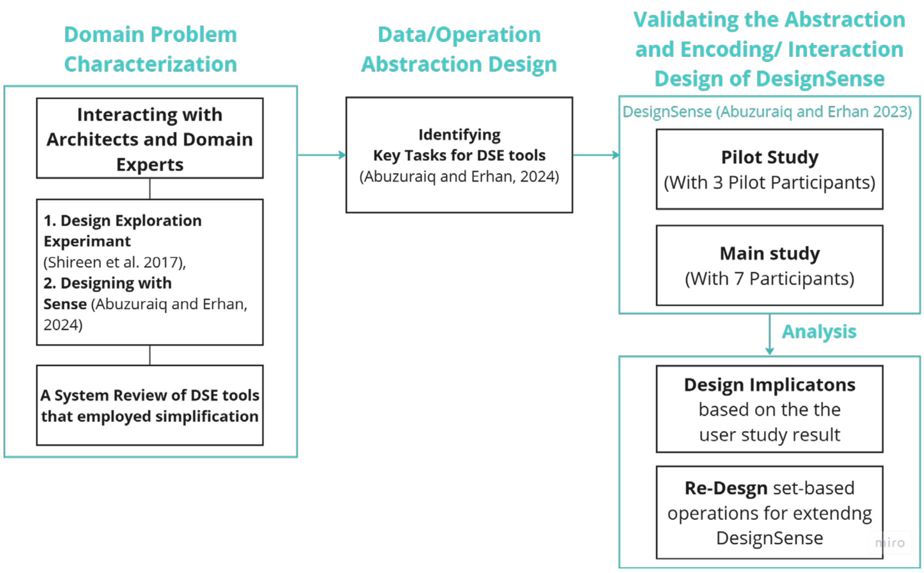

Fig. 2. The research process is based on the Nested Model [21].

The process begins with **domain problem characterization** of Design Space Exploration (DSE). This involved gaining a thorough understanding of the design domain, generative design, and key considerations within this domain. In the context of generative design, we explore how users engage with the generative process. The goal is to narrow down the dataset and the alternatives generated in generative design and understand the design space. This step relied on previous studies, such as those by Shireen et al. [22] and Abuzuraiq and Erhan [2], as well as a critical literature review of DSE tools employing simplification techniques.

The second step, **data abstraction**, translated domain-specific problems into generalized task descriptions, enabling other visualization researchers to interpret and apply these findings. This abstraction revisited key tasks and goals previously identified for DSE tools [2]. With a clear understanding of the domain, Abuzuraiq and Erhan [2] argue that the tools should support the following:

- Goals: Understand, Narrow, Refine, Decide, Communicate.
- Tasks: Relating inputs, outputs, and forms, filtering based on qualitative and quantitative criteria, and externalizing insight (comments, ratings).
- Data: Numeric or categorical inputs and outputs in addition to form data (2D images or 3D geometry), which can be input or output.

The third aspect is **encoding design data on visualizations**, which focuses on how design can be mapped to visual encodings and representations and considers possible interactions with these visual encodings. The goal was to validate the techniques used in DesignSense, ensuring they aligned with task requirements and effectively supported user needs. A study was conducted to evaluate DesignSense as a visual analytics tool, examining its ability to achieve the previously identified goals and tasks while exploring opportunities for segmentation. The key encoding decisions proposed in DesignSense that we evaluated include:

- Coordinated data visualizations: scatterplots, Parallel Coordinates Plots, and image galleries (coordinated on selection and inspection).
- Set-based operations: clustering, Boolean selection, design sets.
- Support features include information navigation (zoom, filter, etc.), a configurable workspace, context menus, and Pareto-frontiers.

The final phase of our methodology involves analyzing the user study findings. This analysis plays a key role in refining the data and visualization task abstractions and the interaction techniques supported by the tool. The results aim to validate and enhance the utility and usability of DesignSense, establish design guidelines for future DSE tools, and propose low-fidelity system improvements to iterate and optimize set-based operations within DesignSense.

4 User Study

This study engaged seven expert participants, including architectural designers and computational design researchers. Among these participants, four were affiliated with the same architectural design firm. Notably, six participants had substantial experience in generative design, while all were proficient computational designers, with three specializing in building performance.

Five participants frequently used data visualizations to analyze building performance, whereas the remaining two did not utilize them as often. Each participant completed the study tasks individually, dedicating an average of approximately 1.5 hours to each session.

We conducted the expert-user study online via the Zoom platform to accommodate our participants' varying locations. The study involved capturing audio, video, and screen recordings. Each participant shared their screen and video while being encouraged to vocalize their actions and thought processes throughout the session. Two researchers facilitated the study: one acted as the interviewer, while the other served as an observer.

4.1 Procedure and Process

Each session started with a brief introduction to the study and an agreement to participate in the study on a consent form confirmed orally in the Zoom session and by email (Fig. 3). A demo and an overview of the interface features followed the introduction. The participants completed a guided exploration of a set of car ad data retrieved from Craigslist, a popular social website. We guided the participants step by step during this part of the study to do the defined tasks.

Following a guided exploration, participants initiated the main task using a dataset derived from a case design scenario. They were tasked with envisioning themselves as architectural design consultants and reviewing 252 facade design alternatives for a high-rise mixed-use building. The solutions were selected based on four key criteria: cost, environmental impact, aesthetics, and functionality.

In the main task section of the study, we specified the tasks participants needed to complete. These tasks were informed by the DesignSense Exploration (DSE) tasks identified by Abuzuraiq and Erhan [2]. They were specifically designed to aid participants in effectively using DesignSense. Comprehensive descriptions of these tasks can be found in [23]. Once the main task was completed, participants were invited to engage in two follow-up surveys: the System Usability Scale (SUS) and the Perceived Utility Survey. An open-ended interview complemented this to gather further insights.

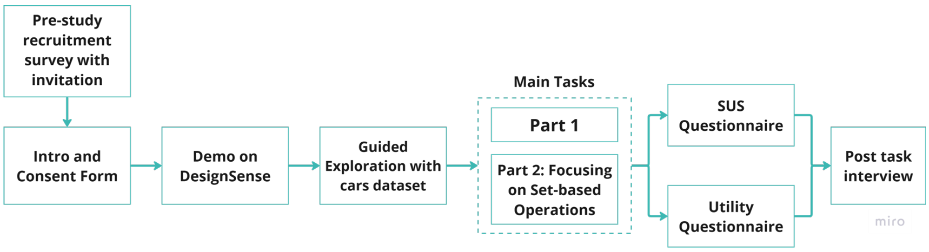

Fig. 3. The expert-user study involved three phases following three pilot studies: (a) introduction of the study and consent completion, (b) task performance, and (c) post-task interview and survey completion.

5 Data analysis

We employed thematic analysis methods to systematically code the collected data [24,25,26,27]. The data were organized into five key categories: responses from the pre-study background questionnaire, notes from initial observations during each session, iterative observations of user interactions—primarily captured from participants' shared screens during Zoom recordings—participants' interview responses recorded via Zoom, and post-task utility and usability surveys.

We used an open-coding method [24] for all categorized data except surveys. This method facilitated the identification of relevant categories. We applied axial coding to enhance further the thematic analysis, which helped refine and organize the identified themes into broader categories through an iterative process [27]. This dual coding approach clarified the relationships between features, tasks, and user feedback. We analyzed and coded the data at task- and feature-based levels during the axial coding phase. This comprehensive analysis allowed us to capture user interactions effectively and the specific features engaged during their tasks. We used MAXQDA [28], a qualitative data analysis software, to efficiently manage and code the data.

5.1 Task-Based Analysis

After coding each participant's exploration process from recordings, interviews and observations, we categorized them based on tasks, steps and participants' interactions with the design alternatives and the tool. The categories focus on understanding how different tasks were performed using the tool, identifying participants' steps to accomplish them, and which feature they used to explore and narrow down (Fig. 4). This approach allowed us to examine user behaviour about specific design exploration tasks, providing insights into the usability and effectiveness of various tool features.

Exploration paths and participant quotes were visualized in diagrams to illustrate navigation through the tool, highlighting decision points, interactions, and transitions between steps. For example, P1 began their design space exploration process by using the PCP view, moving to Gallery, and then narrowing the design space using the scatterplot. P1 was further explored by hovering over the forms in the Gallery, creating sets, and then hovering over them as part of the final decision step.

Table 1. The thematic categories, codes and descriptions from the expert-user study.

Themes	Codes/Steps in each Themes	Description
1. Explore in overview	- Understanding all forms or Scanning forms - See overview of all dimensions - See and understand the relationship between two or more dimensions	Understanding the dataset, variations, and relationships between dimensions to get a broad view of design alternatives.
2. Filter and Sort	- Select or Add Criteria - Filter out - Intersection (Boolean) - Remove/Eliminate/Subtract from selection - Making a new select	Narrowing down alternatives by applying criteria, making selections, using Boolean operations, and refining selections.
3. Focus on Selection	- Zoom into selected (focusing) - Focusing on outliers - Check forms and details (locus of attention) - Hovering or investigating on design alternatives very quickly	Zooming in on specific alternatives, focusing on details and outliers for closer examination.
4. Recall, Revisit, and Review	- Revisit and check forms - Save process in a set - Revisit a set - Comment on sets /annotate - Compare two different sets	Revisiting and reviewing previous selections for further analysis, saving selections and processes into sets and comparing them.

5.2 Results

Each participant's routes include understanding the dataset and narrowing down the design space to identify *satisficing* design alternatives. By trying to relate each step to DSE tasks based on Abuzuraiq and Erhan [2], we aimed to uncover the patterns and strategies employed by participants. We identify four main themes based on the flow diagrams for each participant and relate the observed steps to these tasks. **Error! Reference source not found.** shows these themes, example codes associated with each theme, and their description.

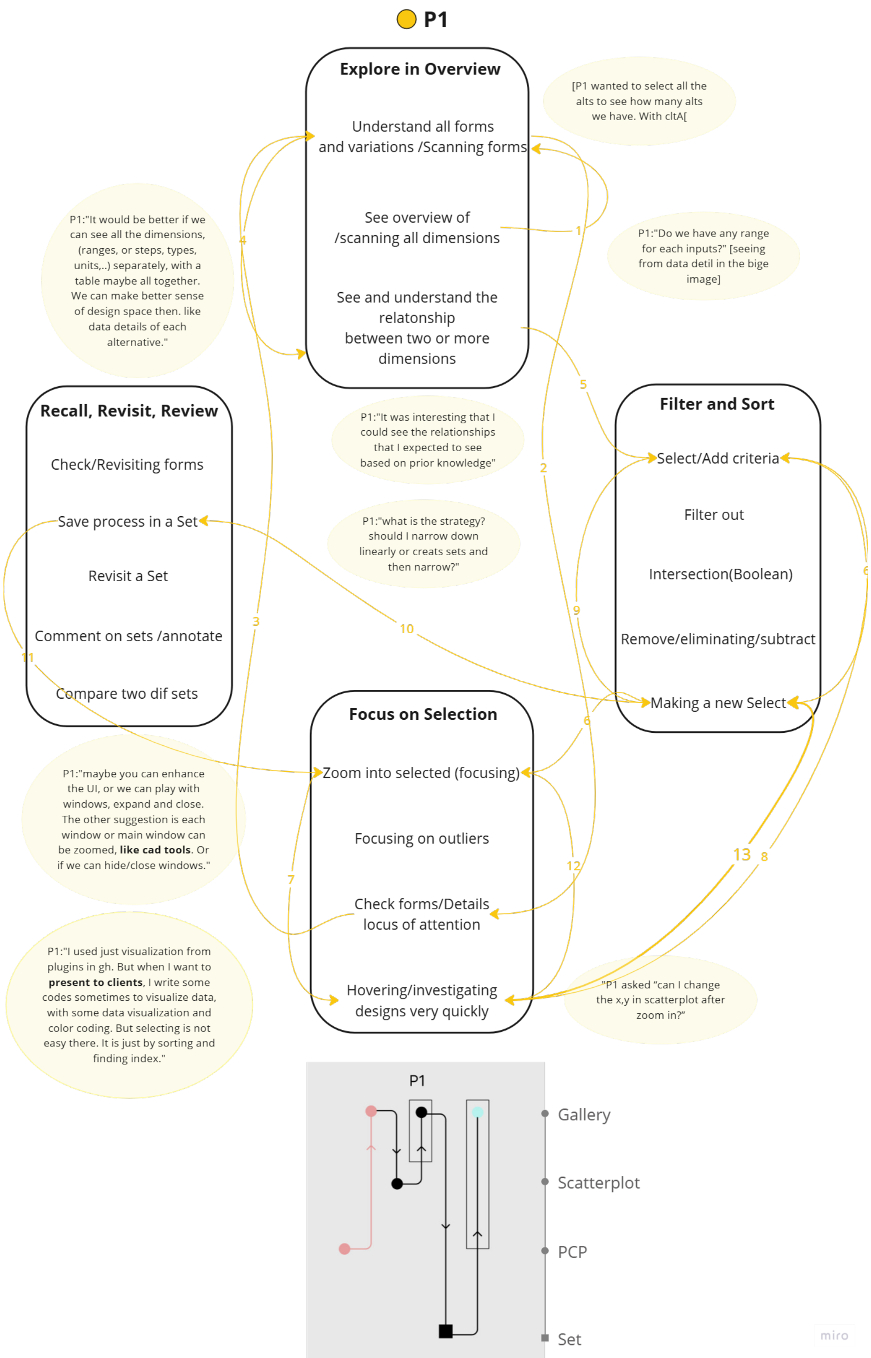

Fig. 4. The tasks and steps that P1 took to explore the design space (understand, narrow and decide) and the features he used during the exploration

Explore in overview

All participants started exploring with an overview of design alternatives. Specifically, most of them started by reviewing and understanding all dimensions (P1-P6). Some participants emphasized the need for features like detailed data tables to comprehend better the design space and relationships between dimensions (P1-P4, P7):

> *P1: " Do we have any range for each input? Also, it would be better if we could see all the dimensions, (ranges, or steps, types, units) separately, with a table maybe all together. We can make a better sense of design space then. like data details of each alternative."*

Filter and Sort

After participants understood the relationships between specific inputs, outputs, and forms, they primarily developed and applied criteria to search for alternatives. This involved selecting, filtering, intersecting, or removing alternatives using the scatterplot or parallel coordinate plot:

> *P6: "I'm trying to understand the data first and gradually applying filters. I'm trying to do is in those sets. Every set is like a step. "*

Participants frequently referenced features familiar with CAD tools, such as window expansion, Boolean selection, and zoom functionalities during this step. This theme highlighted the importance of aligning DesignSense with the existing practices and workflows that designers are already comfortable with. For example, participants were confused when short keys for Boolean operations did not behave as expected, highlighting the need to integrate CAD-like features to improve usability and ease the learning curve.

> *P6: I would like to expand and contract every single piece. Just like Rhino views."*

Focus on selection

In this step, nearly all participants wanted to closely examine the details and forms of their chosen design alternatives by zooming in and hovering over them. They highlighted that the ability to hover and inspect designs was a valuable feature for checking details throughout the exploration process. This aligns with Shneiderman's principle of **details-on-demand** [29], emphasizing the importance of providing detailed information as needed during design exploration.

Some participants highlighted the significance of maintaining an overview of the entire dataset while focusing on specific details. During the 'Focus on Selection' task, many participants lost their context after zooming in and found it challenging to return to a broader perspective. This feedback indicates a need for improved navigation features that enable users to retain an overview while scrutinizing details, helping them preserve a sense of the overall context while concentrating on specific designs.

> *P4: " After zooming in, there is no navigation where we are right now. I had to rely on my memory to remember why I zoomed in to that selection or cluster."*

> *P6: "When I zoomed in, and I lost the sense of context. I would like to have the full picture in the other visualization, for example in scatterplot."*

Recall, Revisit, Review

Participants preferred exploring design alternatives in a non-linear process—much like the design process itself—where they moved between different sets rather than following a sequential path. This approach indicated that DesignSense better supports dynamic, set-based exploration than similar DSE tools. However, their feedback highlighted the need for improved interactions to manage and manipulate these sets, including the ability to save the processes used to achieve the sets and easily recall these processes. For example, participant 6 indicated that:

> *P6: "Set, is like memory. You can create a rout with those. Sets can be anything, cluster, manually created groups. It gives you a sense of navigation. I have a history here at this part of the tool, when I am narrowing down."*

Participants expressed a strong interest in comparing different sets of design alternatives side-by-side. They wanted features that would allow them to quickly see inside sets, compare different sets, and understand the distinctions between them.

> *P2: "Finding how to compare two sets was confusing. I just selected on each and try to see them from anywhere."*

5.3 Feature-Base Analysis

After completing the task-based analysis, we proceeded with a feature-based analysis, systematically coding data derived from participant quotes, challenges, and feedback for each feature. We examined the features within three main categories—"Coordinated Data Visualization," "Support Features," and "Set-Based Operations." These categories exposed patterns and themes rooted in participant interactions, feedback, and the usability challenges and benefits encountered.

Participants appreciated the set-based operations but found managing multiple sets cumbersome. Boolean operations were useful but needed more intuitive access. The clustering feature, although effective, lacked transparency, making it difficult for participants to understand how clusters were generated. Participants experienced frustration when working with design data, citing difficulties tracking exploration steps and interacting with sets. Recommendations included colour coding for clarity and better access to parameters to reduce confusion.

6 Post-Task Survey Studies: Feedback

To assess the utility and usability of DesignSense, in addition to the main tasks, we also conducted post-task surveys focusing on two key aspects: Utility and the System Usability Scale (SUS) [30]. These surveys were enhanced by insights gathered from post-task interviews, centering on participants' satisfaction with its features and ease of use. Key findings revealed high satisfaction with tools such as the scatterplot, image gallery, and clustering, while the ability to reduce bias when identifying relationships between parameters received lower scores, indicating areas for improvement. The SUS provided a moderate usability score (68%), with participants generally finding the tool intuitive and well-integrated, though some acknowledged a learning curve. These insights underscore DesignSense's strengths in facilitating design exploration and pinpointing areas for further enhancement (See 4.4 [23]).

7 Findings

Based on the user study results, we compiled a set of design implications addressing the challenges and requirements identified by participants, which are closely related to selection, cluster, and set concepts. Building on the study findings, we developed enhanced set-based operations extending DesignSense, illustrating how these interaction patterns observed in the user study can be effectively supported with new interface designs. The following presents each design implication, demonstrating enhanced set-based operations extending DesignSense (Fig. 1). The prototype also guides future feature development in DSE systems (Fig. 5).

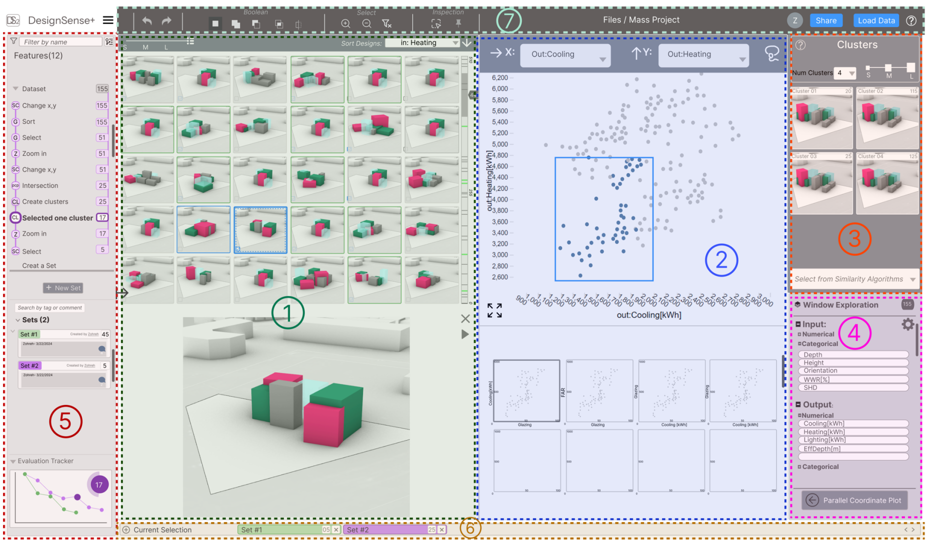

Fig. 5. Proposed interface: 1. Gallery Thumbnail (form view), 2. Scatterplots and SPLOMs, 3. Clusters, 4. Dimensions, 5. Set Evolution Tracker, 6. Different Tabs for Exploration, 7. Filter, Undo/Redo, Boolean Operations, Zoom in/out and Inspection [3].

7.1 Provenance Recording Backtracking

Based on the user study, experts highlighted the need to revisit and visually compare sets. Participants noted that sets served as both a memory aid and a representation of the design process. A provenance-based approach supports reflection on past decisions and exploring new possibilities [18,31,32] by enabling designers to backtrack and reconsider alternatives at any stage. We propose incorporating a provenance recording for set-based operations to enhance exploration and facilitate more informed decisions (Fig. 6). This feature will allow users to use sets and the features used to create them as navigable history. Provenance recording enables users to track the sequence of user interactions and store them in sets as a history that can allow users to recall, revisit, and review [32] operations leading to the creation of each set, allowing them to see not only the resulting sets but also how they were formed. It should also support a visual comparison of sets, allowing designers to analyze creation paths and evaluate design evolution more effectively.

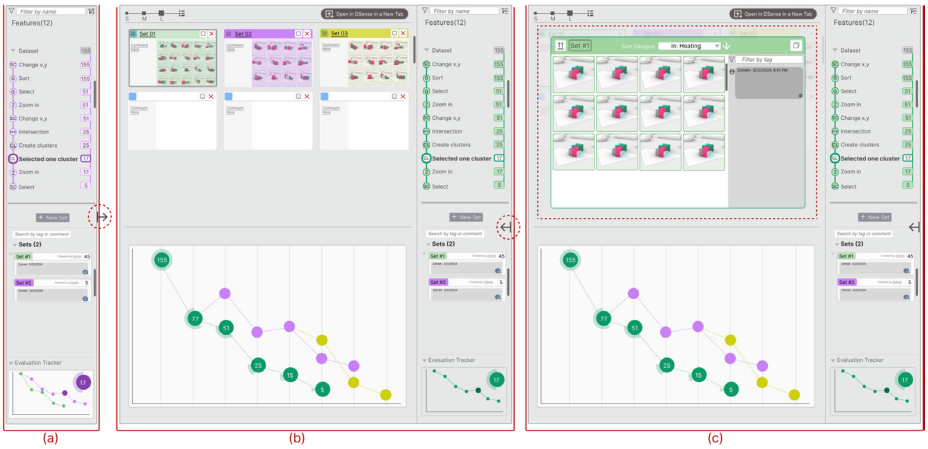

Fig. 6. Set tracker and features of narrowing for each set. (a) Set Tracker Side Bar, (b) Expanding Set Tracker Window, (c) Expanded View of Sets [3].

7.2 Create and Manage Clusters Transparently

The user study revealed the need for greater control over clustering process. Participants wanted the ability to view and manage all input and output dimensions used for clustering and scatterplots more easily. Also, understanding the clustering process was challenging. To address this, they suggested integrating simple visualizations to make clustering more transparent and intuitive. Also, adding different similarity metrics and clustering algorithms to cluster designs enables more control over clustering [19].

7.3 Overview and Check Details

Participants emphasized the need for both a high-level overview and detailed exploration. This dual approach helps users grasp the broader dataset while examining specific details as needed. DesignSense supports this by allowing users to hover over alternatives to view details. However, they also wanted to see all dimensions, their ranges, and the ability to define and normalize ranges for each dimension.

7.4 Natural Mapping to Familiar Tools

Based on the study, designers tend to use interactions similar to those of CAD tools. In line with natural mapping [33], users rely on mental models shaped by their experience with CAD and data visualization tools. Designing the system to align with these models enables users to leverage existing knowledge, reducing learning time and minimizing cognitive load. This approach makes the tool more intuitive and manageable.

8 Limitations

The small sample size (n = 7) limits the generalizability of the findings to a broader population of architects and designers. While qualitative research often focuses on depth, the limited participant pool may not fully represent the diversity of workflows and preferences in design practice. Additionally, varying familiarity with generative and parametric design tools could have influenced results. Future research should involve a larger, more diverse sample to validate these findings and reduce biases related to prior tool exposure.

Second, the expert user study is limited to one DSE tool in a short time. We can add more tools to see different patterns. The third limitation is the dataset and case study scenario of this project. The scope of the case study may encompass broader design issues, incorporating real projects utilized by a firm.

9 Conclusion

This paper addresses the challenges designers face in managing and navigating large-design spaces generated through generative design processes. We conducted an expert-user study to explore how DSE interfaces could support designers in overcoming choice overload by employing simplification techniques, specifically through interactive data visualizations, clustering, and set-based operations. Using DesignSense as a visual analytics tool, we evaluated the tool's utility and usability, focusing on simplifying features like clustering and set-based operations. The results indicate that simplification in DSE through these features can effectively support designers' workflows. Specifically, the qualitative analysis revealed different exploration patterns where participants reviewed, recalled, and retrieved design alternatives within selections, clusters, and sets. The findings indicate that simplification through task-tool alignment—matching interface features to designers' navigation tasks—can significantly reduce cognitive load and improve ease of navigation. By enabling designers to interactively select, algorithmically cluster, and organize design alternatives into persistent sets, DSE tools can support a systematic and data-informed exploration of large design spaces.

The study also demonstrates the importance of interactive selection and coordinated views for navigation. While selections and clusters are transient and help with quick exploration, persistent sets capture criteria groups and provide an organized structure for revisiting and refining choices. Based on these observations, a low-fidelity prototype was developed to illustrate how these simplification recommendations could be practically implemented, enhancing the effectiveness of set-based operations in DSE and extending DesignSense's usability and utility.

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