Simplification of Design Space Exploration

Enhancing generative design by clustering and set-based operations

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Abstract. Generative design processes help architects explore a large set of design alternatives while ensuring they meet specific requirements, constraints, and preferences. This task can be complex and requires new tools that improve the design environment. Even with these tools, designers often face cognitive overload due to inadequate filtering and sorting features that fall short of supporting their tasks. This study explores new tool features that simplify design exploration by integrating segmentation strategies to simplify navigating, understanding, and evaluating design alternatives. Building on a literature review, we conducted a user study following a think-aloud protocol analysis. Participants engaged with DesignSense, a design-space exploration system with extensive features, to identify potential alternatives among more than 250 while justifying their choices. Considering the participants' work with the alternatives, we investigated how well the tool features align with user tasks. Our findings led to employing set-based operations enabled through design analytics interfaces to enhance support for evaluating design alternatives. We outlined design guidelines for the interfaces to simplify design space exploration as one of its main contributions.

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

1. Introduction

Generative design methods enable the rapid generation of a vast set of design alternatives, often exceeding the scope of traditional workflows. Design Space Exploration (DSE) systems are increasingly used to help designers navigate alternatives through generative design methods. 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. This paper focuses on enhancing DSE interfaces to address these challenges by integrating segmentation features like clustering, coordinated views, and

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set-based operations. We investigated how interactive visualizations and set-based operations can effectively support DSE tasks to explore, group, and narrow down design alternatives. We question how tools can better align with designers' workflows.

We conducted an expert-user study using DesignSense, a DSE tool that offers clustering, set operations, and coordinated visualizations. Compared to other tools, DesignSense is relatively well-equipped for investigating how effectively the features proposed in the literature support core DSE tasks. The findings indicate challenges related to usability, cognitive load, and task flow. Based on our observations, we compiled a set of tool enhancements and demonstrated them on the extended version of DesignSense. Our goal is to simplify interactions and reduce task complexity—enabling a seamless flow in exploring and evaluating alternatives.

2. Background: A brief review of earlier tools for supporting DSE tasks

Scheibehenne et al. (2010) emphasize the detrimental effects of cognitive (choice) overload, where an abundance of alternatives can lead to bottlenecks in decision-making. Woods et al. (2002) argue that data overload hinders our ability to focus on relevant information due to cognitive limitations. Cognitive overload (as choice or data) highlights the difficulty in discerning meaningful information within large datasets. In the generative design, data overload causes cognitive overload.

The human information processing theory can guide reducing the effort in handling cognitive overload (Simon, 1978). It explains how cognitive systems manage complex information by ‘chunking’ (Chase and Simon, 1980). From a tool development perspective, chunking can be interpreted as ‘segmentation,’ which breaks a large amount of data into segments (groups or sets) in some meaningful ‘chunks’ to the designers. At the task level, segmentation involves abstraction, generalization, and classification strategies for focusing on relevant information. It allows individuals to offload cognition to the externalized representations manipulated by external tools, such as multimedia, for learning and problem-solving (Simon, 1978). Abstraction is about identifying and focusing on relevant information to reduce the complexity of the task and information. Generalization helps associate new information with retrievable knowledge by recognizing patterns and making inferences when faced with new situations. Information is structured in smaller groups through classification to reduce 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 for creating engaging systems as external tools. We argue that such tools may augment the ability to make decisions when navigating alternatives with complex data without feeling overwhelmed by abstraction, connecting new insights to existing ones, and sorting designs into well-defined categories.

Several DSE tools have been proposed to support generative design over the last decade, such as Cupid (Beham et al. 2014), ParaGen (Chaszar et al. 2016), Fuchkina et al. (2018), D.Star (Mohiuddin and Woodbury 2020), Refinery (Autodesk, 2024), Design Explorer (CORE Studio, 2024), and DesignSense (Abuzuraiq and Erhan 2020). Most of these systems combine interactive visualizations of design data with 2D representations or 3D models in varying degrees of coupling to reveal and filter the design space, which may help designers assess alternatives qualitatively and quantitatively. These tools provide data visualizations, which may implicitly support segmentation. However, despite the effectiveness of data visualization, designers often face cognitive overload due to large sets of alternatives and their corresponding performance and form data (Erhan et al., 2014; Erhan et al., 2017; Shireen et al., 2019). Therefore, the question arises as to whether this is due to the mismatch between the task and the provided visualization.

To address this challenge, segmentation as a strategy has been proposed in research but has not been widely adopted (Abuzuraiq & Erhan, 2020; Abuzuraiq & Erhan, 2024). Proposed approaches include functions like clustering or dimensionality reduction, followed by presentation of 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 (Shireen et al., 2019). Therefore, it involves simplification of the visualizations and functions of the corresponding interfaces supporting the DSE tasks.

The characteristics of systems that support DSE 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 (Sanchez and Erhan, 2014). As a first step, we analyzed eight DSE tools that incorporate clustering and grouping, showcasing results through various visualizations and interactions (Hassanpour Kahnamouei et al., 2024). This analysis included a systematic review of these tools, drawing information directly from research papers or theses. Guided by two prior studies (Shireen et al., 2019; Abuzuraiq and Erhan, 2020), 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.

3. Introduction of DesignSense

DesignSense is a visual analytics system and DSE tool for navigating and exploring design spaces through coordinated views linked by synchronized selections (Figure 1). Its main features include:

Selection Actions: Users interactively choose, replace, add, and access alternatives across all coordinated views.

2D Scatter Plot: Users can display 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): This tool supports high-dimensional exploration by visualizing parameters on vertical axes. Users can reorder, flip, filter, and select dimensions for varied perspectives.

Augmented Gallery: The gallery displays thumbnails sorted and resized as needed. It filters to show selected alternatives, enabling detailed comparisons across data ranges.

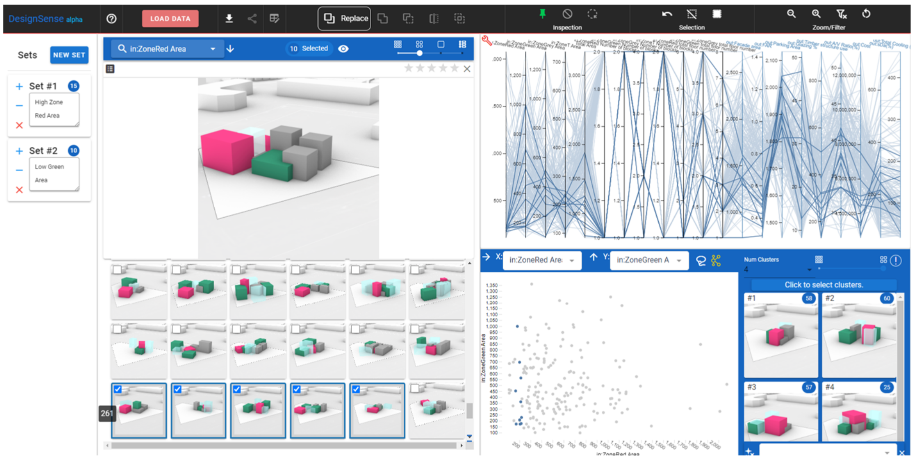

Figure 1. DesignSense includes coordinated views of design spatial and non-spatial data, offering functions such as set-based operations, Preto Frontier, k-means clustering, and storage and retrieval.

Inspecting Alternatives: Users can examine individual alternatives from various views. Enabling "hover mode" offers detailed information on selected alternatives without the need for clicks, with tooltips on PCP displaying precise values.

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

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

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

Clustering: Users group (e.g., similar) alternatives based on selected dimensions, providing a structured overview of the design space. Users choose clustering dimensions, and thumbnails represent clusters. Clicking highlights alternatives and operations like intersection or addition, focusing on exploring specific clusters.

4. Expert-user study to review tool-task matching

We conducted an expert user study to explore how DesignSense supports core DSE tasks and identify areas for improving usability and cognitive load. DesignSense offers clustering, coordinated views, and set operations, positioning it as a tool for evaluating task-tool alignment in DSE. The study involved seven expert participants—generative designers and computational researchers—who used the tool through structured tasks aligned with key DSE activities such as filtering, clustering, and set creation. The user study examined the effectiveness and usability of segmentation features in DesignSense, focusing on how they simplify DSE and support engagement with alternatives and designers' segmentation patterns while navigating data and forms.

The study employed a think-aloud protocol in which participants articulated their thought processes while exploring alternatives. The tasks were based on DSE tasks outlined by Abuzuraiq and Erhan (2024) to engage with design alternatives in

DesignSense. Participants envisioned themselves as architectural consultants selecting solutions from 252 design alternatives in a design case scenario. Following the tasks, a post-task interview and System Usability and Utility Surveys were conducted, yielding qualitative and quantitative data.

4.1. DATA ANALYSIS

We used thematic analysis through axial coding to uncover essential patterns of interaction and challenges. Our analysis involved coding the data on task-oriented and feature-oriented levels to enable us to track interaction flows and the specific features the users interacted with. We identified, examined and reported patterns in the qualitative data. We employed axial analysis to systematically organize and refine the identified themes into broader categories to enhance the thematic analysis, thereby elucidating the relationships among various features, tasks, and user feedback.

Task-Based Analysis. After coding each participant's exploration process, we categorized tasks, steps, and interactions with the alternatives and tools. This approach allowed us to examine user behaviour regarding specific exploration tasks and provide insights into the effectiveness of various features. Participants followed a four-step exploration flow: starting with an overview of the alternatives, then filtering and sorting, selecting among them, and finally revisiting sets and clusters for comparison.

Feature-Base Analysis. Following the task-based analysis, we conducted a feature-based analysis, coding data from participant quotes, challenges, and suggestions regarding each feature. 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.

4.2. FINDINGS

Through thematic and qualitative analysis, we compiled a set of design implications derived directly from the challenges and enhancements noted by participants. Figure 2 illustrates these implications and their relation to domain tasks. Each domain task is related to one design implication, except for Boolean operations, which are universal when working with selections, clusters, and sets. The following presents each design implication, describing the visual encoding decision. In visual encoding descriptions, we demonstrated enhanced set-based operations extending DesignSense (Figure 3). The prototype also serves as a guide for new features in DSE systems, including redesigning DesignSense, which aims to improve its usability and utility while addressing the issues identified in the study.

4.3. PROVENANCE RECORDING BACKTRACKING

Participants emphasized the importance of revisiting previously created sets and visually comparing them. They noted that sets served as both a memory aid and a representation of the design process. This design implication highlights the broader impact of incorporating navigable history in design sets.

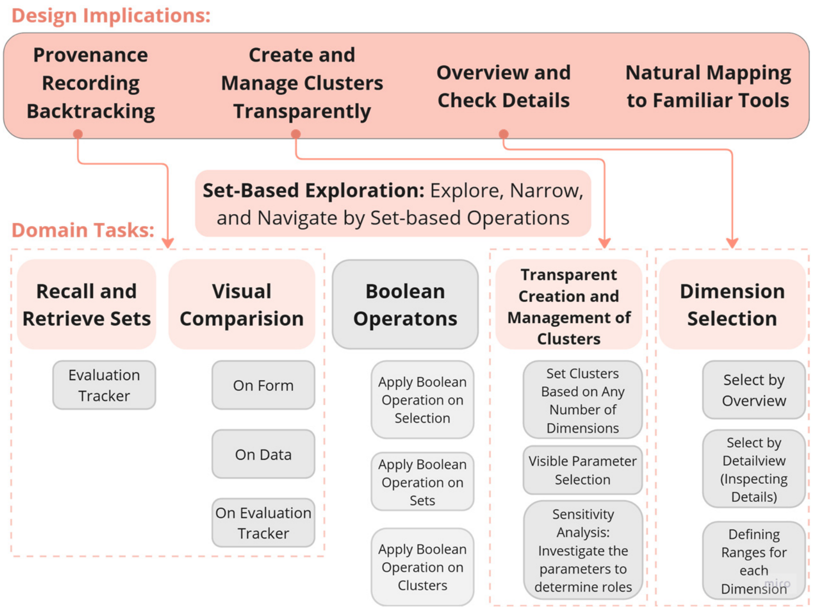

Figure 2. Design Implications and their related domain tasks.

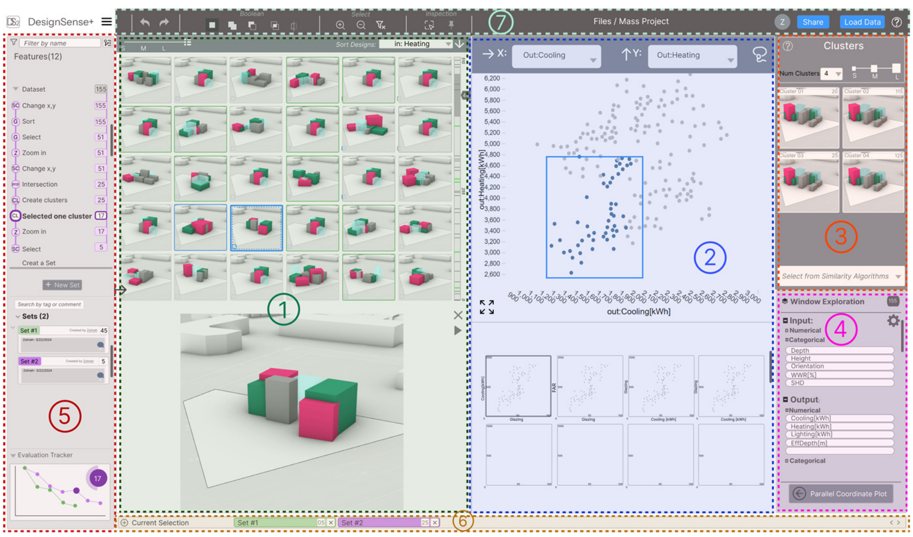

Figure 3. Proposed interface: 1. Gallery Thumbnail (form view), 2. Scatterplots and SPLOMs, 3. Clusters, 4. Dimensions, 5. Set Evolution Tracker, 6. Different Tabs for Exploration, 7. Operations like Filter, Undo/Redo, Boolean Operations, Zoom in/out and Inspection.

A provenance-based approach supports not only a reflection on past decisions but also an exploration of new possibilities (Heer et al., 2008; Sanchez & Erhan, 2014; El Meseery et al., 2018) by enabling to backtrack and reconsider alternatives at any stage of the process. We propose incorporating a provenance recording for set-based operations to enhance exploration and facilitate informed decisions. This feature will allow users to use sets, and the features used to create them as a navigable history. The provenance recording enables users to track the sequence of user interactions and store them in sets as a history that allows users to recall, revisit, and review (El Meseery et al., 2018) operations leading to creating each set.

4.3.1. VE1: Set-Based Exploration

The core structures are selections, clusters, and sets, each playing a distinct role in supporting exploration. Selections are transient views of designs, enabling users to explore and filter alternatives interactively. Clusters are algorithmically created based on parameters, offering aggregation within the workspace. Sets, in contrast, serve as a persistent repository for storing selections or clusters for further iteration in sets. We suggest selections and clusters in the active workspace for uninterrupted flow. Sets are managed in a dedicated interface for tracking decisions and iterative exploration.

The set tracker sidebar (Figure 4) displays the steps taken to create each set, including actions like "select," "zoom in/out," Boolean operations (intersection, add, subtract, toggle), "create clusters," and "select clusters." Steps are labelled by location: SC for scatterplot, G for gallery, and PCP for parallel coordinate plot. Zoom actions, applicable across all views, are marked "Z." Numbers beside each step indicate the number of alternatives in the set at that step. Hovering over a step reveals the number of selected designs. Selecting "New Set" creates a set with the selected content and saves all steps as history. Users can view or search specific steps by name or location and highlight them in the list.

The visual evolution tracker connects to the set steps list, enabling users to backtrack through a history timeline or visual trail that records each step, including set modifications and filters. This feature enhances transparency and allows users to revisit actions. The expandable set evolution section provides detailed information, with distinct colours highlighting sets for visibility. Users can also view a detailed tracker showing set branches and the number of selected alternatives at each step (Figure 4).

Users can perform Boolean operations on sets, selections, and clusters in the expanded tracker view. They can brush or select alternatives and apply Boolean operations (add, intersect, subtract) via a right-click menu, as in interactive dendrograms. The side view allows users to expand sets into a gallery view, where designs appear as thumbnails for sorting and exploration based on criteria or metrics. The layout integrates seamlessly with DesignSense's data views, enabling easy navigation between design forms and associated data.

The new version supports real-time collaboration, letting multiple users comment on sets in a shared exploration document. Users can add, reply to, and view comments in both expanded and non-expanded views, fostering insight sharing. To further enhance set-based exploration, the system now supports hierarchical sets and the ability to merge sets. Hierarchical sets organize sets into multi-level structures, where higher-level sets encompass categorized subsets. This hierarchical organization clarifies relationships among sets, enabling efficient exploration and comparison of complex design spaces while maintaining an intuitive workflow.

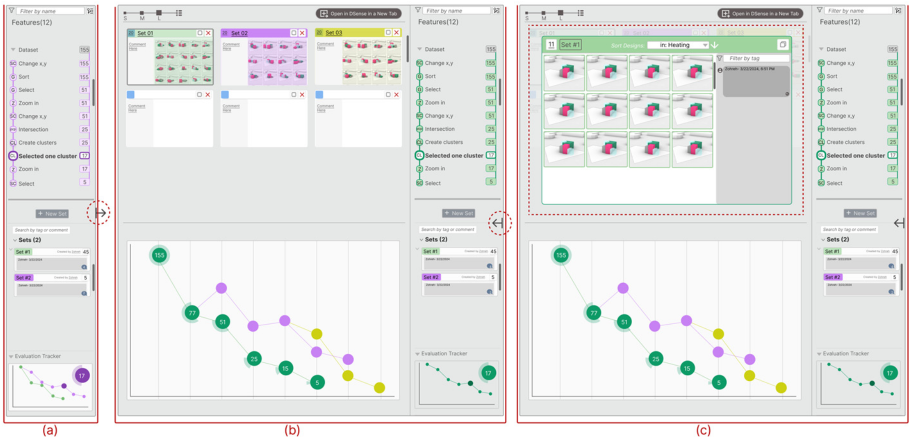

Figure 4. Set tracker and features of narrowing for each set. (a) Set Tracker Side Bar, (b) Expanding Set Tracker Window, (c) Expanded View of Sets.

4.3.2. VE2: Set and selection comparison in Separate Analysis Paths

Based on provenance recording and backtracking, the second visual encoding decision is the ability to open sets and selections in separate analysis paths. Users can explore design spaces in separate tabs to compare and analyze various selections and scenarios without losing context or workflow progress. They can also open sets in different. When sets are converted into new tabs, the evolution tracker is displayed for each set to compare different sets' evolution. As discussed in the literature review, exploring in separate tabs allows users to manage distinct, independent workspaces and paths (El Meseery et al., 2018; Huang & White, 2010). Also, this feature helps users visualize the progression of each set and facilitates comparison by showing the steps taken and the changes made across multiple sets in a unified view.

4.4. CREATE AND MANAGE CLUSTERS TRANSPARENTLY

The second design implication derived from the user study focuses on clustering. Some participants expressed a desire for more control over the clustering process. They wanted the ability to view and manage all input and output dimensions used for clustering and scatterplots more easily. Additionally, understanding the clustering process was challenging for some participants. To address this, they suggested integrating simple visualizations to make clustering more transparent and intuitive.

4.5. OVERVIEW AND CHECK DETAILS

The third design implication emphasizes providing a high-level overview while enabling detailed exploration. Participants sought a summary view of the dataset and the ability to examine detailed information as needed. To address this, DesignSense allows users to hover over design alternatives to view corresponding details. For overviews, participants requested visibility of all dimensions and their ranges and the ability to define and normalize these ranges.

Previously, clusters were algorithmically created (e.g., K-Means). Participants found this unclear due to hidden logic. A dedicated "Dimensions" section was introduced to improve transparency and control, allowing users to view and manage selected metrics. The "Dimensions" section enables users to define target ranges, normalize data, and choose similarity metrics that align with their preferences. The study also showed that participants rarely used the scatterplot and parallel coordinate plot (PCP) together, with most using PCP only to explore dimensions. In response, we introduced Scatterplot Matrices (SPLOMs) as the default view, with PCP as a detail-on-demand view. SPLOMs dynamically display multiple scatterplots for selected dimensions, providing clarity and transparency when creating clusters across multiple parameters.

4.6. 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 (Norman, 1988), users bring mental models shaped by their experience with CAD and data visualization tools. Reflecting these models in the system design leverages existing skills, reducing learning time and cognitive load, making the tool more intuitive and easier to learn and adopt.

5. Conclusion

This paper discusses the challenges designers face in navigating and managing large design spaces, focusing on the role of simplification techniques in DSE. We analyzed existing DSE tools and conducted a user study with DesignSense as an example design analytics tool. We investigated how clustering, set-based operations, and interactive data visualizations can alleviate choice overload.

The findings demonstrate that simplification techniques, particularly task-tool alignment, may support designers' workflows by reducing cognitive load and enhancing navigation. Participants in the study employed exploration patterns involving the review, recall, and organization of design alternatives within clusters, sets, and selections. While transient clusters and selections facilitated quick exploration, persistent sets provided an organized structure for revisiting and refining choices, supporting systematic and data-informed design exploration. Based on the findings, a low-fidelity prototype was developed, illustrating how these simplification recommendations could be implemented to enhance the usability and utility of DSE tools like DesignSense. The limitations include the small group of specialized participants, using one tool, and relying on a predefined dataset. Future research could expand these findings by including diverse participants, evaluating multiple tools, and utilizing real-world generative design datasets to address broader design concerns.

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