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Designer-Centric Spatial Design Support

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A R T I C L E I N F O

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A B S T R A C T

Design-centric systems focus on searching or generating design alternatives using design retrieval or generation algorithms. Conversely, designer-centric systems focus on providing design feedback to refine design ideas through interactions with designers when creating design alternatives. This paper proposes a novel designer-centric design support system that analyzes user design moves and provides real-time feedback to augment the spatial design exploration process. Specifically, we developed a system that integrated sketching, design retrieval, and feedback features for tablet PCs. The user experiments involving 21 professional spatial designers verified that the proposed system helped users interact with their designs, navigate novel design spaces, reevaluate design moves, and embody design ideas. These findings provided implications for developing an interactive design exploration method for coordinating designers and computers, thereby extending design support system research. Further, we discuss applications and challenges in implementing the system on the web, revealing possibilities for data trailing of design moves.

1. Introduction

Spatial designers resolve complicated problems related to the user's perspective [45], floor plans [46], and wayfinding [42]. Overall, spatial design projects are conducted based on plan views by defining the spatial relationships between information, such as the number of rooms, floor silhouette, and room connectivity [33,50]. Thus, designers often focus on exploring floor plan design options in the early stages of design [13]. Designers constantly redesign and redefine floor plan design information throughout the design process to meet the client's needs. Hence, in the design process, spatial designers commonly develop design ideas with uncertainty [1]. To overcome this drawback, researchers have developed design support systems to assist spatial designers. Specifically, design support systems aid designers in a design-centric manner. Design-centric systems focus on searching or generating design alternatives using design retrieval or generation algorithms. For example, designer-centric systems manage and store designers' ideas [22], providing design references through a retrieval function [33,50], or generating various design alternatives through design rules [21,38] and artificial intelligence (AI) algorithms [13,36]. Using this design-centric system, designers can focus on selecting and using the design alternatives provided by the system.

In contrast, a designer-centric system focuses on providing design feedback to refine design ideas through interactions with designers in the design process. Providing design feedback regarding design ideas is essential for the design process. Design feedback plays an important role in identifying design problems and improving design outcomes by helping designers understand their current design status while considering other design variations [39]. Several designer-centric systems that provide design feedback have been proposed. For example, GUIComp [34] provides real-time design feedback by comparing the user's work on GUI sketches with GUI references. FreeD V2 [57] is a designer-centric system that provides real-time sculpting-direction feedback based on the target shape. Similarly, in the spatial design field, Eisenstadt and Althoff proposed MetisCBR [15], which calculated feedback for the next design step by analyzing the user's design action pattern using recurrent neural networks. The users of these systems developed design ideas by deciding whether to accept or reject design feedback. In contrast to a design-centric approach, a designer-centric system can help develop design ideas by stimulating designers thinking through feedback-based interactions.

However, designer-centric systems suffer from two limitations. First, they do not provide feedback regarding any problems that may occur during the design process. The feedback mechanisms of these systems do not consider the relationship between the design ideas created during the design process. Thus, they cannot analyze the design processes based on the design ideas. This means that it is difficult to identify and provide feedback on the design process problems at micro level. Second, these

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systems do not support design exploration or guide designers to a novel design space for generating creative design ideas. In these systems, to explore new design spaces, designers must create and explore new ideas without any assistance from the system. Thus, the latest designer-centric systems do not support the design exploration process for generating novel designs at macro level.

In the design process, ideas are developed over a series of design decisions, also known as "design moves" [18]. Some design moves are minimal and supportive, whereas others are critical or inspirational. Understanding how this type of thought process influences design moves and final designs can help designers think about inspirational ideas, thereby improving their designs. Moreover, inspirational ideas result in creative design processes. Thus, documenting and analyzing how designers think and create ideas is essential for identifying critical or inspirational design moves. Additionally, to gain inspiration and establish a creative design process, it is crucial to explore novel design areas. The newly proposed designer-centric system should consider these two limitations. If these limitations are resolved, it is possible to provide real-time feedback on the design process and allow improved coordination between designers and computers for exploring novel design areas.

In this context, our research aims to propose a novel designer-centric system that can stimulate and encourage designers in the creative design process through inspirational real-time design feedback and a design exploration map. We focused our research on developing a novel designer-centric system considering the following two research questions: RQ1) Can we provide inspirational real-time design feedback based on analyzing design ideas from users? RQ2) If so, based on this feedback, can we enable the design exploration process to influence the design direction of users (idea selection, satisfaction with ideas)? If both are possible, the designer will be able to modify the design move and direction based on the feedback, and the system will provide feedback based on the newly updated design direction. Through this interaction, the system can assist designers with inspirational design ideas and creative design processes.

Therefore, we introduce a designer-centric spatial design support system (D-SDSS) that analyzes user design moves and enables an inspirational design exploration process, thereby facilitating creative design with better informed design decisions. D-SDSS includes sketching, design retrieval, and feedback features for tablet PCs. Further, design feedback is provided in the form of detailed design evaluations (i.e., micro-feedback) and design exploration maps (i.e., macro-feedback) for user-sketched designs (Fig. 1). To this end, we performed five tasks.

- A tablet PC-based interactive system was developed to increase designer accessibility.
- A large-scale design reference database (2101 floor plans) was developed.
- A novel method was developed to measure and analyze design moves quantitatively.
- Methods of two types of feedback (micro and macro) were developed for the creative design process.
- The impact of the developed system was verified through user experiments with 21 professional spatial designers.

2. Related work

2.1. Spatial design support system

In the spatial design process, computer systems support designers in various ways. The electronic cocktail napkin system [22] supports the design process to create and explore various design ideas by storing and managing spatial diagram sketches with diagram analyses. Next, based on case-based reasoning, the a.SCatch [33] and FPRT [50] systems that searches for floor plan designs using the designer's sketch have been studied. In addition, studies have employed computer systems to directly generate design alternatives. For example, the study by Min et al. [38] supported creating a theme park layout design based on design rules. Granadeiro et al. [21] created a building envelope optimized for energy using the shape grammar rules. With the advancements in AI, to support floor plan design generation, studies using genetic algorithms [13] and graph neural networks [36] have been conducted. All these studies indicated that the design support system had assisted the spatial design process in various ways. In summary, existing spatial design support systems performed the following functions: 1) managing design ideas; 2) sketch-based user interface (UI); 3) retrieving designs; and 4) generating designs.

Our study proposes a system that provides inspirational real-time design feedback by analyzing design ideas during the design process. The proposed system supports design retrieval and exploration processes to create novel designs through design feedback, unlike existing systems that directly generate designs. Therefore, among the functions of existing spatial design support systems, excluding generating designs, our system's functions include (as a baseline): 1) managing design ideas; 2) sketch-based UI; and 3) retrieving design retrieval.

2.2. Designer centric support system

The use of computer systems in the design process has led to significant progress in increasing the productivity of designers and improving the quality of results [27]. In such a computer-aided design process, design support systems play various roles in supporting designers. For example, the systems not only recognize and support designer behavior [29,56] but also assist designers by materializing abstract knowledge to solve design problems [35]. Designers could explore various designs using the design retrieval function of design support systems [26,31]. In addition, the evolutionary design generation method generated optimized designs for design situations in various design fields [24,32]. Furthermore, the design generation system responded to the needs of designers using an interactive genetic algorithm [10,30]. To summarize the literature, design support systems have been developed in a design-centric manner, focusing on retrieving and generating a design.

However, Bernal et al. [6] argued that future design support systems

Fig. 1. Designers using the proposed system: a) sketching a design alternative while searching for references, b) reevaluating designs based on detailed design evaluations (i.e., micro-feedback), and c) navigating an unexplored design space based on a design exploration map (i.e., macro-feedback).

should focus on designer-centric rather than design-centric approaches. They explained that the system should perform computer-augmented actions to improve design quality by enhancing designer compatibility through an integrated design process and real-time valuable feedback support. Ban and Hyun [4] proposed an integrated design framework that could transform design sketches into 3D models through interactive reconstructions and evaluate various design alternatives. C-Space [51] was a spatial design collaboration support system that enabled retrieving designs and managing idea through a tangible user interface and AR. With C-Space, users explored various designs and created novel outcomes. FreeD V2 [57] was a sculpting tool with real-time feedback that guided the current sculpting direction based on the target sculpting shape. GUIComp [34] provided real-time design feedback based on the user's design by comparing GUI design references. In the spatial design field, MetisCBR [15] gave feedback regarding the next design step by analyzing the user's design action pattern. The user refined their design ideas based on the design feedback. All these studies supported an integrated design process based on computer-augmented actions.

From this perspective, the following elements should be included in our proposed D-SDSS for conducting computer-augmented actions: 1) a basic sketch UI, design idea management, and design retrieval function to support the integrated design process; 2) a new method for analyzing design ideas during the design process; and 3) real-time design feedback support for designers' ideas.

2.3. Supporting design creativity

Design creativity emerged not only through sudden mental insight [2] but also by exploring novel design areas that were not explored before [11]. Everything the designer observed in the design process influenced design creativity [17]. Furthermore, designers' ideas were created during the creative design process [19].

Previous studies on design creativity defined creativity characteristics. For example, Sarkar and Chakrabarti [47] defined the novelty and usefulness of designs as characteristics of creativity and analyzed product design creativity. Similarly, Grace et al. [20] set design novelty, value, and surprise as evaluation criteria to assess the creativity of 4000 mobile phone designs. Likewise, research analyzing the creativity of design outcomes has been conducted in the field of spatial design. Son et al. [50] investigated the impact of design references used in the floor plan design process by assessing the design novelty, usefulness, and resource effectiveness. As such, previous studies have proposed various characteristics for evaluating design creativity. Among these, design novelty was a commonly analyzed characteristic for evaluation. According to Jagtap [25], novelty was a key element in design creativity. However, previous studies [20,47,50] evaluated creativity based on design outcomes, so it was difficult to evaluate the novelty and creativity of ideas created during the design process.

Goldschmidt [18] viewed the design process as an idea development process and attempted to analyze the design process based on these ideas. To this end, Goldschmidt defined ideas containing the designer's thoughts as design moves and represented the design process as linkography, by forming a link if there existed a common sense between design moves. Based on Goldschmidt's method, many studies have used linkography and employed links to analyze the design process [9,23,28,53]. Specifically, Kan and Gero [28] proposed a design creativity analysis method that calculated the entropy of linkography. Linkography in the literature used a think-aloud or recording method to extract design moves in the design process. Two or three human evaluators judged the design move and links between moves to generate a linkography. However, Kan and Gero's study had two limitations. First, there was no clear definition of common sense between the design moves. Because the linkography depended on the protocol analysis of human evaluators, the result would be inaccurate or different every time [14,43]. For an accurate analysis of linkography, a clear definition of common sense was necessary. Second, there were no definitions of the design moves. Designers used various types of data during the design process. Specifically, pictorial representations [44,48], such as design sketches [41,52,54] and design references [17], were crucial. In addition, designers used search engines such as Google and Pinterest or a design retrieval system to search for references. The input data of the retrieval system represented the area of the design reference required for the design process to propose a crucial design move. Therefore, it was necessary to develop a new design move definition method that considered the sketch created during the design process, references used, and the designer's reference search areas.

Consequently, to overcome the limitations of previous studies, this study proposed three types of design moves: 1) a sketch design move, which is the user's sketch created during the design process; 2) a reference design move, which is the design reference used by the designer; and 3) an input data design move, which is the designer's design reference search space. In addition, we proposed “ideagraphy,” a method whereby common sense could be quantitatively calculated based on design novelty. This study proposed a new method for analyzing the creativity of the design process.

2.4. Providing design feedback

Design feedback is essential for identifying design problems and creating better designs [40]. By identifying the design problem, the designer attempts other design ideas and creates new solutions [16]. From this perspective, research on design feedback was conducted. Previous literature was divided into micro-feedback, which refered to real-time feedback based on the user's design, and macro-feedback, which assisted the design exploration process by comparing it with other designs.

In micro-feedback research, for example, Oh et al. [39] argued that a design critiquing system should automatically store design knowledge and monitor user behavior in real time to provide design feedback. GUIComp [34], a GUI design support system, provided micro-feedback by comparing the user's design with GUI design references. The comparison results were shown to the user as micro-feedback. Another example of micro-feedback research, drawing application, was proposed by Davis et al. [12]. The drawing application system automatically drew a sketch similar to the designer's sketch or drew supplementary sketches. Then, designers viewed the system's sketches in real time and modified or changed their designs. As the literature indicated, micro-feedback stimulated a designer's thoughts and suggested potential design directions. However, because micro-feedback only indicated a direction, which was not a specific solution, designers needed to explore various design spaces by themselves.

Macro-feedback compared a user's design status with design references in the design exploration process. Designers found and used novel designs through macro-feedback to refine their design ideas. Hyun and Lee [24] proposed a car-design framework using a design exploration process. The system provided evaluation results according to the user's design strategy. Then, the user updated their design strategy and explored various car designs in the design exploration map. Dream Lens [37] was a system that assisted in exploring numerous design alternatives created using genetic algorithms. Based on the user's design preference, the system evaluated the attributes of the design alternatives and provided a design exploration map. Yang et al. [55] proposed a system that generated and optimized building designs in terms of energy efficiency and mass design using a genetic algorithm. Similar to the two systems described above, this system provided a 3D design exploration map based on the user's design conditions. In this manner, macro-feedback supported designers in exploring various designs through the design exploration process. However, if the system only provided macro-feedback, the designer had to decide the direction for design exploration. Without analyzing the design process, it was difficult to determine whether novel designs or designs should be explored. Furthermore, the design direction for design exploration significantly influenced the design process and outcomes [17]. Therefore, macro-feedback should be provided in conjunction with design process analyses.

Thus, micro- and macro-feedback were complementary. If a design support system provided the direction through micro-feedback and provided a solution that fit this direction through macro-feedback, the shortcomings of each feedback could be overcome. However, studies on design support systems providing both micro- and macro-feedback have not been reported thus far. Therefore, we proposed a novel D-SDSS that provides both micro- and macro-feedback.

3. D-SDSS

3.1. Conceptual overview

Based on the research questions in Section 1, our proposed system aimed to achieve the following design goals:

D1: Assisting designers in creating novel design moves through D-SDSS feedback-based interaction.

D2: Encouraging designers to generate various design moves by stimulating design decisions and exploration.

To achieve these design goals, the D-SDSS consisted of the following features: First, D-SDSS had a floor plan sketch feature (Fig. 2-a) and a design retrieval function using the user's sketch (Fig. 2-b), which allowed the user to use the retrieved reference in the design process (Fig. 2-c). In addition, design moves containing floor plan design ideas were created and saved based on the three actions of the designer (Fig. 2-d). Then, users checked or reused their ideas from the saved design moves. To analyze the user's process for developing design ideas, we proposed an ideagraphy methodology based on the design moves. Ideagraphy was a graph formed based on the similarity between design moves. Using ideagraphy, D-SDSS analyzed the novelty of the design ideas created during the design process.

Moreover, D-SDSS provided two types of design feedback: micro- and macro-feedback. For micro-feedback, the D-SDSS formed and analyzed ideagraphy that analyzed the design process in detail to provide feedback regarding design novelty (Fig. 2-e) using up/down arrows and a side note. Users identified the weaknesses of the design process through micro-feedback. For macro-feedback, the D-SDSS analyzed the ideagraphy of the design process from a macroscopic perspective rather than micro-feedback. Furthermore, the macro-feedback enabled the design exploration process by comparing the user's design with the design references in the database of the D-SDSS. The D-SDSS provided this macro-feedback in the form of a histogram, and a design exploration map was represented as a scatter plot (Fig. 2-f). Then, the D-SDSS user explored novel designs in the design exploration map and set a new design direction, accordingly.

In this research, to propose the D-SDSS, we conducted the following process (Fig. 3): 1) building a floor plan database, 2) developing four floor plan retrieval methods, 3) defining three types of design moves and developing similarity calculation methods, 4) creating the ideagraphy method, 5) creating the micro- and macro-feedback framework, 6) developing D-SDSS, and 7) evaluating users through professional spatial designers.

3.2. Retrieving designs

For the design reference database of D-SDSS, we collected actual residential floor plan designs from an online real-estate webpage (www.r114.com). We collected 2101 actual residential floor plan designs that satisfied the following three criteria: 1) publicly available residential

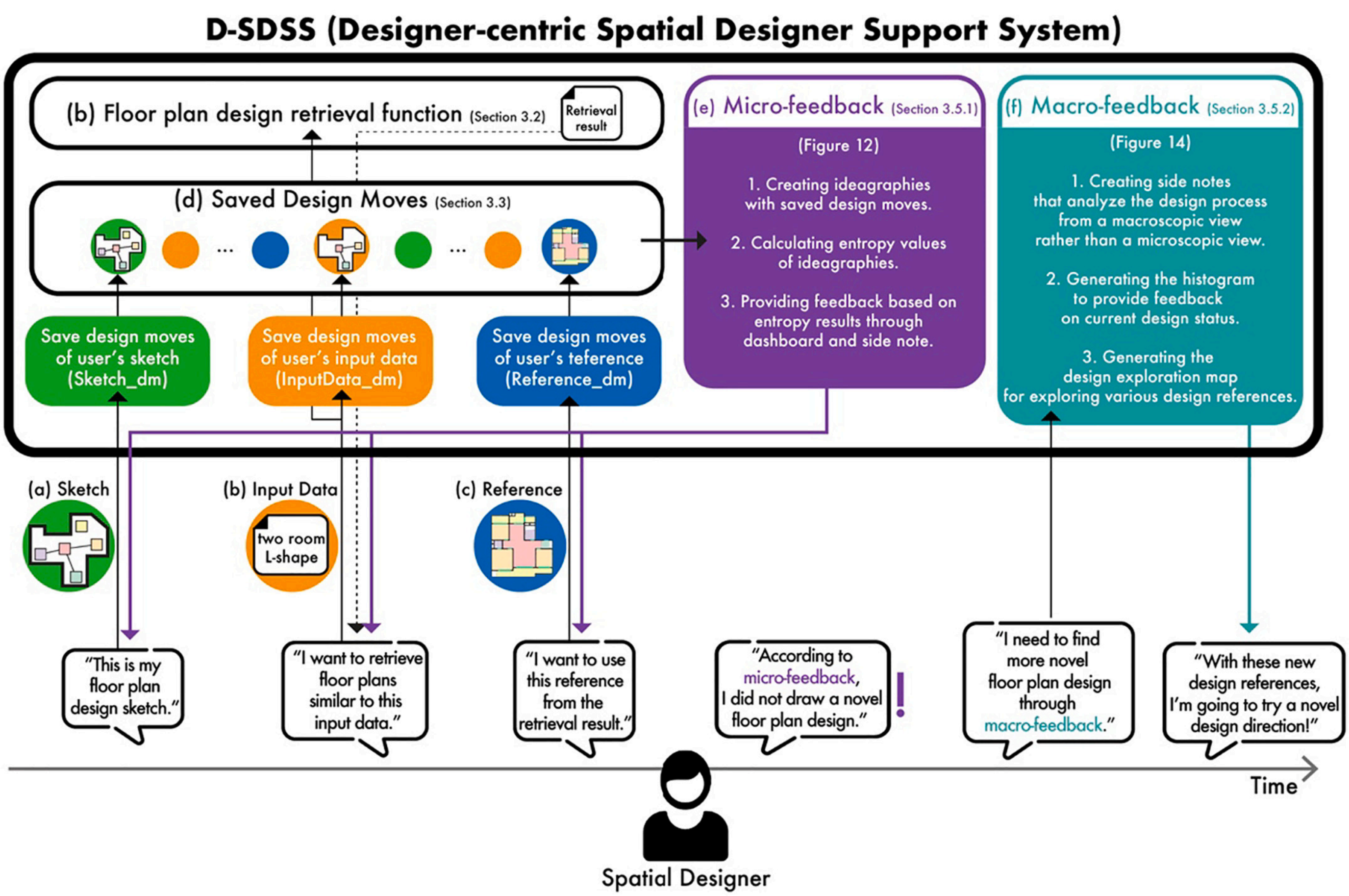

Fig. 2. Conceptual overview of D-SDSS.

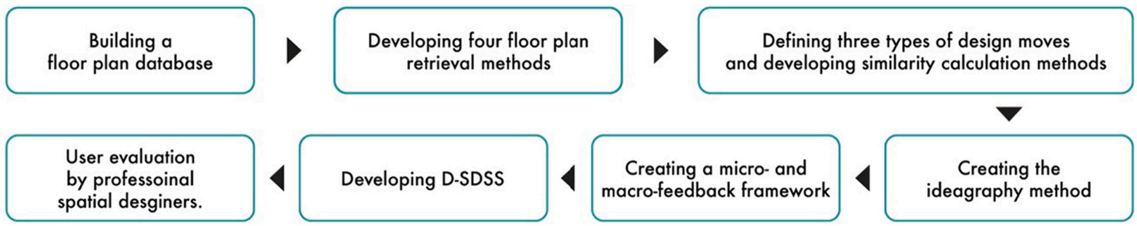

Fig. 3. Research methodology chart.

floor plan design; 2) residential space in Seoul, South Korea; 3) single-floor design. The idea of D-SDSS design retrieval involved searching and using actual floor plan designs in an integrated system. Thus, we collected residential floor plan data that existed in Seoul, and the site conditions of the design brief given in the experiment were unified within Seoul city (Section 4.2). In the design process with D-SDSS, users retrieved the desired references by inputting four design criteria of floor plan: floor silhouette, number of rooms, room location, and room connectivity (Supplementary Video 1). The system used a similarity calculation method that performed topological comparisons for each set of floor plan design criteria to identify the most similar references.

3.2.1. Floor silhouette (fs)

Sixteen grids and the aspect ratio method developed in our previous study [51] were used to calculate the similarity between the silhouettes of the two floor plans (fs). However, we used a final resolution of 64 grids and a bounding box aspect ratio (Fig. 4). The similarity between the two silhouettes was calculated as follows: First, the number of matching grids was divided by the total number of grids; then, this value was subtracted by one. Second, the difference between the aspect ratios of the two-floor plan designs were calculated. Third, we added these two values and divided the result by two to calculate the final similarity score (Fig. 5).

3.2.2. Number of rooms (nr)

There were five types of spaces: living rooms, kitchens, rooms, balconies, bathrooms, and entrances. To calculate the similarity of the number of rooms, we counted the number of matching room types (Fig. 6). If the two floor plans had the same number of rooms of all types, then the value was five. Then, we divided this value by the total number of room types and used the result as the number of rooms similarity (nr).

3.2.3. Room connectivity (rc)

We considered each room as a node and the room connection as an edge (Fig. 7-a) to calculate the similarity of the connection relationships between two floorplans. The graph edit distance (GED) method calculated the number of times a correction had to be applied to make the two graphs identical (Eq. (1)). In the GED equation, g represented graphs, and $\mathscr{P}$ the set of editing paths that converted g_1 to g_2. c was a cost function that measured the intensity of correction e_i. However, the GED was implemented as an A^* algorithm, and it was computationally expensive. Thus, to calculate the GED in real time, we used the bipartite GED algorithm [8]. The bipartite GED was a GED algorithm that applied the original GED method to an assignment problem. Specifically, the bipartite GED method from the Gmatch4py library was adopted. The output of the bipartite GED method was used as a similarity measure for the room connectivity (rc) between the two floor plan designs.

$$GED(g_1, g_2) = \min_{(e_1,\dots,e_k \in \mathscr{P}(g_1,g_2))} \sum_{i=1}^{k} c(e_i) \tag{1}$$

3.2.4. Room location (rl)

Room locations (Fig. 7-b) were identified by constructing graphs under direct and indirect room connections. A direct connection referred to a relationship that existed between rooms connected by a door, whereas an indirect connection referred to a relationship that existed between adjacent spaces without a door. Here, the relationships between rooms at the outskirts and in the east, west, north, and south directions were included to determine the room locations accurately, as discussed in previous research [5,13]. The bipartite GED was used to calculate the similarity of the room locations (rl) between the two floorplans.

3.3. Design move (dm)

In this section, we define three types of design moves for the ideagraphy stored by the D-SDSS. In addition, the common sense used in the ideagraphy of the D-SDSS is defined using a quantitative criterion, and the calculation method is described.

3.3.1. Three design moves

We proposed three types of design moves (Fig. 8). First, a sketch was created by a designer (*Sketch_dm*). The sketch reflected the designer's thoughts and was an essential element of the design process [7]. Second, the reference search results retrieved during the design process were defined as a design move (*Reference_dm*). Further, the references the designers found during the design process had a significant influence on the design process [17]. Third, the designer input data into the system to find references (*InputData_dm*). This represented the reference area that a designer explored [3]. *InputData_dm* helped designers re-explore the target reference search area. D-SDSS automatically saved images and information from user sketches, references, and input data. Thereafter, by clicking on *dm*, users reused their *dm* information (Supplementary Video 2).

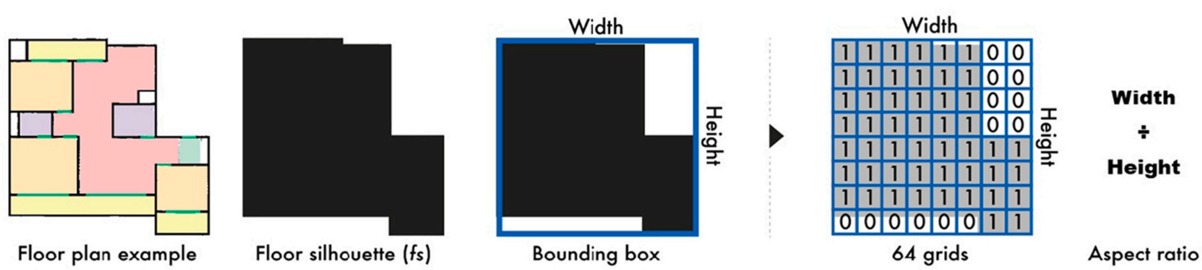

Fig. 4. Floor silhouette (fs) quantification.

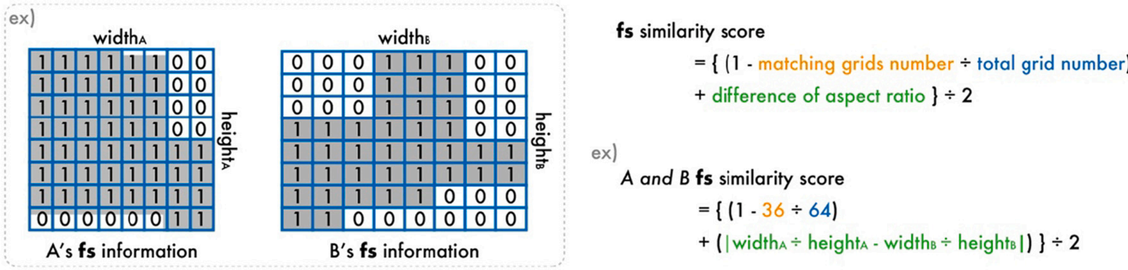

Fig. 5. Floor silhouette (fs) similarity calculation method.

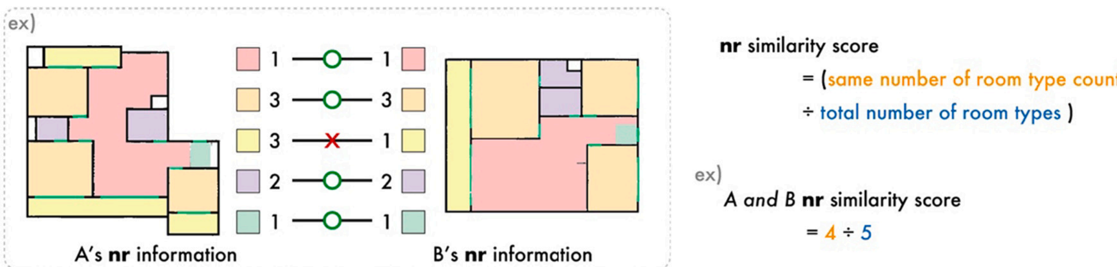

Fig. 6. Number of rooms (nr) similarity calculation method.

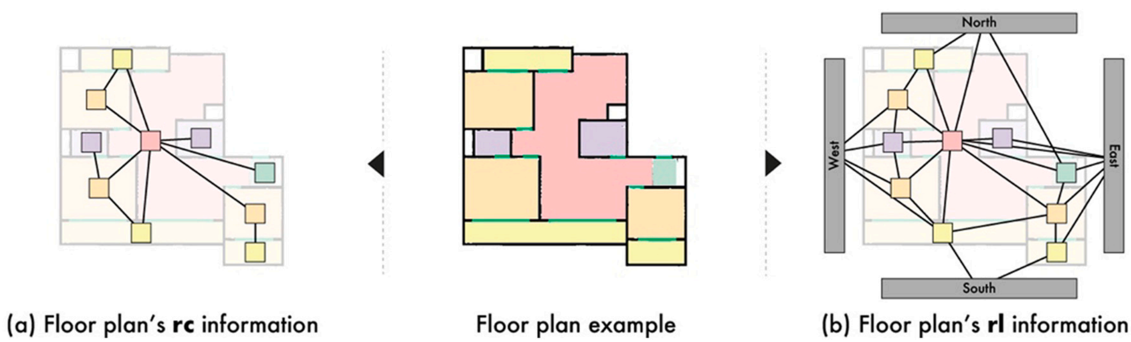

Fig. 7. Room location (rl) and room connectivity (rc) quantification.

3.3.2. Common sense between design moves

A common sense existed between two similar design moves. Previous studies analyzed the design process by expressing this common sense as a link [9,18,23,28,53]. For example, according to Kan and Gero [28], if there were many links among the design moves, it was interpreted that the designer produced many similar ideas during the design process. Using this design process, it was difficult for designers to create novel design ideas. Likewise, if there were too few links, it was interpreted that the relationship between the design moves was insufficient for developing ideas. However, in previous studies, the criteria for determining common sense were qualitative. Thus, a new quantitative criterion for judging common sense between design moves was necessary to accurately identify common sense in real time.

As the D-SDSS supported the process of floor plan design, the design move contained nr, fs, rl, and rc. We defined the case in which a common sense existed when the similarity between the design information of the two design moves exceeded a specific similarity threshold. To set a reliable threshold value, we calculated the threshold of similarity at

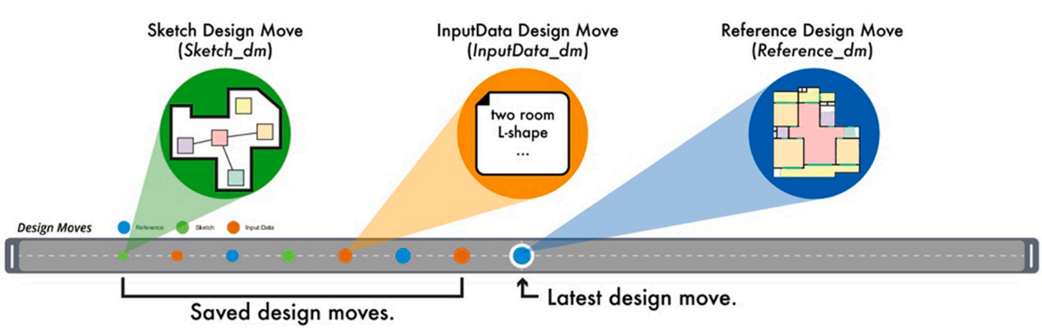

Fig. 8. The three types of design moves.

which people perceived a common sense between the design information. We recruited 500 participants from Prolific, an online survey platform, for this threshold experiment. The participants were divided into groups of 10, and 10 pairs of floor plan designs were evaluated by each group. Four questions were posed to the participants to determine if there were common sense relationships according to the fs, nr, rc, and rl thresholds. The answers took the form of "yes" or "no." The similarity values of the pairs that received the answer "yes" were determined using the proposed method for calculating floor plan similarity, which was discussed in Section 3.2. The average of the similarity values obtained through the similarity threshold experiment was used as the threshold.

3.4. Ideagraphy

Ideagraphy described the proposed design process analysis method. It comprised three newly defined types of design moves, and a link-forming method based on common sense. Ideagraphy required two features: 1) categorizing ideagraphy by design move type and information, and 2) calculating entropy for each ideagraphy.

We analyzed the ideagraphy using the entropy calculation method proposed by Kan and Gero [28]. However, entropy calculations had to be performed for each type of design move. Therefore, the following categorizing approach was adopted. First, a user's design moves (Fig. 9-a) were filtered into four types of floor plan design information (Fig. 9-a to 9-b). Second, by categorizing all the links according to the type and order of the design moves creating each link, ideagraphies containing homogeneous link types were created (Fig. 9-b to 9-c). For example, an ideagraphy containing links to the *Reference_dm* - *Sketch_dm* type for the nr threshold would appear, (see Fig. 9-c). The information in the *Reference_dm* - *Sketch_dm* type of nr ideagraphy (R-S_nr)'s links were interpreted as the following question: "In terms of the number of rooms, do the retrieved references have common sense relationships with the newly drawn sketches?" The ideagraphies created (Fig. 9-b to 9-c) was classified into nine types: 1) S—S (*Sketch_dm* - *Sketch_dm*); 2) R-R (*Reference_dm* - *Reference_dm*); 3) I—I (*InputData_dm* - *InputData_dm*); 4) S-I; 5) I-S; 6) I-R; 7) R-I; 8) R-S, and 9) S-R.

Through this categorizing process, the total number of ideagraphy created was 4 × 9 = 36 (Fig. 10). The types of links created in a single ideagraphy were the same. For example, Fig. 10-(1) depicts S-S_nr, which included links that were formed if a common sense existed between the nr information of two *Sketch_dms*. Fig. 10-(4) and 10-(5) illustrate the ideagraphy composed of links formed between the two *dms* of different types. Fig. 10-(4) shows the S-R_nr diagram that included links formed between the nr information of *Sketch_dm* and *Reference_dm*. Fig. 10-(5) presents the R-S_nr diagram that includes links formed between the nr information of *Reference_dm* and *Sketch_dm*. As Fig. 10-(4) and 10-(5) show, the type of ideagraphy differed depending on the type and order of the design move. Meanwhile, S-S_rc (Fig. 10–28) could not form any links, regardless of the common sense. S-S_rc (Fig. 10–28) was an ideagraphy that included links formed between the rc information of the two *Sketch_dms*. However, because there was no rc information in the first and second *Sketch_dms* under the current design moves (Fig. 10), no link was formed.

Kan and Gero [28] proposed the idea of a horizonlink (Fig. 11-c), which represented the distance between links, in addition to forelinks (Fig. 11-a) and backlinks (Fig. 11-b), which indicated the divergence and convergence of thought in existing links, respectively. To evaluate the creative design process, they determined whether an unexpected novel link was created. They proposed a method for calculating the entropy of forelinks, backlinks, and horizonlinks. For an event to have

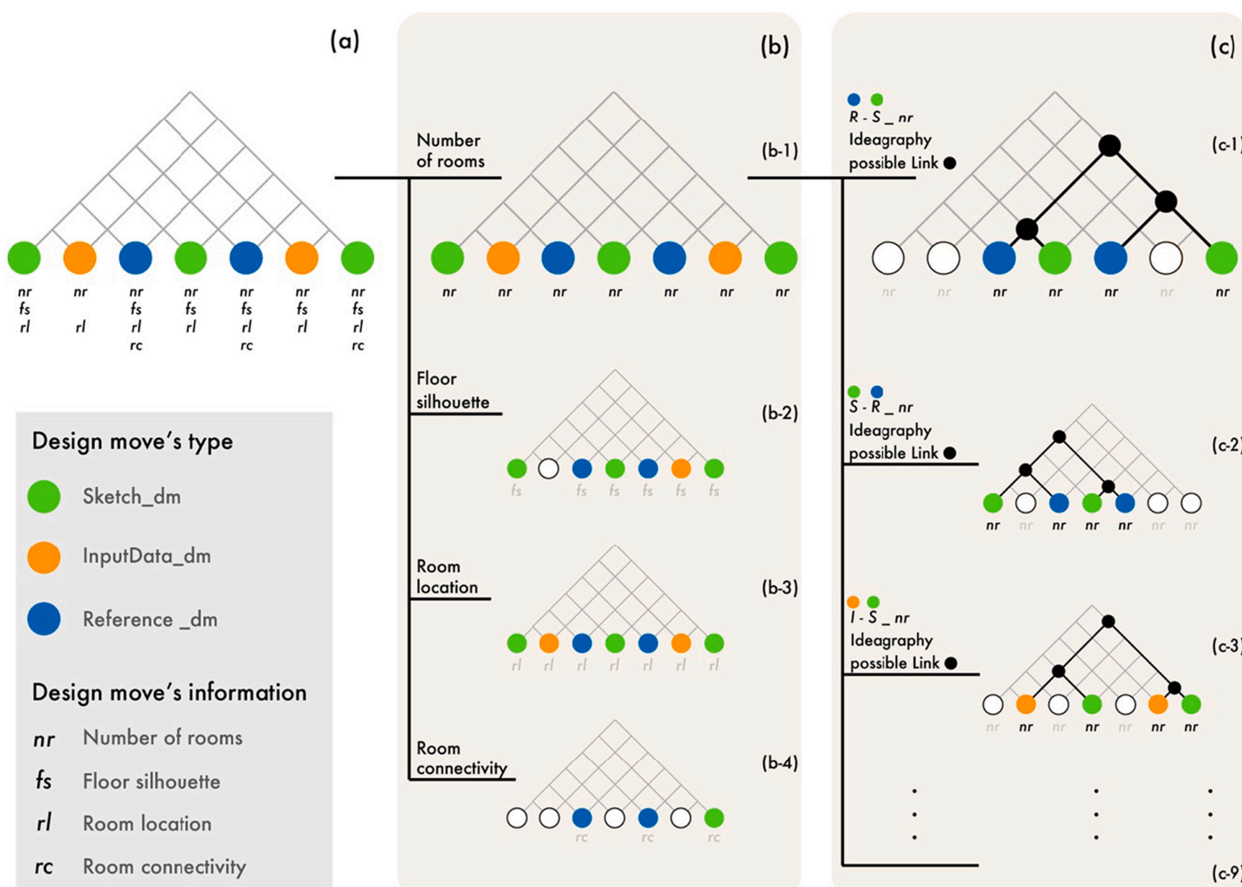

Fig. 9. Ideagraphy generation process: (a) user design move data, (b) classifying design moves using floor plan design information, and (c) classifying links by type and order of design moves.

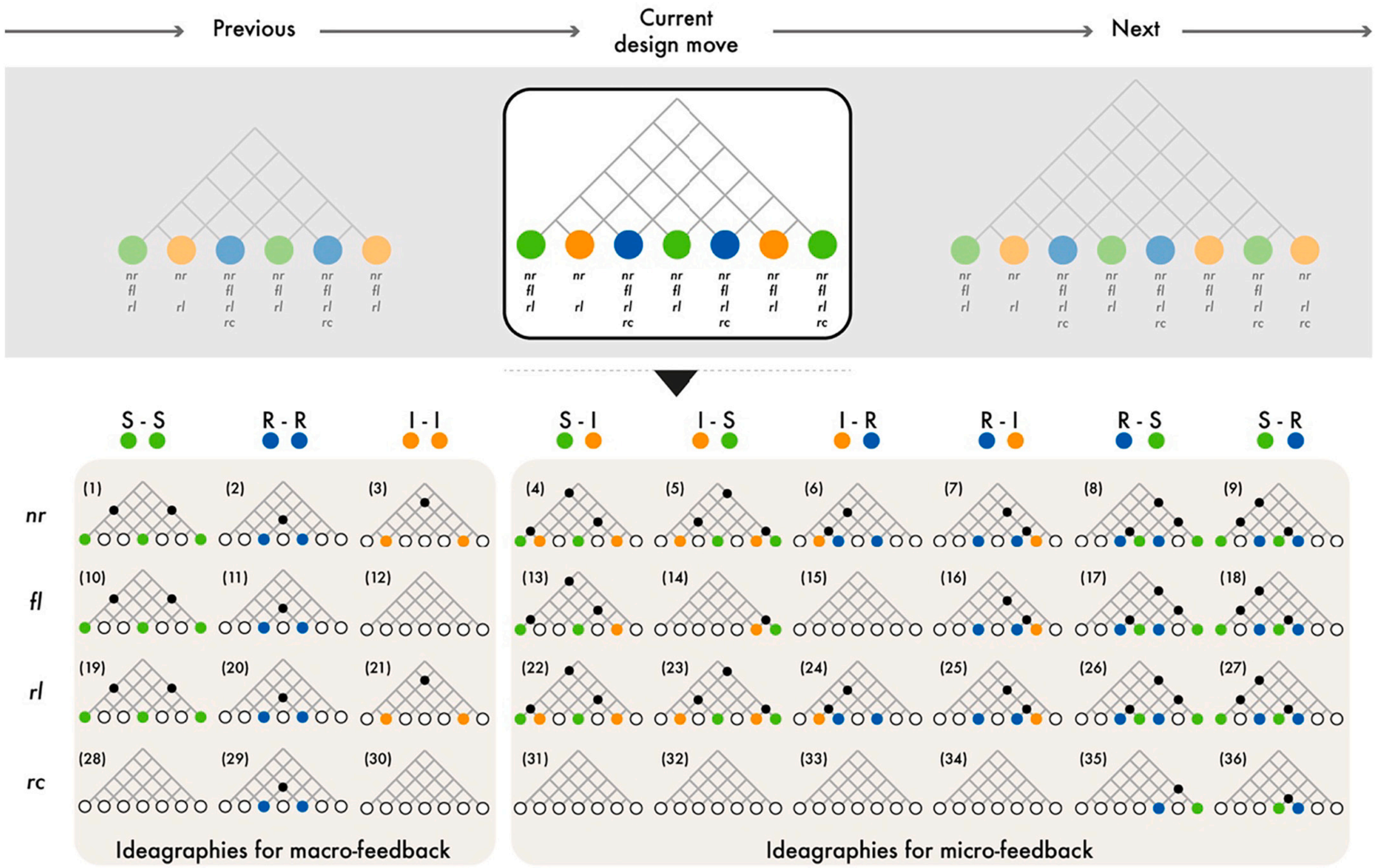

Fig. 10. Example of 36 ideagraphies from current design moves.

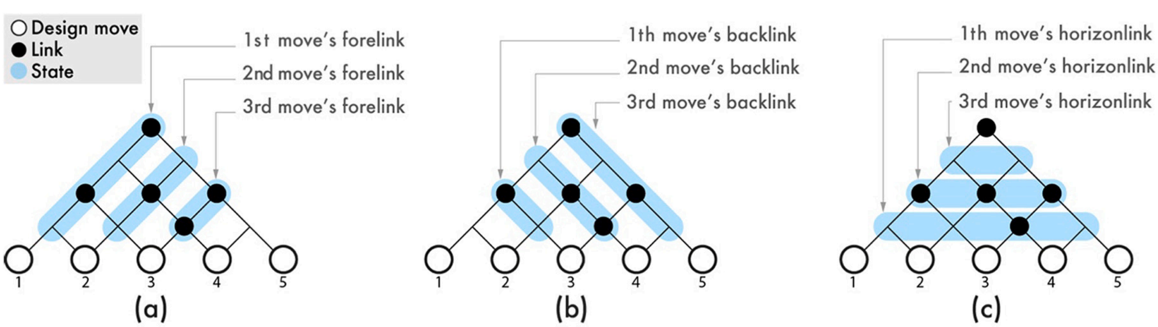

Fig. 11. Ideagraphy of five design moves: (a) forelinks, (b) backlinks, and (c) horizonlinks.

informative value, it had to proceed in an unpredictable direction. The uncertainty of an event was referred to in terms of the amount of information available regarding that event. Shannon [49] proposed a formula for obtaining the amount of available information regarding an event, denoted as $h(p)$ (Eq. (2)). Based on this formula, a method for calculating entropy (H) was developed. Entropy represented the expected value of all event information and was expressed by Eq. (3), where $p_1, \ldots, p_n$ denoted the probability of the occurrence of state $S_1, \ldots, S_n$ for each event. Each event was assumed to be independent.

$$h(p) = -logp \tag{2}$$

$$H = p_1 \times h(p_1) + p_2 \times h(p_2) + \cdots + p_n \times h(p_n) \tag{3}$$

$$H = -\sum_{i=1}^{n} p_i logp_i \ with \ \sum_{i=1}^{n} p_i = 1 \tag{4}$$

Kan and Gero [28] defined $P(on)$ and $P(off)$ for each forelink, backlink, and horizonlink as the events in which links were created and not created, respectively. $P(on)$ denoted the value obtained by dividing the number of links formed by the maximum number of links that could be created, and $P(off)$ was calculated as $1 - P(on)$. These were used to derive Eq. (4), from Shannon's Eqs. (2) and (3), the sum of the events $P(on)$ and $P(off)$ satisfied the condition in Eq. (4). As Fig. 11 shows, when n^{th} design moves were created, $n - 2$ forelinks and backlinks and backlinks, and horizonlink rows were created. Kan and Gero calculated the summation of the entropy of all forelinks, backlinks, and horizonlinks to calculate the entropy value. Using this entropy calculation method, they analyzed the unpredictable link formation in the design and creative design processes. Accordingly, the entropy analysis result of the ideagraphy was interpreted as follows: Ideagraphy with a high entropy value was interpreted as a design process that had a high possibility of forming a new and creative design, i.e., a design process that explored novel *dms* compared to the previous *dms*. In contrast, ideagraphy with a low entropy value indicated a design process that did not create novel *dms*, as compared to the previous *dms*.

For example, S-S_nr's (Fig. 10-1) entropy calculation and interpretation were as follows: S-S_nr had five forelinks, backlinks, and horizontal links. *P*(*on*) of the first forelink is ⅙, *P*(*on*) of the fourth forelink is $^1/_3$, and *P*(*on*) of the remaining forelinks was 0. *P*(*on*) of the second and fifth backlinks was $^1/_3$ and ⅙, respectively, and *P*(*on*) of the third horizonlink was ½. *P*(*on*) of the other backlinks and horizonlinks were all 0. According to Eq. (4), the sum of the entropy values for all forelinks was 1.568, backlink was 1.568, and horizonlinks was 1. Therefore, the final entropy value of S-S_nr was 4.137. If the entropy value of S-S_rl was lowered when a new *dm* was added, during the design process, the system provided feedback of the entropy value that the nr of *Sketch_dms* was not novel compared to the nr of the previous *Sketch_dms*. Based on this feedback, the designer searched for references with new nr information that was different from the nr information of the previous *Sketch_dm*. In this manner, we analyzed the design process in greater detail by calculating the entropy of the 36 ideagraphy entropy values and by incorporating the results in the user feedback information.

3.5. Feedback for design moves

3.5.1. Micro-feedback

Micro-feedback (Supplementary Video 3) analyzed 24 ideagraphies (Fig. 12), i.e., S—I, I—S, I-R, R-I, R-S, and S-R for the four floor plan information types. Micro-feedback was based on the increments or decrements in the entropy values of the ideagraphies. The micro-feedback of the proposed system consisted of two components: 1) a dashboard (Fig. 13-a) and 2) a side note (Fig. 13-b). When a novel design move occurred, the entropy values were calculated and displayed on the dashboard. For example, initially, $link_1$ existed in the S-I_fs diagram (Fig. 12-2-1). Thereafter, $link_2$ in the same ideagraphy was created. If the entropy value of the S-I_fs $link_1 + link_2$ combination was greater than that of $link_1$ alone, then the dashboard displayed an up-arrow sign to symbolize an increase in entropy. As explained in Section 3.4, a high entropy value was interpreted as a design process that created novel *dms* compared to previous *dms*. As Fig. 12 illustrates, the interpretation of entropy values for each design move varied.

The side note presented an interpretation of the ideagraphy with the most significant entropy reduction. A side note was generated based on predefined rules (Fig. 14). First, according to the floor plan design information included in the design move, the first part of the entropy value's interpretation would be "In terms of the" + ["number of rooms," "floor silhouette," "room location," "room connectivity"]. Next, the interpretation of the second part was decided according to the type and order of the two design moves that formed the link. The interpretation of the first *dm* was converted into "you" + ["draw sketch," "found references," "searched for reference areas"] in the order of *Sketch_dm*, *InputData_dm*, and *Reference_dm*. Depending on whether the entropy value increased or decreased, the interpretation of ["novel," "not novel"] was added to this part. For example, if the first *dm* forming a link was *Sketch_dm*, and the entropy value decreased, the interpretation would be "you did not draw novel sketches." Finally, the interpretation of the second *dm* was "based on" + ["drawn sketches," "found references," "searched reference areas"], depending on the *dm* type. As Fig. 10 shows, if the entropy value of S-R_nr was increased, the interpretation became "In terms of number of rooms, you found novel references base on drawn sketches." Further, a user could check the side note for an ideagraphy by clicking on the dashboard arrows. Thus, through this interpretation method, micro-feedback informed the user of the necessary modifications in the design process.

3.5.2. Macro-feedback

The macro-feedback (Supplementary Video 4) of the proposed system consisted of three components: 1) a design exploration map (Fig. 15-a), 2) four histograms (Fig. 15-b), and 3) a side note (Fig. 15-c). The design exploration map and histograms visualized the novel relationships between the current user's sketch and the design references. It was crucial to determine the location of the current design search space to allow designers to explore additional design spaces [37].

The histogram displayed the similarity values between a user sketch and all the reference data for the four types of floor plan design information (Fig. 15-b). Using the histogram, users compared their design and design references for each floor plan design information. However, it was difficult to determine references that were similar to the user's design based on the histogram alone. Therefore, the D-SDSS maps all references to a design exploration map (Fig. 15-a). Then, users selected two pieces of information for setting the exploration map's *x*- and *y*-axes using toggle buttons. Subsequently, users explored and identified unexplored references using a design exploration map. When the user clicked on a reference point, the system allowed the corresponding reference to be opened and used on the sketch board (Fig. 15-d). Thus, the user searched for novel design references according to each floor plan information with macro-feedback. For example, if the user wanted to explore a new fs and rl design that was different from the latest sketch fs and rl, the user first checked the distribution of the design references with the histograms. Then, the user converted the fs and rl information into two axes of the design exploration map. According to the axis information, the D-SDSS maps all designed references of the database

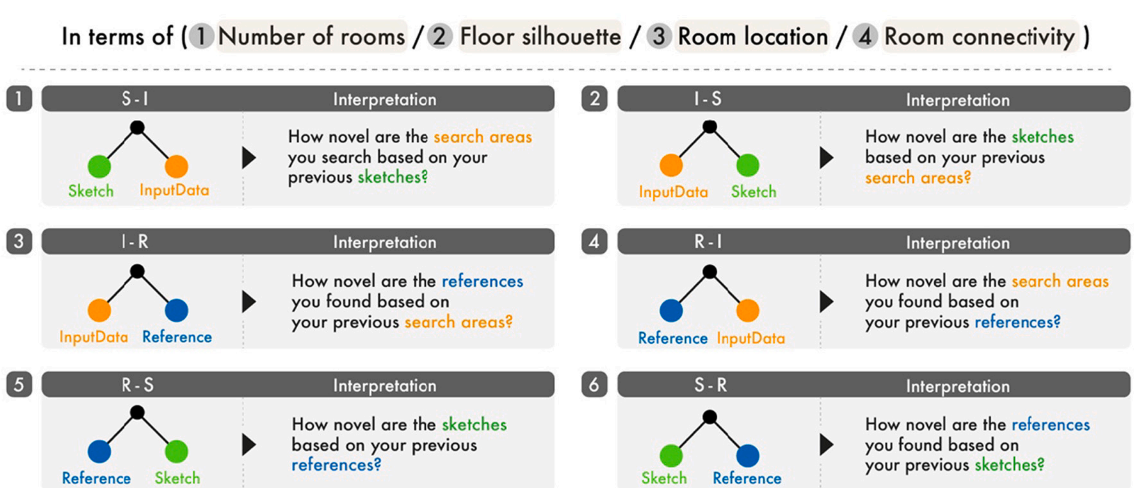

Fig. 12. Interpretation of micro-feedback entropy results according to the type of ideagraphy.

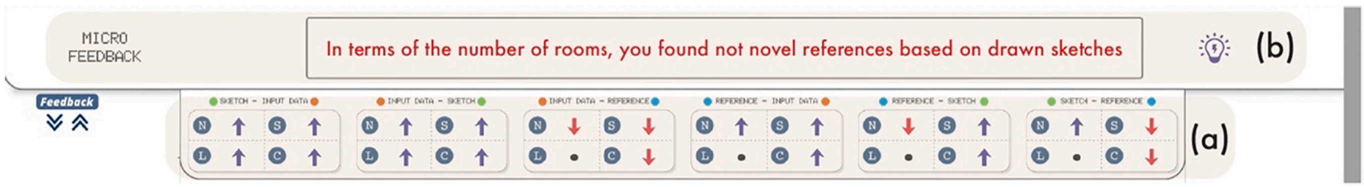

Fig. 13. Micro-feedback overview: (a) dashboard and (b) micro-feedback side note. The up-arrow sign in the dashboard symbolizes an increase in the entropy value.

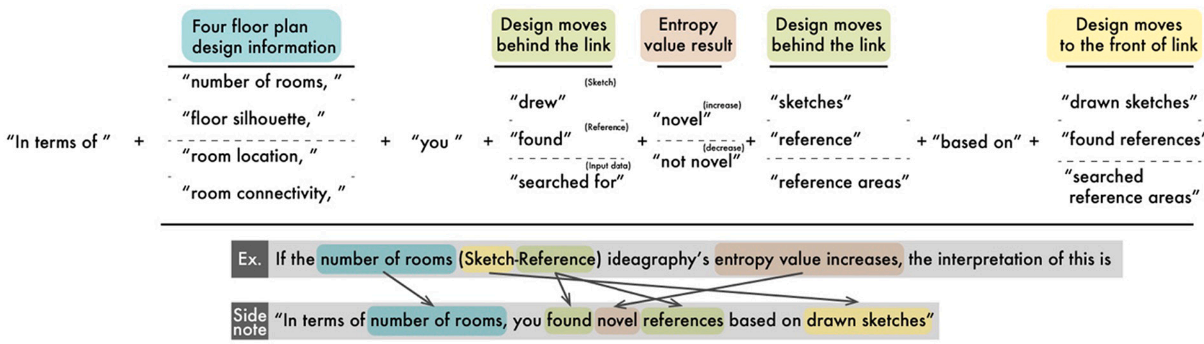

Fig. 14. Side note generation process based on entropy values for each type of floor plan design information and design move.

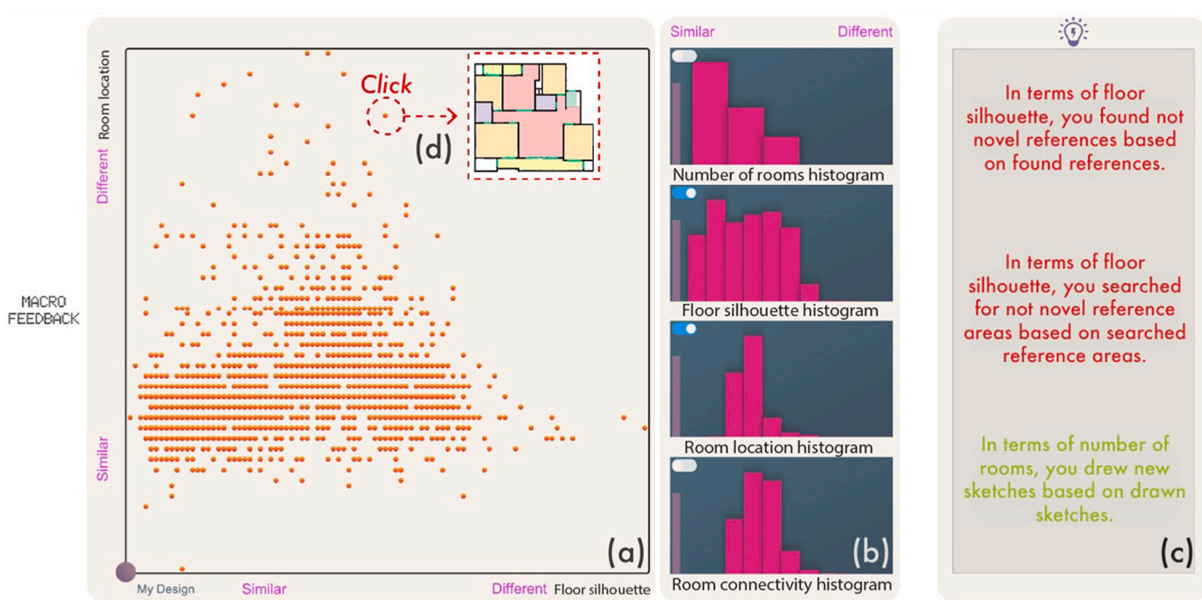

Fig. 15. Macro-feedback overview: (a) reference design exploration map, (b) reference histogram mapping, (c) macro-feedback side note, and (d) accessing a reference on the design exploration map.

based on their similarity to the user sketch. Then, the user selected and used different or similar references during the design process.

In addition, to analyze the design process from a macroscopic perspective rather than the micro-feedback, the macro-feedback analyzed 12 ideagraphies (Fig. 16), i.e., S—S, I—I, and R-R for the four floor plan information types with side notes. The side note for the ideagraphy with the greatest reduction in entropy was presented to the user (Fig. 15-c). If there was no decrease in entropy, then the ideagraphy with the lowest entropy value was presented.

4. Implementation & discussion

Here, to assess the impact of the D-SDSS's micro- and macro-feedback framework in the design process, 21 professional spatial designers were recruited for user experiments ($Age_{mean} = 30.24$, $Age_{min} = 24$, $Age_{max} = 46$, $male = 10$, and $female = 11$). When the study was conducted, the participants were working as studio practitioners in spatial design or as spatial design researchers (work experience $Mean = 5.08$ years and $SD = 5.42$).

4.1. System overview

The D-SDSS consisted of a server and a client (i.e., tablet PC). There were four main functions that facilitated communication between the client and the server (Fig. 17). First, through the floorplan search function, the client sent the input information to the server. According to a client query, the server retrieved reference data related to the input information and corresponded to the four types of floor plan

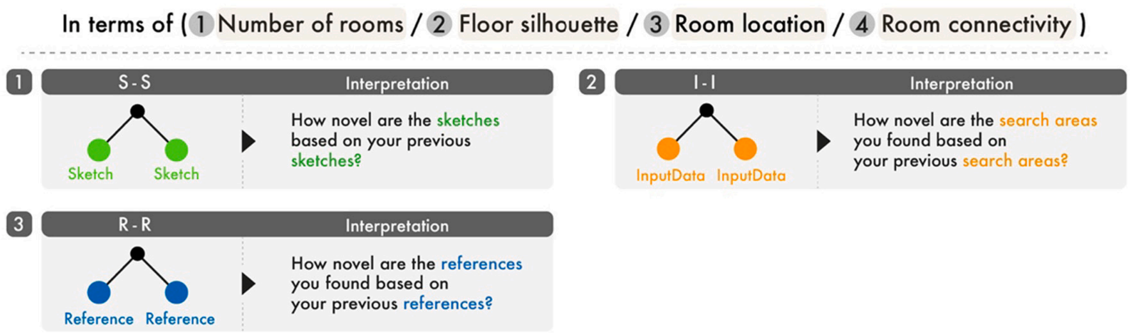

Fig. 16. Interpretation of macro-feedback entropy results according to the type of ideagraphy.

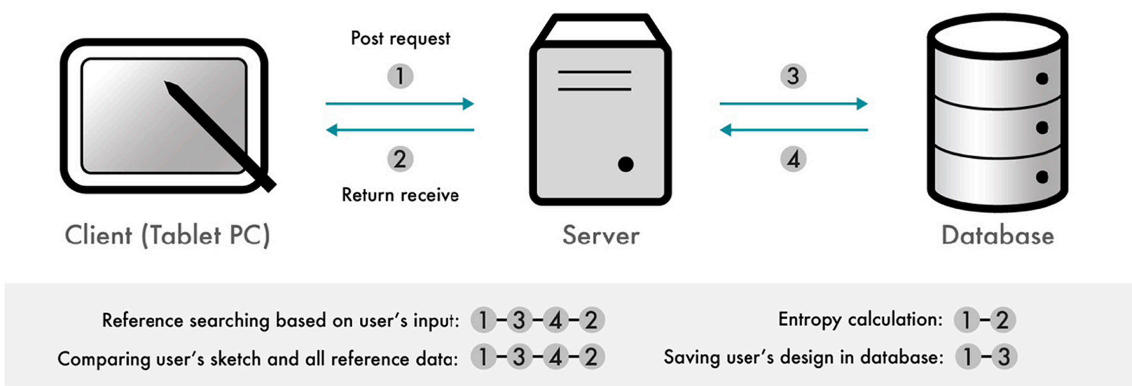

Fig. 17. System overview.

information: number of rooms, floor silhouette, room location, and room connectivity. Then, the server sent the results to the client. Second, for entropy calculation, the client automatically sent a request to the server whenever a new design move was created on the client side. The client sent all the generated design move information, and the server calculated and returned 36 entropy values for the documented design move. Third, the client requested the user sketches contained in the reference data. Client inputs were the most recent sketch information. The server received this request, calculated all the references and similarities in terms of the four types of floor plan information, and returned the relevant sketches as a result. This request was executed when the user turned on macro-feedback in the system. Finally, the client sent a request to the server to save the design. When the save request was received, the server added the current user sketch to the database. This saved user design was retrieved later when the user performed a reference search. Further, the user's design information was saved independently on a tablet PC.

4.1.1. *Apparatus*

The D-SDSS server computer used the Linux OS with an Intel® Core™ i7–7700 CPU, 64 GB of RAM, and a GeForce GTX 1080 Ti/PCle/SSE2 GPU. The client system was a 15 in. Microsoft Surface Book 2 and a surface pen. Surface Book 2 employed Windows OS, an Intel® Core™ i7-8650U CPU, and 16 GB of RAM. The resolution was 3240 × 2160 pixels. The client system was developed using Unity software (version 2019.3.14.f), and the server was constructed using the Python Flask framework. The design reference database was developed using the MongoDB. NetworkX and the Gmatch4py library were used to calculate the GED, which is used as a measure of the similarity between graphs on the server.

4.1.2. *GUI and features*

The main GUI of the proposed system is illustrated in Fig. 18. Users draw their floor plan designs on a sketch board (Fig. 18-a) using sketch tools (Fig. 18-b). The sketch tools include five room markers, a shape pen that allows the user to draw the silhouette of a floor plan, and a free pen that allows the user to sketch freely. Users can create drawings in which two spaces are directly connected, and drawings of rooms adjacent to each other by using the connection functions of the room marker. The shape pen automatically corrects the curves drawn by the user. All sketch tools include an eraser function.

The system automatically recognizes the user sketches. By using the toggle buttons presented in Fig. 18-d, the system can be instructed to search for the information that the user needs. When more than one type of information is required, the priority of information is determined by the order of the pressed toggle buttons. Users can search for a reference by simply selecting the information they need from their sketches (Fig. 19-a). When a specific reference from the search result list is clicked, the user can adjust its size and transparency, as shown in Fig. 19-b, and view the reference image in a movable window. Users can also sketch their designs in the movable window. The system records and visualizes the user's design moves, such as sketching, searching, and reference use (Fig. 18-e). Because the design moves contain all the design information provided by the user, the user can click on a design move to check previously drawn sketches, searched references, and information entered for searching. The feedback module is illustrated in Fig. 18-f. If the feedback module is lowered using the downward arrow shown in Fig. 18-g, the user can view all the feedback functions, as indicated in Fig. 19-c.

4.2. *Experimental design*

To observe the impact of the D-SDSS on the design process, a three-phase experiment was conducted. The designers participating in each experiment were asked to create layouts based on design briefs using the proposed system. However, there was a difference in the feedback

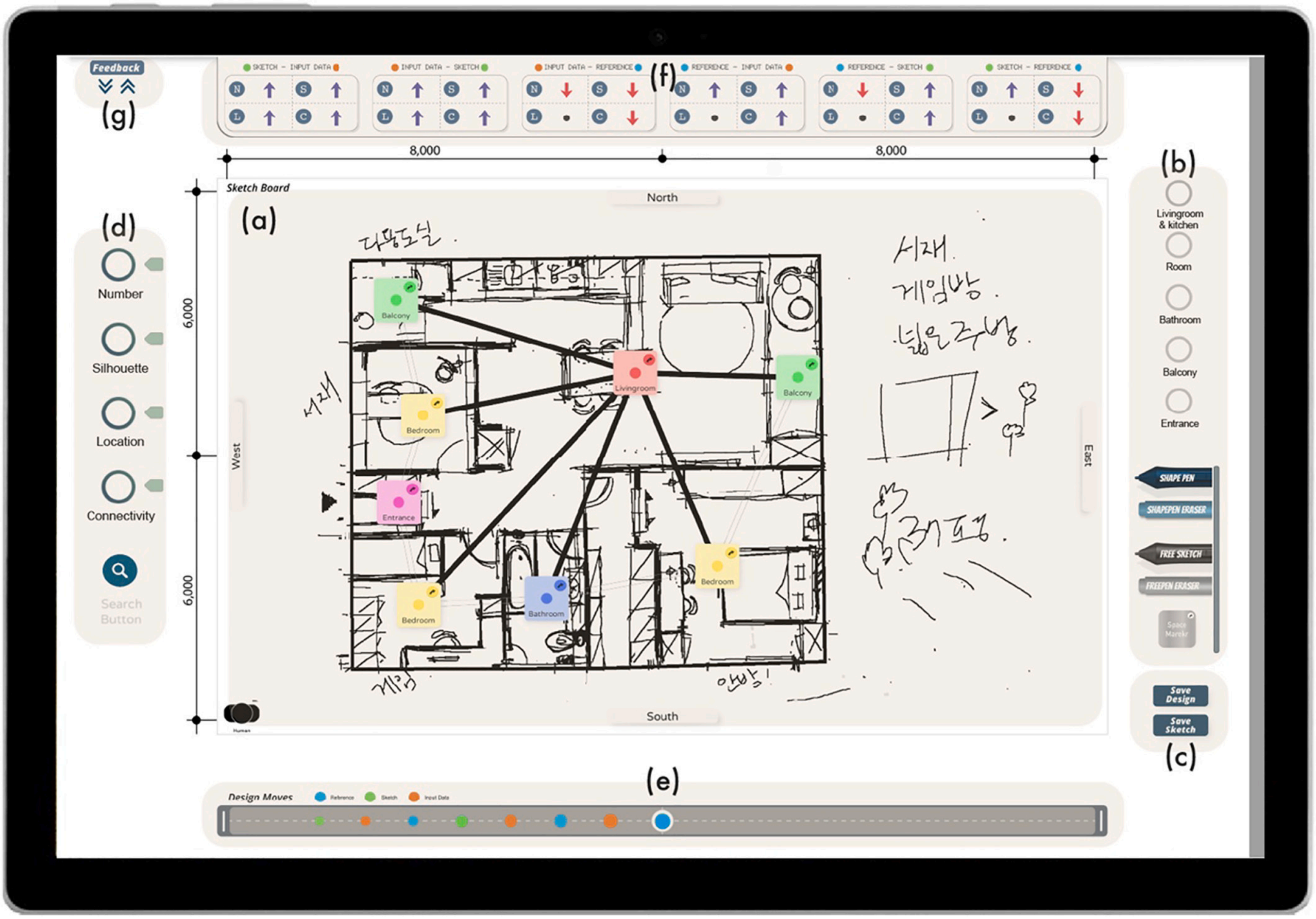

Fig. 18. Overview of the D-SDSS GUI: (a) sketch board, (b) sketch tools, (c) save buttons, (d) search buttons, (e) design moves panel, (f) feedback model, and (g) feedback model controller.

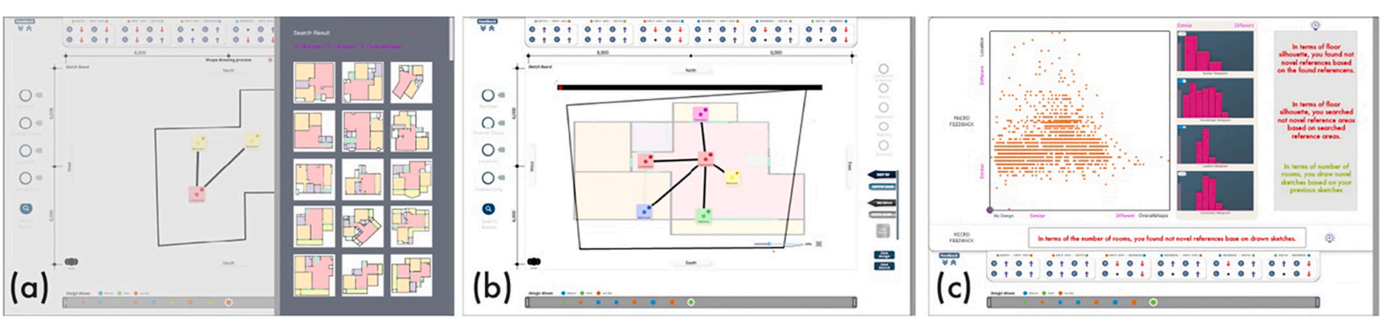

Fig. 19. System functions: (a) searching references, (b) sketching with references, and (c) providing micro and macro-feedback.

functions for each experiment. In the first experiment, a baseline system without any design feedback function was used. In this experiment, participants could use the following basic functions: sketch, reference navigation, and design move. Furthermore, in the second experiment, participants could use these basic functions and receive micro-feedback. In the third experiment, participants could use the basic functions and receive both micro- and macro-feedback. The participants were divided into three groups of seven, and seven participants were assigned to each experiment (Micro+Macro, **M** + **M**: *P1* to *P7*; Micro, **M**: *P8* to *P14*; Baseline, **B**: *P15* to *P21*). To prevent any bias that may occur during the experiment, all the experiments were conducted independently (tutorial: 15 min, experiment: 60 min, and in-depth interview: 30 min). Two design briefs with similar levels of detail were prepared. One brief was randomly assigned to each participant during the experiment. The first brief focused on designing the layout of a house for a three-member family consisting of a college student (son) and a middle-aged couple. The second design brief focused on designing a house for a retired couple in their 60s. The participants submitted their design outcomes in the form of floor plan designs (Fig. 20). After the results of the design briefs were submitted, a survey was conducted. The participants were required to complete a questionnaire based on a five-point Likert scale to evaluate the following parameters: satisfaction, system user experience, and post-task workload. Next, an in-depth 30 min interview was conducted. The participants were queried about the overall usability of the system, the differences compared to existing design methods, and the possibility of using design moves in the design process. Additionally, we asked them

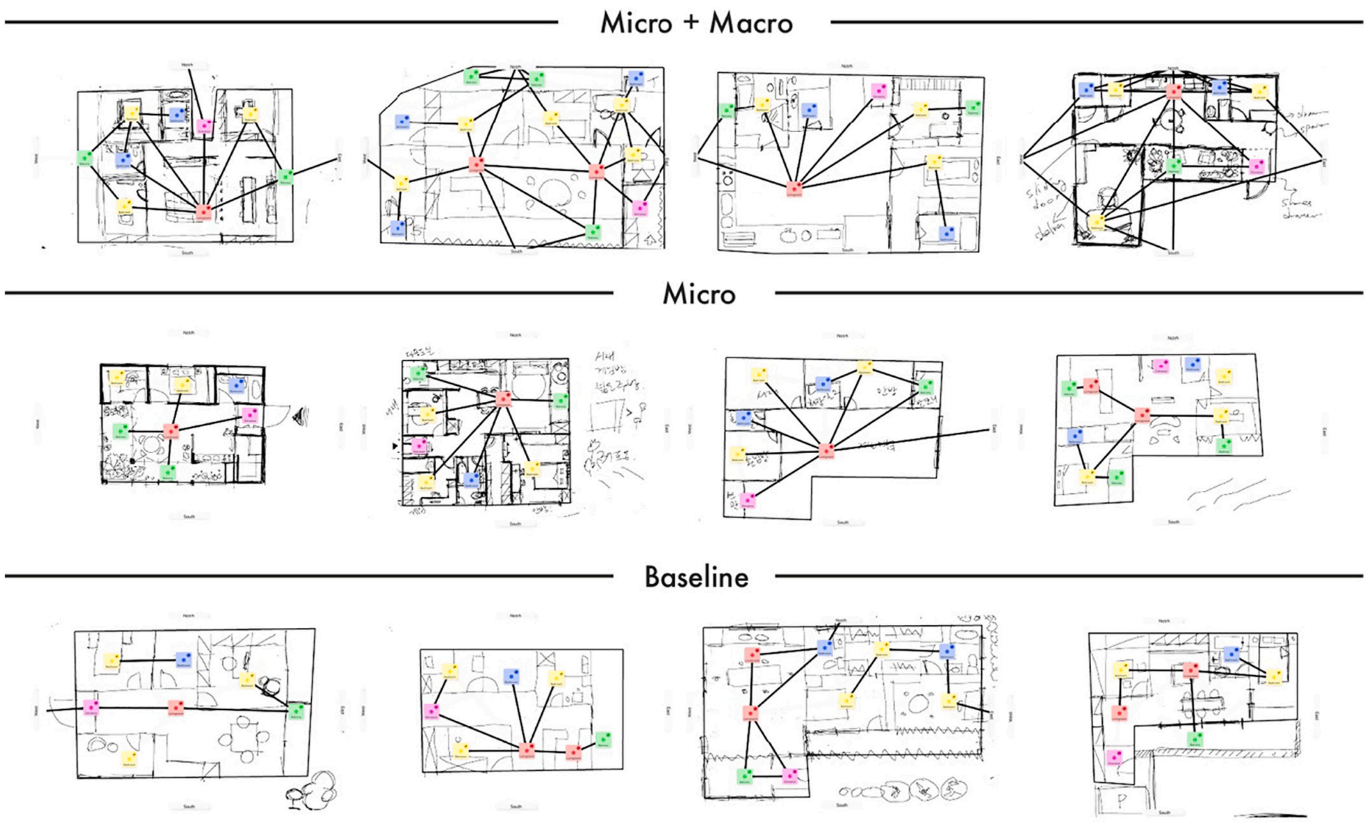

Fig. 20. 12 Design outcome samples (total 21 designs) created by participants.

questions regarding their specific experiences in terms of how the proposed system helped them solve design problems.

4.3. Experimental results and discussion

4.3.1. User behavior overview

The experimental results showed significant differences among the three groups. Generally, the **M + M** feedback system was evaluated to be at a significantly higher level than the other two systems. The **M + M** group was more satisfied with outcome quality, time efficiency, and creativity than **the M** and **B** groups. As shown in Fig. 21, in terms of satisfaction with design outcome quality, the average values of the **M + M**, **M**, and **B** feedback systems were 4.14 (*SD* = 0.38), 3.29 (*SD* = 0.95), and 2.71 (*SD* = 1.38), respectively (**M + M-B**, **M + M-M**: $p < 0.05$). In

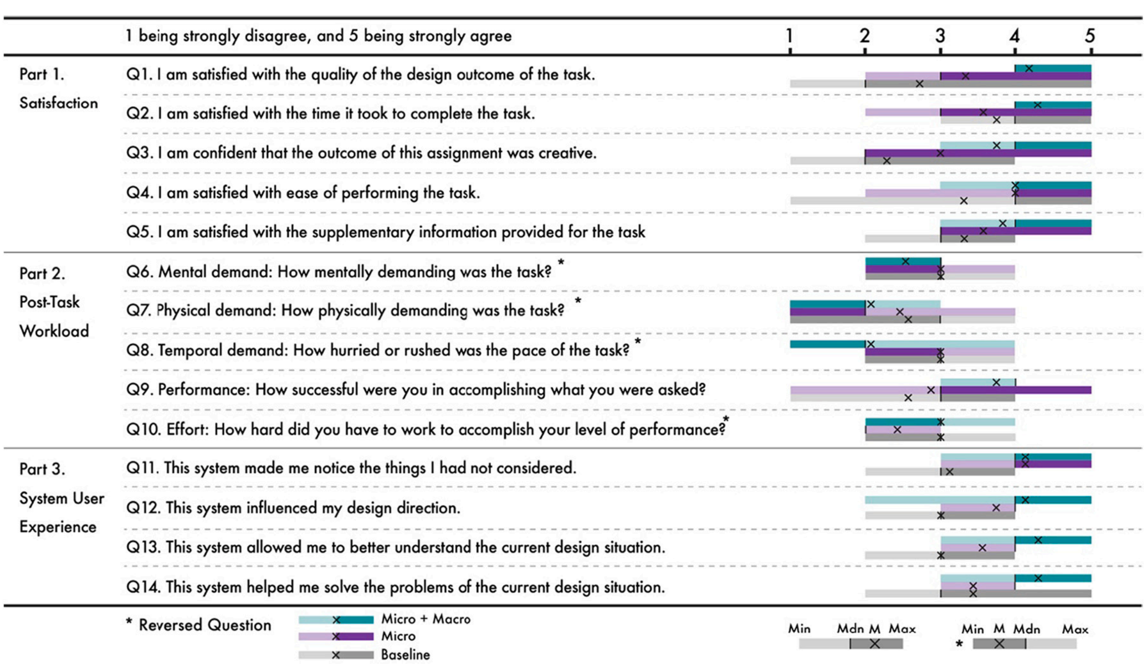

Fig. 21. Survey results on 21 experiment participants.

terms of time efficiency, the mean values for the **M + M**, **M**, and **B** systems were 4.29 ($SD = 0.49$), 3.57 ($SD = 1.13$), and 3.71 ($SD = 0.76$), respectively (**M + M-B**, **M + M-M**: $p < 0.1$). Regarding the creativity of the design outcomes, there was a significant difference ($p < 0.01$) between the **M + M** (3.71 (0.76)) and **B** (2.29 (0.95)) groups. Meanwhile, in the post-task workload questionnaires, there was a significant difference ($p < 0.05$) between the **M + M** (3.71 (0.49)) and B (2.57 (0.96)) and a marginal difference ($p < 0.1$) between the **M + M** and **M** groups (2.86 (1.35)). These survey results were supported by the comments of the **M + M** group members, "With micro-feedback, we have identified not novel design elements of our design moves. The parts identified by micro-feedback were solved by exploring new design ideas through macro-feedback." In contrast, an increase in the type and amount of feedback provided by the system implies that the user has more information to process when using the system. However, although the type and amount of feedback information increased in the order of the **B**, **M**, **and M + M** systems, there were no significant differences in terms of mental demand (**M** = 2.57 (0.53); **M** = 3.00 (0.82); B = 3.00 (0.82)), physical demand (**M + M** = 2.14 (0.69); **M** = 2.43 (1.13); B = 2.57 (0.98)), and effort (**M + M** = 3.25 (0.96); **M** = 2.25 (0.50); B = 3.00 (0.82)). This result indicates **that the M + M** system's feedback supported the designer in effectively solving the design problem, although it contained the greatest amount of information among the three systems. *P18* and *P21* using the **B** system replied, "We need additional information that can use a large number of design references more efficiently." The **M** group also responded, "When I try to think about how to solve the problem identified from micro-feedback, it was difficult to know what to do specifically." These results show that, if the amount of information provided by the system increases, it is crucial to provide both micro- and macro-feedback in the design process.

However, both **M + M** and **M** groups provided design feedback, but there were significant differences between them. We checked the reason for this result in the system user experience survey and in-depth interviews. Through the design feedback, **M + M** and **M** groups could be more stimulated by considering new thinking than the **B** group (**M + M** = 4.14 (0.69); **M** = 4.14 (0.69); **B** = 3.14 (0.90); **M + M-B**, **M-B**: $p < 0.05$). These systems also influenced the user's design direction (**M + M** = 4.14 (1.07); **M** = 3.71 (0.49); **B** = 3.00 (0.81); **M + M-B**, **M-B**: $p < 0.05$). However, **the M + M** system provides micro- and macro-feedback, whereas the **M** system provides only micro-feedback. The impact of this difference was revealed in *Q13* and *Q14* (Fig. 21). Through micro- and macro-feedback, the **M + M** group could better understand the design situation (**M + M** = 4.29 (0.76); **M** = 3.57 (0.53); **B** = 3.00 (0.82); **M + M-B**, **M + M-M**: $p < 0.05$), and the **M + M** system could help the users to solve the design problem (**M + M** = 4.29 (0.76); **M** = 3.43 (0.53); **B** = 3.43 (0.98); **M + M-B**, **M + M-M**: $p < 0.05$). **M** system users (*P9*, *P11*, and *P14*) replied, "It was difficult to figure out a solution using the provided feedback method." Additionally, *P2* stated that "micro-feedback should not only provide information regarding increases/decreases in entropy but also regarding overall design trends." In summary, micro-feedback analyzed the design moves in real time, but it showed no significant difference compared to the baseline system because it did not present specific solutions. In contrast, the **M + M** system, which also provides macro-feedback to highlight unexplored design references, yielded the best results among the three experiments.

A design process with a high entropy value is deemed a creative design process (Kan and Gero, 2008). The entropy values of an ideagraphy change as the participant continually makes either similar or dissimilar design moves. To increase the entropy value, similar design moves should be used sporadically. We analyzed the entropy values of the 36 ideagraphies to evaluate the design processes of the participants (24 ideagraphy values from micro-feedback and 12 ideagraphy values from macro-feedback). The results were derived using average entropy values for each type of ideagraphy. Compared to those of the other experiments, all the entropy values of the **M + M** experiment were higher for every ideagraphy, except for the I—I ideagraphy. The reason for no difference in I—I was confirmed in participants' comments (*P7*, *P14*, and *P21*), "I inputted the floor plan search query consistently to find the references that satisfy the design brief condition." In the entropy result, as shown in Fig. 22, the values related to sketches and references were the highest for the **M + M** group. Of the three groups, the **M + M** group experienced the most novel sketching processes (S-S: **M + M** = 13.12 (3.46); **M** = 6.23 (0.92); **B** = 5.73 (1.04)). The **M + M** group also searched for novel references that differed from their sketches (S-R: **M + M** = 5.93 (5.88); **M** = 3.58 (2.31); **B** = 1.75 (1.59)), created novel sketches different from their references (R-S: **M + M** = 6.10 (4.58); **M** = 3.01 (1.74); **B** = 2.31 (1.97)), and experienced the most helpful reference search process (R-R: **M + M** = 9.97 (1.58); **M** = 5.70 (0.64); **B** = 1.97 (0.21)). There were significant differences between the **M + M** and **M** groups and between the **M + M** and **B** groups ($p < 0.01$).

Moreover, to analyze the differences in the produced design moved among the three feedback conditions, we counted and averaged the number of design move types per group (Fig. 23). Evidently, the **M + M** group produces the most *Sketch_dms* (**M + M** = 7.43 (2.64); **M** = 3.57 (2.07); **B** = 3.57 (1.27)), *Reference_dms* (**M + M** = 6.57 (4.00); **M** = 3.29 (1.38); **B** = 2.00 (1.29)) and *Inputdata_dms* (**M + M** = 5.14 (1.35); **M** = 3.43 (1.72); **B** = 4.00 (1.41)) moves. There were significant differences between the **M + M** and the other groups in the number of *Sketch_dms* and *Reference_dms* ($p < 0.01$). This result indicates that, with the **M + M** system feedback, users can make more design decisions during the spatial design process.

Based on the analyses above, we confirmed that macro-feedback helped users to explore and create novel designs. *P2* replied that macro-feedback was useful for developing designs by exploring novel designs in the late conceptual design phase, where designs might become stagnant. Additionally, *P3* and *P6* stated that "The design exploration map of macro-feedback was helpful in that I was able to define the x and y axes and find novel references." Furthermore, *P4* replied, "I tried to create a novel design by finding novel references using macro-feedback." Despite the different design styles of the participants, the participants had largely positive responses regarding the proposed system. According to the in-depth interviews, the contributions of the proposed system were categorized into the following four sections: 1) navigation of unexplored design space; 2) re-evaluation of design moves; 3) interaction with designs; and 4) design idea embodiment. Subsequently, the application of D-SDSS was described.

4.3.2. Navigation of unexplored design space

Macro-feedback provides a histogram and a scatter plot of the similarity distribution obtained by comparing a designer's sketch to the entire reference database. *P2* replied that, "It helped me find the reference that was the most different from my sketch in the early design phase when nothing was decided yet." Additionally, *P1* and *P6* said, "Macro-feedback told us how to solve the current design problems and functioned as a compass that could help us navigate new areas." Similarly, *P4* replied, "I looked at the problematic area in the side note and reflected it on the scatter plot's axis to search for a novel reference." However, **M** system users (*P8*, *P9*, *P12*, and *P14*) who only used micro-feedback pointed out that micro-feedback informed the designer regarding incorrect areas but did not inform them about specific correction methods. In this respect, the **M + M** group answers indicate that macro-feedback can complement micro-feedback. Therefore, the feedback of the **M + M** system helped designers explore novel reference areas and assisted them in creating new designs.

4.3.3. Re-evaluation of design moves

The recording function for user design moves was included in all the systems used in the experiments. All the participants thought that "It is important to look at the design process that has been performed so far using the design move function." *P2*, *P8*, and *P15* indicated that they recalled their design processes by using the design moves. *P4* replied, "I think design moves can be used when creating a novel design by

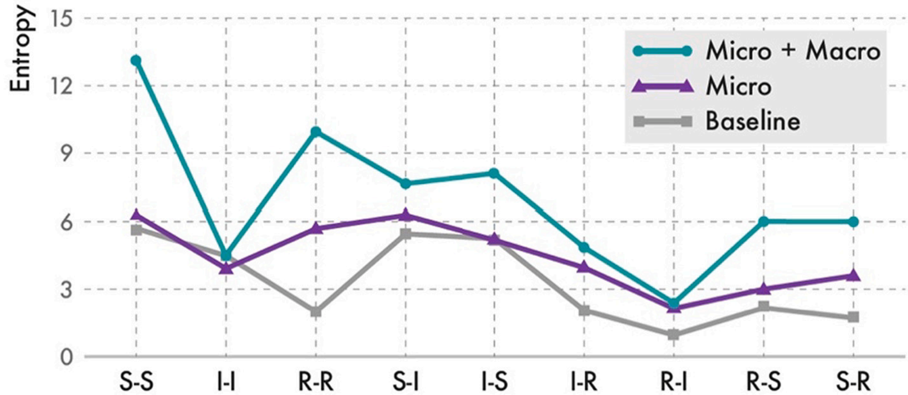

Fig. 22. Entropy Results.

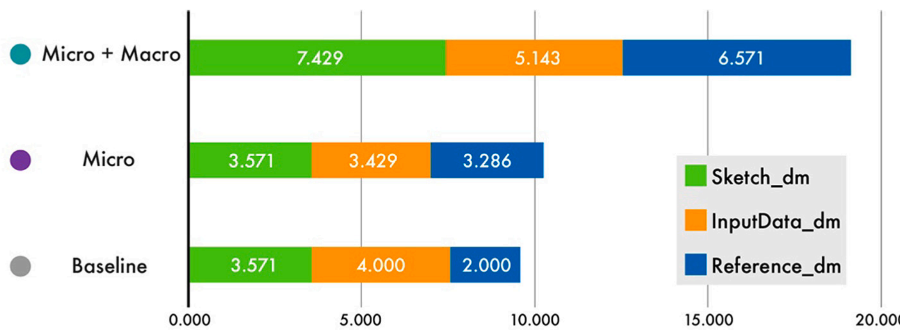

Fig. 23. Produced design moves per group.

combining reference design moves that have been stored previously." *P16* and *P17* replied, "You can check the ideas you thought of initially or information you missed using design moves." *P10* said, "I used a design move to determine what I thought when I was stuck on a design idea." Additionally, *P9* noted that the design moves could be used as a repository to archive client requests. Moreover, *P7* said, "By looking back at the design move list, I can decide the next design move." All the participants answered that the more complex and longer the design process, the more useful the design moves. Therefore, the design move recording functionality of the proposed system helped to check and develop design processes; further, it was useful for complex design processes.

4.3.4. *Interaction with designs to make creative design decisions*

Micro-feedback and macro-feedback were complementary. Micro-feedback evaluated the design status in real time, so that the designer did not feel coerced to finalize the current design. Alternatively, macro-feedback helped designers create novel designs. *P8* and *P14* said, "Because of feedback, I was not complacent with my current design. It seems that feedback provided an opportunity to think about something new." *P10* replied, "when I design by myself, a longer time may be required, but this process was accelerated by the feedback." Additionally, *P9* and *P2* said, "I tried to find a novel reference because I saw the sign indicating that the current reference was stagnant." Based on these responses, we concluded that the feedback stimulated novel design attempts and helped designers when their design ideas became stagnant. **M + M** and **M** group participants, except for *P1* and *P13*, responded saying, "I tried to change my design based on the micro-feedback." However, *P1* and *P13* were not significantly affected by the feedback, as indicated in their reply, "Because there was a design that was already in my mind, feedback did not affect it." Additionally, *P1* identified themself as a stubborn person with strong design ideas. Nevertheless, *P1* and *P13* stated, "Because of the design I had already thought about, the feedback did not affect me, but I think that receiving feedback in real time is a big advantage." Thus, we confirmed that the proposed feedback method stimulated designers and supported them in trying novel design ideas to create creative design outcomes.

4.3.5. *Design idea embodiment through reliable feedback*

In the survey, we queried the participants regarding the best time to provide feedback during the development of design ideas. Responses were divided into two groups. The first group (*P1*, *P3-P10*, *P12*, and *P13*) suggested that when an idea was being developed, feedback should be provided to clarify the ideas or to ensure that the designer did not stagnate on a single idea. The second group (*P2*, *P11*, and *P14*) indicated that feedback should be provided after the overall design idea was determined to confirm their design idea. We also asked participants about the reliability of their feedback. The prevailing opinion was that "the feedback is objective and consistent'." *P10* stated, "I was able to trust the feedback because it was based on my design process." Additionally, *P1*, *P2*, and *P8* answered, "This feedback was different from the one given by a colleague, senior designer, or professor because I could accept or ignore it." Moreover, *P11* replied, "Compared to general design feedback, using this system saves time because less time is required to think about accepting or rejecting feedback." To confirm the reliability of the feedback, the participants were asked to compare design experiences according to the 36 entropy results generated based on their design processes (Fig. 22). For example, if the entropy value of S-S_nr ideagraphy increased, we asked the participant, "Did you keep exploring novel sketches in terms of the number of rooms?" If the entropy value decreased from the middle of the graph, we asked, "Did you design using approximately the same number of rooms starting from the middle of the experiment?" The participants agreed that their design experiences and entropy results were consistent. Thus, we confirmed the reliability and usefulness of the design feedback by comparing entropy results with the design experiences of users.

4.4. D-SDSS for applications and future work

D-SDSS was a designer-centric system that provided micro- and macro-feedback by generating an ideagraphy with design moves. Although our system currently focused on the spatial design process, the D-SDSS feedback framework that stored and analyzed design moves could be used in all other design fields. Moreover, in other fields, such as information retrieval or any other idea creation processes, this feedback framework could be applied if the user's unit actions could be stored, and their similarity calculated. In the near future, we will globally release our D-SDSS on the web, making it available to many spatial designers. However, to globally release D-SDSS on the web, the system should reflect different floor plan representation methods for each country or culture. Therefore, additional sketching functions and different representations of the floor plan would be required in future studies. If D-SDSS was released on the web, it would be possible to collect a large dataset of floor plan designs and various design patterns of designers. Thus, we believe that an extended designer-centric system study was feasible.

5. Conclusion

This paper proposed a novel D-SDSS with inspirational real-time design feedback to augment the spatial design process. The main contributions of this study are summarized below.

First, we proposed "ideagraphy," an innovative method that documented and analyzed the design moves of users in real time. We believe that ideagraphy represented a novel contribution to the evaluation of design moves in real time. Notably, it aided in observing the extent to which one's design was geometrically and structurally different from the designs of other designers and in locating one's design ideas in the entire design space. Second, we developed a D-SDSS that could provide design feedback in real time based on the design moves of users and a large-scale design database. The designers who participated in the user experiments were enthusiastic about the use of the proposed system because it helped them interact with their designs, navigate novel design spaces, and reevaluate design moves (Supplementary Video 5). To the best of our knowledge, this was the first study to describe a system that could dynamically evaluate and provide both micro- and macro-feedback based on user design moves.

However, certain limitations of the proposed method were identified. First, the shape pen features were limited to correcting the curves to straight lines. Therefore, users were unable to draw streamlined curves for floor silhouettes. Additionally, the proposed system did not possess the "layer" or "undo" functions. Therefore, users had to use the "eraser" tool to redraw objects. We aim to resolve these issues in the near future, as we plan to launch the proposed system on the web. By granting access to a greater population, we expect to increase the scope of the system's contribution. Importantly, specific domain data were required to implement knowledge-based systems or case-based reasoning. Here, spatial design drawing data were used. However, the basic structure and methodology of the proposed system could be applied to all fields that require effective feedback based on existing data, such as urban planning, landscape design, and interior design based on the number, location, connectivity, and silhouettes of spatial layouts.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] J. Abualdenien, A. Borrmann, Vagueness visualization in building models across different design stages, Adv. Eng. Inform. 45 (2020) 101107, doi:10.1016%2Fj.aei.2020.101107.
[2] Ö. Akin, C. Akin, Frames of reference in architectural design: analysing the hyperacclamation (Aha-!), Des. Stud. 17 (4) (1996) 341–361, doi:10.1016%2Fs0142-694x%2896%2900024-5.
[3] Y.S.E.-D. Ashour, Optimizing Creatively in Multi-Objective Optimization (Master's Thesis), University of Calgary, Canada, 2015. doi:10.11575/PRISM/27214.
[4] S. Ban, K.H. Hyun, 3D computational sketch synthesis framework: assisting design exploration through generating variations of user input sketch and interactive 3D model reconstruction, Comput. Aided Des. 120 (2020) 102789, doi:10.1016%2Fj.cad.2019.102789.
[5] R. Baušys, B. Juodagalvienė, Garage location selection for residential house by WASPAS-SVNS method, J. Civ. Eng. Manag. 23 (3) (2017) 421–429, doi:10.3846%2F13923730.2016.1268645.
[6] M. Bernal, J.R. Haymaker, C. Eastman, On the role of computational support for designers in action, Des. Stud. 41 (2015) 63–182, doi:10.1016%2Fj.destud.2015.08.001.
[7] Z. Bilda, J.S. Gero, T. Purcell, To sketch or not to sketch? That is the question, Des. Stud. 27 (5) (2006) 587–613, doi:10.1016%2Fj.destud.2006.02.002.
[8] H. Bunke, On a relation between graph edit distance and maximum common subgraph, Pattern Recogn. Lett. 18 (8) (1997) 689–694, doi:10.1016%2Fs0167-8655%2897%2900060-3.
[9] H. Cai, E.Y.-L. Do, C.M. Zimring, Extended linkography and distance graph in design evaluation: an empirical study of the dual effects of inspiration sources in creative design, Des. Stud. 31 (2) (2010) 146–168, doi:10.1016%2Fj.destud.2009.12.003.
[10] F. Cluzel, B. Yannou, M. Dihlmann, Using evolutionary design to interactively sketch car silhouettes and stimulate designer's creativity, Eng. Appl. Artif. Intell. 25 (7) (2012) 1413–1424, https://doi.org/10.1016/j.engappai.2012.02.011.
[11] N. Cross, Creativity in design: analyzing and modeling the creative leap, Leonardo 30 (4) (1997) 311–317, doi:10.2307%2F1576478.
[12] N. Davis, C.-P. Hsiao, K. Yashraj Singh, L. Li, B. Magerko, Empirically studying participatory sense-making in abstract drawing with a co-creative cognitive agent, in: Proceedings of the 21st International Conference on Intelligent User Interfaces, 2016, pp. 196–207, doi:10.1145%2F2856767.2856795.
[13] I.G. Dino, An evolutionary approach for 3D architectural space layout design exploration, Autom. Constr. 69 (2016) 131–150, doi:10.1016%2Fj.autcon.2016.05.020.
[14] A. Dkhil, M. Gardoni, L. Belgacem, R. Houssin, Linkographic analysis of design ideation session: Idea graph representation and additional tools for analysis, in: IFIP International Conference on Product Lifecycle Management, Springer, 2018, pp. 715–725, doi:10.1007%2F978-3-030-01614-2_65.
[15] V. Eisenstadt, K.-D. Althoff, What Is the Next Step? Supporting Architectural Room Configuration Process with Case-Based Reasoning and Recurrent Neural Networks, The Thirty-Second International Flairs Conference, 2019, pp. 335–340. https://www.aaai.org/ocs/index.php/FLAIRS/FLAIRS19/paper/view/18190 (Accessed date: 1 May 2021).
[16] G. Fischer, Turning breakdowns into opportunities for creativity, Knowl.-Based Syst. 7 (4) (1994) 221–232, doi:10.1016%2F0950-7051%2894%2990033-7.
[17] G. Goldschmidt, Avoiding design fixation: transformation and abstraction in mapping from source to target, J. Creat. Behav. 45 (2) (2011) 92–100, doi:10.1002%2Fj.2162-6057.2011.tb01088.x.
[18] G. Goldschmidt, Linkography: Unfolding the Design Process, Mit Press, 2014, https://doi.org/10.7551/mitpress/9455.001.0001 (ISBN: 9780262027199).
[19] G. Goldschmidt, D. Tatsa, How good are good ideas? Correlates of design creativity, Des. Stud. 26 (6) (2005) 593–611, doi:10.1016%2Fj.destud.2005.02.004.
[20] K. Grace, M.L. Maher, D. Fisher, K. Brady, Data-intensive evaluation of design creativity using novelty, value, and surprise, Int. J. Des. Creat. Innovat. 3 (3–4) (2015) 125–147, doi:10.1080%2F21650349.2014.943295.
[21] V. Granadeiro, J.P. Duarte, J.R. Correia, V.M. Leal, Building envelope shape design in early stages of the design process: integrating architectural design systems and energy simulation, Autom. Constr. 32 (2013) 196–209, doi:10.1016%2Fj.autcon.2012.12.003.
[22] M.D. Gross, The electronic cocktail napkin—a computational environment for working with design diagrams, Des. Stud. 17 (1) (1996) 53–69, doi:10.1016%2F0142-694x%2895%2900006-d.
[23] G. Hatcher, W. Ion, R. Maclachlan, M. Marlow, B. Simpson, N. Wilson, A. Wodehouse, Using linkography to compare creative methods for group ideation, Des. Stud. 58 (2018) 127–152, doi:10.1016%2Fj.destud.2018.05.002.
[24] K.H. Hyun, J.-H. Lee, Balancing homogeneity and heterogeneity in design exploration by synthesizing novel design alternatives based on genetic algorithm

and strategic styling decision, Adv. Eng. Inform. 38 (2018) 113–128, doi:10.1016%2Fj.aei.2018.06.005.
[25] S. Jagtap, Design creativity: refined method for novelty assessment, Int. J. Des. Creat. Innovat. 7 (1–2) (2019) 99–115, doi:10.1080%2F21650349.2018.1463176.
[26] S.M. Jeon, J.H. Lee, G.J. Hahm, H.W. Suh, Automatic CAD model retrieval based on design documents using semantic processing and rule processing, Comput. Ind. 77 (2016) 29–47, doi:10.1016%2Fj.compind.2016.01.002.
[27] Y.E. Kalay, Redefining the role of computers in architecture: from drafting/modelling tools to knowledge-based design assistants, Comput. Aided Des. 17 (7) (1985) 319–328, doi:10.1016%2F0010-4485%2885%2990165-4.
[28] J.W.T. Kan, J.S. Gero, Acquiring information from linkography in protocol studies of designing, Des. Stud. 29 (4) (2008) 315–337, doi:10.1016%2Fj.destud.2008.03.001.
[29] J. Kang, K. Zhong, S. Qin, H. Wang, D. Wright, Instant 3D design concept generation and visualization by real-time hand gesture recognition, Comput. Ind. 64 (7) (2013) 785–797, doi:10.1016%2Fj.compind.2013.04.012.
[30] H.-S. Kim, S.-B. Cho, Application of interactive genetic algorithm to fashion design, Eng. Appl. Artif. Intell. 13 (6) (2000) 635–644, doi:10.1016%2Fs0952-1976%2800%2900045-2.
[31] S.-J. Kim, J.-H. Lee, A study on metadata structure and recommenders of biological systems to support bio-inspired design, Eng. Appl. Artif. Intell. 57 (2017) 16–41, doi:10.1016%2Fj.engappai.2016.10.003.
[32] C.K. Kwong, H. Jiang, X. Luo, AI-based methodology of integrating affective design, engineering, and marketing for defining design specifications of new products, Eng. Appl. Artif. Intell. 47 (2016) 49–60, doi:10.1016%2Fj.engappai.2015.04.001.
[33] C. Langenhan, M. Weber, M. Liwicki, F. Petzold, A. Dengel, Graph-based retrieval of building information models for supporting the early design stages, Adv. Eng. Inform. 27 (4) (2013) 413–426, doi:10.1016%2Fj.aei.2013.04.005.
[34] C. Lee, S. Kim, D. Han, H. Yang, Y.-W. Park, B.C. Kwon, S. Ko, GUIComp: A GUI design assistant with real-time, multi-faceted feedback, in: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 2020, pp. 1–13, doi:10.1145%2F3313831.3376327.
[35] J.-H. Lee, T.-C. Li, Supporting user participation design using a fuzzy analytic hierarchy process approach, Eng. Appl. Artif. Intell. 24 (5) (2011) 850–865, doi:10.1016%2Fj.engappai.2011.01.008.
[36] J. Liu, J. Liu, X. Yan, B. Peng, A heuristic algorithm combining Pareto optimization and niche technology for multi-objective unequal area facility layout problem, Eng. Appl. Artif. Intell. 89 (2020) 103453, doi:10.1016%2Fj.engappai.2019.103453.
[37] J. Matejka, M. Glueck, E. Bradner, A. Hashemi, T. Grossman, G. Fitzmaurice, Dream lens: Exploration and visualization of large-scale generative design datasets, in: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, 2018, pp. 1–12, doi:10.1145%2F3173574.3173943.
[38] D.A. Min, K.H. Hyun, S.-J. Kim, J.-H. Lee, A rule-based servicescape design support system from the design patterns of theme parks, Adv. Eng. Inform. 32 (2017) 77–91, doi:10.1016%2Fj.aei.2017.01.005.
[39] Y. Oh, M.D. Gross, E.Y.-L. Do, Computer-aided critiquing systems lessons learned and new research directions, in: Proceedings of the 13th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), 2008, pp. 161–167. http://papers.cumincad.org/cgi-bin/works/paper/caadria2008_19_session3a_161 (Accessed date: 1 May 2021).
[40] Y. Oh, S. Ishizaki, M.D. Gross, E.Y.-L. Do, A theoretical framework of design critiquing in architecture studios, Des. Stud. 34 (3) (2013) 302–325, doi:10.1016%2Fj.destud.2012.08.004.
[41] L. Olsen, F.F. Samavati, M.C. Sousa, J.A. Jorge, Sketch-based modeling: a survey, Comput. Graph. 33 (1) (2009) 85–103, doi:10.1016%2Fj.cag.2008.09.013.
[42] R. Passini, Wayfinding design: logic, application and some thoughts on universality, Des. Stud. 17 (3) (1996) 319–331, doi:10.1016%2F0142-694x%2896%2900001-4.
[43] G.T. Perry, K. Krippendorff, On the reliability of identifying design moves in protocol analysis, Des. Stud. 34 (5) (2013) 612–635, doi:10.1016%2Fj.destud.2013.02.001.
[44] A.T. Purcell, J.S. Gero, Drawings and the design process: a review of protocol studies in design and other disciplines and related research in cognitive psychology, Des. Stud. 19 (4) (1998) 389–430, doi:10.1016%2Fs0142-694x%2898%2900015-5.
[45] K.-F. Richter, B. Weber, B. Bojduj, S. Bertel, Supporting the designer's and the user's perspectives in computer-aided architectural design, Adv. Eng. Inform. 24 (2) (2010) 180–187, doi:10.1016%2Fj.aei.2009.08.012.
[46] E. Rodrigues, A.R. Gaspar, Á. Gomes, An evolutionary strategy enhanced with a local search technique for the space allocation problem in architecture, part 1: methodology, Comput. Aided Des. 45 (5) (2013) 887–897, doi:10.1016%2Fj.cad.2013.01.001.
[47] P. Sarkar, A. Chakrabarti, Assessing design creativity, Des. Stud. 32 (4) (2011) 348–383, doi:10.1016%2Fj.destud.2011.01.002.
[48] J.A. Self, E. Pei, Reflecting on design sketching: implications for problem-framing and solution-focused conceptual ideation, Arch. Des. Res. 27 (3) (2014) 65–87, https://doi.org/10.15187/adr.2014.08.111.3.65.
[49] C.E. Shannon, A mathematical theory of communication, Bell Syst. Tech. J. 27 (3) (1948) 379–423, doi:10.1002%2Fj.1538-7305.1948.tb01338.x.
[50] K. Son, H. Chun, K.H. Hyun, Ambiguous vs., Concrete: Identifying the effect of design references with various level of details on designer's creativity in the early design phase, in: Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), 2020, pp. 587–596. http://papers.cumincad.org/cgi-bin/works/paper/caadria2020_371 (Accessed date: 1 May 2021).
[51] K. Son, H. Chun, S. Park, K.H. Hyun, C-space: An interactive prototyping platform for collaborative spatial design exploration, in: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 2020, pp. 1–13, doi:10.1145%2F3313831.3376452.
[52] C. Tian, M. Masry, H. Lipson, Physical sketching: reconstruction and analysis of 3D objects from freehand sketches, Comput. Aided Des. 41 (3) (2009) 147–158, doi:10.1016%2Fj.cad.2009.02.002.
[53] R. Van der Lugt, Developing a graphic tool for creative problem solving in design groups, Des. Stud. 21 (5) (2000) 505–522, doi:10.1016%2Fs0142-694x%2800%2900021-1.
[54] C.C. Wang, M.M. Yuen, Sketch based mesh extrusion with remeshing techniques, in: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference vol. 80210, American Society of Mechanical Engineers, 2001, pp. 731–738, doi:10.1115%2Fdetc2001%2Fcie-21305.
[55] D. Yang, S. Ren, M. Turrin, S. Sariyildiz, Y. Sun, Multi-disciplinary and multi-objective optimization problem re-formulation in computational design exploration: a case of conceptual sports building design, Autom. Constr. 92 (2018) 242–269, doi:10.1016%2Fj.autcon.2018.03.023.
[56] K. Yang, Z. Li, J. Ye, Freely-drawn sketches interpretation using SVMs-chain modeling, Eng. Appl. Artif. Intell. 25 (2) (2012) 392–403, doi:10.1016%2Fj.engappai.2011.10.001.
[57] A. Zoran, R. Shilkrot, J. Paradiso, Human-computer interaction for hybrid carving, in: Proceedings of the 26th annual ACM symposium on User Interface Software and Technology, 2013, pp. 433–440, doi:10.1145%2F2501988.2502023.