A FRAMEWORK FOR MULTIVARIATE DATA BASED FLOOR PLAN RETRIEVAL AND GENERATION

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Abstract. Spatial designers explore various design references in the design process. These design references significantly impact the quality of design outcomes and the process. Therefore, it is crucial to provide useful designs through the retrieval or generation process to spatial designers. To do this, a methodology must be developed to identify and quantify the floor plan's multivariate design data. Through quantifying various design data, the retrieval and generation process can provide appropriate designs in many ways. This study proposed a new floor plan design framework for retrieval and generation with newly quantified design data. For validation of this framework, we conducted a floor plan retrieval and generation process. Newly quantified design data show usability in both processes. We also compare our framework with previous studies for validation. The comparison results show that our framework utilizes the most diverse design data of the floor plan.

Keywords. Design quantification; Multivariate data; Floor plan design; Design retrieval; Design generation.

1. Introduction

Given that a design is the outcome of a complex design process, spatial design results contain various design data (Sönmez, 2018). Thus, spatial designers are also familiar with exploring design solutions from previous design references (Maher & Silva Garza, 1997). However, the design reference has a significant impact on the results (Goldschmidt, 2011). Therefore, it is crucial to provide the spatial designer with an appropriate design for the situation through the design retrieval and generation process. To do this, a methodology of identifying and quantifying multivariate design data in a spatial design should first be established.

In this context, floor plan design retrieval and generation studies have been conducted. For example, Ahmed et al. (2014) and Son et al. (2020) proposed a floor plan retrieval system a.SCatch and C-Space. These two systems retrieve designs by calculating the similarity of floor plan design data. On the other side, EASE (Dino, 2016), SPG (Das et al., 2016), and Graph2Plan (Hu et al., 2020) generate new floor plan designs through a genetic algorithm and convolutional neural networks (CNNs). These systems use quantified design data as a design constraint when generating new floor plans. Many design data of floor plans

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have been used in the retrieval and generation process. However, previous studies insufficiently used design data, such as a room's shape and relationships crucial in floor plan design (Arvin & House 2002). For more accurate and efficient retrieval and generation results, more various design data should be quantified and utilized.

Upon this background, this study suggests a new multivariate framework of floor plans by identifying and quantifying new design data. To this end, we conducted three tasks: 1. Identifying and quantifying floor plan design data (Room shape layout, Room shape, Adjacency & Connectivity of rooms); 2. Image processing of 2101 actual floor plans to extract quantified design data. 3. Performing design retrieval and proposing new generation methods based on quantified design data.

2. Related works

2.1. DESIGN QUANTIFICATION

A spatial designer considers various design data to create a design. According to Sönmez (2018), the design contains data describing a complex and ambiguous design process. He therefore emphasized the quantification of data from design references to support designers. Many researchers have conducted design quantification studies. Hekkert et al. (2003) suggested design style quantification by identifying a style's design component. Likewise, Hyun & Lee (2018) quantified a car's design data and calculated the similarity between car designs. Through this, they analyzed each car brand's trend as a marketing strategy. In architectural design, Langehan & Petzold (2010) conducted floor plan retrieval by calculating the similarity of design data. Dino (2016) conducted floor plan generation through quantification of design data. As seen in previous studies, design quantification is an essential process for analyzing, retrieving, and generating designs. Thus, as more design data are quantified, more accurate design analysis, retrieval, and generation are possible.

2.2. FLOOR PLAN RETRIEVAL

In architectural design, floor plan retrieval studies were conducted to provide designers with appropriate floor plan designs. Spatial designers consider topological and geometrical design data to create a floor plan (Arvin & House, 2002). Topological data include the relationship of rooms, and the geometrical elements include the shape and size of the rooms. Langehan & Petzold (2010) proposed a retrieval method using the floor plan design's semantic fingerprint data. a.SCatch (Ahmed et al., 2014) is a sketch-based floor plan retrieval system that applies this semantic fingerprint concept. They extracted each room's type and the direct/indirect relationship data from the floor plan into one graph query. However, the query has no location data considering cardinal direction and room shape data. Son et al. (2020) also proposed a C-Space that retrieves floor plan design. C-Space uses the number of rooms, direct connectivity of rooms, and the floor silhouette data. However, C-Space does not consider the room's shape and adjacency data. For an accurate and appropriate design retrieval process, it is necessary to increase the search dimension by quantifying various design data.

2.3. FLOOR PLAN GENERATION

To support spatial designers, floor plan generation research has been conducted. EASE (Dino, 2016) and SPG (Das et al., 2016) are systems that set design constraints with design data, such as the room's width, height, center point, number, and size. They generate a floor plan design with quantified design data and optimize it through a genetic algorithm. Wu et al. (2019) and Hu et al. (2020) generate a floor plan by learning the actual floor plan design based on the Convolutional Neural Network (CNN). They optimized the walls' location in the floor plan to avoid wrong designs. However, as in floor plan retrieval studies, generation studies did not sufficiently consider the room's shape and relationship data. To generate useful and accurate floor plan designs, these data should be sufficiently considered. Therefore, in this study, we quantify the room's shape and adjacency/connectivity design data.

3. Methodology

3.1. IDENTIFYING AND QUANTIFYING DESIGN DATA

Son et al. (2020) used 16 grids and aspect ratio information of a bounding box to quantify the floor silhouette. These 16 grids are the shape's area occupying ratio for each grid. In this study, developing this method, the shape's grids were generated as binary array data depending on whether the shape exists in the grid's center point. Also, to improve the grid resolution, we make 32*32 grids (Figure 1-a). The relationship between spaces is crucial topological design data in the floor plan (Arvin & House, 2002). Hu et al. (2020) quantified all rooms' adjacency relationships in a graph by node and edge (Figure 1-b). Using this method, we quantify the direct and indirect relationship between rooms as an adjacency and connectivity graph.

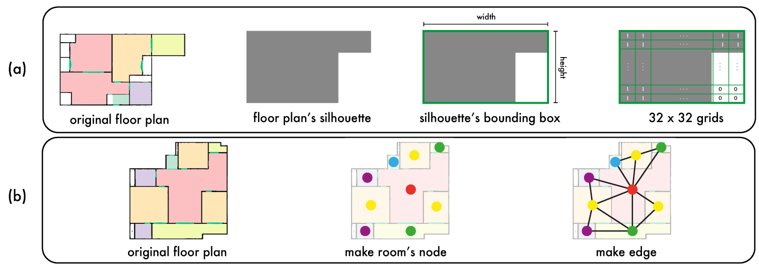

Figure 1. Floor plan's 32*32 grids and adjacency graph.

3.1.1. Room shape layout

Room shape layout (RSL) data indicate the shape and location of rooms on a floor plan. Floor plan design is often conducted within a fixed floor silhouette. Using RSL data, designers can retrieve or generate floor plan designs in any shape and location within a given silhouette. We conducted quantification in the following way. First, we create a bounding box based on a floor silhouette. Next, we make

32*32 grids in this bounding box (figure 2-b). Finally, the width, height of the bounding box, 32*32 grids, and area ratio data of the room are extracted. These data are saved in JSON format. We created RSL data of each room type (figure 2-c).

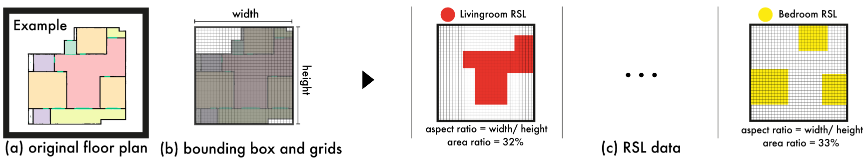

Figure 2. Room shape layout (RSL) quantification process.

3.1.2. Room shape

Room shape (RS) is the shape data of one room. The design data, unlike the room layout, are created with a bounding box for one room. With RS data, it is possible to retrieve or create the room's shape regardless of the floor silhouette. For RS quantification, we extract the 32*32 grids, the corner points and aspect ratio of the bounding box, the area ratio of room, and the room type and ID information (Figure 3).

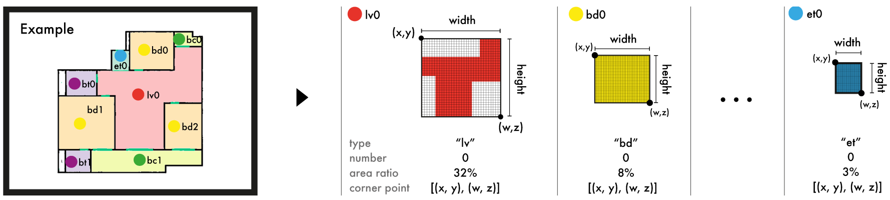

Figure 3. Room shape(RS) quantification process.

3.1.3. Room adjacency and connectivity graph

In the adjacency graph of Hu et al. (2020), the room's direct and indirect relationships are included without distinction. The direct connectivity between rooms is significant in a floor plan design (Arvin & House, 2002). Son & Hyun (2021) created the relationship graph of rooms by separating the direct connectivity and adjacency data (figure 4). In addition, an adjacency graph (figure 4-a) was created by adding the relationship with a cardinal direction. In this study, we use these graphs to conduct the floor plan retrieval and generation.

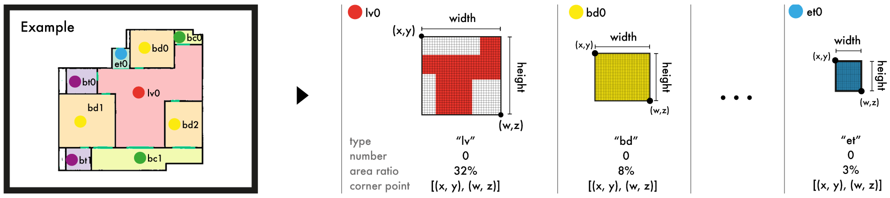

Figure 4. Adjacency and connectivity of room quantification process.

3.2. SIMILARITY CALCULATION METHOD

3.2.1. Room shape layout

RSL contains the 32*32 grids, aspect ratio (width/height) of the bounding box, and area ratio data for each room type. To calculate the similarity of RSL, we utilized these three data. Assuming that two RSL a and b are compared, grid vectors (GV_a and GV_b) are obtained by converting 32*32 grids into one vector. AS_a and AS_b are the aspect ratio, and AR_a and AR_b are the area ratio values of a and b. We use cosine similarity and subtract the result value from 1 (Eq 1) for comparing two GV data. The aspect ratio (AS) represents a scaler of a bounding box. For example, a square and a rectangle have the same 32*32 grids but differ in AS. To reflect the AS difference, we calculated this difference (Eq 2). We also considered the difference in area ratio (AR), which means the relative area (Eq 3). To adjust each value from 0 to 1, we normalized the AR and AS values to their respective maximum and minimum values. Also, to reflect the importance of each element, we multiplied weight values (W_{GV}, W_{AR}, W_{AS}). The final RSL similarity is obtained by averaging the three similarities. This RSL similarity calculation method reflects the rooms' static occupied grid shape, orientation, scale, and relative size, per room type.

$$Similarity_{GV} = \left\{1 - \text{cosine similarity}\left(\vec{GV_a}, \vec{GV_b}\right)\right\} \times W_{GV} \tag{1}$$

$$Similarity_{AR} = |\text{norm}(AR_a) - \text{norm}(AR_b)| \times W_{AR} \tag{2}$$

$$Similarity_{AS} = |\text{norm}(AS_a) - \text{norm}(AS_b)| \times W_{AS} \tag{3}$$

3.2.2. Room shape

The RS similarity is calculated in the same way as the RSL similarity calculation method (Eqs 1, 2, 3). The difference is that RS data are made by creating a bounding box on a room's shape (Figure 3). However, to calculate the RS similarity of a room and a floor plan, or between two floor plans, the RS similarity calculation process should consider the number of rooms to be compared. If the designer inputs two bedrooms, a and b, the floor plan design with only one bedroom cannot obtain RS similarity (Figure 5-a). On the other hand, in the floor plan with two bedrooms (d, e), as shown in Figure 5-b, we can obtain combinations of similarity (a-d, b-e; a-e, b-d). To obtain the final RS similarity value, we calculated the minimum Euclidean distance among the possible similarity combinations. This method can select the two most similar bedrooms, even in a floor plan with more than three bedrooms (Figure 5-c).

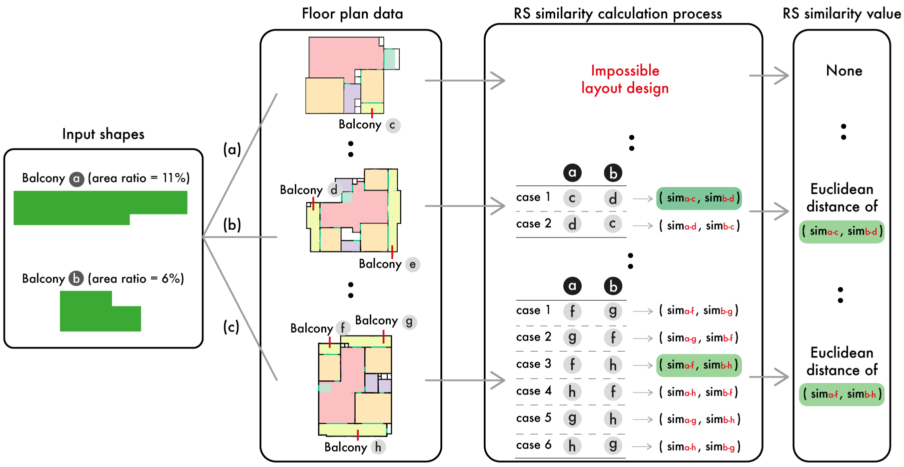

Figure 5. Room shape(RS) similarity calculation process.

3.2.3. Room adjacency and connectivity graph

To calculate the similarity between two graphs, we used the Bipartite Graph-Edit Distance (Riesen et al., 2007). Originally, Graph-Edit Distance (GED) calculates the minimum number of corrections to make the two graphs equal. However, since the original GED based on the A^* algorithm has a huge computational cost, it is difficult to calculate the similarity in real-time. Thus, to solve this problem, Son & Hyun (2021) conducted the graph similarity calculation with bipartite GED. Bipartite GED is a method that applies graph edit distance to an assignment problem. In this study, we used the Bipartite GED of GMatch4py (https:github.com/Jacobe2169/GMatch4py), a Python library.

4. Implementation and Discussion

In this study, we extracted six design data (Figure 9) from the actual 2101 floor plans. Furthermore, we implemented the multivariate framework for the retrieval and generation process, and validated the usability of the proposed design data.

4.1. FLOOR PLAN DESIGN RETRIEVAL

4.1.1. Room shape layout

By using the RSL data, 2101 floor plan design retrievals were conducted. In similarity calculations, W_{GV}, W_{AR}, and W_{AS} were set to 1. The outputs are the top 4 among the 2101 floor plans (Figure 6). The RSL similarity-based retrieval process shows the results reflecting the rooms' location and shape in the floor silhouette.

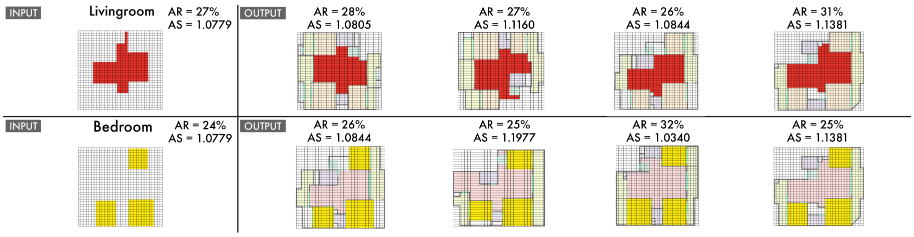

Figure 6. Room shape layout(RLS) retrieval result.

4.1.2. Room shape

RS similarity-based retrieval was performed with one living room and two balconies (Figure 7). Unlike RSL, the RS retrieval result does not consider the position within the floor silhouette. Although all weight values are set to 1, the retrieval system in future work should consider that designers can adjust the weight values according to their situation.

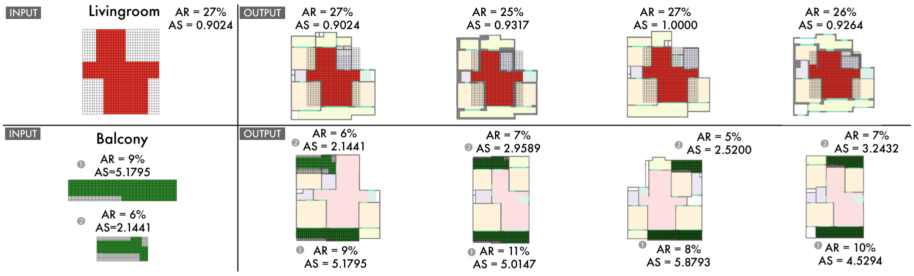

Figure 7. Room shape(RS) retrieval result.

4.1.3. Room adjacency and connectivity

The results of the room adjacency graph and connectivity graph retrieval are presented in figure 8. Since the room adjacency graph considers the cardinal direction, all the rooms' locations show similar results (Figure 8-a). However, room connectivity graphs consider only direct connectivity between rooms. Thus, the result also contains a different room layout, as in the 4th result (Figure 8-b).

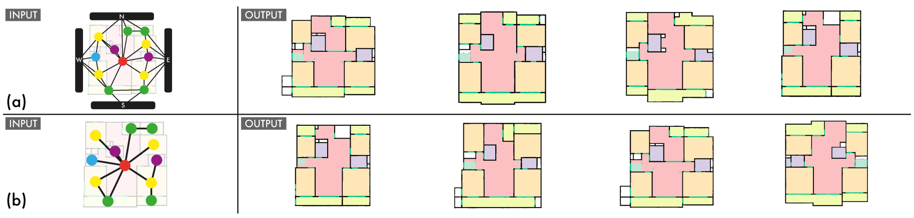

Figure 8. Adjacency & Connectivity graph retrieval result.

4.2. FLOOR PLAN DESIGN GENERATION

4.2.1. Switch and change method

The switch method is a way to generate a new floor plan design by changing all design data of two rooms. When the two rooms are changed, all floor plan design JSON data change except for the number and floor silhouette (Figure 9; 10-a). Unlike the switch method, the change method changed the type of room (Figure 10-b). When changing the type of one room, all design data except the floor silhouette are changed.

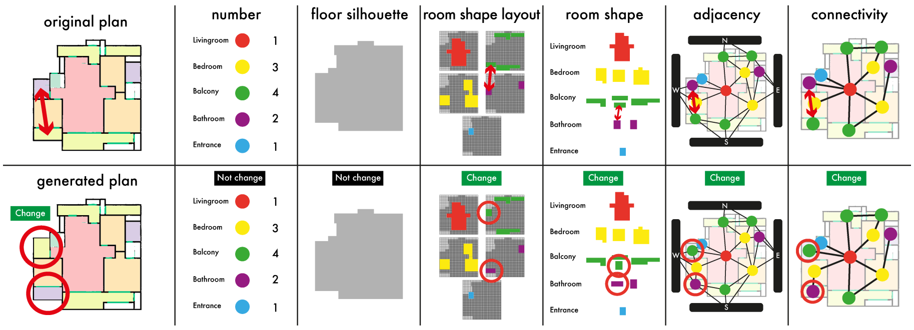

Figure 9. An example of the floor plan data editing process (Switch).

4.2.2. Result

The generated floor plan designs through switch and change are presented in figure 10. These methods are the most straightforward and precise way to use the floor plan's JSON data. When applied to the design system, these methods could also perform generation according to the design constraints. However, the floor plan design data should be further supplemented in the following way. Since the currently quantified information is focused on the room's shape and relationships, the wall and the door are not considered. If the wall and door design data are quantified and represented in the design, a more accurate floor plan image could be generated, unlike Figure 10-(b). It is also possible to create a new room shape and freely add or delete it from the floor plan. Therefore, these additional quantifications should be conducted in future work.

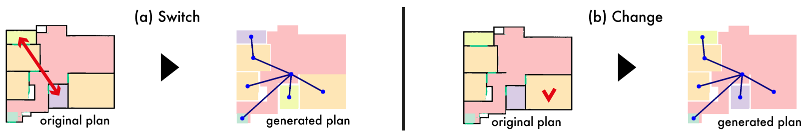

Figure 10. Floor plan design generation result.

4.3. DISCUSSION

A floor plan is a design that contains multivariate data. It is necessary to quantify various design data to retrieve and generate more accurate and useful floor plans. For validation of our framework, we compared design data from the previous floor plan design retrieval and generation research (Table 1).

Table 1. Comparison of our framework with previous studies.

Frameworks (Retrieval / Generation) \ Floor plan's design data	room type & number	floor silhouette	location of rooms	connectivity of rooms	adjacency of rooms	area ratio	cardinal directions	shape of rooms	using previous designs
Langehan & Petzold (2010)	v			v	v				
Ahmed et al. (2014)	v			v	v				
Sabri et al. (2017)	v			v	v	v			
Son et al. (2020)	v	v		v					
Dino (2016)	v	v	v			v	v		
Das et al. (2016)	v	v			v	v			
Wu et al. (2019)	v	v	v						v
Hu et al. (2020)	v	v	v		v	v			v
Our framework*	v	v	v	v	v	v	v	v	v

In the retrieval framework, various retrieval methods must be provided to obtain the desired result (Kim & Lee, 2017). The floor plan consists of many design data, but some data have not been used. Thus, quantifying new design data corresponds with increasing the search dimension. Through higher search dimensions, the designer can retrieve a floor plan design with higher accuracy. As shown in Table 1, our framework uses the most diverse design data of the floor plan. Unlike previous retrieval studies, we quantified adjacency and connectivity as different topological design data. Also, the design data related to room shapes are new data. Likewise, the generation framework needs various design data for an accurate generation. EASE (Dino, 2016) and SPG (Das et al., 2016) are likely to create wrong designs if design constraints are not sufficiently considered with various design data. Wu et al. (2019) and Hu et al. (2020) reduced this weakness through learning from actual floor plans. However, Wu et al. and Hu et al. did not consider room shape and connectivity data sufficiently. Thus, it is difficult to generate floor plans that meet various design constraints. To solve these problems, our framework utilizes the most diverse quantified design data while using an actual floor plan's data. Our generation methods use most of the actual floor plan data (Figure 9). These methods can be applied to the spatial remodeling process in which a large amount of spatial design data is maintained.

5. Conclusion

This study proposed a new multivariate floor plan design framework by quantifying design data. The floor plan retrieval process showed the results that well reflected the characteristics of each design data. In the generation, a new floor plan was generated using the switch and change method. These retrieval and generation methods can be applied immediately to a spatial design support system. As a result, our framework utilizes the most diverse design data than the framework of previous studies. However, for more accurate and various generation methods, design data such as walls and doors will need to be quantified. In future work, we will study additional quantifications and new generation methods.

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