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Research Article

Generative Design of Housing Spatial Layout Based on Rectangular Spaces

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The generative spatial layout design process can generate and optimize a wide range of design responses by complying with all desired requirements and criteria and evaluating them based on one or more specific functions. Considering the complexities and diversity of spatial layout responses, it is important to know the various mechanisms of the product design process related to them. Based on this, the aim of this research is to provide a mechanism for designing a generative spatial layout (GSL) based on a housing design problem. The method of this research with a quantitative approach is the simulation and placement of spaces through coding in Grasshopper and Python software under the Grasshopper platform. The main variables of the research are the dimensions of the spaces of the residential unit, the proximity matrix, and the spatial relationships of the residential unit. With the restrictions made, 440 spatial layout responses were produced in four general shapes, including an incomplete square, a rectangle with a one-to-two ratio, an incomplete rectangle with an incomplete one-to-two ratio, and L-shape. The geometrical data of production plans have been subjected to correlation and linear regression tests in the SPSS software. Two models have been developed based on the perimeter of the plan and the area of its peripheral rectangle. Based on the obtained results, GSL design will be able to provide more favorable solutions. The results indicate that, by providing the design constraints in all the results, the area-oriented approach to the productive design of housing configurations can serve as an assistant mechanism for the designer in providing a variety of floor plans in terms of area for the designer.

1. Introduction

As one of the main indicators of social stability, housing is one of the main factors of interest in sustainable development [1]. The final report of the Brandt Commission presents housing as one of the key needs of developing countries [2]. Therefore, the housing design process is one of the most important aspects of architecture. Designing the configuration of housing space is one of the tasks of housing design, which is very important in the early stages, including "conceptual design" [3] and "design development." In this research, housing spatial layout is defined as the allocation of different housing spaces, and it is decided based on the placement of internal partitions as well as external walls.

Comparing a large set of configuration alternatives is necessary to identify the optimal design solution. But due to the variety of relationships and spatial arrangement, the housing design process has many complications. The computational design process offers an opportunity to automate the generation of design alternatives based on parametric and algorithmic rules. Generative spatial layout (GSL) design is to use a computational process to generate a large set of alternative configurations in a reasonable time frame. In fact, in this structure, the main goal is to help building design professionals explore a larger set of solutions, which a traditional trial and error process can never achieve [4]. Based on this, this research intends to provide a mechanism for the design of generative spatial layout (GSL), by defining a housing design problem, to conduct a comprehensive search in all types of housing spatial layouts. Spatial layout design in this research is defined as finding a set of answers, including the location of spaces and the possible dimensions of each, which meet all design requirements and maximize design quality in terms of design priorities. Spatial layout is related to all physical design problems. Therefore, it is an important area of research [5]. The application of precise mathematical optimization methods to improve architectural layouts has been studied for several decades [6]. In the last few decades, researchers have developed different approaches to create interior building layouts in styles similar to existing well-known or historical design paradigms. This field provides solutions for automating the layout design process.

Reported efforts to automate the layout design process began in the 1970s [7]. Researchers have used several problem representations and solution search techniques to describe and solve problems. Sydora and Stroulia developed a BIM-based rule grammar and described interior design rules in a machine-readable format, by which the automatic generation of interior design models can be realized [8]. Wang et al. implemented a generative algorithm called City Engine and created the texture of blocks as close as possible to real blocks in urban design [9]. A generative grammar was developed in analyzing the spatial shape of case examples of blocks in the city of Nanjing [9]. Architectural arrangement is one of the most important subjects of generative spatial layout (GSL) design. Because in addition to common engineering goals such as cost and performance, architectural design is especially concerned with the aesthetic qualities and usability of an arrangement, which are usually more difficult to formally describe [10]. Also, the components of a building layout (rooms or walls) often do not have predefined dimensions, so each component of the layout can be resized.

This research represents a unique innovation when compared to other related studies in relation to the configuration production process, introduction, analysis of the produced configurations, and the introduction of an analytical parameter to obtain more favorable results. This research focuses on developing a point-finding method based on an area-based approach in the configuration production process. To facilitate future development, we have also analyzed the responses obtained through linear regression based on two dependent variables: the planning environment and the perimeter rectangle. To improve responses and reach more practical configurations, the perimeter rectangle is introduced and analyzed.

2. Generative Spatial Layout Design Approaches

In general, several methods for designing generative spatial layout (GSL) have been of interest among researchers. One of the ways to assign space and define spatial layout is to define the available space as a set of squares in a grid and use an algorithm to assign a number of squares based on a set of restrictions to a specific room or activity [11, 12]. This method is known as grid-base layout in researches. For the grid-based method, dividing a given design into unit spaces can turn this design into a set of grid cells. Since each cell has a fixed position and size, this design involves a two-dimensional matrix, which has ordered points [13]. This problem is inherently discrete and multistate. It cannot be solved due to the complexity of the composition and the problems of the right-sized layout. Several heuristic strategies are developed to find solutions without exhaustively searching the design space. The second method is the zone-based layout, which was proposed in the 1990s by Montreuil [14]. In this method, the range of spaces can be changed based on the end boundaries. This method basically requires a coordinate system to represent the space with corner points. In the area-based design, boundary lines are defined as a measure of central points [13]. Both methods have been studied and used in recent configuration studies with different coding methods [5, 15, 16] (see Table 1).

Another way to represent the design space of a building plan is to decompose the problem into two parts: topology and geometry. Topology refers to the logical relationships between design components. Geometry refers to the position and size of each component in the design. Topology decisions define constraints for the geometric design space [5]. For example, a topological decision that room one is adjacent to the north wall of room two constrains the geometric coordinates of room one relative to room two. In the meantime, combined methods are obtained from the above methods. Based on this, four general methods can be explained. Therefore, the research conducted in the field of generative spatial layout design has been divided according to the four proposed methods, and the design variables of each research have been obtained. Also, the general form of configuration in each research is explained. The results can be seen in Table 2. As it is clear in the table, the network-based approach has received more attention than other methods. After that, the area-based method is the most frequent. Also, various variables have been investigated in researches. The dimensions and location of spaces, as the most important variables in spatial arrangement, have the highest frequency in the investigated researches. In general, the characteristics of the window have been given a lot of attention in researches. But this variable has been considered as a control variable in most of the researches, or it has been placed only in relation to the external space. Other variables, such as orientation, boundary dimensions, and shading, are targeted depending on the research objectives (Table 2).

Based on the investigations, this article introduces an approach to automatically generate plans based on rectangular spaces with the ability to improve and further customize. It automatically reproduces various plans and implements transformation rules to manipulate the spatial relationships between rooms and create modified plans according to specific requirements. This research approach introduces constraints such as the adjacency matrix, the width-to-length ratio, and the bounding rectangle bounding the overall plan to support flexibility for different design requirements. In this research, a graphical user interface is provided for users to perform the automatic production process. An experiment has been conducted to verify the feasibility of this research approach and the time spent in producing floor plans. This shows that the method of this research is able to create a set of customized plans in a reasonable time.

Table 1: Comparison of different approaches to design GSL.

Limitations	Approach	General method	Strengths
An absence of a fixed outer boundary A lack of diversity in the design of interior spaces	Axis area	Using changeable end boundaries to define the scope of each space	Coding is easy Dimensions are not limited
Spaces and cells should be measured according to their dimensions Complex designs require heavy coding	Network oriented	In a grid, assign a set of cells to each space	Different types of spaces are available An outer border that can be fixed
Access to a variety of shapes of spaces is not optimal Some designs have a high level of coding complexity	Topological	A space is defined by its topology and geometry	Spaces that should be prioritized Fixing the outer border may be possible
The complexity of hybrid coding The absence of a written path	Hybrid	Combinations of the three methods described above	Using the potential and avoiding the limitations of different methods

Table 2: Researches in the field of configuration and topics related to it (source: author).

Author	Form	Production method	Design variables
Keshavarzi and Rahmani-Asl, 2021 [17]	One-story multiform	Axis area	Space location, adjacency matrix, and Furniture location
Nauata et al., 2021 [18]	One-story multiform	Hybrid	Space location, adjacency matrix, door location, space dimension, and door dimension
Veloso et al., 2018 [19]	One-story polygon form	Axis area	Space location, adjacency matrix, door location, and space dimension
Boonstra et al., 2018 [20]	Multistorey rectangle	Hybrid	The dimensions of the spaces and the location of the spaces
Schwartz et al., 2017 [21]	Multistorey rectangle	Axis area	The dimensions of the spaces, the location of the spaces, and the window-to-wall ratio
Dino and Üçoluk, 2017 [22]	Multistorey rectangle	Network oriented	Space dimension index, position matrix, space position, window-to-wall ratio, and height-to-area ratio
Sleiman et al., 2017 [23]	Multistorey rectangle	Axis area	Location of space, dimensions of space, and location of crates
Dino and Üçoluk, 2017 [22]	Multistorey rectangle	Network oriented	Space dimension index, position matrix, space position, window-to-wall ratio, and height-to-area ratio
Yi, 2016 [13]	One-story rectangle	Network oriented	Boundary dimensions, space location, space dimensions, and window-to-wall ratio
Su and Yan, 2015 [24]	One-story rectangle	Network oriented	The location of the rooms
Rodrigues et al., 2013 [16]	Multistorey rectangle	Axis area	The dimensions of the spaces, the location of the spaces, the position of the window and the door, the spatial relationship, the floors, and the location. Space, border dimensions, orientation, window orientation, and shading dimensions
Bausys and Pankrasovaite, 2005 [25]	One-story rectangle	Axis area	Boundary dimensions, space position, space dimensions, window position, and window dimensions
Caldas, 2008 [26]	Multistorey rectangle	—	Space dimensions, space height, roof slope, roof orientation, and window dimensions
Michalek et al., 2002 [5]	One-story rectangle	Topologic	Space position, space dimensions, window position, window dimensions, and spatial relationship

3. Methodology

The method of this research is a quantitative approach, simulation, and placement of spaces, and the use of the target space is residential. Finally, evaluation of research findings through organized statistical methods has been considered. The research simulation tool is Grasshopper software and Python programming language in the Grasshopper platform. Based on the main elements of housing design, design parameters should be summarized and defined.

Through the analysis of the overall residential design process, basic design parameters, such as internal circulation space, room function, orientation, room size, functional relationships, building envelope, and layout of a typical floor plan, can be determined. These parameters can be divided into two types. The first type refers to parameters related to sizes, areas, and coefficients, which can be described numerically, and includes the unit area, the room area, room depth, the room depth to width ratio (DWR), floor height, the door size, the window to wall ratio (WWR), and the window width to height ratio (WHR). The parameters of the second type include elements that cannot be described numerically, such as orientation, spatial arrangement, shape of circulation space, and relationships between rooms, which should be converted into parameters that can be recognized by the algorithm. Therefore, two types of design parameters include quantitative parameters that can be described numerically and qualitative parameters that cannot be represented by numbers. In this research, the most important limiting variables of the algorithm include the total area of the residential unit, the variety of interior spaces, the minimum and maximum areas of each interior space based upon its function, the general shape of the plan of the interior spaces, and the proximity of different functions to one another. Depending on the limiting variables, the algorithm produces a different set of residential plans.

The area of the desired residential unit is 90 square meters. In the assumption of the research, all the spaces of the residential unit are defined as rectangular and in the longitudinal and transverse axis of the residential unit. There are six spaces in the residential unit including kitchen, living, W.C, bathroom, and two bedrooms next to an entrance. Also, in order to define the minimum dimensions of the spaces, first through the criteria of the Road, Housing and Urban Development Research Center [24], minimum dimensional standards have been obtained, and then through the Delphi method and by an open questionnaire and interview, its validity has been confirmed by experts. In order to reach the possible area of the available spaces in the algorithm, we act according to the following formula. Assuming the existence of n spaces ($a, b, c, \ldots, n$), the maximum and minimum possible area of space (a) in the desired total area (S_{all}) is based on the minimum standard area obtained for each space.

$$\text{Max}\left(\text{Est. } S_{\text{Space (a)}}\right) = S_{\text{all}} - \sum_{i=1}^{n-1} \text{Min}\left(\text{Sta. } S_{\text{Space}\,(i)}\right). \tag{1}$$

In this formula, the maximum estimated area of each space ($\text{Sta. } S_{\text{Space}\,(a)}$) in the total area ($S_{\text{all}}$) is obtained based on the sum of the minimum standard area of other spaces ($\text{Sta. } S_{\text{Space}\,(i)}$). The estimated area of each space is the area of the space without considering the communication paths and the walls of the space. After obtaining the maximum possible area of each space, the area range of each space has been obtained. Based on this and based on the minimum standard length and width of residential spaces, all the length and width states of each space can be obtained. For this purpose, a set of code has been written in Python. By having the length and width of each of the spaces in each of the states, the range and shape of the space can be drawn. Also, in order to determine and define adjacent spaces in the plan, the proximity matrix of spaces has been determined, and then through the Delphi method with open questionnaires and interviews, its validity has been confirmed by experts in the field of housing. The adjacency matrix defines the spaces that are directly connected to each other.

Based on the proximity matrix and in the form of code written in Python, the drawn spaces are placed together. Finally, the plan obtained from the arranged spaces is enclosed in a rectangle, and the empty spaces between the plan and the rectangle are reduced as much as possible so that the plan is close to the perfect rectangle. Also, the small empty spaces between the six spaces are added to the adjacent space that shares the most perimeter with it. Next, the linear results are entered into the modeling algorithm. The walls have thickness, and the doors and windows are defined according to the standards. Windows are located exactly in the middle of all external walls of the rooms, except for the zero-zero sides of the standard plan. Finally, after producing the final plans, the data of all the plans including the length, width, and area of each space, the perimeter of the final plan, and the area of the rectangle surrounded by the final plan have been collected. These data have been analyzed by descriptive statistics and analytical tests including correlation and regression. It is expected that the results of these tests can ultimately improve the processes of automatic production of spatial layout.

3.1. Findings of Automatic Design of Spatial Layout of Housing and Final Answers. As mentioned, this research aims to design a spatial layout generator through Grasshopper and Python software, and the housing spaces include the kitchen, living room, two bedrooms, W. C, bathroom, and entrance with a general rectangular shape with standard dimensions located next to each other. For this purpose, first, the minimum standard dimensions of each housing space have been obtained based on the criteria of the Road, Housing and Urban Development Research Center [24], and it has been approved by experts in the field of housing, which is as follows (Table 3).

Table 3: Standard dimensions of residential spaces based on the criteria of the Road, Housing and Urban Development Research Center [24].

	Entrance	Kitchen	Living room	Parents' bedroom	Child's bedroom	W. C and bathroom
Minimum length and width	1.4	2.4	3.3	2.4	2.4	1.1
Minimum standard area	2.5	5.8	15	12	7.2	1.25

Based on the dimensions obtained through the standards, the minimum possible area of residential spaces based on the total area of 90 square meters is obtained according to the following formula:

$$\mathrm{Max}\left(\mathrm{Est.}\ S_{\mathrm{Space\,(a)}}\right) = 90m^2 - \sum_{i=1}^{5} \mathrm{Min}\left(\mathrm{Sta.}\ S_{\mathrm{Space}\,(i)}\right). \quad (2)$$

In this formula, the maximum estimated area of each space (Sta. $S_{\mathrm{Space}\,(a)}$) is obtained at 90 square meters based on the sum of the minimum standard area of other spaces (Sta. $S_{\mathrm{Space}\,(a)}$). Based on the findings, by following the standards here, the living can vary from 15 square meters to 50 meters and the parents' bedroom from 12 to 25 square meters. Also, a single bedroom from 2.7 square meters to 17 meters is possible (Table 4).

After obtaining the maximum possible area of each space, the area range of each residential space has been obtained. The sum of these obtained areas plus the area of the building walls and possible communication spaces may be less or more than 90 square meters. For this reason, there is a need to reduce the range of changes in the area of all spaces. For this purpose, first, the domain of each area is converted into a smaller domain according to the following formula. The following formula defines the final minimum and maximum area:

$$\begin{aligned}
\mathrm{Max}\left(\mathrm{Poss.}\ S_{\mathrm{Space}\,(a)}\right) &= \mathrm{Max}\left(\mathrm{Est.}\ S_{\mathrm{Space}\,(a)}\right) - \left[\left(\mathrm{Max}\left(\mathrm{Est.}\ S_{\mathrm{Space}\,(a)}\right) - \mathrm{Min}\left(\mathrm{Sta.}\ S_{\mathrm{Space}\,(a)}\right)\right) \times 0.25\right],\\
\mathrm{Min}\left(\mathrm{Poss.}\ S_{\mathrm{Space}\,(a)}\right) &= \mathrm{Min}\left(\mathrm{Est.}\ S_{\mathrm{Space}\,(a)}\right) + \left[\left(\mathrm{Max}\left(\mathrm{Est.}\ S_{\mathrm{Space}\,(a)}\right) - \mathrm{Min}\left(\mathrm{Sta.}\ S_{\mathrm{Space}\,(a)}\right)\right) \times 0.25\right].
\end{aligned} \quad (3)$$

In this formula, the maximum possible area of each space (Sta. $S_{\mathrm{Space}\,(a)}$) is 90 square meters based on the minimum maximum estimated area of that space (Sta. $S_{\mathrm{Space}\,(a)}$) and the minimum standard area of that space (Sta. $S_{\mathrm{Space}\,(a)}$) will be obtained. Based on this and based on the minimum standard length and width of residential spaces, all the length and width states of each space can be obtained. The findings are as follows (Table 5):

Considering that the variety of answers obtained is very high, the range of changes is divided into two parts to make its calculation easier. By obtaining the different states of length and width of different residential spaces, the different states of all residential spaces are drawn on the zero-zero coordinate axis. In the next step, it is necessary that all the spaces formed for each layout are placed together based on the criteria desired by the designer. This concept should be converted into parameters that can be recognized by the algorithm. Therefore, in order to determine and define the spaces adjacent to each other in the plan, the proximity matrix of the spaces has been determined, and then through the Delphi method and by an open questionnaire and interview, its validity has been confirmed by experts. The final results of this matrix, which is mentioned as follows, show what spaces need to be together and in direct communication according to experts in the field of housing (Table 6).

The process of placing spaces together continues until all spaces are placed together. After placing all the spaces next to each other, the overall shape needs to be close to a rectangle. For this purpose, at the end of the placement process, the set of spaces are enclosed in the smallest possible rectangle. Between the rectangle and the set of spaces, there remains a range of empty spaces. According to a set of Python code, the spaces between are reduced. In each spatial placement, a set of empty spaces remains empty between the residential spaces as well. For these spaces, a range is considered, and if their area is less than a certain value, it will be added to the space that has the most in common with it. And if it was more than the specified value, it should be deleted (see Table 7).

Based on this, with the addition of empty spaces in between, some spaces have become larger than the maximum possible area and have increased to about the maximum estimated area. Finally, a set of results of 440 plans has been obtained, and the variation of the area of the obtained spaces is mentioned in the table. Some examples of the final configuration results are provided in line (Figure 1).

As a result of the algorithm process, two outputs are generated: a visual layout of residential spaces and linear segmentation and geometric evaluation data for each answer. The output of this algorithm can be used in a variety of optimization cycles based on different performance objectives. In addition, the output of the algorithm can be easily transformed into the final form of architecture by placing it in a modeling process.

3.2. Statistical Findings and Data Analysis. As mentioned, the produced plans have been subject to statistical tests for evaluation. For this purpose, the data of 440 obtained plans, including the length, width, and area of each space; the

Table 4: Standard and estimated dimensions of residential spaces (source: author).

	Entrance	Kitchen	Living room	Parents' bedroom	Child's bedroom	W. C and bathroom
Minimum standard area	2.5	5.8	15	12	7.2	1.45
Maximum estimated area	3.5	25	50	25	17	4

Table 5: Standard and possible dimensions of residential spaces (source: author).

	Entrance	Kitchen	Living room	Parents' bedroom	Child's bedroom	W. C and bathroom
Minimum possible area	2.75	23.57	24.12	14.7	8.11	1.75
Maximum possible area	3.25	7.67	48.9	24.03	16.67	3.91
The shortest possible side length	1.5	2.55	3.94	2.98	2.72	1.18
The longest possible side length	1.9	4.92	6.99	5.2	4.2	2.04

Table 6: The proximity matrix of spaces (source: author).

	Entrance	Kitchen	Living room	Parents' bedroom	Child's bedroom	W. C and bathroom
Entrance	1	—	1	—	—	—
Kitchen	—	1	1	—	—	—
Living	1	1	1	1	1	1
Parents' bedroom	—	—	1	1	—	1
Child's bedroom	—	—	1	—	1	1
W. C and bathroom	—	—	1	1	1	1

Table 7: The scope of the final area of produced residential spaces (source: author).

	Entrance	Kitchen	Living room	Parents' bedroom	Child's bedroom	W. C and bathroom
Minimum resulting area	2.28	6.8	22.18	11.36	7.93	1.69
Maximum resulting area	3.5	22.35	25	17	17	4

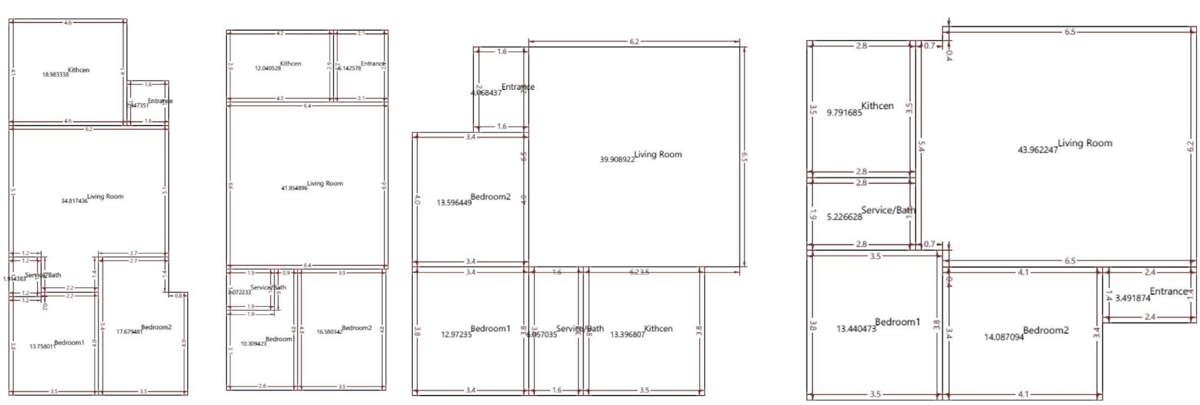

Figure 1: The example of the final answers of the linear configuration of the algorithm (source: the author).

perimeter of the final plan; and the length, width, and area of the rectangle surrounded by the final plan, have been collected. These data were entered into SPSS software and subjected to correlation and regression tests.

First, the correlation between the area of all internal spaces and the four perimeteral variables of the final plan and the length, width, and area of the rectangle surrounded by the final plan has been performed. In this test, the significance coefficient of most of the correlations is less than 0.05. Only in four tests, a significance coefficient higher than 0.05 has been reported. According to Amrhein's opinion [25], the value of the significance coefficient does not necessarily indicate whether the data is meaningful or not, and it is only a report that can help this.

In this test, the highest correlation is between the width and length of the peripheral rectangle. Also, after that, the relationship between the area of the peripheral rectangle and fthe perimeter of the final plan has the highest correlation.

Among residential spaces, the perimeter of the final plan has the highest correlation with the reception area and the lowest correlation with the area of the child's bedroom. The correlation of the plan perimeter with the reception area, the service and bathroom area, and the entrance area is negative and positive with other variables (Table 8).

Also, the highest correlation of the width of the peripheral rectangle is with the W. C and bathroom area, and the lowest correlation is with the reception area. The correlation between the width of the peripheral rectangle and the area of the parents' bedroom, the area of the kitchen, the entrance area, and the length of the peripheral rectangle is negative. In other cases, the correlation is positive. Regarding the length of the peripheral rectangle, the highest correlation is related to the area of W. C and bathroom and the lowest correlation is related to the area of the child's bedroom. Regarding this variable, the area of the child's bedroom, the area of W. C and bathroom, the living area, the area of the entrance, and the width of the peripheral rectangle have a negative correlation with the length of the peripheral rectangle. Also, regarding the correlation of the area of the peripheral rectangle with the area of residential spaces, the highest correlation is related to the area of the child's bedroom and the lowest is related to the area of W. C and bathroom (Table 9).

In the following, the correlation test between the length and width of all internal spaces and the four perimeter variables of the final plan and the length, width, and area of the rectangle surrounded by the final plan has been performed. In this test, the significance coefficient of most of the correlations is less than 0.05, and only in six tests, the significance coefficient is higher than 0.05, which according to Amrhein et al. 2019, shows that it does not matter whether the data are meaningful or not. Regarding the correlation test of the entire plan perimeter with the width and length of residential interior spaces, the width of living has the highest correlation. This is a negative correlation, which indicates an inverse relationship. The lowest correlation in this section is related to the width of the toilet and bathroom. This correlation is also negative. Also, among the correlations of the width of the rectangle surrounded by residential spaces, the highest correlation is related to the child's bedroom and the lowest correlation is related to the parents' bedroom (see Table 10).

In the following, the linear regression test has been performed targeting the perimeter of the plan and the area of the rectangle surrounded by the plan as the dependent variable. First, linear regression has been tested in relation to the areas of internal spaces and the area of the peripheral rectangle (see Table 11).

In the ANOVA test, the significance of the regression test is confirmed regarding the area of the interior spaces and the area of the peripheral rectangle. Based on the results of the test, the areas of the interior spaces predict only 34% of the changes in the area of the peripheral rectangle (Table 12).

The significance coefficient of the three variables of child's bedroom area, parent's bedroom area, and the entrance area is less than 0.05 and is reported to be significant. Other variables were not reported as significant. In the regression test, based on the standardized coefficients, the largest contribution is related to the area of the child's bedroom. After that, the entrance area is the most influential variable in the relationship, which has a negative effect. The living area variable is also reported as a variable excluded from the test. The area variable has been tested individually, which predicts only 16% of the changes in the area of the peripheral rectangle. The living area with a standardized coefficient of −0.406 has a significant effect on the area of the peripheral rectangle (see Table 13).

In the following, linear regression has been tested in relation to the areas of internal spaces and the perimeter of the overall plan. Based on the ANOVA test, the significance of the linear regression is confirmed (see Table 14).

Based on the test results, the areas of the interior spaces predict 25% of the perimeter changes of the final plan. In this test, the living area is reported as a variable excluded from the test (Table 14).

The significance coefficient of all independent variables is less than 0.05, and it is reported as significant. The highest standard coefficient of the regression test is related to the area of the kitchen. The lowest amount is related to the area of WC and bathroom (Table 15). The living area variable has been tested separately. The regression coefficient of the reception area is reported as 0.441 (seeTable 16).

In the following, linear regression has been tested in the relationship between the length and width of the interior spaces and the area of the peripheral rectangle. Based on the ANOVA test, the significance of the linear regression is confirmed (Table 17).

Based on the test results, the length and width of the interior spaces predicts 54% of the changes in the area of the peripheral rectangle. This shows that the width and length of residential spaces make a better prediction of the area of the peripheral rectangle than the area of residential spaces. The significance coefficient of all independent variables, except the width of the living room, the width and length of the kitchen, and the fixed value, is less than 0.05 and is reported to be significant (Table 18).

The highest standard coefficient of the regression test is related to the width of the parents' bedroom. The lowest amount is related to the living width (Table 19).

In the following, linear regression has been tested in relation to the length and width of the interior spaces and the perimeter of the overall plan. Based on the ANOVA test, the significance of the linear regression is confirmed (Table 20).

Based on the test results, the length and width of the interior spaces predicts 35% of the overall plan perimeter changes. This shows that the width and length of residential spaces make a better prediction of the perimeter of the final plan than the area of residential spaces. The coefficient of significance of width and length of reception, length of W. C and the bathroom, and length of entrance is less than 0.05, and it is reported as significant (Table 21).

The highest standard coefficient of the regression test is related to the living width. The lowest amount is related to the width of WC and the bathroom. Based on the regression tests, the linear models of the perimeter of the final plan and the area of the perimeter rectangle based on

Table 8: Correlation between the area of all interior spaces and four variables of the final plan (source: author).

		The area of the child's bedroom	The area of the parents' bedroom	W. C area and bathroom	Living area	Kitchen area	Entrance area	The entire perimeter of the plan	Width of the peripheral rectangle	Length of the peripheral rectangle	Area of the peripheral rectangle
Perimeter of whole plan	Pearson correlation	0.262**	0.344**	−0.168**	−0.441**	0.395**	−0.280**	1	0.004	0.433**	0.597**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000		0.932	0.000	0.000
	N	440	440	440	440	440	440	440	440	440	440
Width peripheral rectangle	Pearson correlation	0.287**	−0.175**	0.328**	0.097*	−0.173**	−0.176**	0.004	1	−0.795**	0.556**
	Sig. (2-tailed)	0.000	0.000	0.000	0.041	0.000	0.000	0.932		0.000	0.000
	N	440	440	440	440	440	440	440	440	440	440
Length peripheral rectangle	Pearson correlation	−0.041	0.429**	−0.440**	−0.383**	0.395**	−0.125**	0.433**	−0.795**	1	0.058
	Sig. (2-tailed)	0.387	0.000	0.000	0.000	0.000	0.009	0.000	0.000		0.228
	N	440	440	440	440	440	440	440	440	440	440
Area peripheral rectangle	Pearson correlation	0.455**	0.354**	−0.064	−0.406**	0.248**	−0.413**	0.597**	0.556**	0.058	1
	Sig. (2-tailed)	0.000	0.000	0.181	0.000	0.000	0.000	0.000	0.000	0.228	
	N	440	440	440	440	440	440	440	440	440	440

** correlation is significant at the 0.01 level (2-tailed). * correlation is significant at the 0.05 level (2-tailed).

Table 9: Correlation between length and width of all interior spaces and four final plan variables (source: author).

		The width of the child's bedroom	The length of the child's bedroom	The width of the parents' bedroom	The length of the parents' bedroom	W. C and bathroom width	Length of W. C and bathroom	Living width	Living length	The width of the kitchen	The length of the kitchen	The width of the entrance	The length of the entrance
Perimeter of the whole plan	Pearson correlation	0.214**	0.291**	0.337**	0.255**	−0.057	−0.196**	−0.520**	−0.132**	0.372**	0.358**	−0.242**	−0.278**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.231	0.000	0.000	0.005	0.000	0.000	0.000	0.000
	N	440	440	440	440	440	440	440	440	440	440	440	440
Width peripheral rectangle	Pearson correlation	0.350**	−0.145**	−0.087	−0.348**	0.289**	0.282**	0.109*	−0.077	−0.092	−0.131**	−0.148**	−0.145**
	Sig. (2-tailed)	0.000	0.002	0.067	0.000	0.000	0.000	0.022	0.105	0.053	0.006	0.002	0.002
	N	440	440	440	440	440	440	440	440	440	440	440	440
Length peripheral rectangle	Pearson correlation	−0.120*	0.344**	0.349**	0.503**	−0.284**	−0.437**	−0.448**	0.023	0.310**	0.365**	−0.101*	−0.153**
	Sig. (2-tailed)	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.629	0.000	0.000	0.033	0.001
	N	440	440	440	440	440	440	440	440	440	440	440	440
Area peripheral rectangle	Pearson correlation	0.447**	0.267**	0.397**	0.148**	0.090	−0.138**	−0.465**	−0.146**	0.264**	0.275**	−0.343**	−0.407**
	Sig. (2-tailed)	0.000	0.000	0.000	0.002	0.060	0.004	0.000	0.002	0.000	0.000	0.000	0.000
	N	440	440	440	440	440	440	440	440	440	440	440	440

**correlation is significant at the 0.01 level (2-tailed). *correlation is significant at the 0.05 level (2-tailed).

Table 10: Regression of the relationship between the areas of internal spaces and the area of the peripheral rectangle (source: the author).

Model	R	R square	Adjusted R square	Std. error of the estimate
1	0.588[a]	0.345	0.338	9.10820

a. Predictors: (constant), entrance area, WC and bathroom area, parent's bedroom area, kitchen area, and child's bedroom area.

Table 11: The ANOVA test regarding the area of internal spaces and the area of the peripheral rectangle (source: author).

Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	18981.548	5	3796.310	45.761	0.000[b]
	Residual	36004.354	434	82.959		
	Total	54985.902	439			

a. Dependent variable: area of the peripheral rectangle. b. Predictors: (constant), entrance area, WC and bathroom area, parent's bedroom area, kitchen area, and child's bedroom area.

Table 12: Regression results of the relationship between the areas of internal spaces and the area of the peripheral rectangle (source: author).

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. error	Beta		
1	(Constant)	96.647	4.240		22.796	0.000
	The area of the child's bedroom	1.652	0.239	0.341	6.902	0.000
	The area of the parents' bedroom	0.312	0.147	0.107	2.127	0.034
	WC and bathroom area	−0.674	0.508	−0.052	−1.326	0.185
	Kitchen area	0.145	0.112	0.059	1.295	0.196
	Entrance area	−3.130	0.428	−0.324	−7.307	0.000

a. Dependent variable: area of the peripheral rectangle.

Table 13: Regression of the relationship between the areas of internal spaces and the perimeter of the overall plan (source: author).

Model	R	R square	Adjusted R square	Std. error of the estimate
2	0.509[a]	0.259	0.250	3.55739

a. Predictors: (constant), entrance area, W. C and bathroom area, parent's bedroom area, kitchen area, and child's bedroom area.

Table 14: The ANOVA test regarding the area of internal spaces and the environment of the general plan (source: author).

Model		Sum of squares	df	Mean square	F	Sig.
2	Regression	1917.787	5	383.557	30.309	0.000[b]
	Residual	5492.274	434	12.655		
	Total	7410.061	439			

a. Dependent variable: perimeter of whole plan. b. Predictors: (constant), entrance area, W. C and bathroom area, parent's bedroom area, kitchen area, and child's bedroom area.

Table 15: Regression of the relationship between the areas of internal spaces and the perimeter of the general plan (source: the author).

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. error	Beta		
2	(Constant)	37.687	1.656		22.760	0.000
	The area of the child's bedroom	0.238	0.093	0.134	2.550	0.011
	The area of the parents' bedroom	0.187	0.057	0.175	3.265	0.001
	Area of W. C and bathroom	−0.550	0.199	−0.116	−2.771	0.006
	Kitchen area	0.249	0.044	0.278	5.708	0.000
	Entrance area	−0.427	0.167	−0.120	−2.554	0.011

a. Dependent variable: perimeter of whole plan.

Table 16: Regression of the relationship between the length and width of the interior spaces and the area of the peripheral rectangle (source: the author).

Model	R	R square	Adjusted R square	Std. error of the estimate
3	0.744[a]	0.553	0.540	7.58759

a. Predictors: (constant), entrance length, WC and bathroom width, parents' bedroom width, child's bedroom width, kitchen width, service and bathroom length, entrance width, parents' bedroom length, living room length, child's bedroom length, kitchen length, and living room width.

Table 17: The ANOVA test on the relationship between the length and width of the interior spaces and the perimeter of the overall plan (source: author).

Model		Sum of squares	df	Mean square	F	Sig.
	Regression	30402.880	12	2533.573	44.007	0.000[b]
3	Residual	24583.022	427	57.571		
	Total	54985.902	439			

a. Dependent variable: area of the peripheral rectangle. b. Predictors: (constant), entrance length, WC and bathroom width, parents' bedroom width, child's bedroom width, kitchen width, service and bathroom length, entrance width, parents' bedroom length, living room length, child's bedroom length, kitchen length, and living room width.

Table 18: Regression of the relationship between the length and width of the interior spaces and the area of the peripheral rectangle on the overall plan (source: author).

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Beta	Beta		
	(Constant)	8.431	40.155		0.210	0.834
	The width of the child's bedroom	12.310	1.643	0.385	7.490	0.000
	The length of the child's bedroom	4.224	1.726	0.177	2.448	0.015
	The width of the parents' bedroom	11.377	1.587	0.535	7.168	0.000
	The length of the parents' bedroom	−8.445	1.019	−0.411	−8.289	0.000
	W. C and bathroom width	5.971	1.906	0.119	3.132	0.002
3	Length of WC and bathroom	−3.712	1.189	−0.132	−3.123	0.002
	Living width	0.029	1.549	0.002	0.019	0.985
	Living length	6.544	1.379	0.352	4.745	0.000
	The width of the kitchen	2.736	1.736	0.172	1.576	0.116
	The length of the kitchen	1.529	1.452	0.075	1.052	0.293
	The entrance width	−4.907	1.905	−0.112	−2.575	0.010
	The length of the entrance	−7.252	1.379	−0.248	−5.259	0.000

a. Dependent variable: area of the peripheral rectangle.

Table 19: Regression of the relationship between the length and width of the interior spaces and the perimeter of the general plan (source: the author).

Model	R	R square	Adjusted R square	Std. error of the estimate
4	0.603[a]	0.364	0.346	3.32239

a. Predictors: (constant), length of entrance, width of service and bathroom, width of parents' bedroom, width of child's bedroom, width of kitchen, length of service and bathroom, width of entrance, length of parents' bedroom, length of living room, length of child's bedroom, length of kitchen, and width of living.

the length and width of the internal spaces are generally more appropriate than the area of the internal spaces. This leads to the following model for predicting the area of the perimeter rectangle of the final plan. This model can predict with 95% confidence about 54% of environmental areas:

Table 20: The ANOVA test on the relationship between the length and width of the interior spaces and the perimeter of the general plan (source: the author).

Model		Sum of squares	df	Mean square	F	Sig.
4	Regression	2696.710	12	224.726	20.359	0.000[b]
	Residual	4713.351	427	11.038		
	Total	7410.061	439			

a. Dependent variable: perimeter of the whole plan. b. Predictors: (constant), length of entrance, width of service and bathroom, width of parents' bedroom, width of child's bedroom, width of kitchen, length of WC and bathroom, width of entrance, length of parents' bedroom, length of living room, length of child's bedroom, length of kitchen, and width of living room.

Table 21: Regression of the relationship between the length and width of the interior spaces and the perimeter of the general plan (source: the author).

Model		Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Beta	Beta		
4	(Constant)	41.469	17.583		2.358	0.019
	The width of the child's bedroom	0.956	0.720	0.081	1.328	0.185
	The length of the child's bedroom	0.753	0.756	0.086	0.997	0.320
	The width of the parents' bedroom	0.898	0.695	0.115	1.292	0.197
	The length of the parents' bedroom	−0.817	0.446	−0.108	−1.831	0.068
	W. C and bathroom width	0.015	0.835	0.001	0.019	0.985
	Length of W. C and bathroom	−1.321	0.520	−0.128	−2.538	0.012
	Living width	−2.003	0.678	−0.411	−2.953	0.003
	Living length	1.836	0.604	0.269	3.040	0.003
	The width of the kitchen	1.063	0.760	0.182	1.398	0.163
	The length of the kitchen	−0.147	0.636	−0.020	−0.232	0.817
	Entrance width	−1.243	0.834	−0.077	−1.489	0.137
	Entrance length	−1.071	0.604	−0.100	−1.774	0.077

a. Dependent variable: perimeter of the whole plan.

$$\begin{aligned}A_{\mathrm{PR}} = 8.431 &+ (12.310 \times W_{\mathrm{SRR}}) + (4.224 \times L_{\mathrm{SRR}}) \\ &+ (11.377 \times W_{\mathrm{MRR}}) + (-8.445 \times L_{\mathrm{MRR}}) \\ &+ (5.971 \times W_{W\&B}) + (-3.712 \times L_{W\&B}) \\ &+ (0.029 \times W_{\mathrm{LR}}) + (6.544 \times L_{\mathrm{LR}}) + (2.736 \times W_{\mathrm{KR}}) \\ &+ (1.529 \times L_{\mathrm{KR}}) + (-4.907 \times W_{\mathrm{ES}}) + (-7.252 \times L_{\mathrm{ES}}).\end{aligned} \tag{4}$$

In addition, the prediction model for the final plan is presented as follows; it can predict with 95% confidence about 35% of the responses to the plan environment:

$$\begin{aligned}P_{\mathrm{FP}} = 41.469 &+ (0.956 \times W_{\mathrm{SRR}}) + (0.753 \times L_{\mathrm{SRR}}) \\ &+ (0.898 \times W_{\mathrm{MRR}}) + (-0.817 \times L_{\mathrm{MRR}}) \\ &+ (0.015 \times W_{W\&B}) + (-1.321 \times L_{W\&B}) \\ &+ (-2.003 \times W_{\mathrm{LR}}) + (1.836 \times L_{\mathrm{LR}}) + (1.063 \times W_{\mathrm{KR}}) \\ &+ (-0.147 \times L_{\mathrm{KR}}) + (-1.243 \times W_{\mathrm{ES}}) + (-1.071 \times L_{\mathrm{ES}}).\end{aligned} \tag{5}$$

In these two models,

The length of the reception room	L_{LR}	The width of the second bedroom	W_{SRR}	
The width of the kitchen	W_{KR}	The length of the second bedroom	L_{SRR}	
The length of the kitchen	L_{KR}	The width of the master bedroom	W_{MRR}	
The width of the entrance space	W_{ES}	The length of the master bedroom	L_{MRR} .	(6)
The length of the entrance space	L_{ES}	The width of the toilet and bathroom	$W_{W\&B}$	
The area of the peripheral rectangle	A_{PR}	The length of the toilet and bathroom	$L_{W\&B}$	
The environment of the final plan	P_{FP}	The width of the reception room	W_{LR}	

According to the amount of R-Score (R-Square), obtained in two models, other parameters, such as the contiguous spaces, play a colorful role in defining the perimeter of a plan and the area of its surrounding rectangle. One of the limitations of this research is that these variables cannot be converted into numerical form for inclusion in the model.

4. Discussion

This paper presents a creative area-oriented approach to generative housing layout design that automatically generates plans for a single unit. Compared to similar studies [18–20], the existing algorithm includes a comprehensive range of design variables for the configuration of residential spaces. Since the simulation of the energy performance of the building was not considered, unlike some researches [16, 22], the three-dimensional variables of the form were not taken into account in the algorithm and the two-dimensional responses sufficed. In comparison to similar studies using an area-oriented approach [17, 19, 21], the final answers of the algorithm possess the necessary performance standards and a desirable variety. The final results of the configuration are all with an area of 90 square meters, and all of them have all the desired residential spaces in compliance with the rules and standards compiled in the algorithm. Based on the findings of the study and the opinions of other researchers [13, 18, 22], the generative design mechanism of housing configuration can be used as a designer's assistant in providing a variety of layouts in accordance with design standards and based on the area. Additionally, the outputs of the algorithm, compared to research with the energy performance optimization approach [16, 22], indicate that the algorithm can be integrated into the functional computing design cycle.

In the research, 440 production configuration samples were examined using the productive design method to determine four general configuration forms, including incomplete squares, rectangles with one-to-two ratios, incomplete rectangles with one-to-two ratios, and incomplete L-shapes. It shows a more practical layout compared to other studies [17, 22] due to the limitation of the plan to two x and y axes and an area of 90 square meters. Additionally, the general structure of the answers indicates that private and public spaces are well separated. The entrance space is always located at the corner of the plan. Due to the proximity relations formulated in the proximity matrix, this issue arises. It is possible to increase the variety of responses by changing the proximity structure of the input space. There is an optimal fit between the spaces of the residential unit and the reception area in all cases, which occupies approximately half of the area of the unit (Figure 2).

In the meantime, the lack of an intermediate space between private and public spaces is clearly felt. This intermediate space can solve the problem of privacy well by defining its direct relationship with two bedrooms and the living room. It also improves the spatial circulation of the residential unit.

Different parts of the algorithm have been found to have limitations. Among them, we can highlight the difficulty of creating indoor spaces other than rectangles in a controlled manner, as shown in other studies using area-based approaches [5, 16, 21]. The spaces are defined by two numbers: the dimensions of the space and the coordinates of one of its vertices. Occasionally, owing to the empty spaces in between, it may be possible to form a space in a form other than a rectangle; however, these responses are based on specific circumstances and are not preplanned. The algorithm also has the limitation of not being able to define the configuration based on a specific outer boundary, which has also been observed in other studies [17, 23]. By using this algorithm, the spaces are placed in proximity to one another by observing the proximity conditions one after another, with only the two x and y axes limiting their proximity. As a matter of fact, the configuration is composed of two limited plans and two unlimited sides. Compared to previous studies [5, 17, 21], this research has performed tests on the final geometric data of the spatial configuration.

Correlation results show that the width and length of the peripheral rectangle are connected. This issue shows that the proportions of the plan in the above four cases have been preserved in all plans. Also, the correlation results show that the area of the peripheral rectangle and the perimeter of the final plan are directly related. This shows that the general form of the plan was almost constant. The correlation results also show that the living area has the greatest effect on the perimeter of the final plan, and this effect is reversed. This issue may be due to the effect of the large dimensions of the living room and its placement in the space, which needs further investigation. Based on the results of the linear regression test, it can be understood that the width and length of the interior spaces are better variables for predicting the perimeter of the plan and the area of the peripheral rectangle. In the case of future researches, it is suggested to identify all the relationships and explain the nonlinear relationship of the variables by using curve regression.

One of the limitations of this research is that it is impossible to control the overall shape of the production configuration; however, in an innovative method, the perimeter rectangle was used and the ratio of the length to the width of the rectangle was tried to be reduced as much as possible. The present study has also introduced two relationships from two linear regression models in the area-oriented approach of automatic configuration generation, which can be conditionally placed in the path of the generating algorithm and control the plan form. To achieve a rectangular configuration, it is essential to establish the following relationship based on the two parameters of the environment and the area, along with the dimensions of the interior spaces:

$$\text{Area of Peripheral Rectangle} \cong \sum \text{Area of Interior Spaces}. \tag{7}$$

In accordance with the linear regression model obtained, the following model can be defined as the configuration of a residential unit of approximately 90 square meters. In this model, if α tends to zero, the configuration obtained is rectangular:

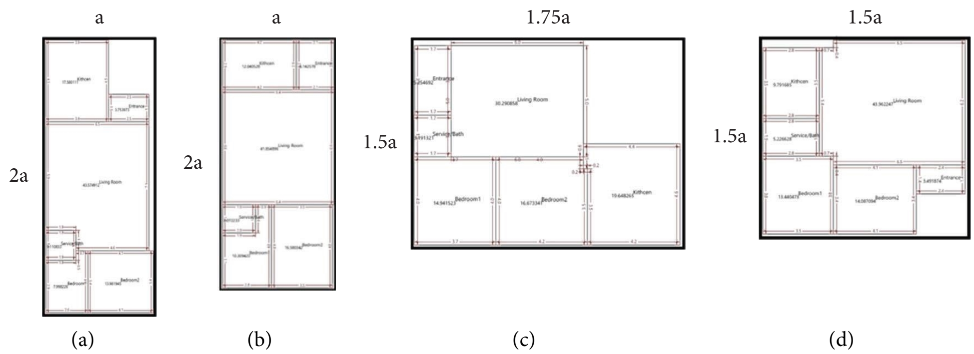

Figure 2: Variation of the final responses of the algorithm (source: author). (a) An incomplete rectangle. (b) A rectangle. (c) Incomplete L-shape. (d) An incomplete square.

$$\begin{aligned}\text{Area} + \alpha = 8.431 &+ (12.310 \times W_{SRR}) + (4.224 \times L_{SRR}) \\ &+ (11.377 \times W_{MRR}) + (-8.445 \times L_{MRR}) \\ &+ (5.971 \times W_{W\&B}) + (-3.712 \times L_{W\&B}) \\ &+ (0.029 \times W_{LR}) + (6.544 \times L_{LR}) \\ &+ (2.736 \times W_{KR}) + (1.529 \times L_{KR}) \\ &+ (-4.907 \times W_{ES}) + (-7.252 \times L_{ES}).\end{aligned} \tag{8}$$

Also, if the two axes x and y are defined for each production configuration, it can be acknowledged that one of the following relations must be established to reach the shape of the rectangular configuration:

$$4 \times \text{Area} \cong \sum x \text{ sides} \times \sum y \text{ sides}. \tag{9}$$

This formula alone can be defined as a condition in the algorithm. It is also possible to reach the following formula by expanding this formula:

$$\sum x \text{ sides} + \frac{4 \times \text{Area}}{\sum x \text{ sides}} \cong \text{Primeterof Generated Layout}. \tag{10}$$

Based on the linear regression model obtained, the following model can be defined as the configuration of an approximately 90 square meter residential unit. In this model, if β tends toward zero, the configuration obtained is rectangular:

$$\begin{aligned}\sum x \text{ sides} + \frac{4 \times \text{Area}}{\sum x \text{ sides}} - 41.469 + \beta &\cong (0.956 \times W_{SRR}) \\ &+ (0.753 \times L_{SRR}) + (0.898 \times W_{MRR}) + (-0.817 \times L_{MRR}) \\ &+ (0.015 \times W_{W\&B}) + (-1.321 \times L_{W\&B}) + (-2.003 \times W_{LR}) \\ &+ (1.836 \times L_{LR}) + (1.063 \times W_{KR}) + (-0.147 \times L_{KR}) \\ &+ (-1.243 \times W_{ES}) + (-1.071 \times L_{ES}).\end{aligned} \tag{11}$$

Area-oriented approaches to generative configuration design can take into account the above conditions. Considering that a similar model was not seen on the production results of the configuration in the investigated researches, it is suggested that in similar researches, the results obtained from the generative algorithm should be evaluated and modeled in order to be able to compare the results obtained. In future studies, it is also recommended to use the abovementioned conditions.

5. Conclusion

Presented in this research is an interactive generative spatial layout (GSL) design process that provides optimized spatial design solutions based on geometric, topological, and functional objectives and constraints as inputs. The shape of the final plans is also evaluated based on the two variables of the plan environment and its central rectangle. As a result of providing geometrical, topological, and functional constraints in all responses, the final results demonstrate clearly that the creative area-oriented approach to the productive design of housing configurations can serve as an assistant mechanism in providing a variety of layouts for the designer. By incorporating this algorithm into the optimization cycle for each functional goal, optimal design responses can be determined. With the existing algorithm, designers can directly obtain and use a set of optimal responses along with a set of geometric and functional evaluations by determining the design objective and constraints.

The development of this algorithm can be divided into several phases in the future. One of the most important aspects of the development is the possibility of planning the spatial configuration based on determining the outer boundaries of the residential units. To reach optimal answers through single-objective or multiobjective optimization algorithms, the second part of the development of this algorithm is to place it in an optimization cycle that combines functional goals such as thermal performance, lighting requirements, and ventilation performance. Another objective of developing this algorithm is to place the residential units generated by the algorithm in apartments and on a larger scale in residential blocks such that their geometric variables are parametrically defined. Based on the results of this process, the functional goals of the residential unit can be reviewed by taking into account the neighborhood's characteristics. Additionally, one of the other development processes of the current algorithm is the use of creative design limitations obtained through regression tests, which may lead to more practical results.

Data Availability

The data supporting the findings of the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they do not have any conflicts of interest.

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