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Generative design and performance optimization of residential buildings based on parametric algorithm

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ABSTRACT

As passive green design and performance optimization are very important in the early design stage of green residences to reduce building energy consumption, energy-efficient green design and artificial intelligence technology are combined in this work for the design of residential buildings. A parametric generative algorithm is developed to automatically generate design schemes of typical Chinese urban residences based on performance-oriented design flow. By summarizing the workflow of architects, the algorithm based on the technical route is as follows: 1) spatial form features extraction of residence database; 2) automatic generation and energy simulation of new design schemes; 3) evaluation and screening of generated schemes. The generative algorithm is formulated with Rhino/Grasshopper and Python. Via a residence design case in Beijing, the design scheme with the lowest cooling and heating load among 1,595 automatically generated schemes is deemed as the optimal scheme. The total load of the optimal scheme is 15.8% lower than that of the worst scheme and 4.2% lower than that of the original scheme. Therefore, the parametric generative design of residences is able to facilitate passive green design in the early design stage and enhance energy efficiency without the increase of construction costs.

1. Introduction

The increasing problems of resource availability and environmental strain have increased the significance of sustainability and energy efficiency for residential buildings. More attentions have been paid to the optimization of building performance in residence design. According to some researches, early design stage is most important in building performance optimization [1–3]. Appropriate green design and optimization method in the early design stage can substantially enhancing energy-saving effect by designing and optimizing building shape, spatial layout and building envelope without the increase of construction costs.

Generative design refers to a design process that utilizes a computer algorithm, with the formulation of parametric algorithms, design results can be automatically generated by computers, which can help designers automatize parts of the design process [4,5]. The definition of generative design was proposed firstly in 1870s as 'devices capable of generating potential solutions to a given problem' [6]. In the 21st century, generative design was defined particularly in the field of architecture design. For Fischer and Herr, generative design was a design process that designers did not interact with materials and products directly, but via computer-aided generative systems which are typically developed for architects [7,8]. Kallioras and Lagaros described generative design as 'the methodology for automatic creation of a large number of designs via an iterative algorithmic framework while respecting user-defined criteria and limitations' [9]. During the third technical revolution, architects are facing the shifting and upgradation of knowledge, positioning, and design flow. Consequently, computer-aided generative design based on digital techniques has become a novel research hotspot in the new round of technical revolution. Singh and Gu reviewed and analyzed researches of five generative design algorithms: cellular automata, genetic algorithms, L-systems, shape grammars, and swarm intelligence [5]. These researches primarily employed existing genetic algorithms rather than develop new algorithms in design process. Sydora and Stroulia developed a BIM based rule language, describing interior design rules in a machine-readable format, by which automated generation of interior design models can be realized [10]. Wang et al. implemented a generative grammar and procedural rule named City Engine, generating the texture of blocks as close as possible to the actual blocks in urban design. The generative grammar was developed in analyzing of the spatial form of blocks case samples in Nanjing [11]. Li and Han [12] developed a building layout generation algorithm based on a complex system model.

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Moreover, some software programs at present were developed to generate design solutions automatically. ArchiGAN, for example, was able to design interior layouts according to the building shape. XKool's intelligent planning system was able to generate urban layouts by improving land utilization efficiency and economic effect [13]. However, few studies have investigated generative design of green residences with the targets of energy conservation.

In architecture design, computer algorithms was used by architects in achieving energy-efficient solutions. In the reviewed papers [14,15], green building design via optimization algorithms have recently been applied widely in lifecycle green architecture design. Ahmed et al. presented a genetic algorithmic method for energy efficient building solutions. The optimization was mainly focused on WWR, window material, construction material and shading devices, etc. [16] Si et al. presented an algorithmic optimization case of building envelope of a tourist center, reducing building load by 11% and average PPD by 8.3% [17]. Keivan et al. employed ant colony optimization algorithm in optimizing of nine parameters in two commercial buildings of Brisbane and Hobart [18], reducing energy consumption by 19% and 26%. Simon et al. combined parametric design with Building Energy Models and managed to reduce the facade's cooling demands significantly through optimization of the building's shading system [19]. However, all those papers generated and optimized some building part in an existing design scheme with computer algorithms, rather than addressing the generation of whole architecture scheme.

Against the background of the widespread application of digital intelligent technology, this research is aimed at constructing a parametric generative design method for residences via the combination of parametric generative design and the performance-oriented green residential design process. This paper puts forward a parametric generative design method for residential buildings based on the performance-oriented design flow, which aims at optimizing the energy performance of buildings. A related algorithm is also developed to facilitate passive green design in the early design stage and promote the energy-saving effects of residences.

2. Establishment of a generative design algorithm for energy efficient design of residential buildings

In this study, a parametric generative design algorithm is developed, the process of which is as follows. First, the user inputs the basic information of the desired residential building scheme, such as the unit area, room function, unit type, orientation, etc. Then, the algorithm automatically generates a large number of corresponding design schemes of typical Chinese urban residences. The optimal design scheme is then selected via a building energy simulation and optimization process. Finally, the algorithm automatically draws a floor plan and 3D model of the final scheme. Fig. 1 presents the process diagram of the algorithm, which mainly consists of four modules, namely the automatic generation of design schemes, the evaluation and selection of schemes, the energy consumption simulation, and the visualization of schemes.

2.1. Summarization of parametric generative rules for residences

The basis of the generative design of residences lies in the summarization and parameterization process of various design features and the construction of generative rules of residential buildings. The parametric generation of residence design schemes entails the extraction of design parameters and the relationships between functions and the spatial layouts in a single residence and an entire typical floor of a residential building. The summarization of the layouts of regular unit types, as well as the analysis of residents' daily behavior patterns, allow for the determination of the relationships between the room functions and spatial layout. In fact, the generative design of residences is the expression of the parametric relationships among building features, room functions, and spatial layouts via algorithms to more efficiently obtain a large number of design schemes that fit into the corresponding spatial features with the assistance of a computer. Moreover, algorithms also promise the rapid prediction of the energy consumption of each design scheme to facilitate the easy comparison and selection of architectures.

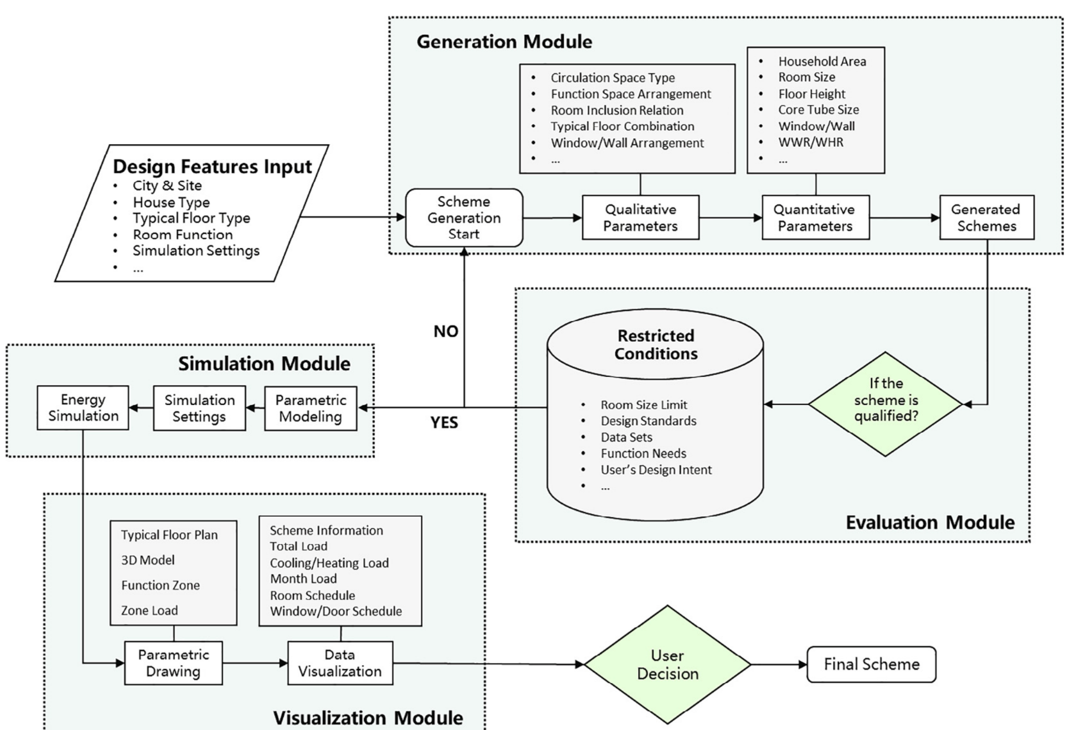


Fig. 1. Process diagram of residence generative design algorithm.

Table 1
Parameters of residence generative design.

Type		Parameter	Description
Qualitative Parameters	Typical Floor	*typical_floor_type*	spatial form features of typical floor
		orient	orient of building
		core_type	type of core-tub
		core_loc	location of core-tub
	Single Unit	*suit_type*	spatial form features of single unit
		trans_type	shape of indoor circulation space
	Functional Room	*room_type*	room function
		room_orient	orientation of rooms
		room_seq	function priority of rooms
		room_nest	inclusion relation of rooms
		room_width_changable	if room width can be adjusted by users
		room_depth_changable	if room width can be adjusted by users
	Window/Door	*w_orient*	orientation of windows
		w_wall	wall of windows
		door_out_orient	opening direction of the entry door
		door_out_wall	wall of the entry door
		door_in_orient	opening direction of interior doors
		door_in_wall	wall of interior doors
Quantitative Parameters	Typical Floor	*width*	building width
		depth	building depth
		area	area of typical floor
		pool_area	ratio of public circulation area
		shape_factor	building shape factor
		core_width	core-tub width
		core_depth	core-tub depth
	Single unit	*suit_area*	area of single unit
		trans_area	indoor circulation area
		trans_ratio	ratio of indoor circulation area
		suit_width	width of single unit
		suit_depth	depth of single unit
		trans_length	length of circulation space
		U	heat transfer coefficient of external wall
		U_inner	heat transfer coefficient of interior wall
	Functional Room	*room_width*	functional room width
		room_depth	functional room depth
		room_area	functional room area
		WDR	ratio of room width to depth
	Window/Door	*W_width*	window width
		W_height	window height
		WWR	window wall ratio
		WHR	window width to depth ratio
		U_win	heat transfer coefficient of window
		door_out_width	entry door width
		door_in_width	interior door width
	Other	*timer_all*	times of scheme generation
		cooling	cooling load of typical floor
		heating	heating load of typical floor
		total	total load of typical floor
		suit_cooling	cooling load of single unit
		suit_heating	heating load of single unit
		suit_total	total load of single unit
		room_cooling	cooling load of room
		room_heating	heating load of room
		room_total	total load of room
		month_total	total load per month
		month_cooling	cooling load per month
		month_heating	heating load per month

To create parametric generative rules of design schemes for typical Chinese urban residences, a large number of existing residence schemes are needed to summarize the design features. This study is anchored on a database of 300 regular typical floor plans in northern cities in China. The database of typical floor plans was collected based on Chinese building standards and local policy requirements, and offers a rewarding case reference.

(1) Parameter extraction

The extraction of characteristic parameters is the summarization of major feature elements in residence design. Via the analysis of the general residential design process, essential design parameters, such as the indoor circulation space, room functions, orientation, room size, functional relationships, building envelope, and layout of a typical floor plan, etc., can be determined. These parameters all serve as influential factors in residential building design and can be divided into two types. The first type refers to parameters involving sizes, areas, and coefficients that can be numerically described, and include the unit area, room area, room width/depth, room depth-to-width ratio (DWR), floor height, sizes of doors/windows, window-to-wall ratio (WWR), window width-to-height ratio (WHR), heat transfer coefficient of the wall/window (U-value), and size of the core tube, etc. The second type of parameter includes elements that cannot be numerically described, such as the orientation, spatial layout, shape of the circulation space, and

Fig. 2. Spatial form features of single units.

the relationships between rooms, which must be converted into parameters that can be recognized by the algorithm. Therefore, the two types of design parameters include the quantitative parameters that can be numerically described and the qualitative parameters that cannot be represented by numbers. Table 1 presents the design parameters summarized in this paper.

In addition, the value ranges of parameters were determined in reference to residence design standards and data sets in China. The missing data were determined by summarization in accordance with typical cases and experience data.

(2) Spatial form features of a single unit

The circulation space is a critical element that connects the entire indoor space in a single unit, and the indoor circulation space informs the entire shape and form of the unit type. Moreover, because all rooms are linked by the circulation space, the arrangement of the indoor space is also determined by the indoor circulation space. As such, the shape of the circulation space must be identified before the arrangement of rooms can be determined. An analysis of a database of typical unit types indicates that the

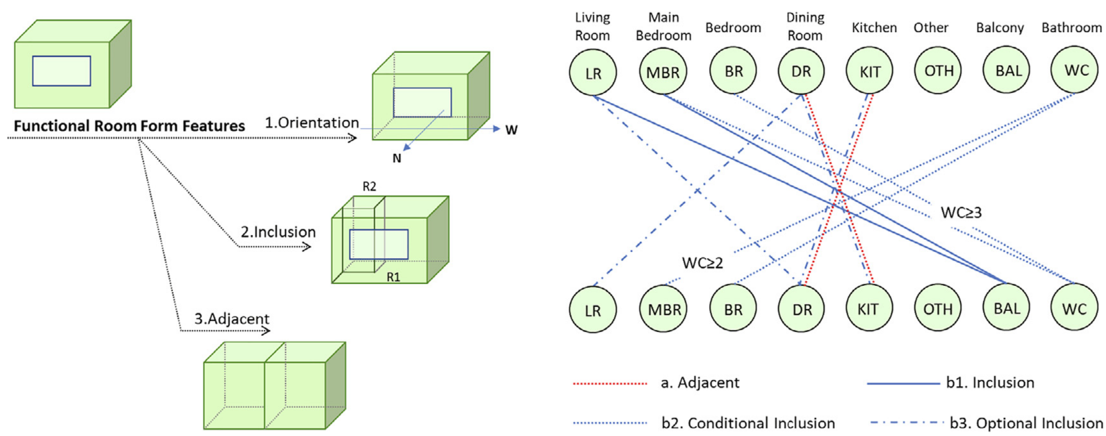


Fig. 3. Spatial form features of indoor functional rooms.

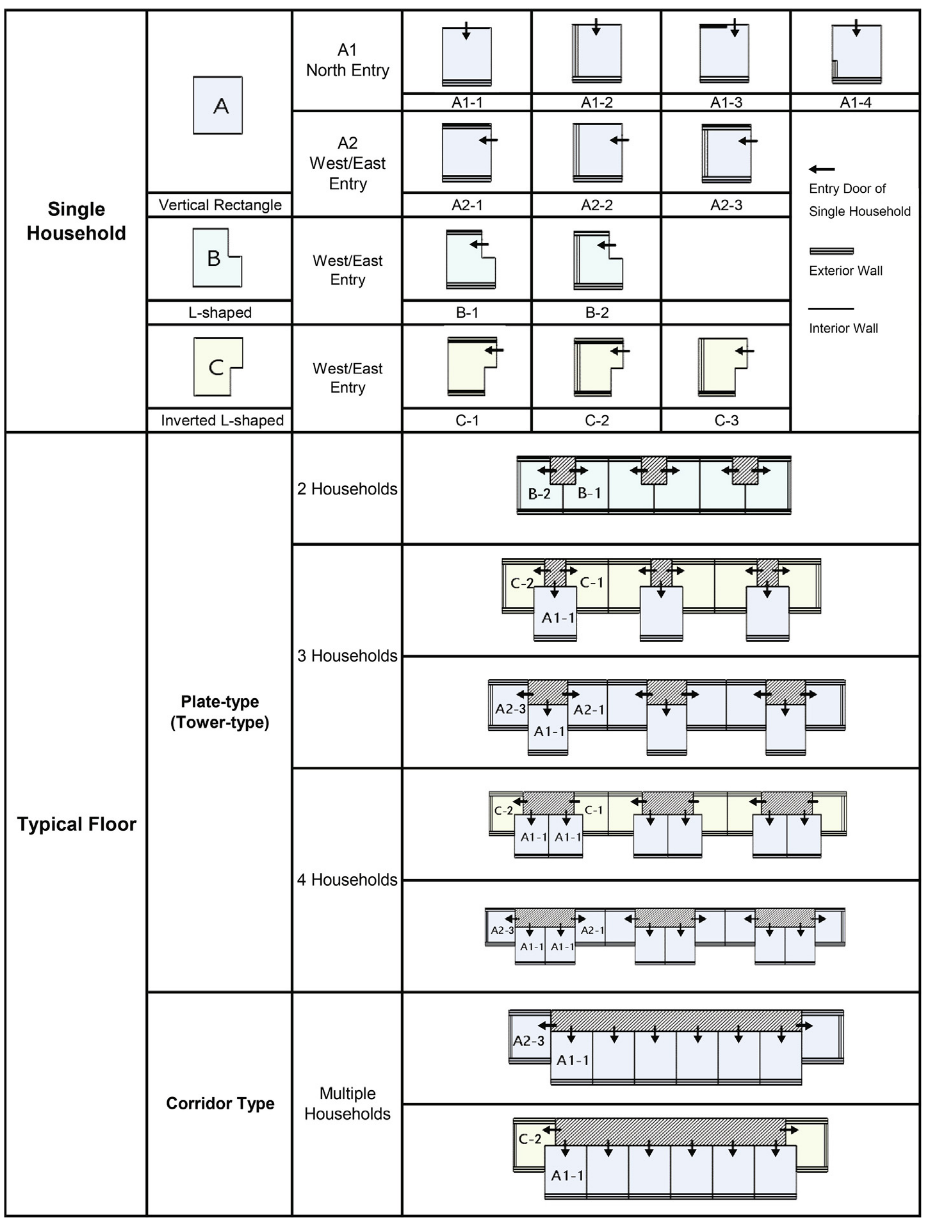


Fig. 4. Spatial form features of typical floor plan.

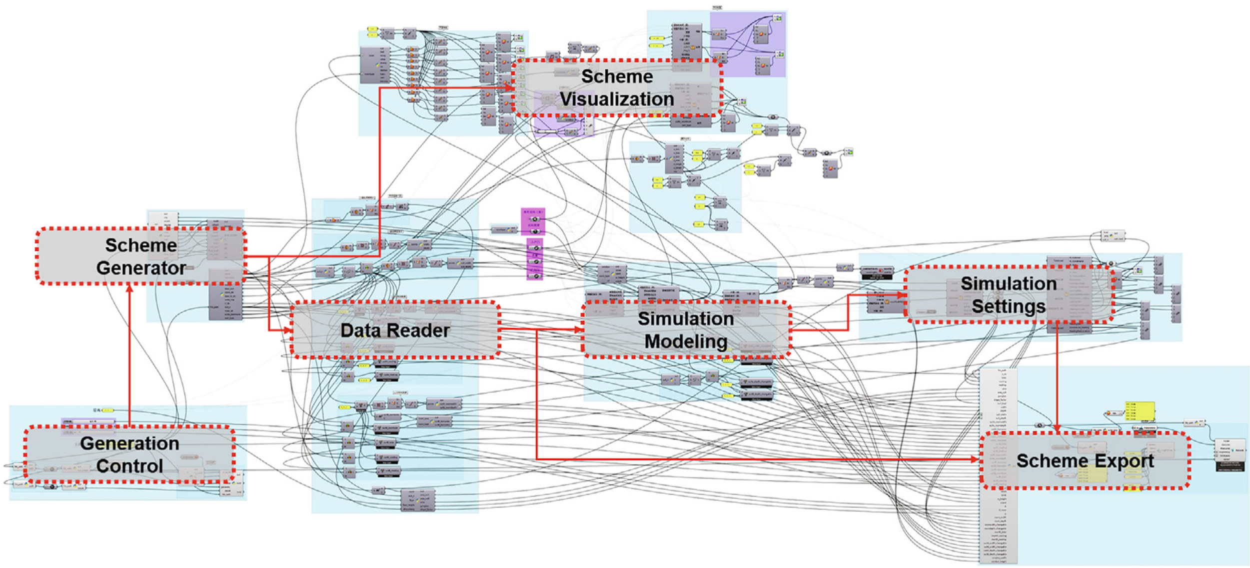


Fig. 5. Algorithm framework built in grasshopper.

indoor spatial arrangement of Chinese urban residences is usually rather compact. Therefore, to enhance the spatial utilization efficiency and decrease the proportion of circulation space, the indoor circulation space is largely arranged in a regular form.

As shown in upper half part of Fig. 2, the shape of indoor circulation space and functional rooms were firstly signed and analyzed on typical floor plan of 300 schemes from the database. Then in the lower half part of Fig. 2, the shape features above were summarized and simplified as I-shaped, L-shaped, T-shaped, and U-shaped circulation space. Moreover, further analysis revealed that the U-shape circulation space is usually accompanied by an enlarged hallway space, and can therefore be classified as a variation of L-shaped circulation space. Furthermore, as there are only a few cases of T-shaped circulation spaces, and because the southward L-shaped circulation space can often be simplified as I-shaped, the T-shaped and southward L-shaped circulation spaces were respectively considered as variations of the northward L-shaped and I-shaped circulation spaces.

After the form of the indoor circulation space has been identified, the spatial arrangement of rooms can be considered. As rooms are linked by the indoor circulation space to ensure the normal operation of indoor functions, each functional space is arranged around the circulation space. Moreover, the arrangement of rooms is affected by the orientation, usage requirements, and interrelation of space functions, and some rooms have inclusion relationships, e.g., the bedroom and bathroom, the kitchen and dining room, the living room and dining room, the living room and balcony, and the kitchen and balcony, which can all be inclusively arranged. Fig. 3 presents the spatial features of indoor functional rooms.

(3) Spatial form features of the typical floor plan

As the typical floor plan in an urban residential building is usually composed of multiple households, to summarize the combination rules of different households in the typical floor plan, the features of a single unit type, such as the shape, location of the entry door, and orientations of windows, were first summarized based on the 300 residence design schemes in the Chinese urban residence database. According to the summarization results of the features, four main unit types were classified as follows: the vertical rectangle type (A), the L-shaped type (B), the inverted L-shaped type (C), and the horizontal rectangle type (D). These four types of residences were subdivided in accordance with the

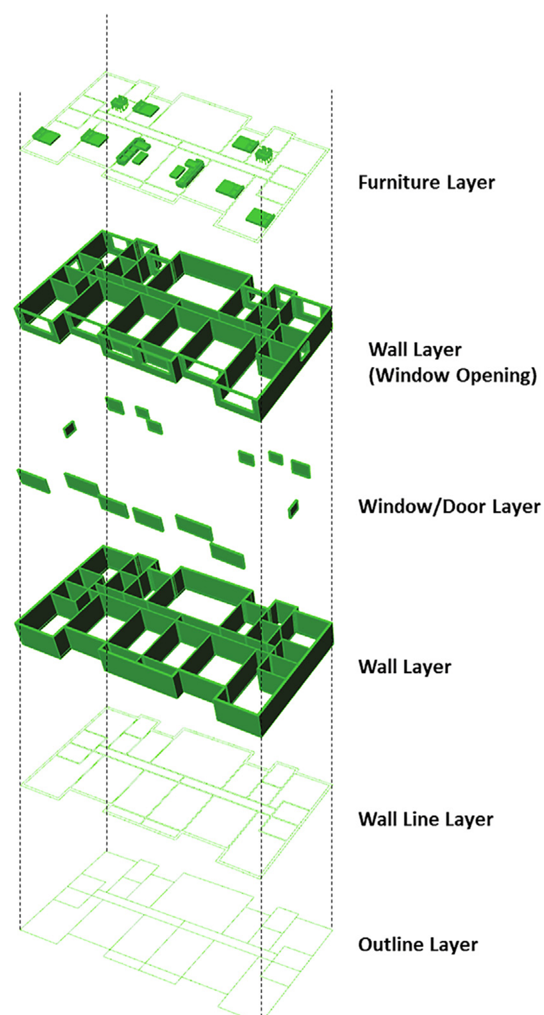


Fig. 6. Generative process of typical floor plan 3D model.

location of the entry door, as denoted by A1, A2, B1, B2, etc. Moreover, based on the orientations of windows, the unit types were further sub-classified and denoted as A1-1, A1-2, A2-1, etc. Fig. 4 presents the detailed information about the unit type classification and the corresponding labels.

Based on the summarization of unit types, the combination rules of different unit types were analyzed. According to the regular typical floor plans in the database, residences can be classified as plate-type and tower-type based on the number of units on one typical floor, or into two, three, four, and multiple households based on the number of households in on one typical floor. However, as the number of typical floors with multiple households (such as six or eight unit types) is relatively few, and substantial differences exist in the combination rules, only the spatial form features of two households ~ four households were summarized, as detailed in Fig. 2.

Core tubes connect different households and provide vertical circulation in residential buildings. They usually have similar arrangements in regular residence design schemes due to functional needs. This means that the prototypes and sizes of core tubes can be classified into several common types, which can be inserted into the typical floor plan as a functional module.

2.2. Establishment of a generative algorithm for residence design schemes

Based on the parametric generative rules summarized previously, a generative algorithm was constructed for typical floor plan schemes of residential buildings via the technical route of the random generation of parameters and selection by restrictive conditions. The algorithm is based on Rhino/Grasshopper and Python to realize the automatic generation of residence design schemes. The framework of the algorithm is shown in Fig. 5.

The algorithm takes between 0.5 and 3 min to generate one scheme that fits into the restrictive conditions after tens of thousands of computations, and the computation time is associated with the input conditions; the harsher the conditions, the longer the computation time. Additionally, a maximum computation duration is set, which means that if no scheme meeting the requirements is found after the maximum computation duration is reached, an error message will be displayed to inform the user that there might be problems in the input design conditions or the restrictive conditions.

(1) Generation algorithm for single units

In accordance with the spatial features of the different unit types summarized previously, the functional relationships between rooms in a single unit are described. In the design scheme generation process, the values of design parameters must be determined to generate a new scheme, and include the orientation (south, north, or west-east), the functions of rooms, the arrangement of rooms, the room size, the connections between embedded rooms (such as the bathroom and the bedroom, balcony, kitchen, dining room, etc.), and the locations of the door and windows.

These parameters are randomly generated within the range of restrictive conditions (some parameters can be directly identified by the known parameters and restrictive conditions and can be exempted from the random generation process). Throughout the process of parameter generation, the parameters that have been generated are compared with the restrictive conditions and discarded for re-generation if they do not meet these conditions.

The scheme generation process is as follows. First, the prototype of the indoor circulation space, namely I-shaped or L-shaped, is randomly selected. The spatial arrangements of functional rooms, including the orientation and the spatial order, etc., are then decided. Next, parameters of the room size are randomly generated within the reasonable range according to the functional priority order of different rooms. Moreover, the outline of the circulation space is drawn based on the room sizes, locations, and type of circulation space. Furthermore, the outline of each room is drawn based on the circulation space to obtain the preliminary floor plan of a single unit. After, the sizes of windows are generated according to the WWR and WHR parameters set by the user. The default WWR value for windows facing the south is 0.5, and that for windows with other orientations is 0.35; moreover, the default WHR value is 1.2, and the default window height is 0.9 m. When the external wall size cannot accommodate the default value of the WHR, the algorithm will fine-tune the value according to the size of the external wall to ensure a practical size. Finally, the relative positions between the rooms and indoor circulation space are identified, and the locations and opening directions of doors are determined.

(2) Generation algorithm for the typical floor plan

The generation algorithm for the typical floor plan of a residential building is constructed according to the spatial form features of the typical floor plan summarized previously and the floor plan of a single unit generated in the previous step. The main steps include the following. First, the unit type generated in the previous step is

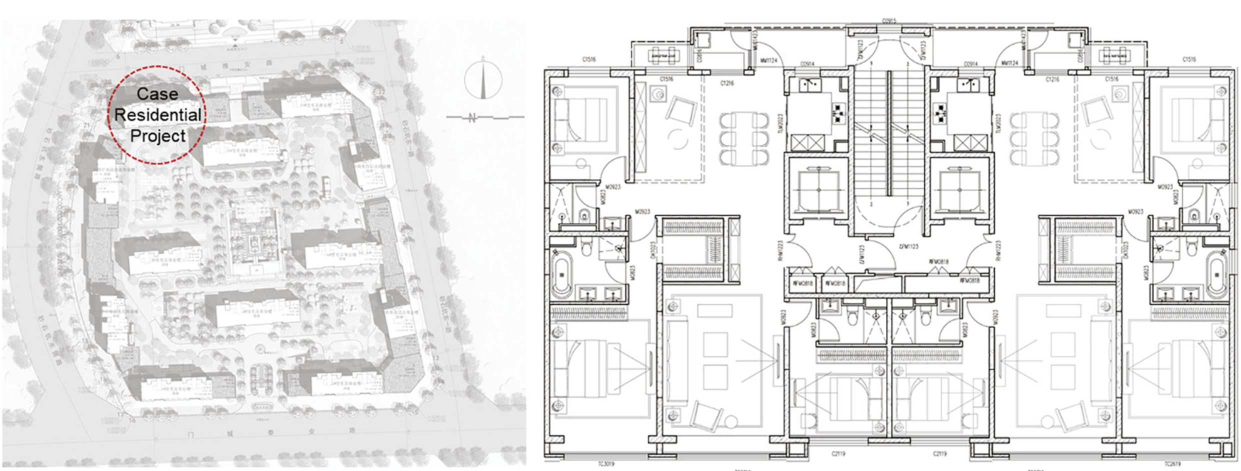


Fig. 7. Project location and typical floor plan of the original scheme.

identified, and the prototype of the typical floor plan is determined in accordance with the unit type. Then, the core tube module is selected according to the floor number. Next, the floor plans of single households are combined via the algorithm, and the outline of the typical floor is drawn. Finally, the final typical floor plan and 3D model of the generated design scheme are drawn, as shown in Fig. 6.

2.3. Summarization of the restrictive conditions for residence design schemes

Building design is a complicated process involving the comprehensive analysis of various design elements, and a generative design algorithm must verify whether the generated scheme can meet all the design requirements and/or the architect's design intent, thereby playing a key role in the parametric generative design process. Thus, it is necessary to examine the rationality of the generated design scheme by setting up an evaluation module and restrictive conditions in the parametric generative process. In this algorithm, the restrictive conditions mainly include the size of the functional space, the design standards, the needs of the residents, and the restrictive conditions defined by the designers.

To reduce the operation time, the generation process introduced in Section 2.2 and the evaluation process introduced in Section 2.3 are conducted alternatively. To be specific, the generation process is suspended under the process requirements for screening the design schemes; this generation process will be directly ended if any restrictive condition is not met, and a new generation process will be initiated. Alternatively, a certain process branch will be halted if it does not meet the restrictive conditions, and the previous step before this branch will be resumed. In this way, this algorithm can avoid invalid computation as much as possible, and keep the overall generation time within a reasonable range.

2.4. Establishment of the parametric energy simulation module

One dominant advantage of the generative design method lies in the performance optimization among many automatically generated design schemes, in which the optimal design scheme with

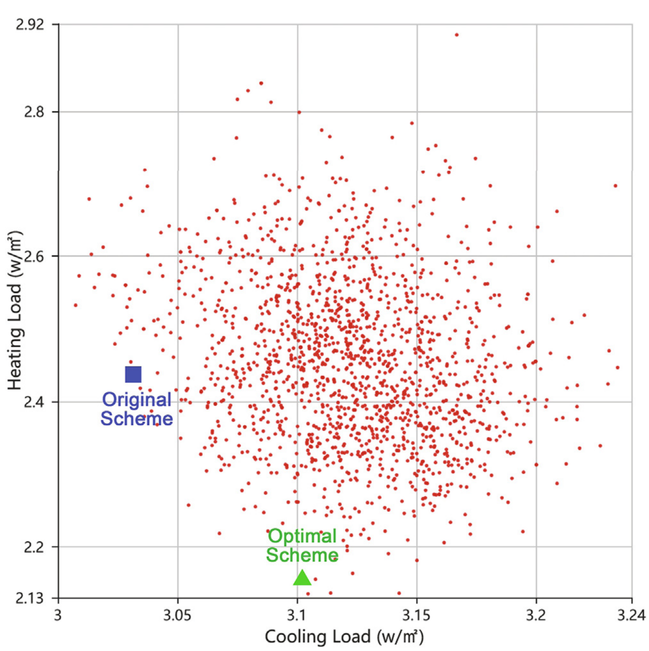


Fig. 8. Thermal load scatter plot of all schemes.

the best energy performance can be selected, an attribute unattainable by the general design process. This depends on automatic energy simulations conducted via the parametric algorithm to obtain a large number of simulation results for comparison and selection among different design schemes. Presently, there exist Rhino/Grasshopper plug-ins that can be applied for parametric performance simulation involving energy, lighting, ventilation, etc. The energy simulation in the proposed algorithm is based on Ladybug and Honeybee, which are based on the EnergyPlus simulation core.

As the simulation method used in this study is primarily targeted for the early design stage, the simulation settings are simplified to enhance the optimization speed. Specifically, the entire building is simplified as a single-layer model, the floor slab, the floor, and walls between households are assumed as heat insulation, and the influence of the relationship between floors and core tubes on the simulation results is ignored. Moreover, each functional room is set as a single heat zone, and the heating load and the cooling load per square meter are calculated to reflect the impact of the spatial arrangement on the energy consumption of the typical floor of the building. The default simulation settings adopt an ideal air-load system. Additionally, the heating period is set from November 15th to March 15th, and the cooling period is set from June 1st to August 31st. The meteorological parameters are sourced from the EnergyPlus database in the corresponding city. In addition, the operating condition settings include the indoor density of 0.018 people/m^2, an absence of human activity between 10:00 am and 4:00 pm, 50% human activity between 7:00 am and 9:00 am and between 5:00 pm and 6:00 pm, and 100% human activity in the remaining time. During festivals and holidays, the operating condition settings include 50% human activity between 7:00 am and 6:00 pm and 100% human activity in the remaining time.

3. Case study of residence design and energy optimization based on the generative design algorithm

To verify the application effect of the generative design method, the proposed method and algorithm were employed in a residential building project in Beijing. The performance-oriented generative design was applied in the early design stage of the typical floor plan. Fig. 7 shows the project location and the typical floor plan of the original scheme which was designed by the conventional design method. In the generative design process of this paper, a large number of typical floor plan design schemes that met the design needs were generated via the algorithm. The energy consumption simulation was then utilized to calculate the total load of the generated schemes as a basis for choosing the optimal scheme. And the generated design schemes and energy consumption simulation data were presented to an architect, who decided the final design scheme via the comprehensive consideration of its performance, functions, and other non-quantitative elements.

The residence design process in this case study primarily included the setting of the basic conditions and design requirements, the automatic generation of design schemes, and the selection of the optimal energy consumption scheme.

The case study area is located in Beijing, China, which is located in a cold climatic zone (AII) as per China's Building Climate Demarcation Standard (GB 50178-93). The residence design needs included a north–south orientation, two households in one typical floor plan, and an area of each household of approximately 130 m^2. The interior functional needs of each household included one main bedroom, two secondary bedrooms, one study room, two bathrooms, one dining room, and one kitchen. Moreover, as the purpose of this design stage rests on the evaluation of the effect of the

Fig. 9. Design schemes with stepped total load.

spatial arrangement on the energy consumption, parameters related to the building envelope were fixed, including the heat transfer coefficient of external walls (0.4 W/(m^2•K)), the heat transfer coefficient of interior walls (1 W/(m^2•K)), the heat transfer coefficient of external windows (1.5 W/(m^2•K)), the WWR for south-facing windows (0.5), the WWR for north-facing windows (0.35), and the height of each floor of the building (2.8 m).

A total of 1,595 sets of design schemes were generated in this study in the total time of about 79 h and 45 min, and each set of schemes was saved in the form of data, graphs, and 3D models. These included the graphs and 3D models of typical floor plans, the plans of functional layouts, the distribution diagrams of cooling and heating load, and the basic information of each scheme. The data of each design scheme mainly included the heating, cooling, and total load of the typical floor, as well as the floor area, room area, shape coefficient, ratio of the residential pool area, ratio of the indoor circulation space, room size information, window and door placements, etc.

4. Discussion of the case study results

In the case design process, the final optimal design scheme was selected out of 1,595 generated schemes based on the energy simulation results. Fig. 8 displays the scatter diagram of the cooling and heating load for all generated design schemes, in which the scheme with the lowest total load (the triangle symbol) and the original design scheme (the square symbol) are marked for comparison and analysis. For the design scheme with the best energy performance, the total load was 5.24 w/m^2, the cooling load was 3.10 w/m^2, and the heating load was 2.14 w/m^2. For the design

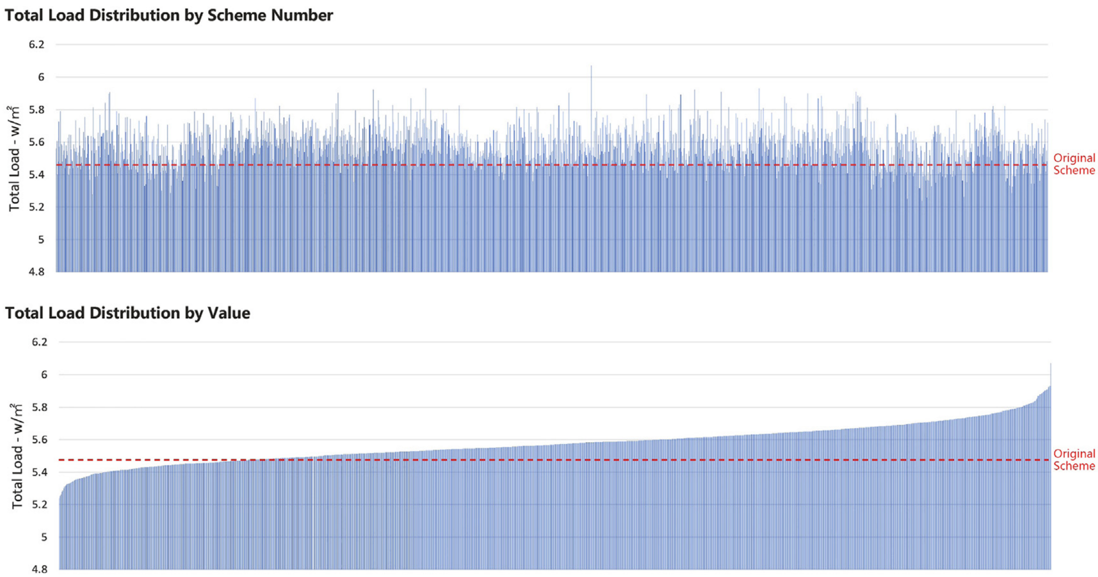


Fig. 10. Total load distribution for all generated schemes.

scheme with the worst energy performance, the total load was 6.07 w/m^2, the cooling load was 3.17 w/m^2, and the heating load was 2.90 w/m^2. Furthermore, to compare the energy consumption of the original and generated design schemes under the same parameters, the building envelope parameters and the building floor height of the original scheme were set to the same values as those in the generated scheme to perform an energy simulation; the results reveal that the total load was 5.46 w/m^2, the cooling load was 3.03 w/m^2, and the heating load was 2.43 w/ m^2. As such, the total load for this optimal design scheme was reduced by 4.2% as compared with that in the original scheme, and by 15.8% as compared with that in the scheme with the highest energy consumption.

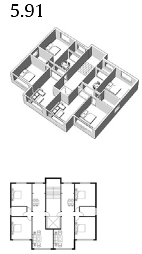
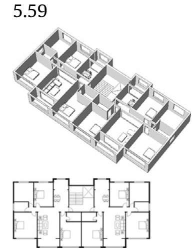
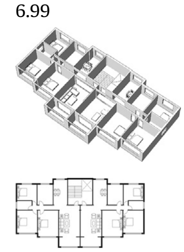
Fig. 9 presents the comparison of the spatial forms of the 30 design schemes with stepped total load. Compared with the shapes of the worst schemes, those of the optimal design schemes have less concave and irregular surfaces, which is in line with the general principle of energy-efficient design.

Additionally, as presented in Fig. 10, which displays the total load for all generated schemes, the total load of the original scheme was located in the middle and lower levels among all the generated schemes. This indicates that, while the energy performance of the design scheme produced based on the general design method was relatively superior, there remains the potential for further optimization. Moreover, the parametric generative design method exhibited a certain advantage as compared with the general design method.

5. Verification

In order to verify the effect of energy efficient generative design algorithm of residences, three groups of schemes were generated under different input conditions, and a total of 1294 schemes were generated. Among them, the first group was located in Beijing, with a building orientation of 30 degrees south by east and a suit area of 90 m^2; the second group was located in Tianjin, with a

Table 2
Input conditions and results of verification process.

Verification Process		**Group1**	**Group2**	**Group3**
Sample Size		445	335	514
Input Conditions	**Location/ City**	Beijing	Tianjin	Shenyang
	Suit Area/m^2	90	130	110
	Suit Area Range	20%	20%	20%
	Orientation	Southeast 30 degrees	South	Southwest 15 degrees
	Room Function	1LR 2BR 1WC 1DR 1Kitchen	1LR 4BR 2WC 1DR 1Kitchen	1LR 3BR 1WC 1DR 1Kitchen
	Floor	6	6	6
Generation Time /min	1326	1245	1442	
Total Load(w/m2)	**Min**	5.55	5.36	6.56
	Max	6.57	5.94	7.59
	Average	5.91	5.59	6.99
Optimal Schemes				

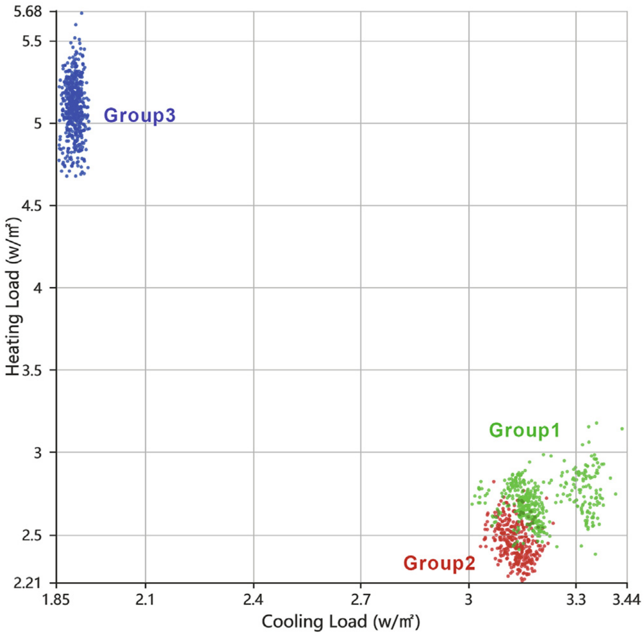


Fig. 11. Thermal load scatter plot of verification schemes.

building orientation of south and a suit area of 130 m^2; the third group was located in Shenyang, with a building orientation of 15 degrees south by west and a suit area of 110 m^2. The floating range of suit area was 20%. The specific input conditions and results of the three schemes were shown in Table 2.

Fig. 11 is the scatter diagram of thermal load of all verification schemes, in which different colors represent different groups. Table 2 shows the most energy efficient schemes in the three groups. Among the generative design results of three groups, total load of the lowest energy consumption schemes was 5.55w/m^2, 5.36w/m^2 and 6.56w/m^2 respectively, and total load of the highest energy cost schemes was 6.57w/m^2, 5.94w/m^2 and 7.59w/m^2 respectively. Total load of the optimal schemes in each group was 18.4%, 10.8% and 15.7% lower than that of the worst schemes respectively. According to the above data, the energy-saving effect of the three groups are similar to the case study project. Normally, the larger the sample size of the generated scheme is, the more sufficient the energy optimization is.

6. Conclusion

The parametric generative design method proposed in this paper includes an automatic residence design process developed through a series of algorithms. Its strength rests on the acquisition of a large number of design schemes via the establishment of parametric algorithms, the rapid generation and modification of design schemes, and the enhancement of the rationality and accuracy of the design process via the data-based design. Additionally, the proposed generative algorithm for the typical floor plan of residential buildings in northern China was realized by Rhino/Grasshopper and Python. The main process of the algorithm includes the following. 1) The residence design features are summarized by extracting the characteristics from a database of regular residence design schemes in northern China, which include the spatial form features of single residences and the typical floor plan of a residential building. 2) The residence design schemes are automatically generated by parameterizing the extracted features and setting up the parametric model. 3) The evaluation module is set with restrictive conditions, such as the design standards, the data set, and the functional needs, to determine the rationality of the generated design schemes. Moreover, an open module is provided for subjective evaluation by architects to improve their leading role in the computer-assisted decision-making design process.

As proven by the generative design process of a case study in Beijing, the total load of the generated optimal design scheme was respectively decreased by 4.2% and 15.8% as compared with those of the original design scheme and the scheme with the highest energy consumption. The design schemes and data diagrams acquired via this generative algorithm can offer visual references for architects, thereby helping them analyze the spatial layouts and performances of design schemes, and to comprehensively consider the spatial features, human behavior, aesthetics, and other non-quantitative factors capable of assisting design decisions via the human–computer interactive process.

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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