11 Spatial configuration evaluation of Chinese rural houses through visual graph analysis for adaptive thermal comfort

11.1 Introduction

In chapter 9, it was found that the spatial indicators can reflect the airflow performance. There is a positive or linear correlation between the spatial indicators (connectivity, integration and depth) and the airflow indicator (airflow rate). The indicators that reflect the accessibility of the spatial configuration, i.e. connectivity, integration and depth, reflect the potential of achieving natural ventilation of a particular spatial configuration. In the other words, a high degree of connectivity, integration and low depth value mean a high accessibility of the spatial configuration and a high potential of obtaining natural ventilation. This result is useful for the architectural design practice, especially in the early design stage. In chapter 10, the extended space syntax methods in the program of Depthmap for natural ventilation potential analysis were proposed by the author. In this chapter 11, the proposed methods for spatial analysis will be used for design practice. The spatial configurations of a number of Chinese rural house designs in the area studied will be evaluated in terms of natural ventilation potential for thermal summer comfort by the proposed spatial analysis methods.

The rural houses as a case study in this research is chosen because the Chinese rural houses normally using passive ways to achieve thermal comfort in summer, therefore the spatial configuration for natural ventilation is important, as the author concluded in part 1 in this thesis. In addition, the rural population in China accounts for 40% of the total population with a total amount of approximately 560 million at the end of 2018 (NBSC, 2018). At the end of 2014, there were more than 585,451 villages in China and the rural housing area is at present 22.6 billion m², within a total area of more than 40 billion m² of China's urban and rural housing together. The amount of rural housing is constantly rising. According to 2010 data, the total floor space of newly built houses is 1.6 billion m², and half of them are rural residential buildings (NBSC, 2018). Therefore, improving the living environment for Chinese rural residential buildings is important for the sustainable development of China. Moreover, previous studies have been carried out on the sustainable development of Chinese rural residential building. However, many investigations and studies related to energy conservation and indoor thermal comfort have been proposed for northern China's rural houses (Jin & Zhou, 2008; Lai, Zhang, Wei, & Zhang, 2011; Sun, 2003; Yang, Yang, Yan, & Liu, 2011; Zhao & Jin, 2007; Zheng, Li, & Yang, 2008), focusing on winter comfort. Studies of the Chinese rural residential building in the hot humid climate regions are scarce (Han, Zhang, & Zhou, 2009; Jin, Meng, Zhao, Zhang, & Chen, 2013; Liu, Tan, Chen, Chu, & Zhang, 2013; Xie & Shi, 2012). Studies of spatial configuration for passive cooling of rural residential building design are very scarce.

11.2 Rural house design in the area studied

The rural houses studied are located in the rural area of Chongqing, China. Chongqing is located in the Sichuan Basin in the western part of the hot summer and cold winter zone. The annual average temperature is 18°C, the highest temperature in a typical climate year is 37.7°C in August, the lowest temperature is 2°C in January and the annual relative humidity is around 70-80%. The maximum average temperature reaches 28.1°C in July and the relative humidity is generally between 75-80% in summer. In summer, the prevailing wind comes from the north-west and the average wind velocity is 1.6m/s. The summer here is extremely hot, humid and uncomfortable. Therefore, the use of air conditioning is continually rising in the studied rural area.

11.2.1 Improvement opportunities for rural houses design

The Chinese government has put forwarded several important policies to improve the living environment of Chinese rural areas because of the huge unbalanced development between urban and rural areas. According to Chinese policies, the local governments provide financial and technical support for rural residents to build or rebuild their houses in order to improve the occupants' living conditions.

There are three routes to improve rural residential buildings.

- The first route is to protect and renovate existing buildings in the historical traditional villages. For historical houses, the major refurbishment is to replace parts that are damaged, and to improve the poor facilities, i.e., bathroom and kitchen. The local government plays a major role in the reconstruction process.
- The second route is to move rural residents to a new site and build a new village or town. The advantage of this route is that it is easier to build infrastructure, which is necessary for improved living environments than that the rural residents build their houses isolated. However, new residential buildings in a new village or town are ever more similar to urban residential buildings, which have many critical problems.
- The third route is to renovate the existing building or demolish and rebuild on the same site as the independent house, when the occupant does not want to move. In this way, the occupants are responsible for the construction of their own houses. The local government provides some financial and technical supports to the farmers.

In the Chongqing area, in recent years a great number of rural residential buildings have been built, refurbished or rebuilt. In 2017, around 8.7 million square metre of rural residential buildings was finished (NBSC, 2018). Figure 11.1 shows some of the rural residential buildings built in the Chongqing area, as investigated by the authors. Dwelling types 1-8 are built in the new rural communities by the local government. Dwelling types 9-16 are built by the occupants themselves, but the local government proposed some suggestions on, for example, the appearance. Dwelling types 17-28 are completely built by the occupants themselves. The living environment and the residential communities are changing rapidly. The living environment has been improved significantly.

However, there are still many critical problems in the local rural house design, especially in the thermal design which this study focuses on. The rural environment is further extremely suited for passive techniques due to a lower building density, a lower air pollution rate, and lower thermal expectations than in urban areas. However, through this investigation, we found that the passive cooling techniques are not commonly used by the local occupants and the thermal environment of the existing rural houses is unsatisfactory. Many of the rural houses lost the ideas for passive cooling used in traditional houses and they copy the city model, in which many environmental problems have been found. For example, the use of air-conditioning is growing in rural houses, but most of the houses do not have insulation in the outer wall due to the low price of the house and the cheap construction. To save energy, the opening area in the outside wall was reduced in some of the rural houses. But this reduces the potential for natural ventilation as well. Consequently, it is a great opportunity to implement research knowledge in the countryside construction to improve the building performance of the rural houses.

FIG. 11.1 Typical rural residential buildings built in the Chongqing area in recent years (photographed by author)

11.2.2 The local occupant's living habits in summer

Occupants' living habits are significant for the design of a house and for the passive cooling strategy. In the rural area studied, the occupants' living habits are different from the living habits in urban areas. To adapt to the hot and humid summer climate, the local rural residents have typical living habits. As findings from a field survey by the author, the following aspects should be taken into account:

- Even with the increase in air-conditioning use in the rural area, most of the occupants have adapted to the free-running building environment.
- The occupants move between the different spaces in the house. In the morning, they prefer the courtyard, veranda or the inside of the house. In the afternoon, they always stay in the living room or on the veranda. In the evening, they prefer to stay on the veranda or in the courtyard. If there is good ventilation, they also prefer to stay in the living room. The living room is an especially important space: most of the activities take place here.
- Generally, the occupants go to the bedroom after the heat has disappeared through the open windows. Sometimes, on the hottest days, they sleep on a temporary bed in the living room if there is no air conditioning used in the bedrooms.
- The occupants prefer to dress in short and thin clothes. Their arms and legs are generally uncovered the whole day.
- The occupants use a hand fan or a mechanical fan for cooling. If air-conditioning is used, generally, it is only used in the bedrooms.

11.2.3 Dwelling types proposed by the local government

The great difference between the urban and rural living environment encourages the local government to improve the rural living environment. Based on the investigation of local rural occupants' living habits and demands in 2011, the local building construction sector of Chongqing proposed 24 dwellings for the rural occupants to choose from. Figure 11.2 shows the floor plans and typical appearance of the 24 types of dwellings. The dwellings are divided into three price categories. Translated from the Chinese they are called: economic house, practical house and well-off house. All of the houses have two floors. The houses can be free-standing houses or terraced houses. Table 1 shows the basic information of the proposed dwellings.

Comparing the proposed dwelling types by the government and the existing dwellings, the living standard of the proposed dwelling types is much better. For example, the indoor layout is improved for modern life; the function and service facilities are more complete than before.

The general features of the house designs are:

- Double width (a width of two rooms) was used for the small area house types and triple width (a width of three rooms) was used for the large area house types.
- Some of the house designs have a room for business (such as a small store).
- The living room and dining room are the major public spaces on the ground floor. The kitchen, bathroom, storage room and bedroom are the private rooms. There are 1 to 2 bedrooms on the ground floor. In some dwellings, there is no separate dining room, but the dining room is included in the living room or kitchen.
- Some of them use a corridor to connect the different rooms and in some of them, the rooms are connected directly.
- Of the 24 types of dwellings, 22 have a courtyard, 8 have 2 courtyards, 3 have a patio.
- All of the dwellings were designed with transitional spaces (verandas). Most of them have these at the main entrance. Some of them have a veranda at the back entrance.
- All of the types have at least a terrace or a balcony on the first floor.
- Some of the windows and doors are according to traditional style, in which windows and doors can be opened completely.
- Building orientation was not proposed for any type of dwelling.
- Most of the dwellings have no shading devices for the windows.

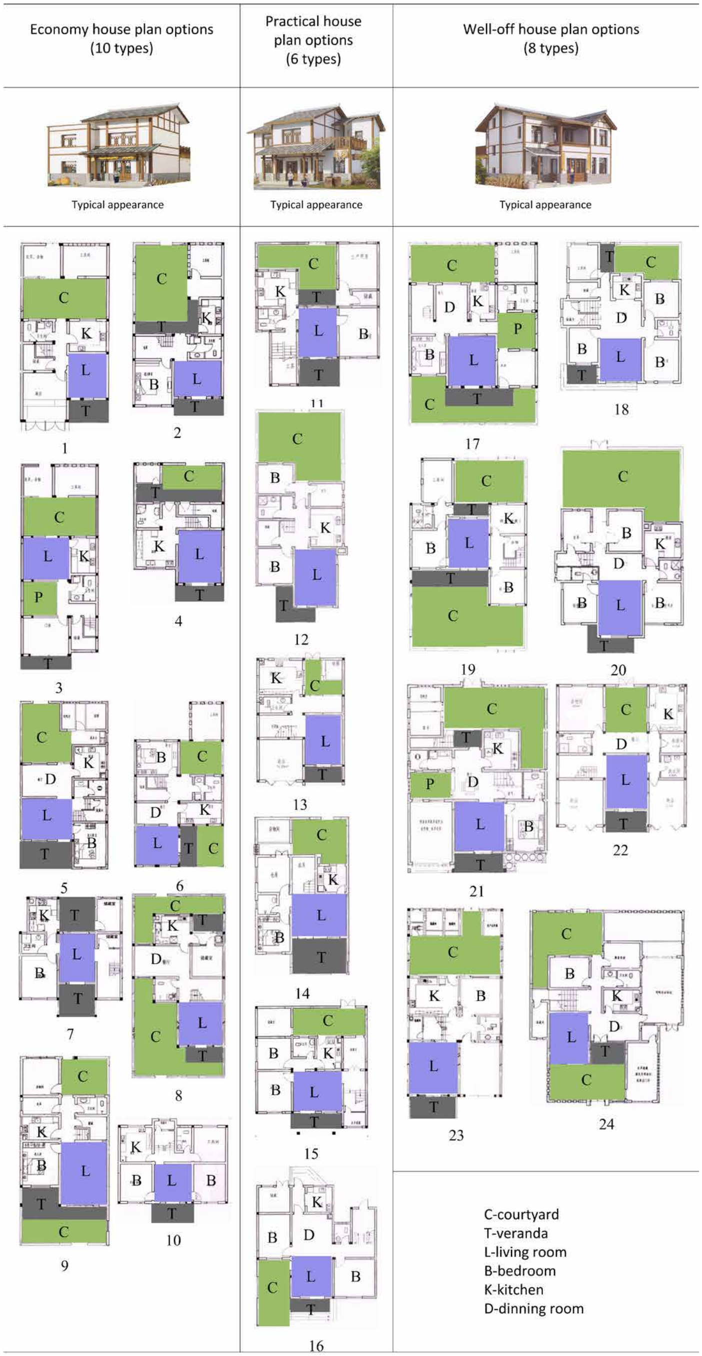

FIG. 11.2 The ground floor plans and typical appearance of the 24 types of dwellings proposed by the local government (CCC, 2011)

TABLE 11.1 Basic information of the dwelling types proposed by local government

No.	Plot area (m²)	Area of building (m²)	Area of courtyard (m²)	Total Area (m²)	Area of ground floor (m²)	Area of first floor (m²)	Width (m)	Depth (m)	occupants	Living room +dining room	Dining room	Bedroom	Terrace	Balcony	Veranda	type
1	126	98	28	155	98	57	7.8(2)	16.1	3-4	1	0	3	1	1	1	Economic
2	138	100	38	159	100	59	8.7(2)	15.8	3-4	1	0	3	1	0	1	Economic
3	135	95	40	159	95	64	7.2(2)	18.3	3-4	1	0	2	1	0	1	Economic
4	93	72	21	132	72	59	8.1(2)	11.1	3-4	1	0	2	0	0	1	Economic
5	126	100	26	155	100	55	8.4(2)	16.2	3-4	1	1	3	2	1	2	Economic
6	133	105	28	179	105	74	9(2)	16.8	4-5	1	1	3	1	0	1	Economic
7	85	85	0	165	85	80	9.6(3)	9.6	4-5	1+1	0	4	1	1	2	Economic
8	226	100	126	181	100	81	9.1(2)	24.3	4-5	1+1	1	3	1	1	2	Economic
9	147	94	53	175	94	81	8.1(2)	13.8	4-5	1	0	4	2	0	2	Economic
10	98	98	0	167	98	69	11.4(3)	8.8	3-4	1	0	4	1	0	1	Economic
11	122	101	21	164	101	63	10.8(3)	12.6	3-5	1	0	3	1	1	2	Practical
12	154	104	48	182	104	78	7.8(2)	13.8	5-6	1+1	0	4	1	1	1	Practical
13	106	91	15	180	91	89	8.4(2)	12.0	3-5	1	0	3	1	1	2	Practical
14	120	99	21	177	99	78	8.7(2)	12.9	5-6	1+1	0	4	1	1	2	Practical
15	130	106	24	190	106	84	11.1(3)	12.0	5-6	1+1	1	5	2	1	1	Practical
16	133	112	21	192	112	80	11.7(3)	11.1	3-5	1+1	0	5	2	0	2	Practical
17	222	135	87	234	135	99	12.3(3)	17.6	5-6	1	1	4	1	0	2	Well-off
18	150	128	22	228	128	100	11.4(3)	13.4	5-6	1+1	0	6	1	2	2	Well-off
19	253	138	115	244	138	106	12.3(3)	15.6	4-5	1+1	0	4	1	1	2	Well-off
20	197	128	69	224	128	96	11.7(3)	11.7	5-6	1+1	0	5	1	1	1	Well-off
21	160	117	43	221	117	104	11.1(3)	14.4	5-6	1+1	1	4	1	1	2	Well-off
22	169	150	19	293	150	143	12.3(3)	13.5	5-6	1+1	0	5	0	1	2	Well-off
23	158	126	32	203	126	77	8.7(2)	17.4	4-5	1_1	0	3	1	0	1	Well-off
24	277	179	98	283	179	104	15.4(3)	19.4	5-6	1+1	1	4	2	1	2	Well-off

11.3 Methods

In this study, in order to investigate the spatial features of the local rural house quantitatively, 12 house types proposed by the local government were selected for the extended space syntax analysis in terms of VGA and isovist analysis. Because most of the public area of all the types is on the ground floor, only the ground floor was studied. In figure 11.10, the layouts of the 12 selected types were shown.

The VGA analysis consists of two parts. Part one is focused on the occupants' movement behaviour on the ground floor; it is a traditional VGA analysis. The boundary in the analysis is the border of the layout in which the indoor spaces and courtyards are involved. The doors are assumed completely opened so that the occupants can pass through. The windows are assumed closed because they are not for occupants' movement. In the second part, VGA and isovist analysis are focused on the accessibility of the air movement on the ground floor. The method was proposed in chapter 10. In order to include the influence of natural ventilation, the boundary was extended 5 meters outside the outline of the layout (figure 11.4). The courtyards and veranda were included in the outside environment. Because the proposed types are for farmers in this area, the orientation of the houses are not fixed. Therefore, the wind direction is not considered at this stage, i.e. the wind can come from all directions. The doors and windows are assumed completed opened to encourage the largest cross ventilation. The connectivity (C value), visual integration (I value) and mean depth (D value) were selected as indicators. According to the method proposed in chapter 10, a higher connectivity and integration value, and a lower mean depth mean that a particular layout is more accessible for people movement and airflow. And, a higher isovist area in a particular space means more openness for air flow.

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11.4 Results

11.4.1 Results of the visibility graph analysis (VGA)

Results of occupants' movement

Figure 11.3 shows the connectivity map, visual integration map, mean depth map and convex map for occupants' movement. The following can be seen:

1. For all types, the courtyards, corridor, living room and dining room always show high C and I values and a low D value. These spaces are the public spaces. Courtyards and corridors always have the highest C and I value and lowest D value.
2. For all types, relatively low C and I values and a high D value were observed in the bathrooms, kitchens, bedrooms and storerooms. The bathroom always has the lowest C and I value and highest D value.
3. For types 1,2,6 and 11, the living room, the most important public space does not have a very uniform distribution of the C, I and D values, i.e., some parts of the space have high C and I values and a low D value and some have low C and I values and a high D value.
4. The convex map shows the living rooms of type 4, 7, 8 and 10 have the highest C and I values and lowest D value comparing to other rooms, corridor and courtyards. However, the living room of type 5 and 6 have very low C and I values and a high D value.

The results of the occupants' movement analysis show that the accessibility in the public spaces (courtyard, corridor, dining room and living room) is the best. The occupants' living habits described in section 11.2.2 show that the occupants perform most of their activities in these spaces as well. Therefore, it can be concluded that the indictors in space syntax analysis not just reflect the occupants' movement behaviour but also show the occupants' preference of spaces and how long they would like to stay. or they prefer to move to these spaces. The corridor is used more for traffic space. This matches with the occupants' behaviour described in section 11.2.2. Most of the design of the 12 layouts are good with respect to occupants' behaviour. If the indoor space is considered, types4, 7, 8, and 10 are the best, while types 2, 5,6 and 12 are not so good.

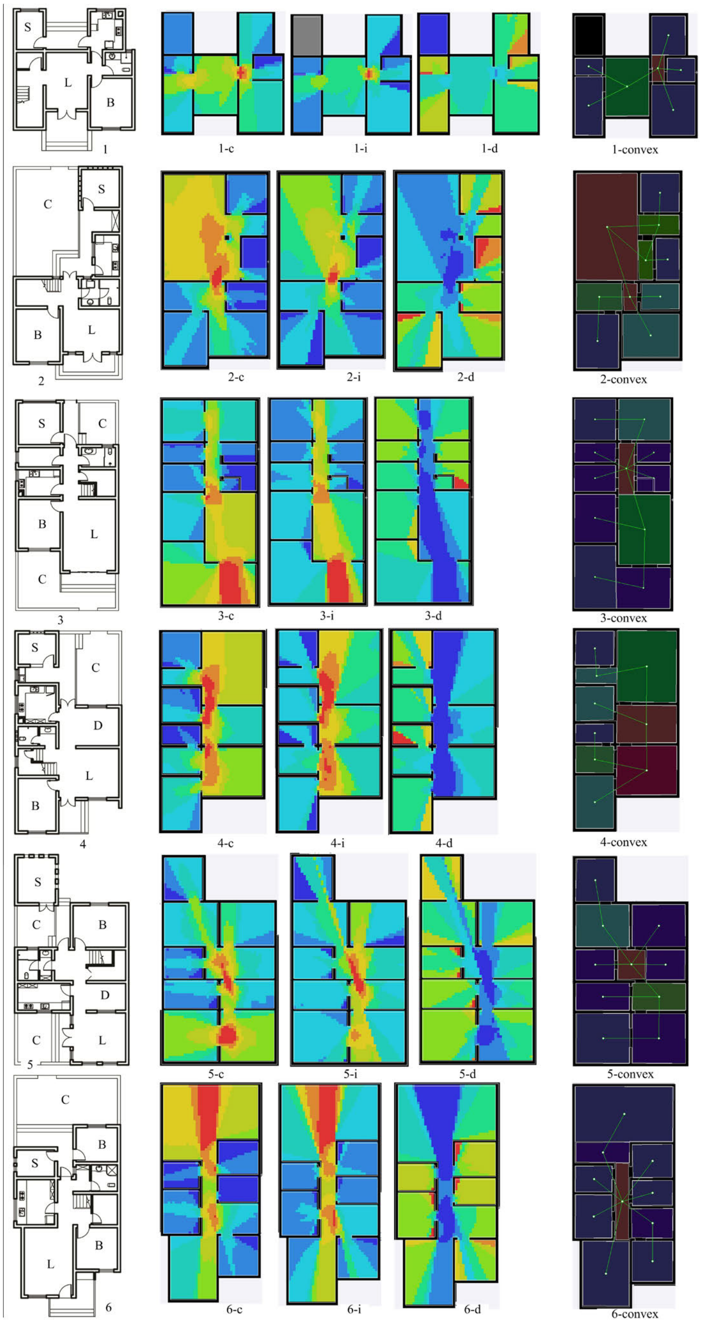

FIG. 11.3 / 1 The layout of the selected 12 house types and occupants' movement analysis (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; 1-convex: convex map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

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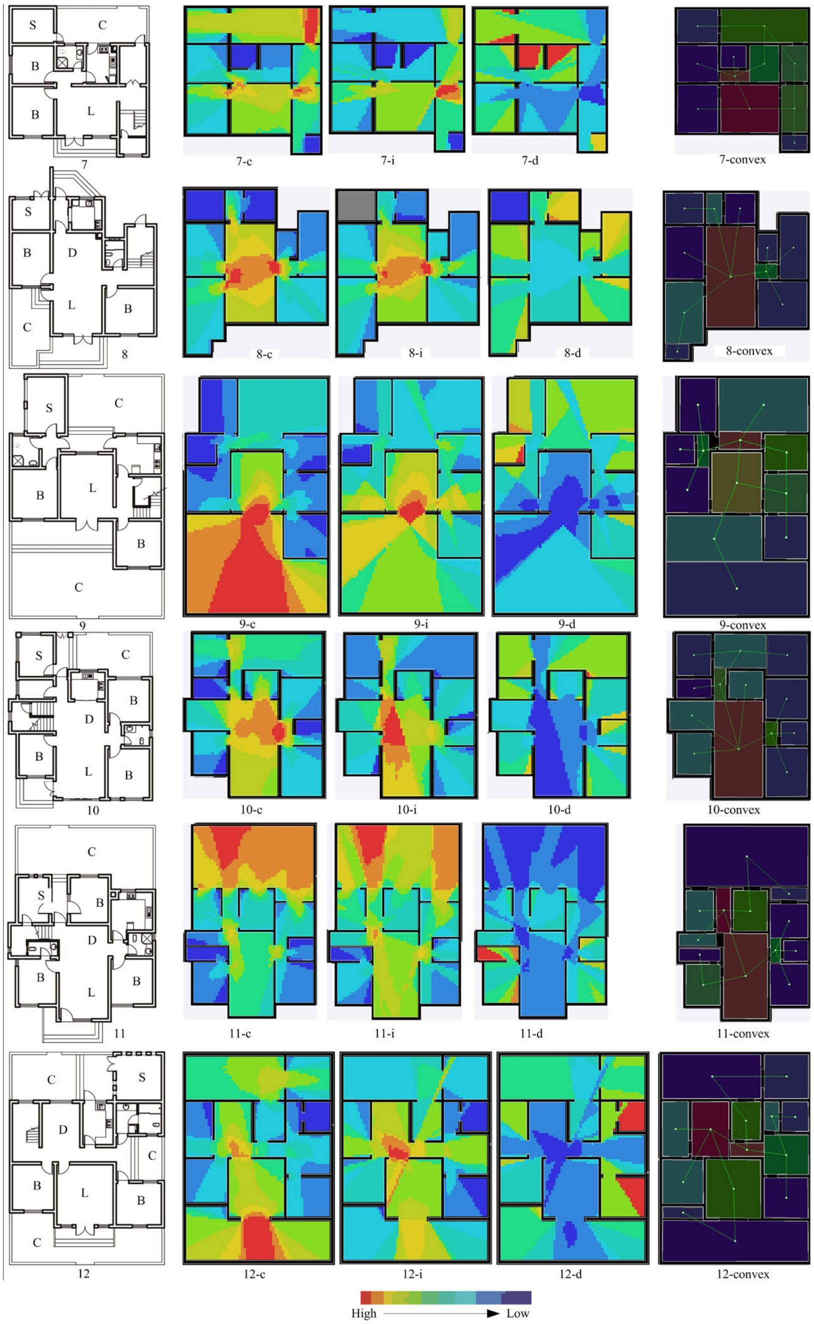

FIG. 11.3 / 2 The layout of the selected 12 house types and occupants' movement analysis (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; 1-convex: convex map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

Results of the air movement analysis

Figure 11.4 shows the connectivity map, visual integration map and mean depth map for air movement. It can be seen:

1. The corridors, living rooms and dining rooms show relatively higher C and I values and a lower D value for all types. Especially the corridors have the highest C and I values and the lowest D value (except the outside spaces).
2. The relative lower C and I values and a high D value were observed in the bathrooms, kitchens, bedrooms and storerooms.
3. In type 8, 9,10,11, and 12, the highest C and I values and lowest D value (except the outside spaces) were observed in the living rooms or dining rooms, especially in type 9.

The results of the air movement analysis show that the air accessibility in the public spaces (corridor, dining room and living room) is the best. That means there are more opportunities in the corridor, dining room and living room to achieve natural cross-ventilation than in other rooms (except the outside spaces).

Table 11.2 shows the mean integration, mean connectivity and mean depth values of the entire layout and the living room, and figure 5 shows the comparison between the different types.

Firstly, the indicators of the living room were compared. As we can see, type 10 has the highest integration, followed by type 9; type 1 has the lowest integration, followed by type 7 (figure11.5 (a)). Type 10 has the highest connectivity, followed by type 9; type 1 has the lowest connectivity, followed by type 6 (figure 11.5 (b)). Type 10 has the lowest depth, followed by type 9; type 1 has the highest depth, followed by type 7 (figure 11.5 (c)). All of the indicators show that the living room of type 10 has the greatest potential for natural ventilation, followed by type 9. However, type 1 has the worst conditions for natural cross-ventilation, followed by type 7. Comparing the design of types 10 and 9 and types 1 and 7,some design features can be found that the potential of natural cross-ventilation of type 10 and 9 is better than type 1 and 7. In type 10, the living room can get the cross-ventilation through the opening on one side and the corridor and kitchen on another side. In type 9, the living room has openings on two sides through which the cross-ventilation can pass directly. The opening area of the living room in type 10 is larger than in type 9, which causes the connectivity and integration of type 10 to be a little bit greater than of type 9. In type 1 and 7, the living room has only one side opening directly to the outside environment, which makes cross-ventilation difficult.

Secondly, the indicators of the whole layout of the ground floor were compared. The variation of the indicators for the layout is smaller than for the living room. Type 10 has the highest integration, connectivity value and lowest depth value; type 1 has the lowest integration, connectivity value and highest depth. This indicates that type 10 has the best and case 1 has the worst potential for natural ventilation, even at the whole floor scale. The spatial configuration of type 10 is much better than type 1 in terms of achieving natural cross-ventilation.

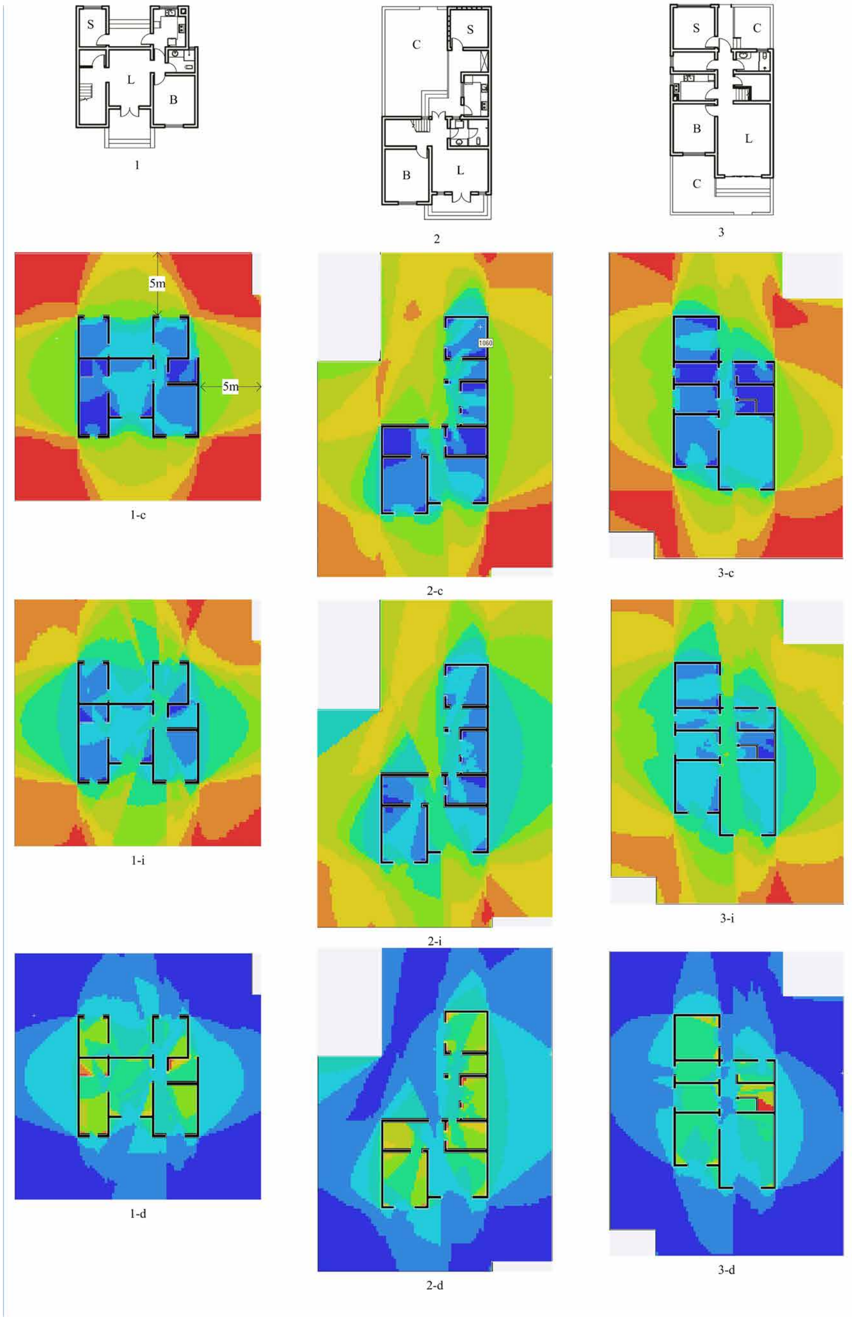

FIG. 11.4 / 1 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

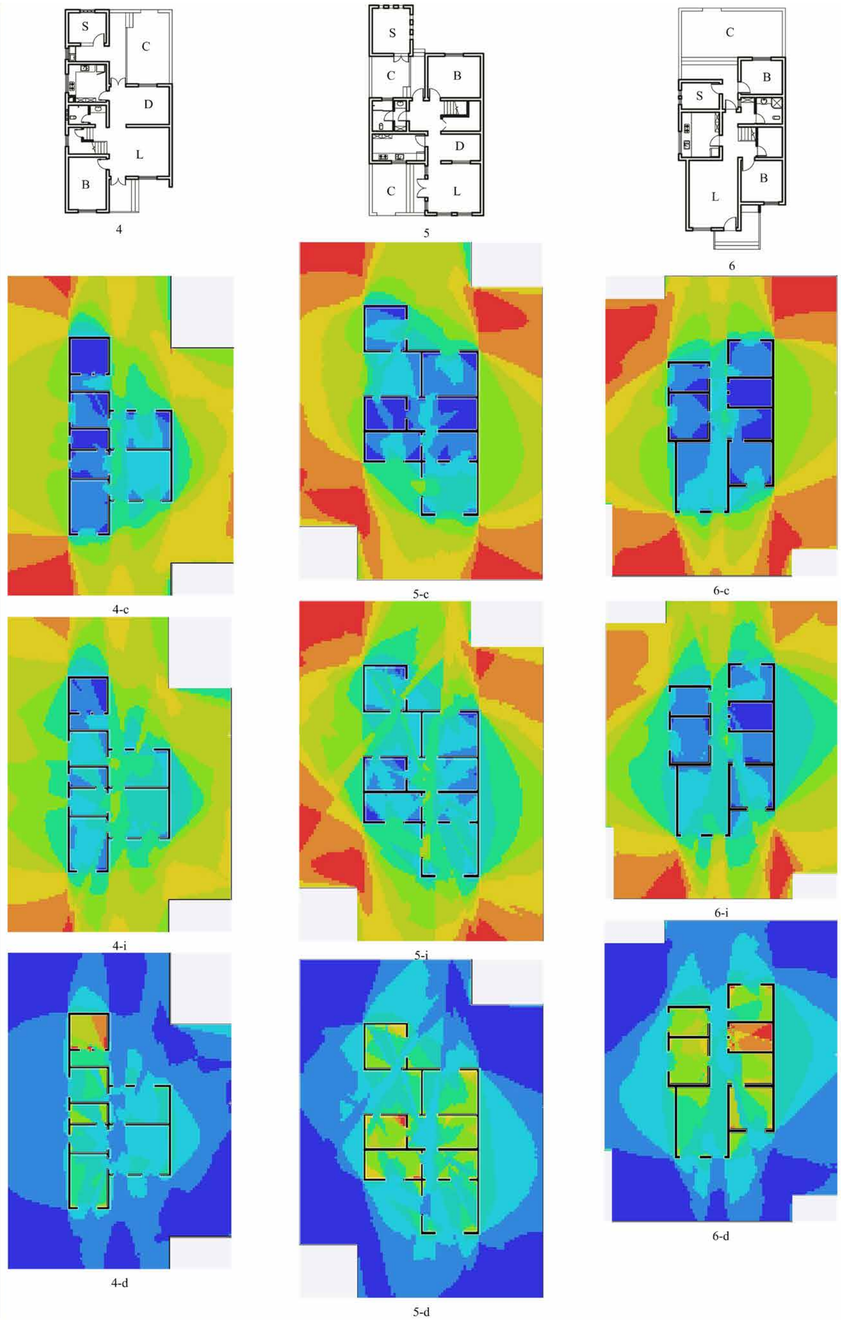

FIG. 11.4 / 2 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

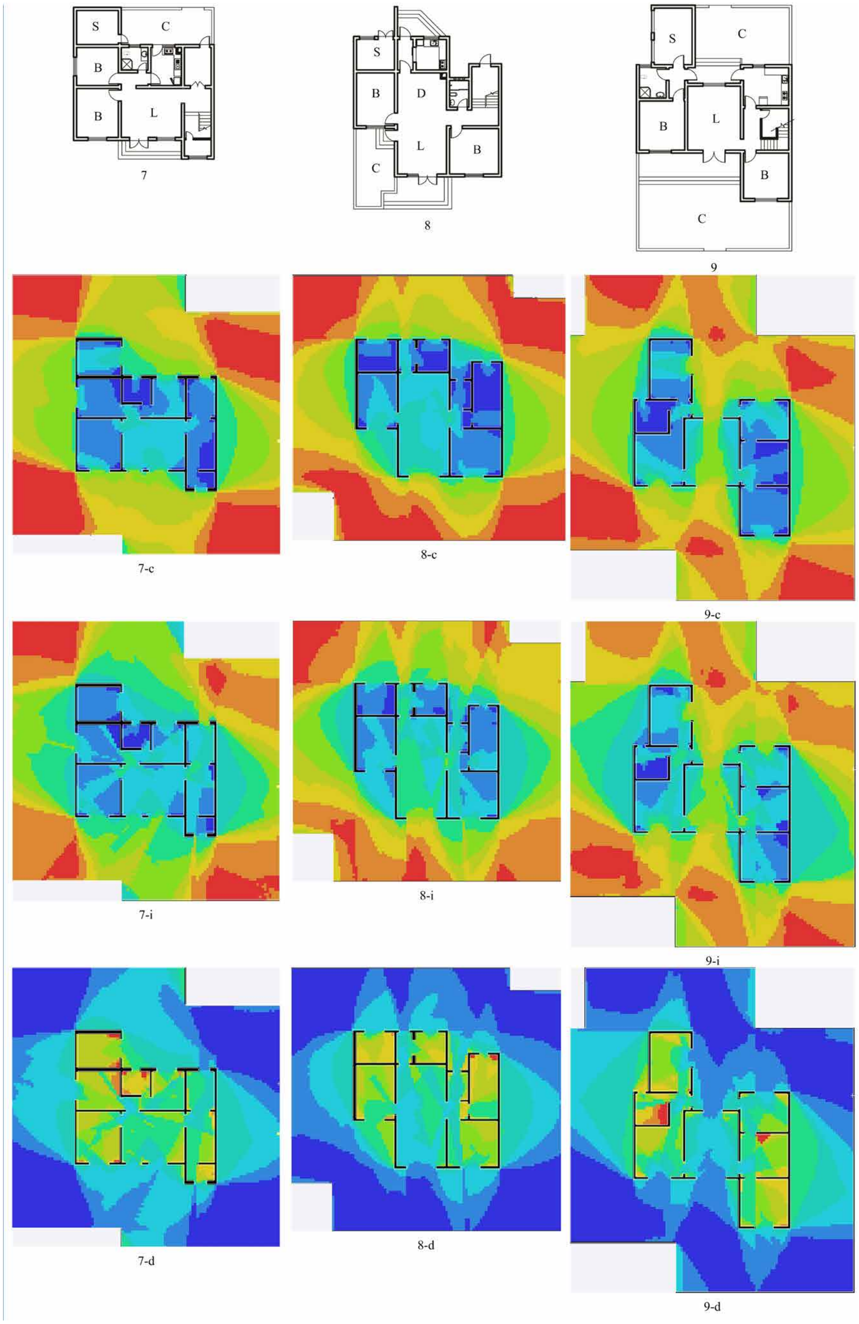

FIG. 11.4 / 3 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

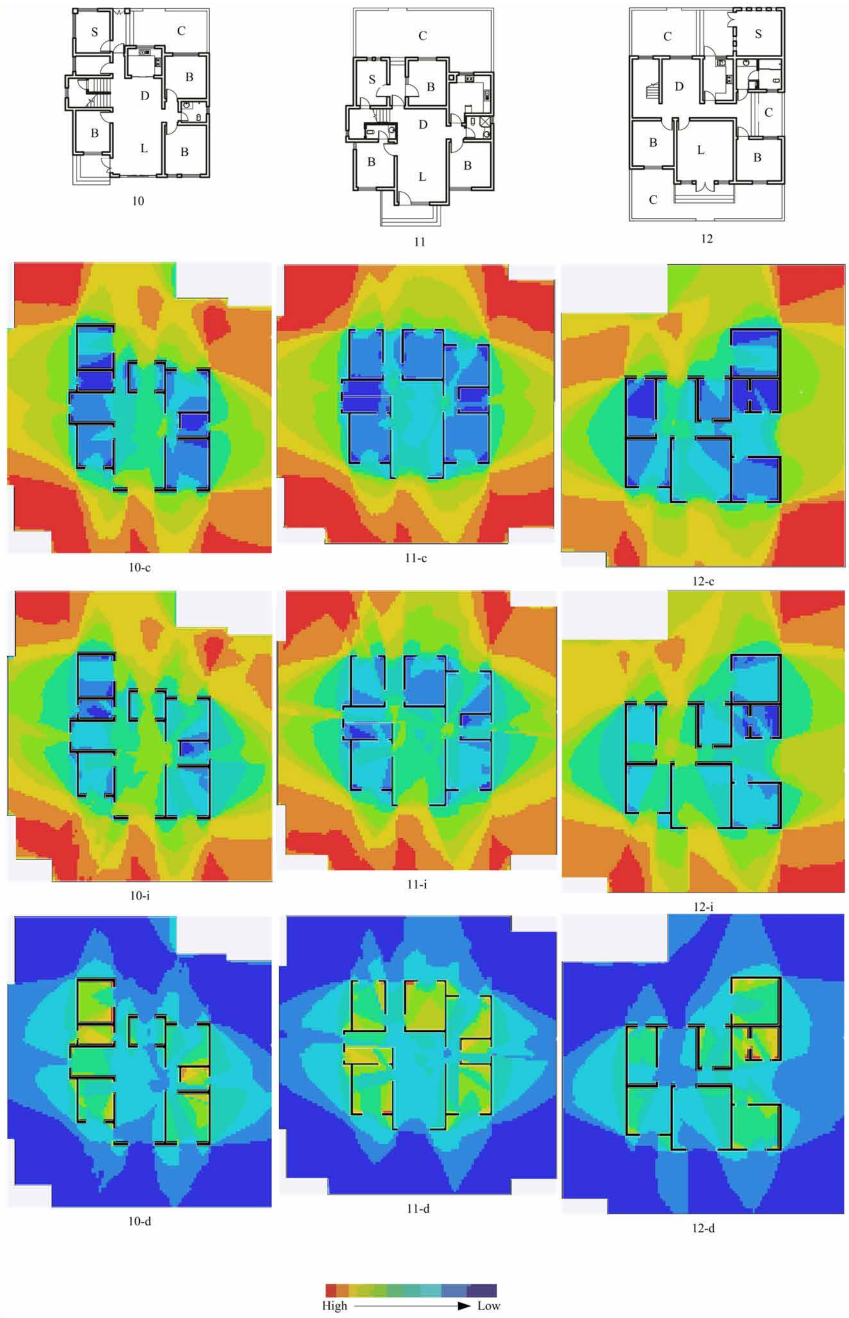

FIG. 11.4 / 4 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

TABLE 11.2 The mean integration, connectivity and depth value of the entire layout and the living room

House types	Mean Integration		Mean Connectivity		Mean Depth	
	Layout	Living room	Layout	Living room	Layout	Living room
1	14.81	*9.61*	3197	*1070*	1.78	*2.12*
2	14.44	*11.28*	3393	*1571*	1.79	*1.98*
3	14.71	*10.67*	3457	*1448*	1.79	*2.03*
4	14.61	*11.78*	3381	*1747*	1.78	*1.93*
5	13.88	*11.13*	3400	*1907*	1.83	*2*
6	14.59	*11.02*	3315	*1390*	1.79	*1.99*
7	13.79	*9.87*	3288	*1517*	1.83	*2.1*
8	14.11	*11.32*	3268	*1685*	1.82	*1.97*
9	14.12	*12.64*	3454	*2447*	1.82	*1.88*
10	15.19	*13.62*	3600	*2478*	1.75	*1.8*
11	14.45	*12.31*	3363	*1792*	1.8	*1.89*
12	13.63	*10.88*	3443	*1637*	1.86	*2.03*

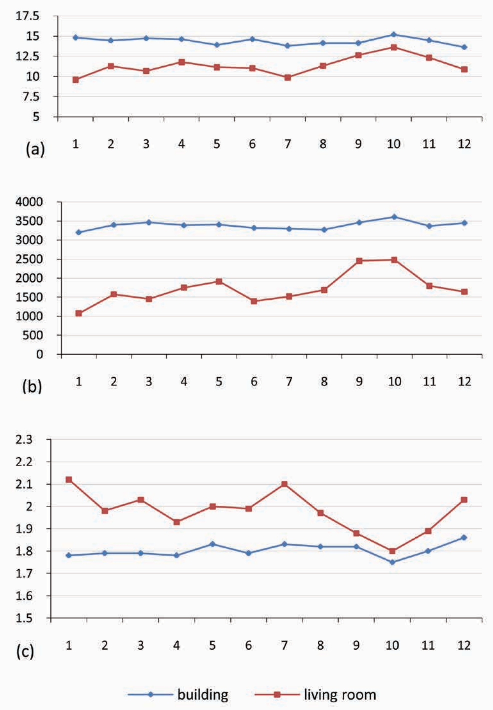

FIG. 11.5 Comparing of the mean integration (a), connectivity (b) and depth value (c) of the layout and the living room

11.4.2 Results of isovist analysis

Figure 11.6 shows the isovist viewshed polygons in the living room of different types and table 11.3 lists the measured isovist variables. The viewpoint is in the middle of the living room. In this study, the isovist area not only expresses the visual area, but also the area where natural ventilation is most effective. Figure 11.7 shows the comparison of the isovist area (a) and perimeter (b). The results show the isovist area of type 9 is the largest, followed by type 10, and the isovist area of type 1 is the lowest, followed by type 6. The perimeter value of the types also shows the same trends. The results mean that the living rooms of type 9 and 10 are more open than the other types, and that these have a greater chance of natural ventilation.

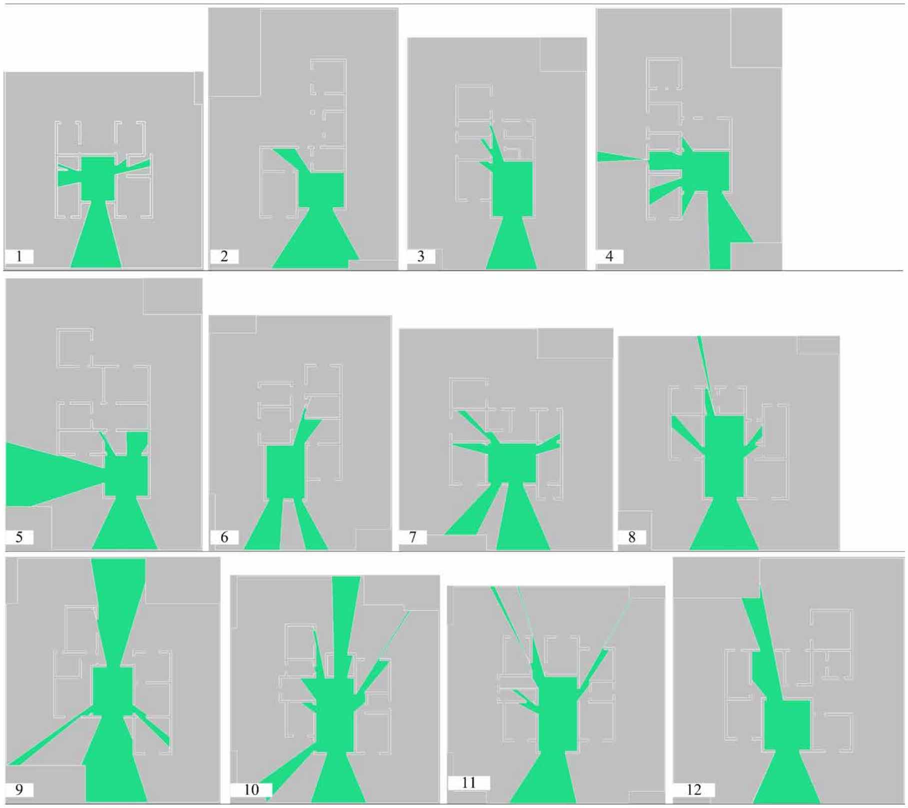

FIG. 11.6 Isovist viewshed polygons in the living room of different types

TABLE 11.3 Measured isovist variables in the living room

Ref	Area	Compactness	Drift Angle	Max Radial	Min Radial	Occlusivity	Perimeter
1	4.44E+007	0.17	266	9543	1598	33489	57340
2	5.31E+007	0.34	260	9326	1680	18941	44036
3	4.92E+007	0.26	263	9065	2049	22811	48924
4	5.63E+007	0.13	253	11273	1788	43615	73827
5	8.60E+007	0.20	197	12345	1884	40451	73288
6	4.86E+007	0.18	273	9401	1945	32686	57414
7	6.15E+007	0.14	259	10185	1807	45018	73930
8	6.58E+007	0.14	230	14060	1901	45114	78163
9	12.20E+007	0.14	86	14512	2093	65127	106061
10	9.45E+007	0.08	94	16056	1945	82812	119007
11	6.47E+007	0.07	215	15718	1875	74248	105952
12	6.57E+007	0.16	165	14362	2234	41467	71096

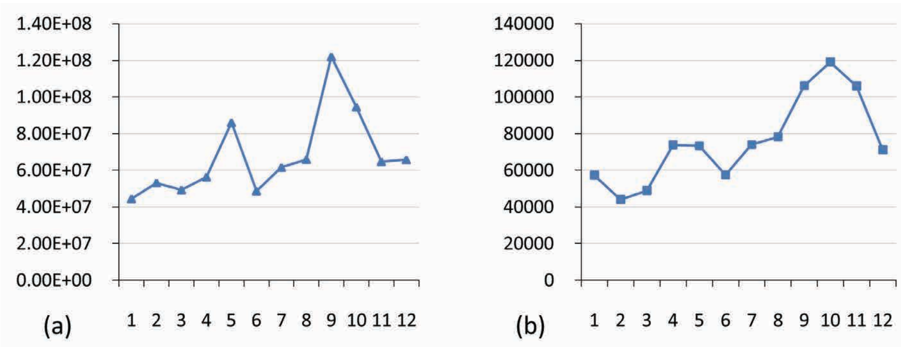

FIG. 11.7 Comparison of the isovist area (a) and perimeter (b)

11.5 Discussion and conclusions

Comparison of the occupants' behaviour analysis and the air movement analysis, the public spaces show relative high accessibility in terms of high connectivity and integration values and a low mean depth value in both the occupants' behaviour and air behaviour. This means that the space that has the highest potential to obtain natural ventilation is also the area most public and most used. In this sense, the layouts of the 12 types are good.

Combining the results of VGA and isovist analysis, the spatial features for natural cross-ventilation and thermal summer comfort of the proposed houses by the local government can be summarised as follows:

1 Most of the types have clear public spaces and a central area: courtyards, a corridor and a living room (sometimes dining room is involved). The occupants perform most of their activities in these public spaces. Fortunately, in these public spaces, there is higher potential to obtain natural cross-ventilation according to the spatial analysis. According to the adaptive thermal comfort theory, occupants always take actions to adapt the thermal environment to achieve thermal comfort. Movement is one important adaptive behaviour for the local occupants. In this case, the VGA analysis proved that the occupants' movement behaviour can be matched with the air movement. So, the occupants prefer to move the public space to where they can easier obtain natural ventilation.

1 In some of the types, the accessibility and openness of the public spaces are generally better than other spaces, but within a single public space, the potential to obtain natural ventilation is different in different locations, especially in the living room. In some cases, only a part of the spaces in the living room have a high potential to obtain natural ventilation.

2 The public space is not so diverse in most of the types. The courtyard is the major outdoor space and the veranda is the major semi-outdoor space. For the indoor space, the dining room and living room were set together in most of the types. The lack of diversity of the public spaces in the indoor spaces makes that the occupants have little choices for their movements.

3 The accessibility and openness of the layout and the public spaces still needs to improve. In some of the types, the mean integration and connectivity value are very low, both in the entire layout and the living room, which means a low potential for natural ventilation. In this sense, some of the layout designs of the proposed houses are not so good for natural cross-ventilation.

4 Considering the local occupants' living habits, the high accessibility and high potential to achieve natural ventilation of the public spaces in the rural houses design, the public spaces should be the focuses in the local house design for passive cooling. The private spaces, such as the bedrooms, are difficult to achieve natural ventilation for thermal comfort due to the private design which makes them enclosed.

Type 10 will be chosen as the optimised layout design for the new house design in the next chapter.

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