Computational Generation of Hutong Neighbourhoods

A procedural modelling framework to represent their urban structure

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The Hutong neighbourhoods, composed of Chinese courtyard dwellings (Siheyuan), are historically and socially significant urban spaces that embody traditional Chinese philosophy. There is a global interest in these spaces many of which face oblivion, this study presents a formal grammar for parametrically generating Hutong neighbourhoods, which replicates the morphological characteristics of historic cases. This research investigates traditional principles of urban planning of ancient Beijing, based on examples on the historical map Qianlong Jingcheng Quantu, to derive the lost design rules. These rules are then used to build up a procedural modelling process, which reveals the development of Beijing urban structure from Yuan (1271-1368) to Qing (1368-1911) dynasty. The grammar presented in the procedural modelling process contributes to the understanding of the generation of Hutong neighbourhoods. In support of traditional Chinese urban design, the grammar will be translated into an algorithm to be implemented in a computational environment by visual scripting that will generate new instances of Hutong neighbourhoods.

Keywords: *urban morphology, Siheyuan neighbourhood, procedural modelling, shape grammar*

BACKGROUND

It is believed that the planning of Beijing followed the rules recorded in *Kaogong Ji* (*Record of Trades*), in which Confucianism was embedded (Steinhardt, 1990). Hutong neighbourhoods are historically and socially significant part of Chinese urban heritage that embodying the traditional Chinese philosophy. Except for the Imperial and governmental sectors of ancient Beijing, the urban area was divided into four-sided sectors as residential neighbourhoods under the constraint of an orthogonal grid system. During the Qing dynasty, these neighbourhoods were reformed due to population increase, after which they were composed of variants of a vernacular dwelling type- Chinese courtyard housing (Siheyuan). Since these neighbourhoods usually existed between two Hutong (alley), they were called Hutong neighbourhoods. The Hutong neighbourhoods are rectangular on plan, whose basic units are Siheyuan. A typical Siheyuan consists of axially aligned courtyards symmetrically surrounded by individual buildings, connected by orthogonally located corridors, walls, and gates, as illustrated in Figure 1.

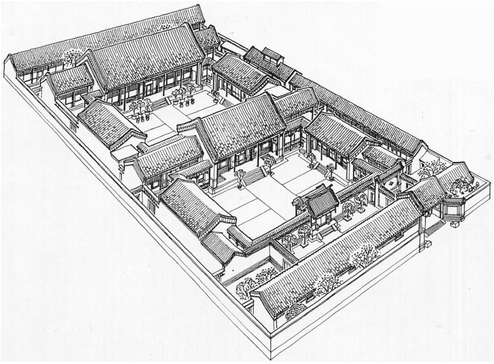


Figure 1
Beijing Siheyuan, Ma, 1999.

After many historians and urbanists' proposals to preserve historical Beijing city were rejected by the Beijing government in 1950, vast areas of traditional Beijing Hutong neighbourhoods were cleared to give way for the modern construction industry (Yu, 2008). One of the consequences of this destruction is that current architects lack physical examples to study. Due to insufficient historical literature and the linguistic difficulties in understanding them, it is hard for architects and urban designers to learn the original design knowledge. On the other hand, although many urban renewal projects of Hutong neighbourhood successfully transformed this old urban structure into a modern style to satisfy the needs of contemporary life, some of them are not based on any original design concepts. These projects may be considered to lack traditional Chinese characteristics. Providing a tool for rapidly generating Hutong neighbourhoods replicating the traditional morphological characteristics may help architects and urban designers in their design work.

Since the Hutong neighbourhoods were composed of Siheyuan dwellings containing a large number of variants, morphological studies of the neighbourhoods were linked to the typological analysis of Siheyuan. Li (2009) revealed the principles explaining how the archetype of Siheyuan evolved variants that compose Hutong neighbourhoods on the Beijing's orthogonal grid. Similarly, Liu (2019) investigated several types of Siheyuan precedents within five Hutong neighbourhoods drawn on *Qianlong Capitial Map* (*Qianlong Captial Map*, 1750) by classifying the courtyards of Siheyuan into five categories to understand how the different Siheyuan layouts were deformed to adapt themselves in the various site contexts within the Hutong neighbourhoods.

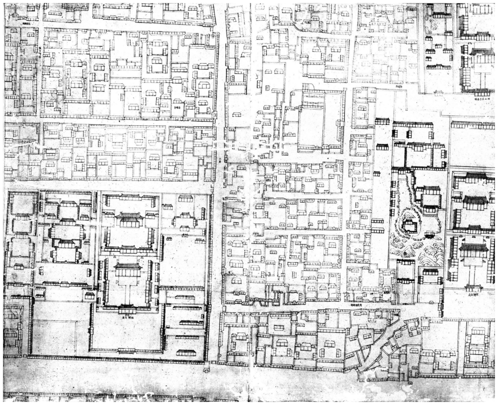


Figure 2
A section of Qianlong Jingcheng Quantu (Qianlong Capital Map, 1750) indicating the urban planning of historical Beijing is based on a grid system.

One common conclusion of these studies is that the rules underlying the evolution of Hutong neighbourhoods are complex. However, computational approaches are powerful to make generative rules explicit and to develop the design iterations. The Shape Grammar, invented by George Stiny (1980) to interpret the generation rules of objects graphically, was implemented by Rudi Stouffs (2018) and his colleague (Hou and Stouffs, 2018, 2019) using algorithms developed in Rhino/Grasshopper environment. An analytical shape grammar has its advantage in straightforwardly demonstrating the morphological iteration of shapes, which was employed to explain historical styles or languages of designs in procedural modelling approaches, such as 'Rome Reborn 2.0' project (Dylla et al., 2008) and urban blocks of nineteenth-century Camden London Flora et al. (2018).

AIMS, METHODS, AND MATERIALS

Our overall aim is to investigate the design rules underlying historical Hutong neighbourhood design in order to translate them into an algorithmic tool to generate variations of traditional Beijing Hutong neighbourhoods. To achieve this aim, the following questions are addressed:

- What were the social and cultural forces that determined the form of Hutong neighbourhoods and how did they influence the neighbourhood form?
- How could these rules be translated into shape grammar to simulate the procedural generation of Hutong neighbourhoods?
- How could such a shape grammar be implemented as an interactive algorithmic tool in a computational environment to generate Hutong neighbourhood variants replicating their original morphological characteristics?

The current paper is focusing on the first stage. The second and third stages will be briefly discussed in the discussion and conclusion section and are the subject of ongoing research.

The derivation of rules is based on secondary sources from other studies, such as the morphological studies on Hutong neighbourhoods by Li (2009), Li and Wang (2006), Liu (2019), and Ni (2009), and the historical studies on ancient Beijing urban planning principles by Deng and Mao (2003). The *Qianlong Capital Map* recorded the urban plan of Beijing around 1750 at a scale of 1: 650, including all the Hutong neighbourhoods and Siheyuans they contained. It is believed that this map offers an accurate representation of each Siheyuan plot in the top-view and each Siheyua building in elevation-view.

THE HUTONG NEIGHBOURHOOD GRAMMAR

By observing the *Qianlong Capital Map*, it is noted that there were a large number of Hutong neighbourhood variants, which resulted in the diverse urban structure of ancient Beijing within its orthogonal grid system. We chose the most representative the east-west oriented Hutong neighbourhoods, from the Yuan dynasty to be our case study.

Generation of Hutong neighbourhoods plan and Siheyuan plots

In the Yuan dynasty, each neighbourhood's depth (length in south-north orientation) was planned to be 67.76 metres and its width (length in east-west orientation) was 677.6 metres. The Hutong alley between two adjacent neighbourhoods was 9.24 metres wide. These key urban elements and dimensions are determining the initial shapes of the Hutong grammar. Each neighbourhood was averagely divided into ten plots aligned in an east-west orientation, as demonstrated in Rule 1a in Figure 3. We defined these neighbourhoods as 'Type A Neighborhood' (TAN). It is noted that the form of some neighbourhoods was re-planned in the Qing dynasty. In the south-north orientation, two neighbourhoods were combined as a whole and were divided into three new neighbourhoods, with an alley width of 10.01 metres between each of the two adjacent new neighbourhoods as shown in Rule 2 in Figure 3. We defined these new neighbourhoods as 'Type B Neighborhoods' (TBN). The neighbourhoods planned in the Yuan dynasty (TAN) were divided into 67.67x67.67m Siheyuan plots. Although the development of neighbourhoods in the Qing dynasty changed the depth of both Siheyuan plots and neighbourhoods, the width remained. Rule 1b represents the division of a TBN into Siheyuan plots.

Defining Siheyuan plots

Division of plots into sub-plots. A Siheyuan plot in the Yuan dynasty could be divided into two to four sub-plots in the east-west orientation. Each sub-plot could include several courtyards aligned in south-north orientation (Type A sub-plot, TASP) or an empty space (Type B sub-plot, TBSP). Based on this finding, Li and Wang's investigation of examples on the *Qianlong Capital Map* (2006) concluded on several types of sub-plots. As shown in Rules 3 in Figure 3, there are six dividing patterns, in which the plot is constituted of one or two sub-plot types. We found that the width of most TBSP is within the range or much smaller than TASP. Therefore, we define the width of TASP ranges from 12 to 35 metres and TBSP from 5 to 12 metres. The three division patterns of the plots are defined as Rules 3a to 3f respectively.

Sub-plot combination. Some TASPs and TBSPs were combined to regenerate new sub-plots. According to Liu's investigation of selected Siheyuan examples shown on the map (2019), we inferred the principles that one TASP could be combined with one adjacent TBSP to become a combined sub-plot, called Type AB sub-plot (TABSP). Then the TABSP could be used to construct a Siheyuan. This combination is defined as Rule 4a and Rule 4b, shown in Figure 3. Since the TABSPS are wider than other types, it enables a Siheyuan to be built on it and contains two courtyards in the east-west orientation. Normally, on a TABSP, a set of courtyards are aligned in a south-north orientation, with a side courtyard next to these courtyards in parallel and connecting the south and north boundaries.

Sub-plot disaggregation and recombination. The Siheyuan with a side courtyard usually belonged to rural upper-class owners. In many cases, the TABSP disaggregated into many smaller sub-plots, called a Type ABd sub-plot (TABdSP), on which a one-courtyard Siheyuan is constructed. The disaggregation may also happen to some TASPs, whose disaggregated sub-plot is called a Type Ad sub-plot (TAdSP). Two Type Ad sub-plots or two Type ABd sub-plots adjacent in north-south orientation may be recombined to become a new sub-plot, called Type Ad2 sub-plot (TAd2SP) and Type ABd2 sub-plot (TABd2SP) respectively. In the disaggregation, the number of generated TAdSPs or TABdSPs in a north-south orientation, constrained by the depth of the neighbourhood, is 3 or 4 in most cases. For simplification, we assume it is 4 in TAN and 3 in TBN. The number in the east-west orientation, constrained by the width of the sub-plot, is 2 or 3 mostly. We define it as 3 if the width is bigger than 20 metres, otherwise 2. Rule 5 is defined as the disaggregation of TABSP or TASP. Considering the neighbourhood depth and Type of sub-plot, the rule includes variants such as Rule 5a, Rule 5b, Rule 5c, and Rule 5d. The recombination of two TABdSPs is defined as Rule 6a and two TAdSPs is defined as Rule 6b. Except for the above disaggregation, there was another mode that a TASP separates into two Siheyuans by dividing the boundary of the second and the third courtyard, in which the original type of each courtyard remains. This is defined as Rule 7. We call the separated sub-plot on the south side as Type ASS sub-plot (TASSSP) and the one on the north as Type ASN sub-plot (TASNSP). The rules are shown in Figure 3.

These Siheyuans built on disaggregated sub-plots are clustered, in which many Siheyuans are not adjacent to the urban fabric. To create access to these Siheyuans, the west and east edges of disaggregated sub-plots shrink to give space to generate a small south-north oriented alley. The alley may cross the neighbourhood to connect the alleys on the south and north side of the neighbourhood or not cross. To simplify, we assume that an alley crosses the neighbourhood in all cases. In the shrink, as defined in Rule 8, the movement distance of each edge is different, which makes the alley geometrically irregular.

Courtyard division and type definition

After the sub-plot type is defined, it is divided into courtyards depending on the Siheyuan to be built on the sub-plot. When describing the word 'courtyard' in the Siheyuan context, it usually means the space enclosed by walls, which includes both the open courtyard space and all the buildings surrounding that space. In many cases, some parts of the 'courtyard' are not completely enclosed by walls. Instead, the rear boundary of a building is extended in east-west orientation to define the boundary of a courtyard. Borrowing the idea of categorizing courtyard into types based on the courtyard location, the room type that a courtyard contains (Wang et al., 2019), we classify courtyard types as northern boundary courtyard (NBC), southern boundary courtyard (SBC), east side courtyard (ESIC), west side courtyard (WSIC), standard courtyard (SC), and non-standard courtyard

(NSC). A TASP is used to build a Siheyuan with 3 or 4 courtyards aligned in a north-south orientation, in which the southernmost and northernmost ones are non-standard courtyards while the middle one or two are standard courtyards. The only difference between as TASP a TABSP is that a side courtyard is additionally aligned to the east or west. Generation of a three-courtyards Siheyuan on a TASP is defined as Rule 9a and a four-courtyards one as Rule 9b. Three courtyards with an east side courtyard on a TABSP is defined as Rule 10a, three courtyards with a west side courtyard as 10b, four courtyards with an east side courtyard as Rule 10c, and four courtyards with a west side courtyard as 10d. A Siheyuan built on a TAdSP or TABdSP usually contains one courtyard (defined as 11a), on which no shape iteration happens on the plan view, while on a TAd2SP or a TABd2SP two non-standard courtyards connected in a north-south orientation, is defined as Rule 11b. Siheyuan built on a TASSSP always divides the site into two courtyards: a standard one on the north and a non-standard one on the south. This iteration is defined as Rule 12a. On the contrary, on a TASNSP the division may allocate a non-standard courtyard on the north and a standard one on the south, which is defined as Rule 12b. The type of sub-plot determines the courtyard division by defining courtyard types and numbers, which, consequently, determines the type of the Siheyuan.

Moving the edges of the courtyard

In the initial neighbourhood planned in the Yuan dynasty, the south and north edges of each Siheyuan plot were ideally divided into segments from the corresponding edges of the neighbourhood, which are straight lines, enabling the elevations of Siheyuans arrayed smoothly. After the reconstruction in the Qing dynasty, the edges of many Siheyuans have been moved to a south-north orientation, which caused the courtyards adjacent to the urban fabric in south-north orientation to extend or shrink. The shrinking and extension are defined as Rule 13 and Rule 14 respectively. The movement of edges also took place to the east and west edges of non-standard courtyards and boundary courtyards. These edges could move in east or west directions to extend or shrink the courtyard area. Since Siheyuans were adjacently aligned in the east-west, this movement consequently influences adjacent Siheyuans. There are two modes of movement influencing adjacent Siheyuans. In the A mode, an east or edge of the courtyard moves in the east direction or a west edge moves in the west direction to extend the courtyard area, and the corresponding adjacent Siheyuan's edge moves to shrink its area. In the B mode, the west edge of a non-standard courtyard or a boundary courtyard in the east Siheyuan extends in the west, and the east edge of a non-standard courtyard or a boundary courtyard in the west Siheyuan extends in the east, which swallow up some area of the Siheyuan in the middle. This only took place in courtyards located in the rear. Due to social factors, normally a larger Siheyuan's edge extends while a smaller Siheyuan's edge shrinks. The two modes are defined as Rule 15 and Rule 16 respectively, as shown in Figure 3.

Room layout pattern

Borrowing the approach of Wang et al. (2020) to categorize courtyard type, the room layout pattern on the courtyard are identified based on two criteria: courtyard location (on the southernmost, on the middle, and on the northernmost) and the room type(s) the courtyard contains. Specifically, a boundary courtyard normally contains an east-west crossing row room, which is located on the south if the courtyard lies on the south boundary while it is located on the north if the courtyard lies on the north boundary. Boundary courtyards may also contain one or two secondary rooms. Similarly, a side courtyard contains a south-north crossing row room, which locates on the east if the courtyard lies on the east boundary while it locates on the west if the courtyard lies on the west boundary. A standard courtyard normally contains a primary room on the north and two secondary rooms pairwise axisymmetric about the courtyard's central axis. This layout contains more variants regarding the criteria of the existence of wing rooms and secondary wing rooms. Secondary room components have not been considered in this research due to their low importance in Siheyuan. For non-standard courtyards, the determination of the room layout was improvised by craftsmen. We concluded on eight variants by observing examples on the *Qianlong Capital Map*. The generation of room layout patterns in plan view is defined as Rules 17- 33, as shown in Figure 3.

Location of building elements

The algorithmic underlying Gongcheng Zuofa Zeli (1734) defines a parametric system that generates variants of single buildings, many of which are the rooms in a Siheyuan. Once the rooms are generated, they are located according to the layout patterns shown in Figure 3. The constraint of the layout pattern to room location is loose, which means the rooms could be slightly moved and rotated. The movement is defined as Rule 34 and the rotation is defined as Rule 35, as shown in Figure 3.

The location of the Siheyuan entry gate is determined by the urban fabric. For most Siheyuans it is located in the southeast of the front courtyard. If the south edge of the site is not connected to urban space such as a Hutong alley or a street, the entry gate is located elsewhere. There is a sequence to rank the priority of four patterns of entry gate location, regarding the urban fabric context. The sequence is east of south edge> south edge of east edge> south of west edge> west of north edge. In some cases, a secondary entry gate exists in the rear courtyard. To simplify, we ignore the secondary gate. Four patterns of location of an entry gate are defined as Rule 36a, Rule 36b, Rule 36c, and Rule 36b, as shown in Figure 3.

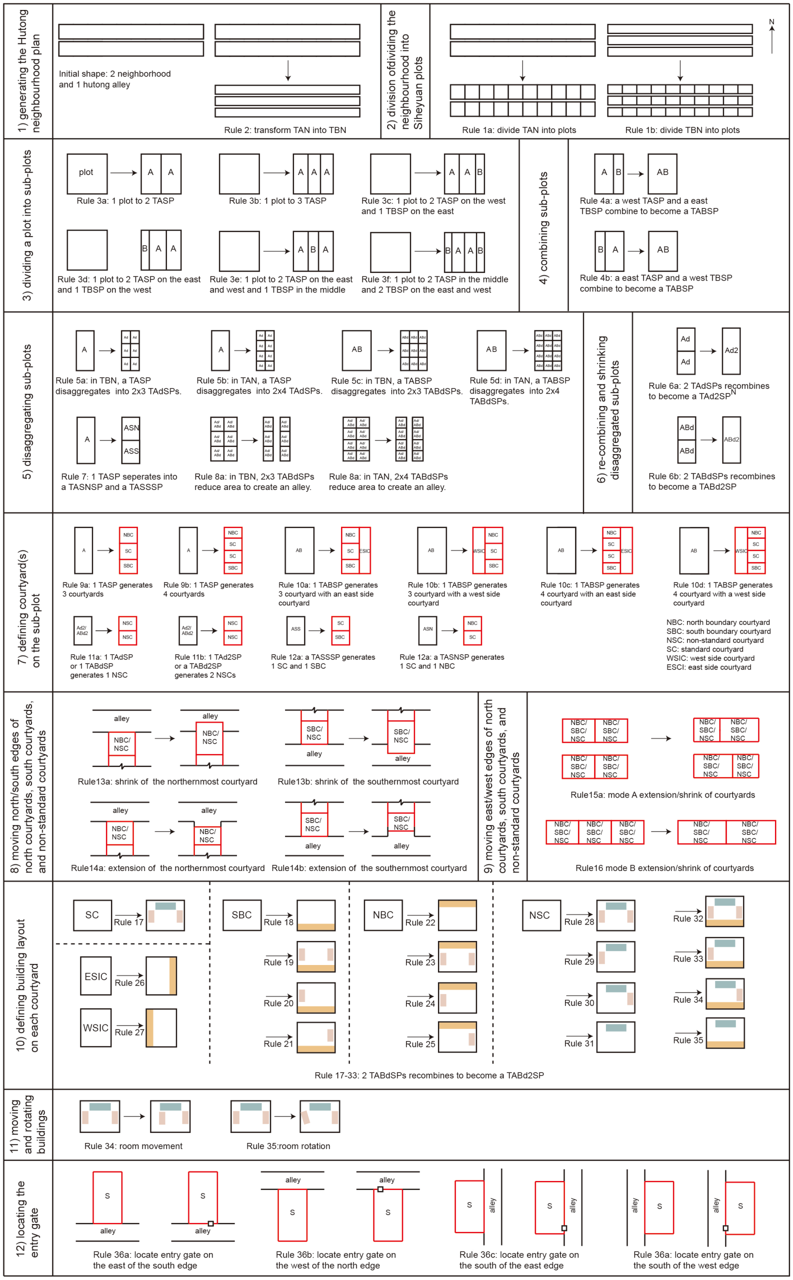
GENERATION OF HUTONG NEIGHBOURHOOD EXAMPLES

Once the rules and procedures of Hutong neighbourhood generation are captured, the grammar for its procedural modelling is constructed, as shown in Figure 3. The procedures include 12 steps: 1) generating the Hutong neighbourhood plan, 2) dividing the neighbourhood into Siheyuan plots, 3) dividing a plot into sub-plots, 4) combining sub-plots, 5) disaggregating sub-plots, 6) re-combining and shrinking disaggregated sub-plots, 7) defining courtyard(s) on the sub-plot, 8) moving north/south edges of north courtyards, south courtyards, and non-standard courtyards, 9) moving east/west edges of north courtyards, south courtyards, and non-standard courtyards, 10) defining building layout on each courtyard, 11) moving and rotating buildings and 12) locating the entry gate. By applying different rules in each step, the Siheyuan variants in neighbourhoods could be generated. Using the procedures with the application of the rules randomly, the plan of two Hutong neighbourhood examples that respect the traditional morphological characteristics is generated. The modelling process is illustrated in Figure 4.

DISCUSSION AND CONCLUSION

Researchers and architects are concerned about the use of mathematical thinking in contemporary architectural design but overlook the computational rules underlying historical design. Re-visiting historical design with a computational perspective can inspire us not just to design the contemporary world by exploring new forms but also to inherit traditional architectural knowledge. This paper revealed the mathematical considerations embedded in the generation of Siheyuan neighbourhoods by a shape grammar corresponding to their original generative rules, which grasped the essence of understanding their historical iteration. The shape grammar shows how the development of Siheyuan neighbourhoods is based on implicit rules that caused various morphological variants. Urban context, iteration pattern of the plot, and courtyard prototype are contextual forces shaping the Siheyuan neighbourhood forms. As an outcome, the posted Hutong neighbourhood grammar shown in Figure 4 could be employed by architects as rules to design Siheyuan dwelling neighborhoods in

Figure 3
The procedures and grammar of Hutong neighbourhoods generation.



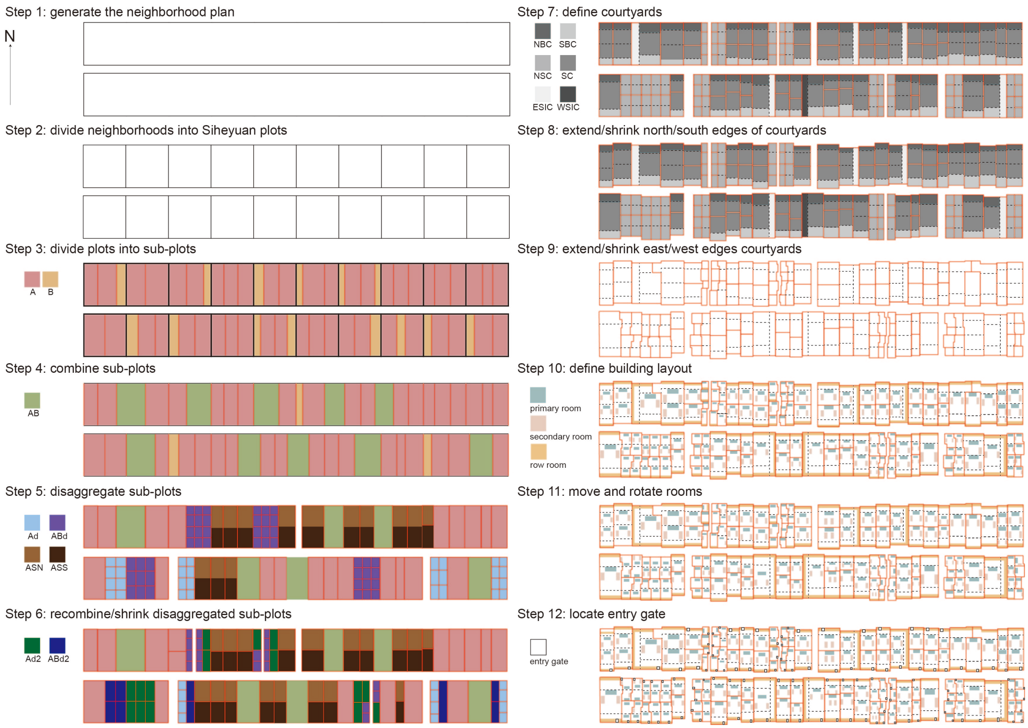


Figure 4
The procedural modelling process of two Hutong neighborhood examples.

traditional style based on procedural modelling.

Procedural modelling is usually implemented in a computational environment, enabling the computer to rapidly generate visual models. In future work, the rules of the proposed grammar will be implemented in Rhino 3D/Grasshopper environment to procedurally generate the virtual three-dimensional Hutong neighbourhood models. The Grasshopper script, in association with the grammar, is a new way to understand Hutong neighbourhoods. Meanwhile, in support of Hutong style neighbourhood design, the script could be a digital tool to generate neighbourhood models. It is noted that in some steps of the modelling process, the rules are not unique and to be chosen to generate variants. With the aim of generating diverse design projects, the choice of rules of each object in each step will randomised, with a set of weighting parameters to control the ratios between types of Siheyuan. To verify the tool, examples of neighbourhoods from the *Qianlong Capital Map* will be selected to derive the values of the weighing parameters by counting the number of each Siheyuan type. Then the values will be inputted in the tool to generate new designs, which could be mixed with the those on the map in the same form. The mixed models could be used in a questionnaire, which will be posted to architects and urban designers with knowledge of Siheyuan and historical Beijing planning to see if they can distinguish them, in order to verify whether the tool can generate new neighbourhood instances replicating the original morphological characteristics.

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