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A PARAMETRIC APPROACH TO CONNECTIVITY RELATIONS IN THE PLANNING OF TRADITIONAL CHINESE PRIVATE GARDENS

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Abstract. This research describes the production of a parametric system for generating spatio-typological and connectivity features derived from the Traditional Chinese Private Garden (TCPG). The research commences with an analysis of three historic TCPGs using connectivity graphs, a space syntax technique. Three measurements derived from this analysis – total depth, mean depth and integration – are then extracted to capture essential connectivity patterns in the TCPG. This data is then used to shape the rules of a parametric system to generate new TCPGs. Three new TCPGs connectivity and spatio-typological systems are then generated and tested against the original mathematical properties of the historic cases. Through this process the paper demonstrates a method for capturing social and spatial properties in a parametric system and possible new insights into the properties of these important heritage sites.

Keywords. Traditional Chinese private gardens; space syntax; connectivity analysis; parametric design.

1. Introduction

The origin of the Traditional Chinese Private Garden (TCPG) is typically traced to the Tang Dynasty (circa 800 AD) although examples of private hunting reserves, with artificially constructed landscapes, can be found in China in the 11th century BC. By the 17th century AD, the TCPG had become a special type of landscaped space characterised in part by its rich spatial arrangement. Today the TCPG is renowned for exhibiting high levels of spatial complexity and variety, properties which have led to them being accepted as having unique aesthetic and experiential properties (Peng 1986, Tong 1997).

Past researchers have analysed the TCPG from various qualitative perspectives (Chang 2006, Lu 2009, Lu 2010, Li 2011) and a small number of studies have also examined their spatial properties using quantitative methodologies. Despite this past research, the spatial properties that make TCPGs unique have rarely been measured and generalised mathematically. Without such a set of measures, the spatial properties of TCPGs cannot be replicated in current landscape design practice or maintained as part of the restoration process for these sensitive heritage structures. Thus, the purpose of the present paper is to begin to develop a system that can generate new TCPGs using parametric design.

This study commences by exploring the mathematical and spatial characteristics of TCPGs using connectivity graphs (Hillier and Hanson 1984). Three plans of 16th Century TCPGs are analysed using this method. As part of the process, different types of garden spaces are categorised into various spatial-types. Then an inequality genotype is developed for each TCPG and the mathematical value ranges of the measurement for each spatial type are identified. In the second part of the paper, new connectivity and spatial-type graphs are generated using parametric rules in Grasshopper. These rules shaping the new graphs use the mathematical relationship identified in heritage TCPGs as their starting point. Finally, the measurement results of the generated parametric diagram are tested against the results from the previous step to see if the new TCPG connectivity and type graphs conform to the patterns found in the historic examples.

The ultimate purpose of this study is to begin to develop and test a method for generating new designs that conform to the styles and qualities of the TCPG. However, this stage of the research is limited to generalise only one major quality of TCPGs, connectivity relative to spatial type. It is not concerned with the location or distribution of specific landscape elements (bridges, statues, streams etc.), but with the larger network of typical spatial relations present in the trafficable sections of a TCPG. Furthermore, a sample of only three historic TCPGs is used to generate the values used for this study. A larger sample, possibly divided by region or dynasty, could be used to develop a more nuanced set of parametric rules that would take into account additional factors.

2. Background

2.1. FORMAL AND SPATIAL QUALITIES OF THE TCPG

A typical TCPG is made up of a dense network of paths and spaces, punctuated with artificial landscape features, ponds and small streams, paved squares and covered corridors or bridges. All of these features are organised in a relatively small and clearly defined area (Figure 1). The rich spatial and aesthetic qualities found in TCPGs have been examined from various perspectives including attempts to understand their dense spatial configurations and the variable changing vistas experienced while navigating through them (Peng 1986, Li 2011). For example Keswick (1978) and Zhou (1999) explored the spatial character of TCPGs from a historical and social perspective. Chang (2006) studied the Lin-family garden using space syntax to examine 310 spatial units using a quantitative analytical method. Chang's study effectively provided a new way of understanding the spatial characteristics of this garden-type in terms of their spatio-functional qualities. Lu (2009, 2010) studied the Yuyuan Garden using a combined method drawn from space syntax and shape grammar approaches. Lu's study provides a new formal language for examining Chinese private gardens as well as showing an effective approach to linking the physical system to cognitive processes. Li (2011) studied the visual perceptual character of the Lingering Garden also using space syntax techniques. That study was focused on visual analysis using isovists and integration results. However, Li's study did not conduct a quantitative analysis of large scale planning and connectivity issues, which are often described as critical spatial features of the TCPG.

Figure 1. Images of selected TCPGs (source from website: http://www.szzzy.cn/products_list/&pmcId=34.html)

2.2. SPACE SYNTAX

Space syntax is a theory and associated set of techniques which have grown out of the work of Hillier and Hanson (1984) on the social structure of space. Extensively developed over the last few decades, space syntax methods have been widely applied in research in urban planning, architectural design and landscape design, amongst other areas. One of the strengths of the space syntax approach is that it provides a way of understanding architectural and urban spatial configurations by translating their properties into topological graphs which can then be mathematically analysed (Ostwald 2011, Ostwald and Dawes 2013). One of the earliest applications of this theory, known as a Convex Graph or a Justified Plan Graph, creates a graph from a set of nodes, which represents spaces and the connection lines between them, being trafficable or permeable boundaries. Simplistically, this is seen as an analysis of rooms and the doors that connect them, although the same method is used for the analysis of accessibility and connectivity in a wide range of examples including fragmented landscapes (Minor and Urban 2007).

2.3. PARAMETRIC MODELLING

Parametric design is a digital design method which is characterised by rule algorithm design and multiple solution generation (Karle and Kelly 2011). Woodbury (2010) argues that it supports the creation, management and organisation of complex digital design models. The term "parameters" is used to describe factors which determine a series of variations leading to a potentially infinite range of possibilities being generated (Kolarevic 2003). In architectural design, parametric tools are mainly used for complex form generation, multiple design solution optimisation, as well as structure and sustainability control. There are several different types of parametric design software currently in commercial use. For the present study Grasshopper was chosen for the parametric application.

3. Research Method

The method used for the present study is divided into two parts. First, it examines the spatial characteristics of three historic TCPG cases focussing on connectivity analysis using plan graphs of key spatial types. Second, it uses data derived from these three cases to define the rules for a parametric system that generates connectivity graphs for possible future designs that conform the styles and qualities of these TCPGs. Three new designs are then generated before their graph-derived properties are compared with those of the historic gardens, to confirm that the method works.

3.1 CONNECTIVITY ANALYSIS USING PLAN GRAPHS

For each of the three historic TCPGs studied, a plan graph was developed for connectivity analysis. Connectivity or permeability graphs are normally constructed to represent and study the relationships between either visible zones (convex spaces) or functionally defined areas. For the present research a variation of the functional areas method was chosen. Thus, regardless of the precise shape of a space, if it has a single function it is regarded as one node in the graph. However, garden spaces do not have strict functional definitions, every part of the TCPG effectively serves as a place of passage, contemplation or social activity. Nevertheless, there are distinct spatial types present in each TCPG which provide an alternative way of graphing their connectivity patterns. For the present research six distinct spatial types were identified: (1) large rooms, (2) small rooms, (3) pavilions, (4) yards/squares, (5) covered corridors and (6) pathways. Large and small rooms are physically and often visually bounded, exterior spaces. Pavilions are covered or semi-enclosed spaces within bounded or open spaces, yards and squares are small paved and visually delimited zones. There are also two distinct types of long, narrow spaces; covered and semi-enclosed corridors and more open pathways.

The method commences by identifying these six spatial types in each TCPG then determining how they are linked. After the linking of those nodes the graph is generated (Hillier and Hanson 1984, Hillier and Kali 2006, Ostwald 2011), from this graph ,the step depth of each node can be determined, then the total depth (*TD*), mean depth (*MD*) and integration (*i*) values are calculated to explore the characteristics of each functional space type within the larger plan network. The step depth suggests the connectivity depth from the entrance node, mean depth (*MD*) is the average depth for each node which represents the degree of isolation of the spaces. While the degree of integration (*i*) is suitable to compare with the other parts in a distributed plan (Ostwald 2011) and develop an inequality genotype (Bafna 2001). In this way the mathematical characteristics of the spatial types and their connectivity in the TCPG are identified.

3.2. PARAMETRIC SYSTEM GENERATION

Using the identified mathematical characteristics of the three TCPGs as a basis, a parametric system is then authored to generate a series of spatial type and connectivity graphs which conform to these characteristics. Grasshopper was used to develop the system wherein the categorised nodes are connected according to rules identified from the three selected garden cases. Then the measurements of total depth (TD), mean depth (MD), and integration (i) are calculated in the built parametric system, which could be tested against the inequality genotype identified in the case studies. With the flexibility and changeability feature of parametric design (Fischer et al. 2003), it is possible to generate several garden diagrams which reflect the connectivity and spatial type characteristics of TCPGs. Three new gardens were generated in this way, using the same external site constraints.

4. Three Historic TCPG Cases

The three selected cases are typical TCPGs, two of which are regarded as being amongst the four most famous Chinese gardens. In order to have sufficient number of spaces and connections to analyse, all of the cases have total areas of over 20,000 m^2. This decision was taken to ensure that the graphs would have a sufficient number of nodes and connections to produce statistically valid results. Figure 2 is the initial plan analysis undertaken using UCL Depth map software (http://www.spacesyntax.net/software/ucl-depthmap/), the conventional space syntax method.

Figure 2. Plan Graph map of the three TCPG cases

4.1. CASE 1: YUYUAN GARDEN

The Yuyuan Garden is located in the city centre of Shanghai, in southern China. It was built in the 16th century and has an area of around 20,000 m^2. Parts of the garden were destroyed during the Second World War; although most parts of the garden have since been repaired or rebuilt. The Yuyuan garden is well known for its delicate and subtle planning and for its artificial mountain with water in its centre. Table 3 shows the connectivity analysis results for the Yuyuan garden graph. The pavilion has the highest MD value (MD = 4.73), which means it is the most isolated spatial type. The pathway has the lowest MD value (MD = 3.53). The integration value (*i*) suggests that the pathway is the most integrated space (*i* = 12.04), and the least integrated space is the covered corridor (*i* =0.27). The results confirm the common expectation because in TCPGs the pathway provides the major connection to other space types.

Table 1. Connectivity analysis of Yuyuan Garden

Spatial type	Number of spaces	*TD*	*MD*	*SD* of *MD*	*i*
Large room	10	39	4.33	1.29	1.20
Small room	18	79	4.65	2.28	2.19
Pavilion	12	52	4.73	1.56	1.34
Yard/Square	7	22	3.67	2.54	0.94
Covered Corridor	5	13	3.25	1.67	0.67
Pathway	63	219	3.53	2.31	12.04

4.2. CASE 2: ZHUOZHENGYUAN GARDEN

Zhuozhengyuan Garden is located in Suzhou also in southern China. It was built in the beginning of 16^{th} century with the area of around 41,334 m^2. There are three main parts of the garden although its essence is regarded as being found in the middle section. Water in the Zhuozhengyuan garden occupies almost one third of its area with its pavilions, artificial mountains and other buildings all following the water's edge. The eastern part of the garden fell into disrepair for many years and has only been rebuilt in recent years. As shown in Table 2, the pavilion space has the highest mean depth (MD = 6.17), this is followed by the courtyard (MD = 6.10) and the path type has the lowest mean depth (MD = 3.98). This is the same pattern as the one found in the Yuyuan garden, the integration value (*i*) also shows that the pathway is the most integrated space and the least is the covered corridor (*i* = 0.11).

Table 2. Connectivity analysis of Zhuozhengyuan Garden

Spatial type	Number of spaces	*TD*	*MD*	*SD* of *MD*	*i*
Large room	9	42	5.25	2.45	0.82
Small room	14	64	4.92	2.06	1.53
Pavilion	13	74	6.17	1.93	1.06
Yard/Square	11	61	6.10	2.02	0.88
Covered Corridor	3	11	5.50	1.15	0.11
Pathway	62	243	3.98	2.38	10.05

4.3. CASE 3: LIUYUAN GARDEN

Liuyuan garden is also located in Suzhou, south China. It occupies approximately 23,300 m^2 and it was built in the late 16^{th} century. There are four main parts in the Liuyuan garden, the middle section being dominated by water and an artificial mountain. The unique element in the Liuyuan garden is the 600 meter long covered corridor which links through courtyards, buildings and water features. Table 3 is the connectivity analysis results of Liuyuan garden. It shows that the covered corridor has the highest MD value (MD = 8.40), followed by the pavilion (MD = 6.80). This partially differs from the other two gardens tested, because in the Liuyuan garden the covered corridor is the most isolated space. However, as with the other two, the integration values (*i*) suggest that the pathway is the most integrated space (*i* = 3.22) and the least integrated is the covered corridor (*i* = 0.27).

Table 3. Connectivity analysis of Liuyuan Garden

Spatial type	Number of spaces	*TD*	*MD*	*SD* of *MD*	*i*
Large room	7	36	6.00	1.35	0.50
Small room	13	81	6.75	2.28	0.96
Pavilion	6	34	6.80	2.34	0.34
Yard/Square	10	52	5.78	2.66	0.84
Covered Corridor	6	42	8.40	0.89	0.27
Pathway	33	186	5.81	2.38	3.22

In summary, the mathematical results from the analyses above suggest the following. First, for all of the gardens the most integrated (i) spatial type is the pathway, followed by the small garden room and the least integrated spatial type is the covered corridor. Second, for the Yuyuan garden and the Zhuozhengyuan garden, the pavilion spatial type has the highest mean depth (MD), and for Liuyuan garden, the highest mean depth (MD) is the covered corridor, followed by the pavilion. Finally, all of the gardens have the smallest MD value for the pathway. For the Yuyuan garden and the Liuyuan Garden, the second smallest MD value is for the yard/square and for the Yuyuan Garden, it is the small garden room followed by the yard/square. These results suggest that for different types of functional spaces, there are common mathematical characteristics that can be generalised. Furthermore, the connectivity analysis based on MD and *i* values is meaningful to explore the spatial characteristics of TCPGs.

4.4. INEQUALITY GENOTYPES

The *i* value can be used to develop an “inequality genotype”, which is the ranking of the spatial types in the order from the highest to the lowest *i* values (Bafna 2001). Table 4 shows the average connectivity analysis values of the three TCPG cases. The spatial types are ranked according to the average *i* value for each type, from the highest to the lowest as following: pathway > small garden room > pavilion > yard > large garden room> covered corridor. The value differences between three of the types, the pavilion (i= 0.92), yard (i= 0.89) and large garden room (i= 0.84) are relatively minor, so for the purposes of this stage we have ranked the three together leading to the following inequality genotype: Pathway > small garden rm. > pavilion/yard/large garden rm. > covered corridor. Furthermore, in order to set a more precise set of limits for the process, the standard deviation of the *i* value was calculated to set its testing range (Table 5). According to the testing range, the Yuyuan garden has three space types within the range and the Liuyuan garden has four while all of the space types in the Zhuozhengyuan garden are within the *i* testing range. Figure 3 shows the connectivity map of the three TCPG maps.

Table 4. Average values of the convex space analysis of the three garden cases

Spatial type	Number of spaces	*TD*	*MD*	*i*
Large room	8.67	39.00	5.19	0.84
Small room	15.00	74.67	5.44	1.56
Pavilion	10.33	53.33	5.90	0.92
Yard/Square	9.33	45.00	5.18	0.89
Covered Corridor	4.67	22.00	5.72	0.35
Pathway	52.67	216.00	4.44	8.44

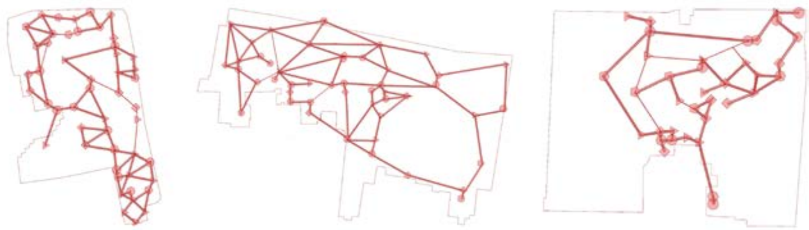


Figure 3. Connectivity map of the three TCPG cases

Table 5. Testing range of i values

Spatial type	*i*	*SD of i*	*Testing range*
Large room	0.84	0.35	0.49~1.19
Small room	1.56	0.62	0.96~2.18
Pavilion	0.92	0.51	0.40~1.43
Yard/Square	0.89	0.05	0.84~0.94
Covered Corridor	0.35	0.29	0.06~0.64
Pathway	8.44	4.63	3.81~13.07

5. A Parametric system for generating TCPGs

5.1. RULE SETTING OF THE PARAMETRIC SYSTEM

In order to generate a parametric system which reflects the mathematical characteristics of the above TCPGs, the following steps were taken. First, some mathematical characteristics of different spatial types derived from the three TCPG cases were set as rules in Grasshopper. For instance, the pavilion has only one connection; some of the yards are connected to large garden rooms, etc. Second, the number of each spatial type, such as the number of large rooms or small rooms, were set as input parameters. Other input parameters included site factors. For this demonstration a pre-determined entrance, generic site boundary and main path curve were selected (Figure 4), as well as the distance range of the nodes to the pre-determined main path. Here we pre-defined a rectangle site boundary, which could be adapted to the actual site form. Third, example parametric diagrams of new TCPG designs were generated, each suggesting a possible connectivity planning schema reflecting the characteristics of the historic TCPGs. Finally, the *TD*, *MD*, *i* values of the generated parametric diagram were tested against the inequality genotypes produced for the three TCPG cases studied. When performing the *i* range testing of an example parametric diagram, if the *i* value is within the range (see Table 5), the outcome is “true”. The more “true” values the system generates, the more closely the characteristics of the new TCPG design reflects those of the three historic TCPGs.

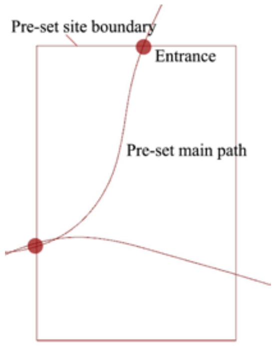
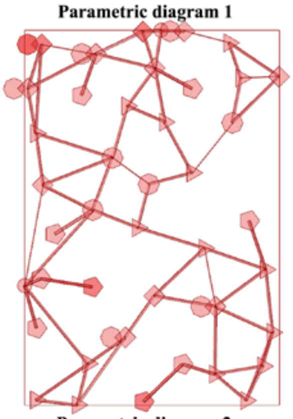


Figure 4. Generic site curve

5.2. EXAMPLES OF THE PARAMETRIC GRAPHS GENERATED

Figure 5 shows three examples parametric diagrams of new TCPG designs generated and tested in Grasshopper. Different symbols represent the six spatial types of the garden, which is large garden room, small garden room, pavilion, covered corridor, yard/square and entrance. The testing of the parametric diagrams suggests that all of the three examples comply with the inequality genotype test. In terms of the *i* range test, parametric graph 2 best reflects the characteristics of the three historic TCPG cases analysed because it has the highest number (4) of “true” properties in the outcome test amongst the three examples.

Parametric diagram 1



Connectivity analysis results of parametric diagram 1

Functional type	Number of space	TD	MD	i
Large garden room	11	41	4.10	1.45
Small garden room	16	51	3.40	2.92
Pavilion	9	36	4.50	1.00
Yard/Square	10	38	4.22	1.24
Covered Corridor	8	30	4.29	0.91
Pathway	49	158	3.29	10.25

Range testing results

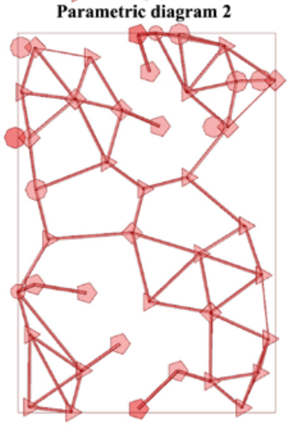
Functional type	i range Testing
Large garden room	False
Small garden room	False
Pavilion	True
Yard/Square	True
Covered Corridor	False
Pathway	True

Inequality genotype test

Pathway >small garden room > …. >covered corridor

Totally comply with the inequality genotype test

Parametric diagram 2



Connectivity analysis results of parametric diagram 2

Functional type	Number of space	TD	MD	i
Large garden room	20	24	3.43	1.24
Small garden room	8	64	3.37	3.80
Pavilion	8	24	3.43	1.24
Yard/Square	7	23	3.83	0.88
Covered Corridor	4	12	4.00	0.33
Pathway	55	177	3.28	11.63

Range testing results

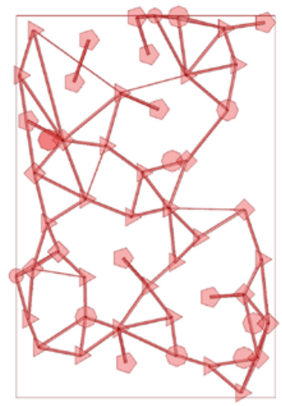
Functional type	i range Testing
Large garden room	False
Small garden room	False
Pavilion	True
Yard/Square	True
Covered Corridor	True
Pathway	True

Inequality genotype test

Pathway >small garden room > …. >covered corridor

Totally comply with the inequality genotype test

Parametric diagram 3



Connectivity analysis results of parametric diagram 3

Functional type	Number of space	TD	MD	i
Large garden room	9	33	4.125	1.12
Small garden room	24	85	3.70	4.08
Pavilion	10	34	3.78	1.44
Yard/Square	8	29	4.14	0.95
Covered Corridor	6	20	4.00	0.67
Pathway	65	227	3.55	12.37

Range testing results

Functional type	i range Testing
Large garden room	True
Small garden room	False
Pavilion	False
Yard/Square	False
Covered Corridor	False
Pathway	True

Inequality genotype test

Pathway >small garden room > …. >covered corridor

Totally comply with the inequality genotype test

Symbols

Covered corridor — Small garden room

Pathway — Pavilion

Yard/square — Entrance

Large garden room

Figure 5. Three examples of new TCPG designs as parametric diagrams and their properties

6. Conclusion

This paper explores two related mathematical characteristics of the TCPG – connectivity and spatial type – using space syntax methods. Parametric design is then used to generate and test new TCPG designs in the form of parametric diagrams.

This research extends the use of space syntax beyond the conventional design analysis to the generation of new spatial relations. Further, it contributes to a new understanding of TCPGs from a mathematical perspective. Future research will focus on exploring the form and size of each spatial type within the new TCPG designs, effectively converting the graph into a design, or conceptually shifting from a design syntax to its formal grammar.

Reference

Bafna, S.: 2001, Geometric intuitions of genotypes. *Proceedings of the third international symposium on space syntax*, A. Alfred Taubman College of Architecture and Urban Planning, University of Michigan, MI.

Chang, H.: 2006, The Spatial Structure Form of Traditional Chinese Garden－A Case Study on The Lin Family Garden. *Master Thesis*, Chenggong University, Tainan.

Fischer, M., Burry, M. and Frazer, J.: 2003, Triangulation of Generative Form for Parametric Design and Rapid Prototyping. *Proceedings of 21th eCAADe Conference*, Graz, Austria.

Hillier, B. and J. Hanson: 1984, *The Social Logic of Space*, Cambridge University Press.

Hillier, B. and T. Kali: 2006. Space syntax: the language of museum space in M. Sharon (eds). *A companion to museum studies*. London, Black well**:** 282-301.

Karle, D. and B. Kelly: 2011, Parametric Thinking. *Proceedings of ACADIA Regional 2011 Conference*.

Keswick, M.: 1978, *The Chinese Garden: History, Art and Architecture.* New York, St. Martin's Press.

Kolarevic, B.: 2003, *Architecture in the digital age : design and manufacturing.* New York, NY, Spon Press.

Li, Z.: 2011, Visual perception of traditional garden space in Suzhou, China: A case study with space syntax techniques. *2011 19th International Conference on Geoinformatics,.*

Lu, S.: 2010, Hidden orders in Chinese gardens: irregular fractal structure and its generative rules. *Environment and Planning B: Planning and Design* 37(6), 1076-1094.

Lu, S. M.: 2009, From Syntax to Plot: the spatial language of a Chinese garden *Proceedings of the 7th International Space Syntax Symposium.* Stockholm: KTH.

Minor, E. S. and D. Urban: 2007, A graph-theory framework for evaluating landscape connectivity and conservation planning. *Conservation Biology* 22(2), 297-307.

Ostwald, M. J. : 2011, The mathematics of spatial configuration: Revisiting, revising and critiquing justified plan graph theory. *Nexus Network Journal* 13(2), 445-470.

Ostwald, M. J. and M. J. Dawes: 2013, Differentiating between Line and Point Maps Using Spatial Experience: Considering Richard Neutra’s Lovell House. *Nexus Network Journal* 15(1), 63-81.

Peng, Y.: 1986, *Analysis of Chinese Classical Garden.* Beijing: China Architecture and Building Press.

Tong, J.: 1997, *Glimpses of Gardens in Eastern China.* Beijing: China, Architecture and Building Press.

Woodbury, R.: 2010, *Elements of Parametric Design*. New York, Routledge.

Zhou, W.: 1999, *Classical Garden of China*. Beijing, Tsinghua University Press.