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Optimization of settlement layout based on parametric generation

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Abstract. Design of settlement space is a complicated process while reasonable spatial layout bears great significance on the development and resource allocation of a settlement. The study proposes a weighted L-system generation algorithm based on CA (Cellular Automation) model which tags the spatial attributes of cells through changes in their state during the evolution of CA and thus identifies the spatial growth mode of a settlement. The entrance area of the Caidian Botanical and Animal Garden is used a case study for the model. A design method is proposed which starts from the internal logics of spatial generation, explores possibility of spatial rules and realizes the quantitative analysis and dynamic control of the design process. Taking a top-down approach, the design method takes into account the site information, studies the spatial generation mechanism of settlements and further presents a engine for the generation of multiple layout proposals based on different rules. A optimal solution is acquired using GA (Genetic Algorithm) which generates a settlement spatial layout carrying site information and dynamically linked to the surround environment. The study aims to propose a design method to optimize the spatial layout of the complex settlement system based on parametric generation.

Keywords: parametric design; Cellular Automaton; L-system; genetic algorithm; layout optimization

1. Introduction

Since the middle of the 20th century, the development of complicated science theories has set humanity free of the constraints of classic science and we have started to transcend the boundary of natural geometry from design to manufacturing. Jencks (2007) have studied “When sciences based on non-linear mathematical relations begin to replace classic Newton mechanics and become the fundamentals for people’s understanding of nature or the cosmos; and when theories such as chaos and self-organizing are used to explain the contradiction between cosmic expansion and species evolution, some basic concepts of people’s thinking on form design were shaken, therefore, the emergence of architectural form full of complexity becomes inevitable”, French philosopher Gilles Louis Réné Deleuze also argues, described by Yu (2011) and Leng (2011), that the fundamental attribute of event is generation which is a dynamic movement; the concepts from different field maintain differences and communications which give birth to another field, i.e.,

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generation. These ideas serve as the philosophical foundation of parametric design and point out an approach to study of complicated urban spaces.

Development of complicated science and philosophy offers the foundation and driving force of parametric design while the progress of computer science and algorithms in particular changes the way of urban and architectural design because they render possible non-linear parametric control and presentation. The role of computers in design has evolved from the aiding the drawing to facilitate the designing. In the traditional approach, the subjective judgment of designers dominates the design process which the corresponding relationship between space and form can hardly be quantitatively expressed. The emergence and application of visual programming software and parametric design methods have fundamentally changes the traditionally approaches of design and made quantitative analysis and dynamic control possible in the designing process. When different parameters are input, the corresponding model changes, which makes the design result controllable. At the same time, the application of algorithms makes design more logical and rational, for example, algorithm based on neighborhood rules such as CA can help generate forms expand the possibility of design; while algorithm for optimization such as GA can help optimize design by simulation natural evolution mechanism and exploring optimal solution.

2. Algorithm based form generation and optimization

2.1 Algorithm based form generation

Soddu(2015) have studied Algorithm based form generation or generative design can be defined as a iterative design process with increasing complexity. Designer controls the design process by choosing the proper algorithm and different parameters, which starts from unexpressed ideas behind a design and ends with a generative engine, a set of manually written code.

Form-find by hanging, as used by Spanish architect Antoni Gaudi i Cornet while designing the curved surface of the dome of the Güell Chapel is the earliest example of architectural form generating. Later, German architect Frei Otto used upside-down cable network to simulate the form of architectural structure under self weight. These two examples use physical models to find forms.

Growth models, as represented by the fractal model, emerged alongside with the rapid development computing science and is a derivative of the dynamics model. Fractal refers to a shape whose part is similar to the whole in a certain way, i.e., a form with self similarity. The fractal approach is mostly commonly used in architectural design while sometimes used for analyzing the complexity of a city. Typical fractal algorithms include L-system, DLA model (Xu 2012), IFS model (Lin 2013) etc. Among the above, L-system model incorporates a series of grammatical rules by simulating plant growth; with recursive growth, the model becomes increasingly complex which is applicable for the generation of static and single function such as road (Li 2015).

However, as Leach (2009) described thatL-system is a modeling pattern for limited growth in which agents behaviors are restricted and could not adjust their behaviors in response to external stimulations. In contrast, CA is a system model based on neighborhood rules which can interact with its surrounding environment and can correspond to the neighborhood relationship on the settlement scale. At the same time, the self-organized recursive mode of CA is also in line with the self-organizing attributes settlements. The spatial attributes of CA and its logical rule of responding to neighborhood conditions offers an applicable and efficient model for the spatial generation of settlements. As a discrete dynamic system, CA divides a region into serve units with identical size and form, these units are called cells and are the most fundamental building blocks of CA. The spatial nodes of all cells comprise the cellular space. CA model can adjust the property of cell units according to some simple neighborhood rules, covering four elements, namely, unit, state, neighborhood area and transition rule. This discrete dynamic model is usually employed in the generation and design of small-sized individual architecture or small-scale settlements.

2.2 Optimization algorithm

In the form generating phase of a generative design process, various predictable and unpredictable spatial forms may emerge whose number is usually large and often difficult to control. Therefore, algorithms need to be optimized in order to narrow down suitable choices. In architectural design, the more often used optimization algorithms are SI (Swarm Intelligence), SA (simulated annealing) (Li 2009), GA, etc. which all fall into the category of intelligent optimization algorithms (Luo 2015).

Swarm intelligence refers to the intelligent behavior of individuals in a group based the simple rules between each other. Typical algorithms include ACO (Ant Colony Optimization), ABC (Artificial Bee Colony), AIS (Artificial Immune System), PSO (Particle Swarm Optimization). During the long evolution, life forms have developed from a chaotic diversity into the current order and harmony. Many life forms are demonstration of evolution and optimization. Enlightened by these, humanity analyzed the phenomena and applied them in computer simulation and identified the laws of optimization algorithm.

SA is a statistical optimization method which draws on the annealing mechanism of statistical thermodynamics for the purpose of combinatorial optimization. Through random searching of neighborhood functions, SA comes up with a global optimal solution.

GA is based on a series of proposed designs and identifies the optimal solution among these parallel proposals. Therefore, it is an optimization method of finding optimal solution by simulating natural evolution. GA uses a population to represent the optimal solution or solution set which comprise a certain number of individuals. Encode by genes, an individual bears certain attributes and together constitute the original population which then evolve into better later generation, i.e., approximate solution; during each phase of the iterative process, individuals are selected according to their fitness to the problem domain and are mixed with the randomly generated new individuals. The process means that the emergence of new population is just like that in a natural evolution in which the later generation can better fit the environment. Eventually, the optimal individuals in the last generation are encoded and presented as the appropriate optimal solution to the problem. Galapagos is a GA module in the Grasshopper software known for its easily operability and rapid converging speed. In this module, the gene interface corresponds to the independent variable of the optimization problem, while the fitness interface corresponds to dependent variable. Galapagos sets no limits on the problem to be solved, as long as a relation exists between independent variables and depend variables, the problem can be soluble (Lin 2015).

For a professional problem with an extremely large solution space, GA is capable of searching for an excellent solution in a short period of time; thanks to the searching process and optimization mechanism in the algorithm, it is good at solving global optimization problems. Beside the three above-mentioned ones, intelligent optimization algorithms also include ANN (Artificial Neural Network), local searching, etc.

It should be noted that, the optimizing of urban or architectural design does not mean finding the optimal solution quantitatively, it also covers cultural and aesthetical elements. Therefore, the optimization process calls for the participation of designer to work together with computers. On the other hand, computers are not only tools for drawing and the final design proposal is not the sole result of designers' imagination but rather an outcome supported by the computation and optimization abilities of computer programs (Song *et al*. 2009). Thus, the creativity of planners or architects can reach a high level – a creativity towards more complex and more systematic design.

3. Generation and optimization of settlement spaces

At present, most studies at the settlement scale focus on its spatial features and few looks into its generative design. Taking the entrance area of the Caidian Botanical and Animal Garden as a case, the study proposes a design method based on parametric generation which starts from the internal logics of the design process, adopts the CA algorithm for the generation of architectural spaces and L-system algorithms for road generation, then overlaps various sub-systems for adjustment and comes up with an optimal solution through GA. The study aims to identify the mechanism of settlement generation through the us of CA and propose a new generative approach to the design of the complex settlement system.

3.1 Site condition

The site for case study in the Caidian Botanical and Animal Garden has a level topograhy suitable for construction. The site also boast beautiful surroundings and sound ecological environment with a lotus pond in the west, Wumei Hill in the east, farmland in the north and the West Lake in the south. It covers a total area of 36,711 m^2 including 12,732 m^2 of water area. Land for construction is designated at 23,979 m^2 with a FAR (Floor Area Ratio) at 0.5-1.0. Site plan also demands a setback of buildings 5 m from road boundaries, 5 m from pond boundaries, 10m from hill boundaries while building height should not exceed the 45°view control line, sunlight spacing coefficient should be no smaller than 1.1. Site conditions are presented in Fig. 1.

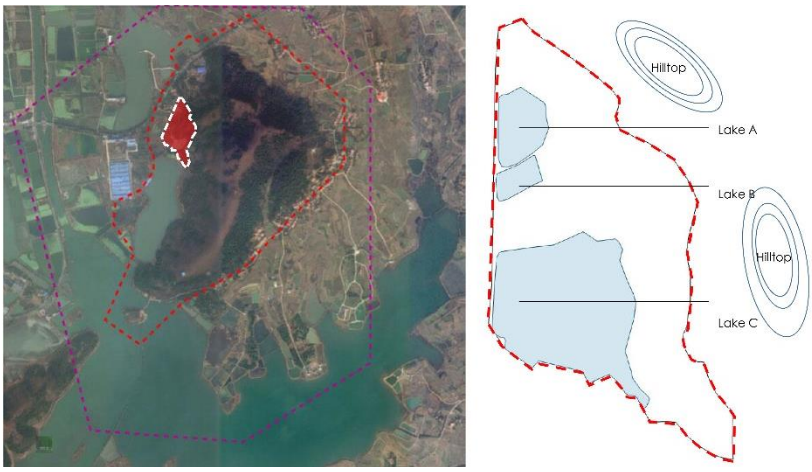


Fig. 1 Site boundary and condition

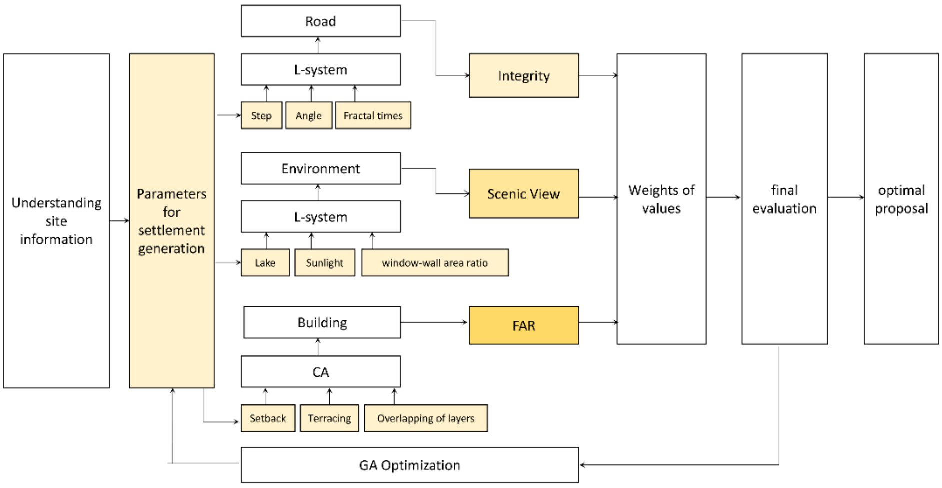


Fig. 2 Diagram of design procedure

3.2 Algorithm based form generation

3.2.1 Design procedure

Generative design of architecture begins with the understanding of the site and the building. Road and nature environment are two primary elements of a site which may affect the logic of building generation from different aspects. For example, road density indicates the traffic of human flow in the area, natural lighting affects building orientation and layout. While individual building design should is subject to strict control of building code, the relationship between various buildings needs to be properly balanced so as to acquire maximum amount of spaces with optimal quality. Since the final design is decides by multiple factors, the producing of a design is not a linear process but rather a complex logic based on repeated comparison, feedback and modification.

Applying CA and L-system algorithms into the generative design of buildings can facilitate the realization of the complex logic with multiple variables as two algorithms incorporate continuously iterative processes. In road generation, step, angle and fractal times are major iterative factors which represent roach shape, intersections, etc; as for the environment, lake, sunlight, widow-wall area ratio are the iterative factor of L-system which ensure the maximum scenic view from building. In CA, each cell represent a column unit which can assume two different properties: one represent the void, i.e., the open space with no physical building element where the cell is located; the other is the architectural space, i.e., the space occupied by physical building element where the cell is located. The status and attributes of cells are decide by various factors including building code (such as setbacks), surrounding environment of site, spatial quality of site, surrounding condition and attributes of cell (building unit), as well as preset rule of generation.

Combination of these factors with different values can result in an extremely large number of design proposals which offer rich source materials for study of settlement generation. To further identify the optimal combination, the ultimate impact values of road, environment and building are calculated by integrity, scenic view and FAR; in accordance with the demand of designers (or design requirements), these three values are given different weights and a final solution is acquired using GA. The three final values correspond to the respective form and space of road, environment and building and together comprise a generative settlement design proposal.

3.2.2 Rules for circulation generation

Generation of the road system starts from analyzing the historic fabric of the site and reconstructs roads to retain users spatial behavior. Based on the topological maps of road extracted from the site analysis, and in accordance with L-system grammar (F: take a step of L forward and draw a line at the same time, f: take a step of L forward but not to draw a line, +: turn left，-: turn right，[start branch], end branch), the rule of road generation is set as: F=F[-F]F[+F][-F], so as to reproduce the spontaneously developed road fabric; unit length of a step is set at the two times the standard width of a storefront, i.e., 8 m; road networks are generated at step lengths of 8 m, 16 m and 24 m (Fig. 4).

Based on the road system, together with site analysis, parameters of entrance locations area acquired; then in accordance with the line density of L-system generated road, together with entrance and other environmental parameters, locations of squares are generated.

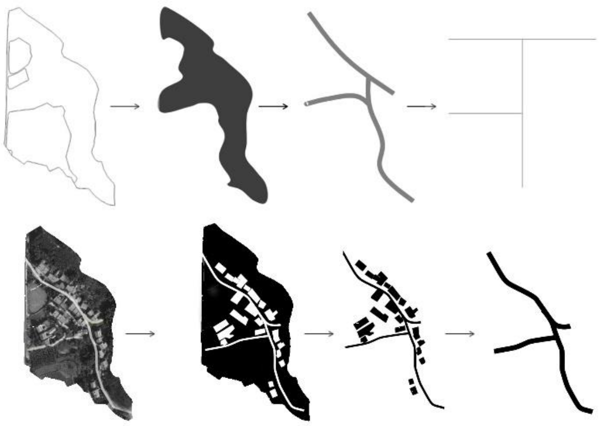


Fig. 3 Extraction of site topology from historic fabric

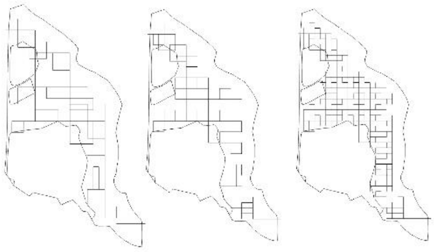
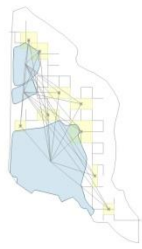
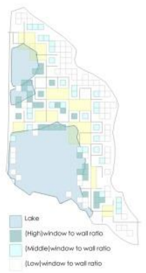


Fig. 4 Generation of road system

3.2.3 Rules for site plan generation

Table 1 Rules for plan generation

Storey number		Rules for plan generation	Diagram
One	1	5 m building setback from site boundary	 Visual corridors
	2	Buildings should stay away from lakes but can cantilever over Lake A and Lake B for 4 m; due to the larger size of Lake C, 8 m of cantilevering is allowed	
	3	Avoid roads and squares	
	4	Gaps for viewing and daylights are set at a D_1m interval vertically on buildings	
	5	On a visual corridor linking the center of the square and that of the lake, buildings have the highest window-wall area ratio; in the D_2m radius of the square, buildings have a medium window-wall area ratio	 Square perimeter  Window wall ratio schematic
Two	1	5 m building setback from site boundary; other building outside of the above-mentioned have the lowest window-wall area ratio	
	2	Buildings should stay away from lakes but can cantilever over Lake A and Lake B for 4 m; due to the larger size of Lake C, 8 m of cantilevering is allowed	
	3	Not to avoid roads as buildings two-storey or above can strut over roads; avoid squares	
	4	Gaps for viewing and daylights are set at a D_1m interval vertically on buildings	

Continued-

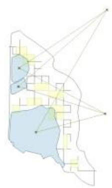
	5	To ensure overall terraced forms of buildings and views of lake from different directions, distance of two-storey buildings from lake center are subject to the following: distances of all two-storey buildings to the centers of Lake A and Lake B should be greater than D_3m; due to the larger size of Lake C, that to the center of Lake C should be greater than D_4m	 Diagram of the relationship between architecture and lake
	6	The same rules on visual corridor for one-storey buildings applies here: On a visual corridor linking the center of the square and that of the lake, buildings have the highest window-wall area ratio; other buildings have a lower ratio	
Three	1	5 m building setback from site boundary	 Lake C center line of sight
	2	Buildings should stay away from lakes but can cantilever over Lake A and Lake B for 4 m; due to the larger size of Lake C, 8m of cantilevering is allowed	
	3	Not to avoid roads as buildings can strut over roads; not to avoid squares as buildings can strut over squares	
	4	Gaps for viewing and daylights are set at a D_1m interval vertically on buildings	 View corridor at peak and lake center
	5	Similar to Rule 5 of two-storey buildings: Distances of all three-storey buildings to the centers of Lake A and Lake B should be greater than D_5m; due to the larger size of Lake C, that to the center of Lake C should be greater than D_6m	
	6	For day lighting and ventilation, three-storey buildings should not block one-storey buildings	 Location of buildings in the view corridor at the top of the mountain and the lake center
	7	Three-storey buildings are planned in the following three areas under the precondition of satisfying the 6 rules above: a. The D_7m radius area around the center of Lake C and in a 60° vertical view angle; b. Areas along the lines linking the hilltop and the centers of the three lakes; c. Areas along the lines linking the entrances/exits and the center of Lake C	 Location of buildings in the view corridor at the top of the mountain and the lake center

Table 2 Rules of overlaying

<table>
<tr><th>Property</th><th>First Floor</th><th>Second Floor</th><th>Third Floor</th><th colspan="2">Number</th><th>Rules</th></tr>
<tr><td rowspan="4">Whether building exists at a certain floor</td><td>No</td><td>Yes</td><td>No</td><td colspan="2">40</td><td>Columns at four corners of the block extend to the ground while the encompassed become public space</td></tr>
<tr><td>No</td><td>Yes</td><td>Yes</td><td colspan="2">2</td><td>Columns at four corners of the block extend to the ground, an attached spiral outdoor staircase connects to the second floor.</td></tr>
<tr><td rowspan="2">No</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td rowspan="2">15</td><td>7</td><td>Columns at four corners of the block extend to the ground, an attached spiral outdoor staircase connects directly to the third floor.</td></tr>
<tr><td>8</td><td>Column is designed in integral tree shape (as for units in central locations)</td></tr>
</table>

Although the generation rules of various sub-systems are defined independently, in fact, they influence and restrict one another. For example, rules for road generation are based on parameters such as site boundary and conditions; rules for squares are based on road locations; while building plans are generated based on the circulation system, even plans on different floors are interconnected. Given a set of rules, changes of a sub-system or parameters may incur corresponding changes in various components of a settlement space. In addition, rules of natural light and ventilation also affect the design. Thus, the design of the settlement space on the whole involves feedback of various information and iterative adjustment.

3.3 Site condition

On the basis of the above rules for site plan, the rule for overlaying on the vertical direction are further identified as in Table 2 when a second floor or a third floor exists on top of an overhead space on the first or/and second floor.

When the above rules for site plan and overlaying are established, a generation engine is put forward as encoded by Grasshopper (Fig. 5). Further, the Galapagos algorithm module is employed to optimize the design procedure.

The value range of the 7 parameters in site plan rules are decided in accordance with their correlation and then put in as the independent variable (the “gene” input).

1. To control building masses, circulation system variables D1 and D2 are based on 8 m module length; to ensure flexibility of settlement space and control over natural-lighting gaps, the range of D1 is set between 0 m-24 m; to connect outdoor squares with indoor spaces, the range of D2 is set between 0 m-24 m.

2. Since Lake C is larger compared with Lake A and B, so D3 < D4; according to the site scale, the value ranges for D3 and D4 and are further set as 30 m-100 m, 50 m-200 m respectively.

3. To achieve an overall terraced form of buildings which gradually lowers from the hills to the lakes, where also D5 > D3 and D6 > D4. Similarly, according to the site scale, the value ranges for D5 and D6 and are further set as 30 m-100 m and 30 m-100 m respectively.

4. Considering the size of Lake C, D7 > 48 M; and according to the site scale, the value range of D7 is set as 50 m-200 m .

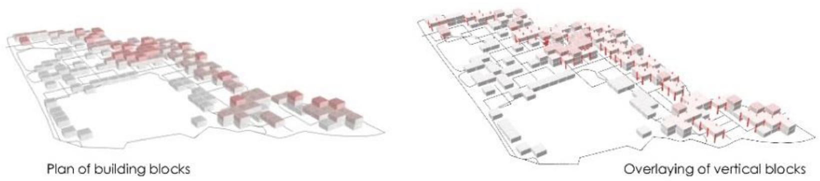


Fig. 5 System overlaying and generation engine

Till this point, the attributes, value range and restricting rules of independent variables are identified.

Based on the topographic condition of the site, three major elements are chosen for optimization, namely, FAR, scenic view and integrity. In accordance with the design assignment, the site condition with lakes and hills, and the spatial attributes of the settlement, the weight of the three elements for optimization are decided at 20%, 50% and 30% respectively (which are subject to change according to different site conditions and project requirements). On basis of the design engine, a battery group is written to add up information of elements for optimization which is then put in as dependent variables ("fitness" input) of GA (i.e., Galapagos). In the series of design proposals generated, an optimization is conducted to look for the design proposal with the maximum value of dependent variable. The algorithm runs iteratively and through a series of selection, crossover and mutation, each later generation approaches closer to the optimal solution than its previous generation. In the case study, the Galapagos module ran 127 iterative processes to achieve the optimal solution: L=16 m, N=6, A=90, which generates the road and square system (Fig. 5); D1=16 m, D2=8 m, D3=52 m, D4=65 m, D5=68 m, D6=75, D7=98 m, which produces the optimal solution model correspondingly.

Fig. 6 System overlaying and generation engine

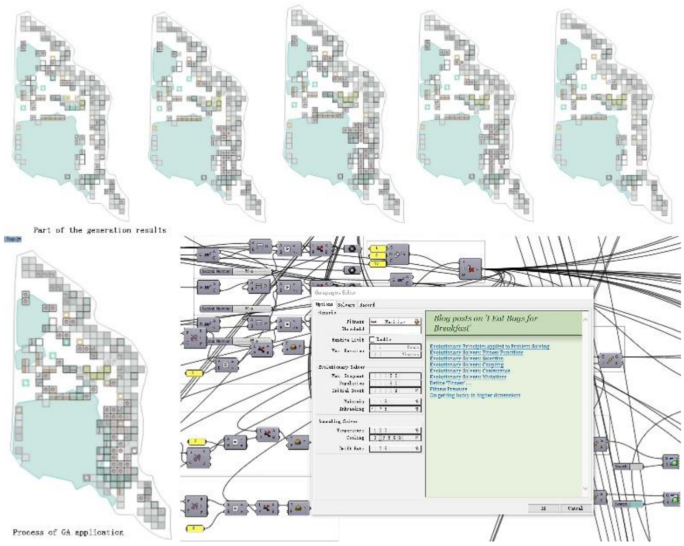


Fig. 7 GA optimization

Fig. 8 Renderings of the final design proposal

4. Final design proposal

Generated and optimized by algorithms and based on an optimal solution of integrity, scenic view and FAR, the final design proposal seeks a high spatial quality and a terraced architectural form by the lakes and hills. Meanwhile, supported by the L-system algorithm, the road and square system connects a series of courtyard settlement spaces at different sizes. The sharp contrast between the openness of the courtyard and depth of the corridor enriches the spaces inside of the settlement.

Through further visual corridor and view analysis, different window-wall area ratios of buildings at various locations are identified for building façades while achieving optimal visual corridor and scenic view.

With the above sub-system generation and overlaying, details adjustment and improvement, the final design is given a rich spatial composition, open and diverse façades, ordered yet varied overlaying of box-like building forms. The open space system, generated by the overlaying of the square system and site plan system, offer diverse forms of public spaces, such as courtyards, arcades, view-corridors, etc., which attract and retain visitors and in turn offer sound business values and scenic views.

On each floor, locations of buildings are decided by parameters such as site boundary, hill and lake locations, etc., in an effort to connect buildings and site into an organic whole(Fig. 8).

5. Conclusions

The study proposes weighted L-system generative algorithm for a CA based model which offers more possibilities for settlement plan generation. Furthermore, taking an approach of restricted generation, this method differs from the exhaustive generation. The method introduces a set of rule regarding natural lighting, ventilation, skyline, terracing towards hills or lakes, etc.; through a continuous iterative process and the use of GA, an optimal design propose is selected out of a series of parallels so as to make the result more controllable and efficient. Taking a top-down approach and based on CA algorithm, the design method starts with relevant site information, overlays sub-systems such as road generation system, square generation system and site plan generation system for the generation of multiple plan proposals based on different rules. With the support of parametric design software, an engine for the generation of multiple design proposals is built and the results from which are then optimized and selected. The study aims to propose a new design approach to the generative design of settlements as complex systems.

In the case study, the planning and design of the entrance area of the Caidian Botanical and Animal Garden, the spatial attributes of cells are recognized by changes in their state during the evolution of CA; parameters such as locations of hills surrounding the site, lakes in the site, site boundary, entrances and exits, unit width of storefront along the commercial water street, etc. are put in to facilitate the generation of plan proposals, which stresses the spatial zoning and inner logic of the plan. With more accurate use of the parameters of site environment, the zoning and logic of the settlement space become more rational. As a complex system, the design of a settlement is affected by many factors besides site parameters, natural lighting, vertical circulation, etc., such as skyline, human experience in spaces, economic efficiency of cell module selection which can be encoded as new rules and in turn add to the complexity of the generation system. Therefore, this generation engine changes with different site condition.

Compared with the traditional outside-in or top-down design approaches which lack systemic connections between complicated element, parametric generative design adopts a bottom-up solution and can also incorporate into rules of design, the complicated environmental information around the buildings. In this effort, the parameters and sub-systems are interconnected, interactive, overlaid and bound together into a complex living organism.

Acknowledgments

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References

Celestino, S. (2015), Generative Design Futuring Past.

Charles Jencks (2007), Critical Modernism: Where is Post-Modernism Going What is Post-Modernism, Academy Press.

Leng, T. (2011), *Digital architectural design guide by complexity theory*, South China University of Technology, 140-142.

Li, X. (2009), R*esearch and application of particle swarm optimization based on simulated annealing method in the urban layout of the land space*, Shandong Normal University, 11-13.

Li, X. and Xu, W. (2015), "The application of algorithm and digital modeling techniques in architectural design", *New Architecture*, (5), 10-14.

Lin, Q. (2013), "Architectural fractal generating based on 3D IFS methodology", *World Architecture*, (9), 106-109.

Lin, Q. (2015), "Particle system and fractal movement", *Urbanism and Architecture*, 1-3.

Luo, Y. (2015), *Optimization research of the parametric architecture based on optimizing method*, Southwest Jiaotong University, 55-68.

Neil, L. (2009), "Swarm Urbanism", *World Architecture*, 1-2.

Shen, J. (2012), *Research on methods of using technical analysis in grasshopper for green building design*, South China University of Technology, 41-49.

Song, J., Zhao, B., Xiong, Y. and Guo, X. (2009), "Quantitative analysis of contributing factors in settlement generation", *J. Civil. Architect. Environ. Eng.*, **31**(2), 110-115.

Xu, W. (2012), "Parametric design and generating by algorithm", *Urban Environ. Des.*, (1), 250-253.

Yu, H. (2011), Parametric Urban Design Based on Rhinoceros: A Case Study of Jixian Urban Center.

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