Research on Algorithm-based Urban Design: A Case Study in Chefoo Bay

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Abstract: Since the start of the digital computing age, algorithmic languages have penetrated urban design from many perspectives. Based on the theory of complexity, urban researchers attempt to model the evolution process of urban factors and to construct mathematical urban prototype models using the emergence of different forms and structures. However, the simple 'overlay' between factors does not prove nor explain the essence of the interactions among urban elements (SCHUMACHER & LEACH 2009). Therefore, most of the existing parametric design method only have the appearance of morphology and lack a deep understanding of the urban structure formation principles. The effects caused by unforeseeable events, such as capital flow (DAVID 1985), ecological processes (JAMES 2004) or personal preferences on spaces, were not taken into account in the modelling processes. Hence, this research is devoted to the coherence and differentiation of digital and traditional urban design and, most importantly, to develop a prototype parametric urban design toolkit, based on the Grasshopper platform, that improves the interaction between the traditional urban design experience and modern algorithm-based urban factor models. With alterable set rules and different variables, the toolkit would help practitioners to dynamically construct reasonable urban structures, road networks and function blocks. The researchers carried out a case study on the Chefoo Bay regeneration project, and the result was a series of urban spatial structure prototypes with a dynamically-oriented urban road network, different functional structures and composite green networks.

Keywords: Parametric urban design, port city regeneration, translation methods of planning logic

1 Introduction

Traditional planning and design often present descriptions of land use prospects (WANG 2014) and are strongly empiricist. As a complex adaptive system (QIU 2012), the evolution process follows a non-linear logic. In rapidly developing urban cities, the complex and high-frequency interactions between various elements reveal that the tradition of 'blueprint-style' (ZHANG 2012) urban planning methods lack dynamic adjustment mechanisms. Therefore, with the development of digital age, urban design studies based on new technology and algorithm design have gradually emerged. For example, urban think tanks that use big urban data, digital reconstructions of urban networks and urban analysis of spatial geometric dimensions. Such parametrical design methodology focusses on the wider aspects of parametric factors that are proven to have deterministic power in the urban design process, and their dynamic interactions (PHILLIPE 2016). The process is different from the traditional evidence-based urban design process, which emphasises substantial data support and explicit urban development logic, and can cover many more urban parameters than traditional methods. On the other hand, the parameterised design of human-computer interaction, adjustable parameters and visualised features of the results satisfies the users' abilities to judge and obtain sensible potential solutions in a short time (KARLE & KELLY 2011).

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However, simply throwing all the urban factors and data into models to computerise the design process would fall into the data mining trap. In essence, the model would only focus on finding mathematical correlations between urban factors, rather than looking for logical interactions between the factors. Such results do not prove nor explain the essence of the interactions among urban elements, and would typically risk producing misleading or non-sensible design results. For example, SCHUMACHER'S (2009) parametric urbanism and Neil LEACH'S (2001) swarm urbanism pursue the 'automation' of the urban planning and design process that transforms urban space dynamically. However, such parameterisation often has the disadvantage of simplifying complex urban problems into simple technical problems. The majority of the current practices are, for example, 'the shortest path network structure' (FREI 1996) and 'the maximum building density ratio'. They are mostly shallow explorations at the spatial topological level.

Therefore, it is vital to have a reliable computational algorithm that translates the inherent evolutionary logic of urban space into the parametric design language. It is also the key basis for the application of parametric design in urban planning. This research develops research-oriented design using the topic of the Chefoo Bay regeneration project and explores the innovative application of parametric urbanism (SCHUMACHER 2009) design methods in urban renewal processes. The aim is to develop an algorithmic toolkit that would combine the evolutionary logic of urban space and parametric urban factor design process with human-machine interactions to maximise the practicality of the model-produced urban design result.

2 Research Background

At the city scale, the current theoretical research of parametric design mainly focusses on the geometric calculation of urban spatial topology and the self-organisation of urban elements. In terms of geometric topologies, spatial syntax is a popular theory in which urban space is abstracted into points, lines and surfaces. It is mainly used in the preliminary analysis of planning and design (HILLER 1984). The self-organisation of urban elements can be traced back to the 'rules' and 'adjacent influences' mentioned in Cellular Automata. Cluster urbanism (GOLDSTEIN 2001) and parametric urbanism (SCHUMACHER 2009) are both pursuing the automation of the urban planning and design process, with a view to the transformation of urban space from 'top-down' to self-organisation.

The practice of parametric urban design can be roughly divided into two categories. Firstly, it can be implemented by software, such as City Engine (JEFFRIES 2014) and Xkool (XKOOL 2019), that quickly generates scheme. Users can generate multiple arrangement schemes by entering volume ratio parameters or building types (Figure 1). However, the downside is that the calculation logic inside the software cannot be modified. Secondly, with more modification freedom, the design process can be accomplished through visual programming tools, such as Grasshopper. It not only allows users to combine existing modules to form urban blocks but also allows professionals to form their own design logic via targeted toolkits. For example, both the Landscape Common Elements Toolkit (LANTING 2019) in the area of urban factors, and the DeCodingSpaces Toolbox for Grasshopper (Figure 2) (DECODINGSPACE 2019) in the area of urban design, simplify the complex design rules into modules and allow users to utilise complex algorithmic logic via the platform. Details of how the DeCoding-Spaces toolbox works can be found at https://toolbox.decodingspaces.net/.

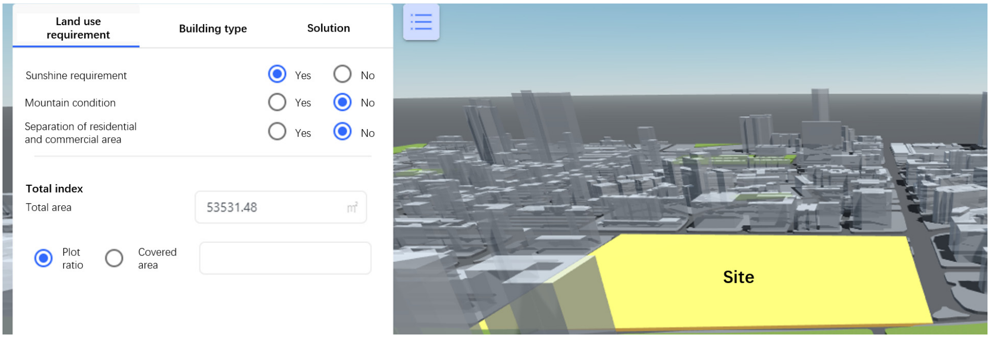

Fig. 1: The user interface of Xkool

Fig. 2: The interface allows users to change the dimensions of the parcels within a defined parameter range using sliders to adjust the width and depth of the parcels (REINHARD 2018)

Due to its powerful parametric design ability and ease of use, Grasshopper has been used as the major parametric design tool in landscape design practice. Grasshopper is a visual programming plug-in for the 3D modelling software Rhinoceros. It shares the characteristics of the programming environment and geometric functions. Such data programming characteristics allow great adjustability of the parameters, calculating functions and output results (DAI 2016). In urban design, Grasshopper's main feature is to shape the target following user-set rules and analyse the result based on user-defined ad hoc requirements. The analysis function mainly depends on external data interfaces, such as elevation and sunshine information. Therefore, this research is carried out based on that platform.

The application of Grasshopper in urban design has ended the design judgements dominated by experience and intuition and replaced them with a clear, rule-based operation. In terms of city-scale analysis, compared to traditional geographic information software (GIS), Grasshopper requires users to understand the meaning of each parameter or change in the plug-in module (PHILIP 2016). When formulating the rules of formation, it needs clear logic to turn the traditional experience into alternative mathematical functions. As shown in Figure 3, a traditional Grasshopper parametric urban design process includes: 1) Initial Information module, including basic parameters comprising unit parameters and external content at the place. For example, x-coordinates and edge length (unit), and primary school location and block geometry (external content). 2) All initial information is passed into the Calculation module, which defines the calculation algorithm to generate the output module with newly calculated parameters. 3) The output module's data are passed to the Urban Function Condition module, which defines all the urban function parameters, such as boundary, number of blocks per type and greenway area. 4) The final layout output is generated.

Fig. 3: Basic Grasshopper components in the parametric urban design process

JACOBS (1961) introduced city complexity theory as a system where all the factors are linked and influence each other simultaneously in subtly interconnected ways. Later, HOLLAND (1998) expanded the idea to emergence theory, where simple urban factors can generate extremely complex emergence phenomena, providing a 'the whole is greater than the sum' effect. Based on the two theories, urban researchers attempted to construct urban prototypes through computer simulation of micro-organisational movement and the emergence of shapes and structures (GOLDSTEIN 2001). However, the disadvantages of the current parametric urban design theory and practice are that complex urban problems are often interpreted by forced bionic concepts or a single spatial topology, or are regarded as simple technical problems. It can be seen from the process in Figure 3 that the formalistic representations and vague explorations ignore the core objectives established by traditional urban planning and design disciplines. Hence, they lack the in-depth study of the main objects and the inherent nature of urban development. Therefore, the inherent logic of urban space evolution elements should be the key basis for the application of parameterised urban design.

3 Translation of Traditional Planning Logic

3.1 Self-organisation of Urban Elements

The geospatial concept of urban space was redefined in the process of the informatisation from space of places to space of flows (MANUEL 1999). The spatial distance of traditional geo-relationships was shortened, the degree of freedom was improved, and the urban spatial structure became dynamic instead of rigid space forms and functional zones (CEN 2013). Space of flow is the spatial logic of the dominant interests and functions of the network society (LIU 2018).

Based on complexity theory, urban field theory and field logic of parametric urbanism were introduced. Urban field theory declares that any city can be considered to be similar to an electric field (ZHANG 2016). The economic flow of a city is like the current in a magnetic field, which forms the urban field. Moreover, each flow parameter influences others as they move or evolve. Field logic of parametric urbanism emphasises the interrelationships among urban social structure adjustments (fabric modulation), street systems, and the system of open spaces (SCHUMACHER 2009). Both theories attempt to parametrically transform urban ontology (LIU 2018) and regularise evolutionary logic. Urban ontology refers to the city's characteristics of its container functions and self-regulating ability (LIU 2018), and the evolutionary logic refers to the internal logic of urban space, such as the economic operating mechanism that helps to form different urban spaces' expression. Such logic is the key when trying to model urban space in mathematical or algorithmic languages in parameter design. However, the logic of urban spatial evolution presents both certainty and uncertainty, which increases the difficulty of such a transformation (SCHUMACHER 2009). The certainty is the predictive rule and even specific mathematical models of space formation, while the uncertainty is from the impact on urban space produced by things such as capital liquidity (DAVID 1985), ecological processes (JAMES 2004) and other unknown events or personal preferences.

3.2 Factor Simplification and Driving Analysis

The main focus of this study is the translation of traditional planning logic, including the simplification and analysis of urban elements, the small-scale manual design and unreasonable local manual adjustments that were not considered due to the nature of their lack of fixed rules. Hence, the study simplifies the deterministic urban elements to urban streets, functional blocks and greenway. The definition of greenway in this study is the ecological connection zone of composite urban functions, which passes through different functional blocks in the form of auxiliary green spaces, and its shape is affected by the attractiveness of functional blocks. The common schemes are mostly simple element overlays, and the greenway has not been considered as a functional composite band in urban space by parametric models. This study attempts to integrate the influence of urban vitality points on the shape of the street network, the influence between functional blocks, and the influence between the street network and greenway functions to synchronise the urban space formation process. In the algorithm structure, the deformation of the street network and the greenway refer to SCHUMACHER'S (2009) field logic's attraction and repulsion model. In addition, this research increases the number of parameters by adding a probabilistic statistical model to simulate the interrelationships between parameters.

The metaball algorithm is a common potential function used in graphical modelling practice. The main variable is the distance 'r' from the space point to the defined key variables. It was developed by NISHITA (1998) and mainly used to build 3D models using its equipotential surface calculation to represent implicit surfaces (GRAVES 1993). By calculating the probabilistic influence between each point, it can dynamically generate different outputs when a certain variable is changed. Since the basic algorithm of this research is based on the principle of field theory where each parameter is intercorrelated. Therefore, the calculation is based on the simple and common metaball algorithm. The prerequisite for the stability of the interior points of the magnetic field is that the forces are balanced, but in reality, such balanced stability is hard to achieve. Therefore, this study pioneered a semi-controlled location probability statistical model, using the Elements Function Correlation Degree, the Grayscale of Location Probability Table and the Function Block Information Table as the parameter configuration files to improve the reliability of the field logic model.

3.3 The Steps of Translation of Traditional Planning Logic

Based on the traditional planning rationality, the translations of the generation rules of the street network, functional block and greenway in Grasshopper are divided into four main modules: Initial Grid, Grid Modification, Urban Functional Condition, and Greenway Distortion (Figure 4). The processes are as follows:

1) The Initial Grid contains the information extracted from the original urban landscape, such as unit parameters and external contents.
2) As an input, the initial grid information is passed to the research defined metaball-like algorithm to calculate the Grid Modification module's information. The metaball algorithm's parameters focus on the urban layout, such as boundaries, interference points, attractive points and area figures.
3) Then the Urban Functional Condition module uses the Grid Modification module's information as input, with its own user-defined conditional functions and alterable parameters to generate the first design draft – Ouput 1 (All parameters in the Urban Function Condition module are alterable).
4) All the new urban functional plots' central points (in Output 1), together with original greenway lines, are put together through the metaball-like algorithm to generate the new Greenway Distortion module. At this stage, the algorithm's parameters are more focussed on the extracted new functional plot's central points and greenway distortion configurations.
5) The new greenway layout output by the Greenway Distortion module is then combined with the original Output 1 to form the final layout of the design

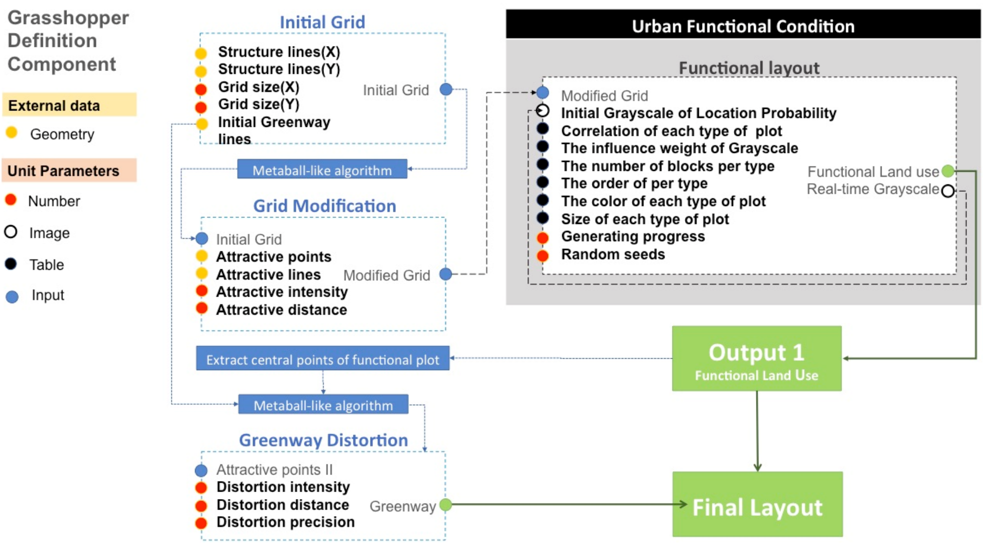

Fig. 4: Grasshopper planning logic

3.3.1 Initial Grid: Initial Homogeneous Street Network

The initial grid of urban space is defined as a square street network structure without distinguishing grades. The shape and direction of the street network must conform to the site. The generation process is based on the outline of the site, and the average block size is determined manually. There are four major sections in Grasshopper for this module: X & Y street direction reference lines, X & Y street grid density, street grid intersections and the total number of grid lines. The calculation shares the same principle as the tween curve in Grasshopper.

3.3.2 Grid Modification and Metaball-like Algorithm

The study reflects the attraction of the urban vitality points or major traffic arteries to the street flow by the deformation of the street network structure in the physical space. The initial grid information is modified by the metaball-like algorithm with parameters of reference points, lines and the influence intensity and range of attraction forces, which are set manually. These parameters can be tailored according to practitioners' potential requirements or ideas.

This part is simulated according to the field logic, using the metaball-like algorithm. The actual algorithm was implemented in the program as a field function that calculates the required outputs. The field function f(r) and a series of control points or lines on the design plane can be set manually, where 'r' is the distance from a point on the plane to the control point or control line, and the intensity in the field can be considered as the superposition of intensities of all control points and control lines. In theory, the field function can be extended to infinity, but considering the efficiency of the operation, distance l can be set to the maximum distance, and the field intensity greater than the maximum distance is set to 0, which saves calculation time. The commonly used field intensity formula of metaball is:

f(r) = a[1 – (r/l)^2]^2 (r<b)

f(r) = 0 (r = b or r < b)

With an alteration for the research purpose, the actual function used is:

f(r)=a[1 – (r/l)] (r<b)

f(r)=0 (r = b or r < b)

- r – distance from a point on the plane to the control point
- a – coefficient to represent the intensity of the alteration
- b – distance for the intensity level to decrease to 0

Considering that the modified grid still needs to maintain the topological relationship of the original lines without new intersections, the value range of 'a' in the field function is set to (0, 1) and the actual deformation of the grid does not exceed its distance from the corresponding control point. After the initial grid was modified by the attraction of dynamic points, a relatively defined spatial structure was formed for the street network. The central points of each grid were considered as a representative of every block.

3.3.3 Urban Functional Condition

Urban functional condition is the core of the parametric model generation process, and its mandatory parameters include nine parts as shown in Figure 4, among which are three major influential configurations: 1) 'Initial Grayscale of Location Probability' sets the location probability so that each type of function may appear according to traditional planning practice; 2) 'The influence weight of Grayscale' sets the probabilities of a given function's impact on other elements or functions within a certain geographical distance; 3) 'The number of blocks per type' and 'Size of each type of plot' set the area and number of the urban function blocks required for each function according to the landscape plan. The output will be a land-use distribution map (Figure5). There are mainly three calculation steps:

6) Statistics of location probability: The research transforms the design of function blocks on the site into a generation mode according to location probability. Each grid on the site has the probability of generating each function, and the functional areas that are generated first will affect the probability of other functions in the surrounding grid. The influence is the correlation degree of each function, and the influence of such probability is mathematically recorded to facilitate the algorithmic model. Regarding the initial probability of a function appearing on the site, a two-dimensional grayscale can be used to describe the probability of the functional area appearing at a specific location; the higher the probability, the darker grey it will appear. In such a way, the abstract information is transformed into intuitive probability distribution mapping for designers to consult. All grayscale values are stored as float numbers between (0 and 1). Each time a specific function block is generated, the pixel grey in the function's grayscale of location probability will be summed together with an externally imported random sequence to determine the location of each functional block that is generated.
7) Generated in sequence: A specific functional area is sequentially generated by a given generation sequence. In order to ensure the reproducibility of the results, each generation uses a random number sequence from a given random seed. Throughout the process, users can check any position in the generated sequence and its real-time grayscale of location probability for each function at that time. After each occurrence, the position is determined based on the probability, and the given single functional group radius determines the range of each group.
8) Generate a specific type of scheme by adjusting the influence weight of grayscale and correlation degree: Through parameter modification, the planning results can be completely random based on the initial grayscale of location probability, or they may show obvious results of manual intervention. In the statistical superimposing step, by weighting both the grayscale probability and the correlation degree, a functional layout dominated by one probability type can be produced.

3.3.4 Greenway Distortion

The principle of greenway distortion also uses the metaball-like algorithm. At this time, the new attraction points from Ouput 1 are the central point of each block in the last module.

4 Case Study

This research uses the Chefoo Port Urban Regeneration Project as a case study to apply the developed algorithmic urban design model. Chefoo Port, with a total area of 730 hectares, is located in northeast China. The coastline is U-shaped and 21.14 kilometres long. The port is currently in the transformation period from industry-oriented to life-oriented. After the removal of old industrial activities, it has obvious 'regional vacuum' characteristics (BIRD 1971). The blank texture of the port brownfield and the surrounding city plan became incompatible.

Therefore, local authorities proposed a comprehensive demolition and reconstruction of the port area. In addition to the need for ecological awareness in urban renewal, the mode of distribution of new functional spaces should achieve optimal allocation of resources, combining the current situation of the local area with the three typical strategies for the port revitalisation: walkability, functional replacement and integrity with nature. Based on this background, this study tries to apply the developed parametric urban design Grasshopper toolkit to address the above dilemma and aims to ensure road network, functional blocks and greenways can be generated to form a more reasonable urban structure under different conditions.

4.1 Analysis of Main Parameters

According to the plan of Chefoo Port's Urban Renewal project, its vision is to build a liveable city with economic vitality, and it is divided into three categories: 1) Living base: living and ecological space; 2) Road space; 3) Economic and social activities space.

The living base space accounts for 50 % of the total land use according to the 2020 master plan (Zhejiang Urban and Rural Planning Design Institute 2017); therefore, the size of the initial grid should be based on an appropriate size for the residential plot. Based on the types of land use in the current regulatory plan, combined with the analysis of land-use types, this study proposes 12 types of economic and social activities space and two types of living base space and their ratios; all of the economic and social activity spaces are generated with the help of algorithmic models. In addition to the number of areas for each function, the function correlation degree is set according to the theory of industrial agglomeration to control the surrounding areas of different functions, and the initial grayscale of location probability is set according to the traditional planning rationality. The residential land provides vitality for the economic function space, and the green maintenance base is ecologically sustainable. The greenway is separated from the traditional green infrastructure. It combines the industrial economic space and the historical and cultural context so that the greenway can carry stronger urban functions and play an important catalytic role for function blocks. Chefoo Port's ecology displays a north-south fault, and the coastline is severely artificial. In order to repair the north-south ecological chain and introduce ecological resources from the hinterland to the seashore, six greenway reference lines are planned for the north-south main road, the coastline; the east-west main roads of each jetty are twisted after being attracted by the adjacent function blocks, connecting the economic spaces in series.

4.2 Generation of the Specific Scheme

Throughout the process of parameterised urban space regeneration, all the correlated urban factors together affect the probability that each type of land use may appear in each block, and the adjustment of the weighting parameters for the grayscale of location probability and function correlation degree affects the final layout plan's bias toward location probability. In this case, two reasonable types of schemes were selected by adjusting the generation sequence and influence weights. The specific operations are as follows: 1) Industry cluster-oriented scheme: Taking the activation of commercial activities as an example, in the generation sequence, the user can adjust the entertainment function or business function to be first, increase the value of the correlation between entertainment and business functions, reduce the weight of the grayscale of location probability and increase the influence weight of function correlation degree. Finally, the multiple solutions produced by random number adjustment will have the same characteristics, with the cluster of business and entertainment;

2) Zoning-oriented scheme: If the planner has a clear idea of the functional zoning of the block, then this can be achieved by increasing the weight of the grayscale of location probability. After determining the keynotes of the different biased schemes above, users can adjust the random value sequence to generate different schemes that fit this bias. Finally, the scheme can be adjusted randomly by adjusting the value of random seeds (Figure 5).

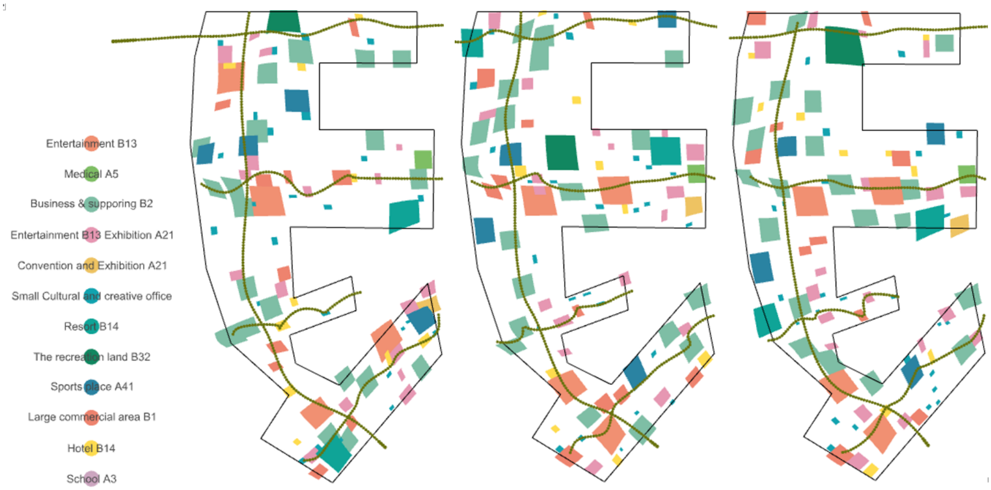

Fig. 5: Functional layout and greenway distortion: from left to right, the influence weight of the grayscale is respectively 0.01, 0.50 and 1.00, showing the bias from industrial aggregation to functional zoning

5 Discussions

The study aimed to develop an algorithmic toolkit that would combine the evolutionary logic of urban space and the parametric urban factor design process with human-machine interactions to maximise the practicality of the model-produced urban design result. However, it has come up with a model that can not only help to improve the human-machine interaction in the process but also found a way to alter and effectively produce a preference-biased result. The case study results proved that the toolkit could be effectively applied to planning and design practices such as large-scale urban renewal, industrial structure adjustment, and ecological connection, and also provides a reasonable means for the general direction adjustment of the initial period of planning.

Among the Urban Functional Condition module parameters, the Initial Grid module information, Calculated Grid Modification module information, initial grayscale of location probability and correlation of each type of plot are basically unchanged in the later stage. The debugging options to obtain different results by adjusting the parameters are mainly: the influence weight of grayscale, the generating progress and the random seed. The parameter adjustment that affects the weight can make the scheme lean to a clearly functional divided or an aggregated design result. Because the level of grid modification does not have an exact standard reference, the significance of tuning parameters is, therefore, more towards the comparison of different spatial structural forms under different conditions. Any change in the metaball-like algorithm would influence the overall shape of grid changes, and the functional layout of the entire plan will also change.

The adjustment of the greenway distortion intensity does not affect the other formation results of the site. It is subject to the functional layout, and the adjustment only changes the greenway near the adjacent function plot. By adjusting different parameters, the user can quickly compare the pros and cons of generated results with different ideas and preferences. If the user did not obtain a satisfactory result in the above parameter adjustment process, the random seed parameter could create a large number of potential solutions for comparison.

The current parametric urban design practice mainly focusses on urban street generation in three aspects: road network, block layout and building layout, as well as street network analysis, spatial visibility analysis and hydrogeographic analysis based on big data. These practices are mainly aimed at the formation and analysis of a single aspect. They are carried out with simpler geometric rules and mathematical formulas and rely heavily on existing data and automatic mathematical model function calculations. The focus of this study is to systematically reflect on the internal laws of the urban system in the formation process and results. The algorithm emphasises a semi-controlled process that enhances the humanmodel interaction and retains traditional planning wisdom in the parametric urban design process.

The model's main weaknesses are: 1) In terms of complex urban systems: as a preliminary study, the model cannot account for all urban factors, but only counted the researchers' identified factors as a starting point. It is likely that certain potential influencing factors were neglected in the process of model and algorithm development; 2) From an algorithm aspect: the research algorithm structure might not be the most effective one, a more dynamic algorithm could be evolved based on the current results.

Therefore, as a preliminary study, the model results should be employed carefully in real projects. However, it has been proven to provide efficient and diverse solutions to practitioners as guidance and scenario analysis. The study has opened up very interesting and diverse future work directions: 1) Improve the algorithm: explore more urban factor formation mechanisms to develop the toolkits to improve the integrity of urban system modelling, and make the computation process closer to the urban evolution process; 2) Introduce more dimensions to the key computation model development: the current model mainly focusses on the horizontal dimension of the urban structure. Hence, more vertical dimension factors could be introduced, such as building density ratio and skyline standards. This would expand the parametric modelling of the urban structure to a more comprehensive level; 3) Dynamic tracking feature: try more mathematical and physical models to improve the algorithm structure, so that the algorithm will have the ability to dynamically update the solutions once a change in urban factors is identified. 4) Artificial adjustment: explore the extent to which the city needs artificial creation to make it more vivid for living, leaving room for such alterations in the algorithmic urban design process.

6 Conclusion

The research developed toolkit and process integrates traditional planning logic into parametric design systematically, which is different from the previous parametric urban design practice that was dominated by formalism and abstract concepts. The toolkit is suitable for initial planning of large infrastructure land renewals. With the existing urban space information, the user can use the toolkit to obtain different urban design planning results by tailoring different local urban space parameters and comparing the implications of different potential designs.

With the development of science and technology, the use of algorithmic design technology will continue to improve in urban planning and design from both research and practical perspectives. With the constant evolution of urban space mechanisms, it is essential to keep studying, tracking and identifying the key factors of urban systems and thereby improving the computational algorithms that mimic urban transformation in a spiral reciprocation. In the process of model enhancement, it will not only help us to understand the dynamics of urban factors better but also improve our approaches and probabilities for a new and more dynamic urban design process, which will maximise the quality of urban lives.

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