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# Dense Urban Typologies and the Game of Life Evolving Cellular Automata

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**Abstract.** The ongoing rate of urbanization in China is the motivator behind this paper. As a response to the observed monotonous housing developments in Suzhou Industrial Park (SIP) and elsewhere our method exploits Cellular Automata (CA) combined with fitness evaluation algorithms to explore speculatively the potential of existing developments and respective building regulations for increased density and diversity through an automated design algorithm. The well-known Game of Life CA is extended from its original 2-dimensional functionality into the realm of three dimensions and enriched with the opportunity of resizing the involved cells according to their function. Moreover our method integrates an earlier technique of constructivists namely the “social condenser” as a means of diversifying functional distribution within the Cellular Automata as well as solar radiation as requested by the existing building regulation.

The method achieves a densification of the development from 31% to 39% ratio of footprint to occupied volume whilst obeying the solar radiation rule and offering a more diverse functional occupation.

This proof of concept demonstrates a solid approach to the automated design of housing developments at an urban scale with a ,yet limited, evaluation procedure including solar radiation which can be extended to other performance criteria in future work.

**Keywords:** Evolutionary Design, Generative Urbanism, Integrated Strategy

## 1 Introduction

Accelerating urban development has been – and still is [1]- one of the key strategic plans of China in increasing its economic development. This strategy has worked well as an economic development tool but has also created a real estate market full of vertical towers, or horizontal sprawl, but always monotonously repeated- building arrangements for housing [Fig. 1].



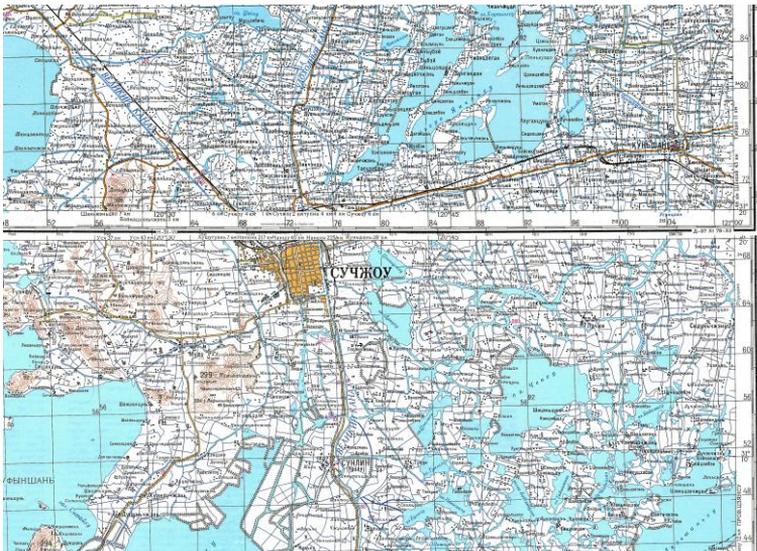
**Fig. 1.** Repeated tower and horizontal sprawl at the case study HuDieWan and wider environs.

The towers, where the present paper focuses on, are essentially two dimensional in the sense that typical floor plans are simply extruded almost arbitrarily regardless of any context. To conform to existing building regulation the towers are just moved apart as much as needed to let enough sunlight reach the individual apartment while the speed of design forces the architects to rely on previously tested solutions. As such the efficiency of the land usage is very low and at the same time the architects lose the opportunity to explore the potential of the third dimension in the architecture produced. The case study under examination is located in the city of Suzhou in the Yangtze River delta and its new Industrial Park (SIP), constructed 25 years ago in a collaboration between the government of Singapore and the government of the People's Republic of China [2].

In Suzhou Industrial Park [13], the acceleration of construction of housing for urban population has eroded the agricultural land use in the area of Suzhou to about 1.5% of the total while the need for urban growth has not subsided [3]. Apparently, there is a discrepancy between the still increasing demand for housing supply and the very limited availability of land for new developments. A solution to this discrepancy can be the densification of existing housing developments. A higher density achieved through densification above ground – in the third dimension – would sustain the existing greenery within the developments whilst providing more living space. A densification whilst obeying existing building regulations would result in a more efficient land use while sustaining an equally high standard of living. We examined one

example of a monotonous tower housing development, analysing the determining building parameters including building regulations and their impact on the actual planning and architectonic decisions made by the local planning office which led to the repeated tower pattern. The project then employed architectural computational techniques to investigate how to increase housing density. We transformed a standard cellular automata mechanism into an integrated generative and evaluative parametric system along evolutionary principles. In this paper we examine the possibility for optimisation of the building density, expressed as a ratio between maximised volume and to minimised footprint, along with the optimisation of the sun exposure of the surfaces of the building, expressed as solar incidence number, as per regulations.

A novel introduction into the proposed algorithm, is the parametric representation of the social condenser, a constructivist concept of overlapping and intersection of programs within a building, employed by in the 20th century by architects such as Rem Koolhaas & OMA, Ivan Leonidov, Mosei Ginzburg [4, 5]. We were able to produce results with increased density and similar parametric profile of the current residencies, thus in theory similar quality of life. Apart from the integrative nature another innovative part of the system is the inclusion of programmatic variety in three dimensions, thus breaking the functional monotony we encounter in Chinese megacities and walled communities [6]. The project is expected to provide an understanding of how housing density contributes to the sustainable development of the built environment of new towns like Suzhou Industrial Park, by stopping the transformation of land from agricultural and rural to urban [Fig. 2, 3].



**Fig. 2.** Map of Suzhou area circa 1970: Soviet military map. Clearly visible is the difference between urban and agricultural land



**Fig. 3.** Suzhou Industrial Park with red hatch indicating the location of the case study HuDieWan or Butterfly Bay compound.

## **2 Background**

### **2.1 Cellular Automata**

Cellular Automata are not new in the areas of designing dense towers or dense housing environments. Herr [7] has explored the mechanism of Cellular Automata as a tool for architectural designing and adapting an existing strategy of tower design with increased density. Subsequently Herr [8] has also explored the adaptation and exploitation of Cellular Automata in architectural design computation processes, ranging from the deterministic for generating a plan to the playful, conversational-with-the-designer use of Cellular Automata. Others such as Khalili & Stuffs [9], equally recently have used Cellular Automata as an engine for architectural design in dense housing conditions in the Netherlands, focusing on accessibility and light exposure, however at a significantly smaller scale and density than the present China study. In other earlier cases Kwaczyk [10] has looked into adapting Conway's game of life to develop three dimensional rules for architectural designs that handle functional requirements.

The rule based creation of morphologies by the Cellular Automata is not able to discriminate different individual according to their potential performance. Cellular Automata apply generative rules within a clearly defined framework but they are not able to evaluate whether any created individual performs differently towards certain

performance criteria. Within a Cellular Automaton all solutions are equally valid since they are all compliant with the applied rules. However, the introduction of an evaluation algorithm connected with a search procedure allows to discriminate solutions based on performance criteria. The present paper drives cellular automata and their subsequent evolutionary evaluation using the basic parameters of the building regulation in the Suzhou Industrial Park. At the same time the novelty of our method extends to the use of the ‘social condenser’ as an urban center and functional diversification tool of the monotonous housing towers in SIP, and by extension China.

## 2.2 Simulated Annealing

The “Simulated annealing” algorithm as inbuilt into Grasshopper is a computational search algorithm which refers to a method in metallurgy where through the increase of temperature the bonds between atoms in a metal sample are weakened enabling them to take positions of lower energy state. As the sample cools down subsequently contained atoms form larger areas of stable metal grid than before. Analogous to this method, simulated annealing in computation as a search algorithm uses temperature as a controller for the search algorithm. The algorithm typically starts with an initial temperature  $T_i$ . The temperature  $T_i$  allows the algorithm to pick a random point of the solution space in a certain distance  $d$ . The distance  $d$  is proportionally related to the temperature  $T$ . Thus, through reducing the temperature  $T$ , the distance  $d$  also decreases and limits the search radius of the algorithm. By picking a random point  $q$  on the solution landscape and subsequently picking another point on the solution landscape within a certain distance  $d$ , where  $d$  is depended on the current Temperature  $T$ , the search algorithm compares the quality value  $q_i$  with  $q_{i+1}$ . If  $q_{i+1} > q_i$  the algorithm jumps to the point  $q_{i+1}$  and resumes the previous steps. If  $q_{i+1} < q_i$  the algorithm typically stays at the position  $q_i$  and resumes with a different random pick within the set distance  $d$ . Yet to increase the variance and decrease the danger of early convergence to a local maximum of the solution landscape of the search function you could allow the search area to move even if  $q_{i+1} \ll q_i$ . Reducing the temperature  $T$  step by step the related search radius  $d$  which determines the pick of the next iteration of quality comparison will be reduced and the search will narrow down towards the locally best result of the search. Typically the search comes to an end when a certain predefined temperature  $T$  or a predetermined quality value  $q_t$  is achieved.

The “Simulated Annealing” is a robust search algorithm which unfortunately doesn’t guarantee to lead to the global maximum of the solution landscape, but it is efficient and successful in discontinuous and fractal solution spaces since the algorithm can overcome local maxima peaks and minima valleys in the landscape.

In the presented case, the fitness of the respective solutions is established through the evaluation of solar radiation and density as the ratio of volume to footprint using different simulation and geometric evaluation tools to establish a single value of quality  $q$  which can be fed into the “Simulated Annealing” algorithm to enable an efficient search for sufficiently good solutions.

The morphologic representation of the solution is the result of the applied Cellular Automaton which itself includes elements of randomness inbuilt into the growth

algorithm but based on predefined starting conditions. The starting conditions which are to some extent the predetermining factors for the morphology of the solution are mapped towards the quality values of the fitness function. Depending on the results of the fitness function the initial conditions of the growth algorithm are adapted and the next (i+1) iteration of the morphological representation is grown and will undergo a fitness examination.

### **2.3 Evolutionary Methods**

Evolutionary development is based on the selection of individuals from a larger group discriminated by their compliance to defined characteristics. Through the selection according to the characteristics these characteristics develop predominantly within the selected generations. Individuals can represent the entities or units in the before described groups or generations. The creation of individuals, in this case representing an instance of a potential tower, by the Cellular Automaton is based on few parameters such as the grid size, the height and number of floors and specifications of the “Game of Life” itself. These parameters contained in the genome of the created individual are mapped against a quality value which represents the individual’s performance per the set solar radiation and density requirement. The before described search algorithm selects the best 50% of the created individuals and creates a new population through a randomized cross over recombination of selected individuals together with the selected individuals itself. This evolutionary process creates a dynamic solution landscape constantly improving driven by the discrimination within the search algorithm. The discriminating search algorithm simulating a metallurgic annealing process, will diminish the search radii as the ‘temperature’ decreases focusing on different areas of search within the solution landscape. Thus, the convergence of the process can be controlled through the speed of ‘temperature’ decrease and the number of selected individuals for reproduction.

The combination of the search algorithm and the evolutionary process are implemented in Rhino Grasshopper™ and respective plugins thereof. The current implementation allows for population sizes of around 100 individuals to keep the system with an acceptable and reasonable response time using standard personal computation power, namely a 16 Gb Ram, i7 2200 Ghz laptop.

## **3 Research Methodology**

### **3.1 Qualitative Markers**

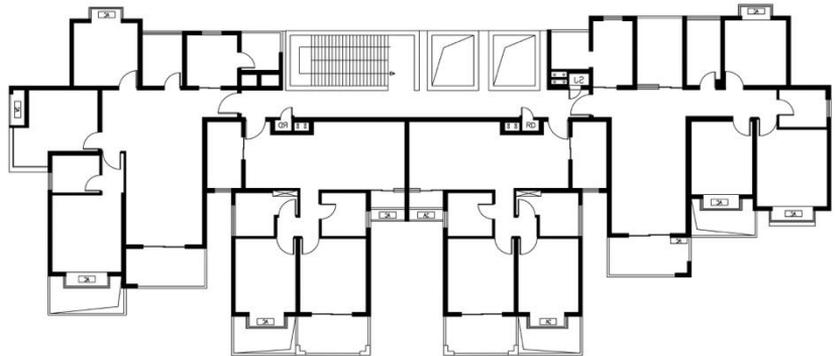
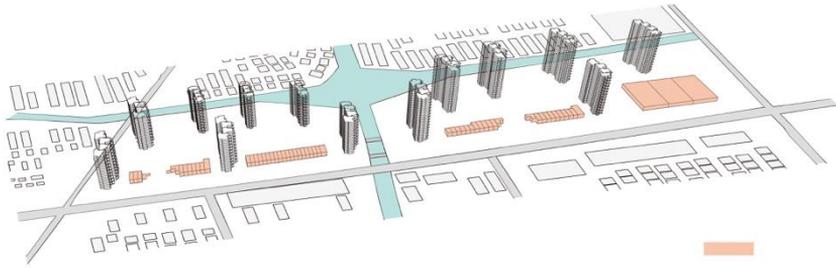
Using interviews with real estate agents of the region and the specific neighbourhood HuDieWan is based in, we attempted to establish the expected quality benchmarks that HuDieWan tried to achieve. These were: a production of a majority of 80% of one-child family units, that could also serve as affordable housing to be given to the community by the government, along with a series of apartments that serve as

investment opportunities for middle class families in the area. We also attempted to evaluate the case studies' morphologies as qualitative factors including spatial configuration, spatial integration and functionality. The interviews with real estate agents, uncovered the modular and cellular nature of most of the housing complexes in SIP, revealing for example that most plans were similar, and only through uniting units by knocking down walls were they able to get any kind of diversity in plan. In this we wanted to make certain that the cellular and modular nature of Butterfly Bay/HuDieWan was a feature which is reinforced and enabled in other repeated tower patterns. Another notable feature of the design of HuDieWan was the fact that it was designed by a remote Design Institute, not a local one in Suzhou- It was designed by a design Institute in Shenzhen, perhaps making the case that similar strategies are employed all over China. However the low numbers of case studies in China that we had in our hands made it impossible for us to positively verify this as with the real estate agents. Other interesting facts, established by the interviews, was that some of the apartments were bought as investment by parents for their children, or that to get a custom apartment was only possible by combining and retrofitting 2-3 other apartments that had a typical configuration.

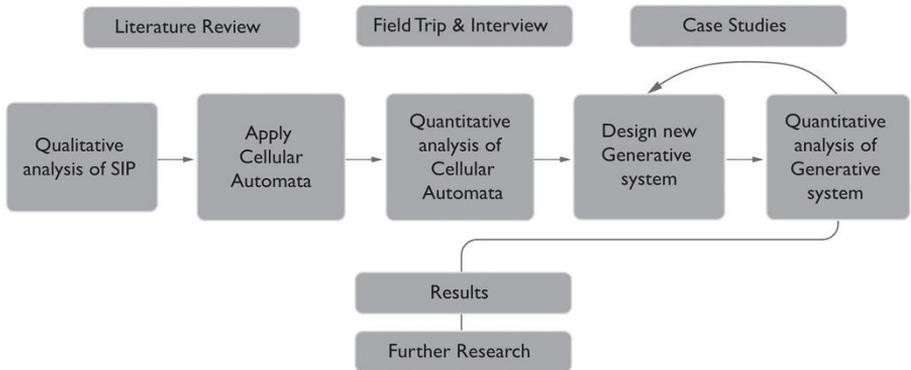
### **3.2 Case Study Butterfly Bay / HuDieWan Compound in Suzhou Industrial Park.**

The project began with an examination of the volumes that repeated housing towers create in the Chinese urban landscape. By looking at the case study of Butterfly Bay though we discovered that the repetition of 10 cellular types of apartments defined the limited diversity of the towers. These cellular types, drove us to use cellular automata as the main engine in our generative system. Unclear termination rules in the cellular automata paradigm, i.e automata can run indefinitely, drove us to use evolutionary methods as optimization techniques.

The project examined one housing case study in Suzhou Industrial Park [Fig. 1, 3] and employed computational design methods to speculate about possible outcomes on increased density in SIP. The methods employed in the research were qualitative and quantitative in nature. [Fig. 5]



**Fig. 4.** Digital model of the residential area called Butterfly Bay / HuDieWan and typical floor plan



**Fig. 5.** Research Methods

### 3.3 Quantitative Research Objectives

The quantitative methods were focused in the speculative design experiment using computational design methods. Initial benchmarks were established by the Suzhou

Industrial Park case study Butterfly Bay to other known case studies in Asia, known for their effectiveness and high density.

**Setting Parameters and criteria for the cellular automaton.**

The basic parameter to be included into the algorithm are taken from the official building code for SIP [12]. ‘Technical specification for planning and design of residential area in Suzhou Industrial Park’ (In Chinese: 苏州工业园区住宅区规划设计技术规定). The regulation refers to the exposure of a residential unit to sunlight and the distance of the building to the site boundary. Table 1 indicates how the parameters are represented in the geometrical model and how their suitability or conformity is evaluated. Additionally to the building regulations the table [Table 1] includes parameter to establish the evaluation of the quantity of public space and the achieved density [14] of the respective proposal.

**Table 1.** Parameters and evaluation criteria

Parameters	Sub-Parameters	Geometry and definition in Rhino-Grasshopper	Evaluation
<b>Building Regulation</b>			
Site	Shape of Site	XY Polyline	minimum size
Lighting	hours of exposure per day	rectangular 2d area on side of wall & Line of sight from Sill to Sun	over 3 hours per day
Building Height	N/A	Z vector	>1.3 X width of S Facade.
Floor Height	N/A	Z vector	2.8 -3.5 m
Distance from site boundary	N/A	XY line Polyline	>15m
<b>Cellular Automata</b>			
Neighbourhood Rule	Game of Life	Cellular Automata: Born in a, Survive in u-v	Number of housing blocks
	Public Space	Void Space	ratio of housing to public space
Social Condenser	Shape of Condenser	Box XYZ Size; Centre Point; Type	Qualitative
	Condenser attraction	Sphere Service radius;	Distance of Cell from condenser

Other criteria such as fire truck and ambulance access, sizes and numbers of parking, being established in the building code are not considered at the current state.

### **3.4 Implementation: Rhino- Grasshopper**

The computational modelling environment was Rhinoceros with Grasshopper handling the parametric and evolutionary roles. We used the Rabbit cellular automata plugin, with our own extension in the three dimensions. The evolutionary algorithms used were shape annealing and the Galapagos evolutionary solver. For the lighting simulation we used the Ladybug grasshopper plugin, connected again with the Rabbit and Galapagos solvers. To measure lighting we did not just restrict ourselves in the initial measurement at the sill of the opening, but established a grid of points on the surface of each cell that would measure incidence of light. This proved cumbersome and computationally expensive making the resulting lighting model difficult to handle and unresponsive.

The actual algorithm is a Cellular Automaton based on Conway's Game of Life extending it into the third dimension [Fig. 4]. In Conway's original algorithm a two-dimensional grid of cells is initially populated randomly by objects. Subsequently rules of density determine whether a cell will be generated, kept alive or be removed depending on the number of occupied or unoccupied neighbouring grid cells.

In the proposed novel extension of this cellular automaton each cell in the 3dimensional grid communicates with the neighbouring 25 cells determining whether or not a cell lives or dies. This also includes the consideration of cells that are not sharing a surface but share a corner. For evaluating the neighbourhood we use the 3d concept of the Moore Neighbourhood. We parameterise the rules in this form: if a cell has  $K$  neighbours then a new cell is generated, with the usual minimum  $K=2$ . If the cell has  $N-M$  neighbours, then the cell dies because of loneliness or from being overcrowded.  $N$  represents the full Neighbourhood of 25 voids that the individual cell can have as neighbours while  $M$  represents the number of voids actually occupied by Cells. The subtraction  $N-M$  represents the voids still left after we have counted all occupied cells [Fig. 6].

The second amendment to Conway's cellular automaton is the introduction of a variety of architectural function to each of the cells. This allows to diversify the functional and volumetric arrangement of the building spatially in three dimensions [11]. To explain our strategy in this, we have to first explain the functional arrangement of 'Neighbourhood Centres' around SIP and the subsequent strategy that we employ in extending their framework in three dimensions. During the design of the Suzhou Industrial Park, Singapore authorities transferred knowledge and urban design guidelines to the Chinese authorities, either directly or via training of architects and urban planners. One result of this knowledge transfer is the establishment of Neighbourhood Centres, places in the urban grid that are engineered to centralise various disparate functions in one location that cannot be found anywhere else at a distance of 400meters. As a consequence the monotony of the housing estates is intensified as functional diversity is established only in the Neighbourhood Centres. These centres do not always resemble the literal centre of the neighbourhood in terms of urban configuration but are essentially a block which combines service functions.

The closest articulation of the concept is the social condenser, a space that combines disparate functions, without any need for coherence or explanation of relevance. A function is needed for an area so therefore it is added or pre-programmed by the planners. In certain cases like neighbourhood centres in the Higher Education Town, the centres are located jointly with other supra-local functions, like a kindergarten, a school, a police station, a hospital, and a community centre [Fig. 7].

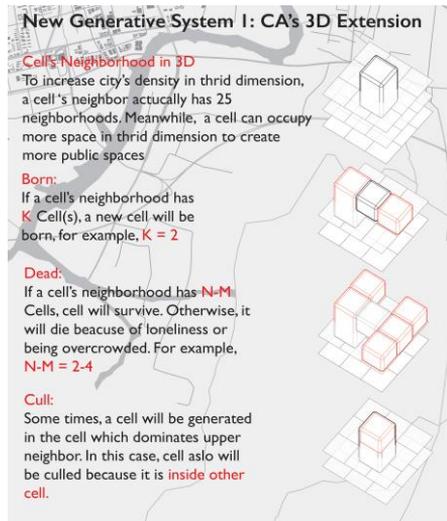


Fig. 6. Extension of CA game of life in three dimensions.

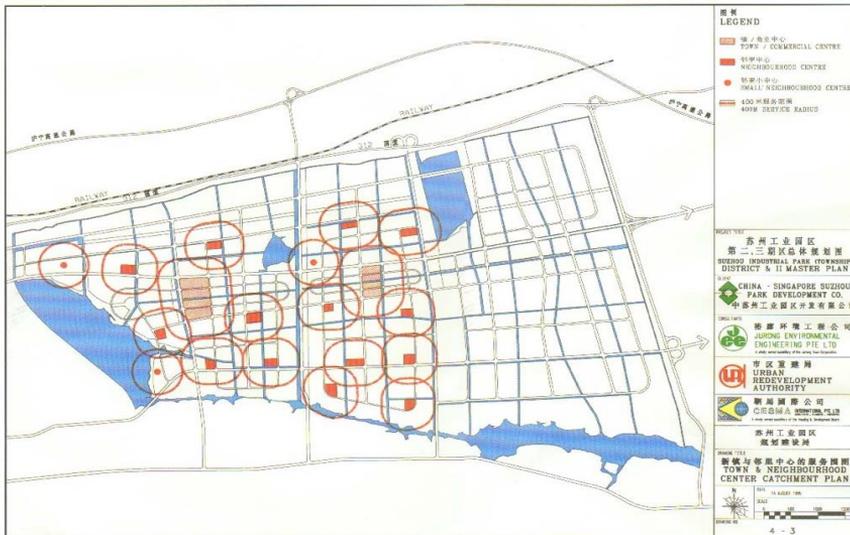
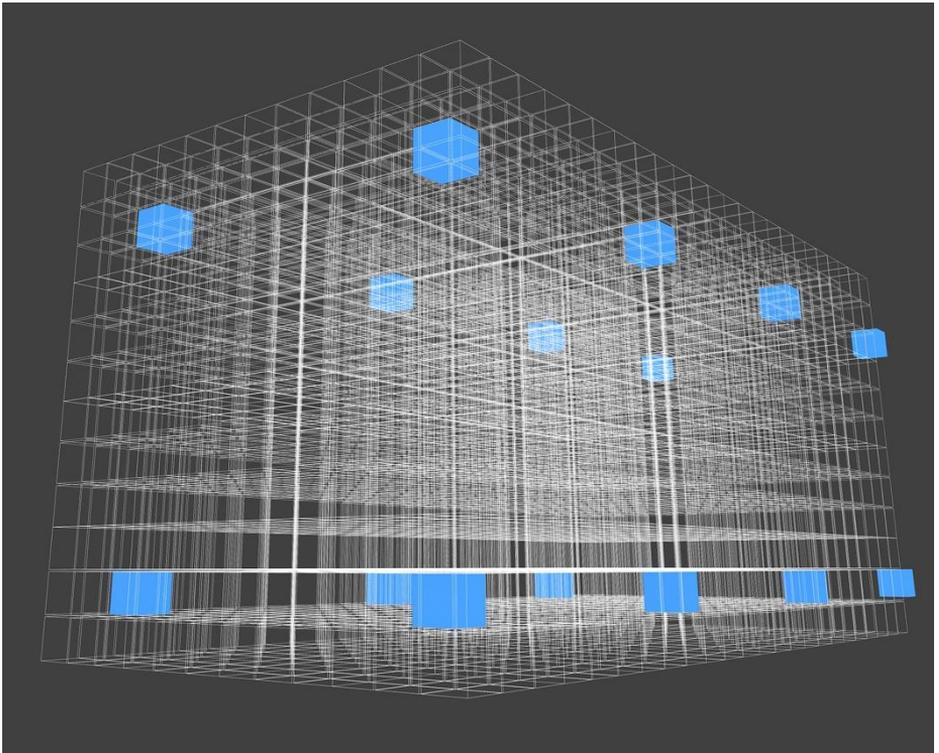


Fig. 7. Neighbourhood centres as social condensers dispersed on the SIP grid-east (source: SIP Masterplan 1994)

The main articulation of our algorithm in terms of the social condenser is the extension of this strategic operational device into three dimensions. Instead of building a generative system only for housing the prescription of the algorithm is to drive the generation through the careful positioning of the social condenser, i.e hyper-local functions, within a three dimensional grid. The grid then can be filled with the housing functions one desires and evaluated according to their proximity to the social condenser. One can imagine an initial placement of the social condensers as if on grid with a standard distance between them at the initial positioning, where the distance starts to vary according to the generative system parameters [Fig. 8].



**Fig. 8.** Social Condensers placed on a three dimensional grid instead of a two dimensional urban one.

The current proof of concept presented in this paper employs a fitness function with a multi-objective optimisation consisting of two parameters: the maximisation of density together with the maximisation of sun exposure of specific cells. Based on the same initialising parameter in the Cellular Automaton, the evolutionary algorithm was set up to maximise floor area and building volume by sustaining sun exposure of every cell at a minimum of three hours daily, since this is a crucial element for obtaining building permission within SIP. Measuring the available building volume in relation to the site footprint we find that the algorithm increased this ratio from 31% at the initial

generation of towers to 39% in the conversed state of the evolutionary algorithm. Sustaining the number of hours of daylight exposure this can be interpreted as an increase in efficiency of site usage by maintaining the same quality of residential units at least in terms of daily sun exposure.

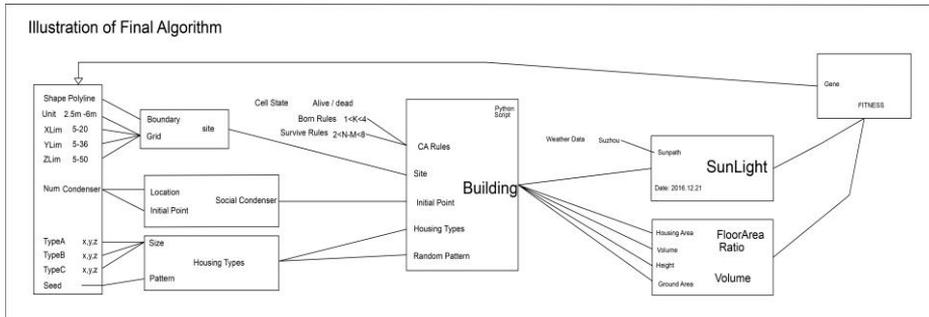
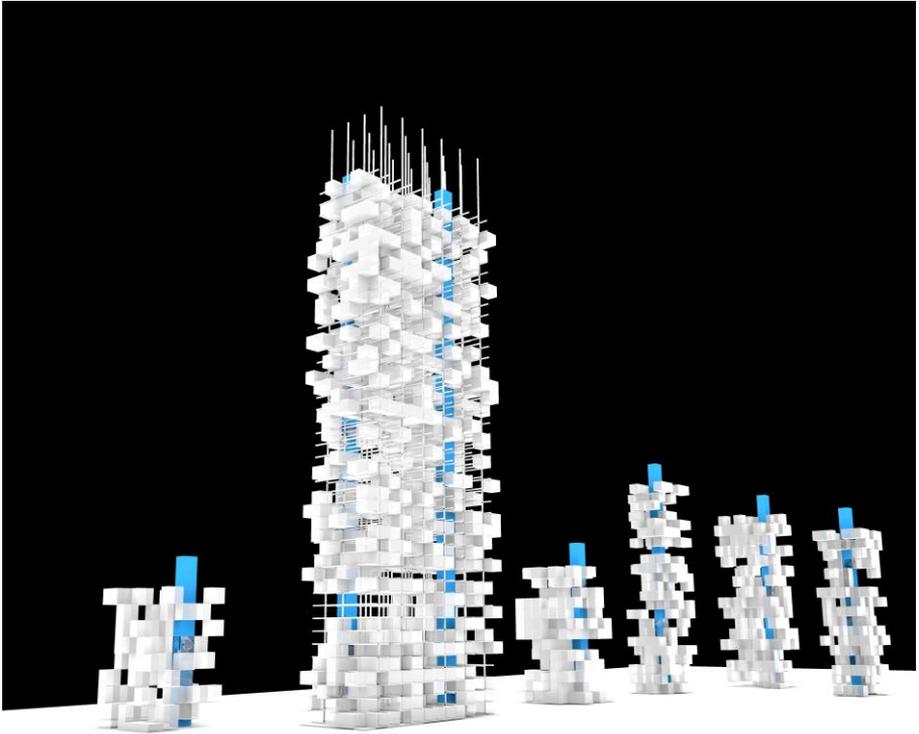


Fig. 9. Diagram of the algorithm including morphology generation and quantitative evaluation.

## 4 Results – Discussion

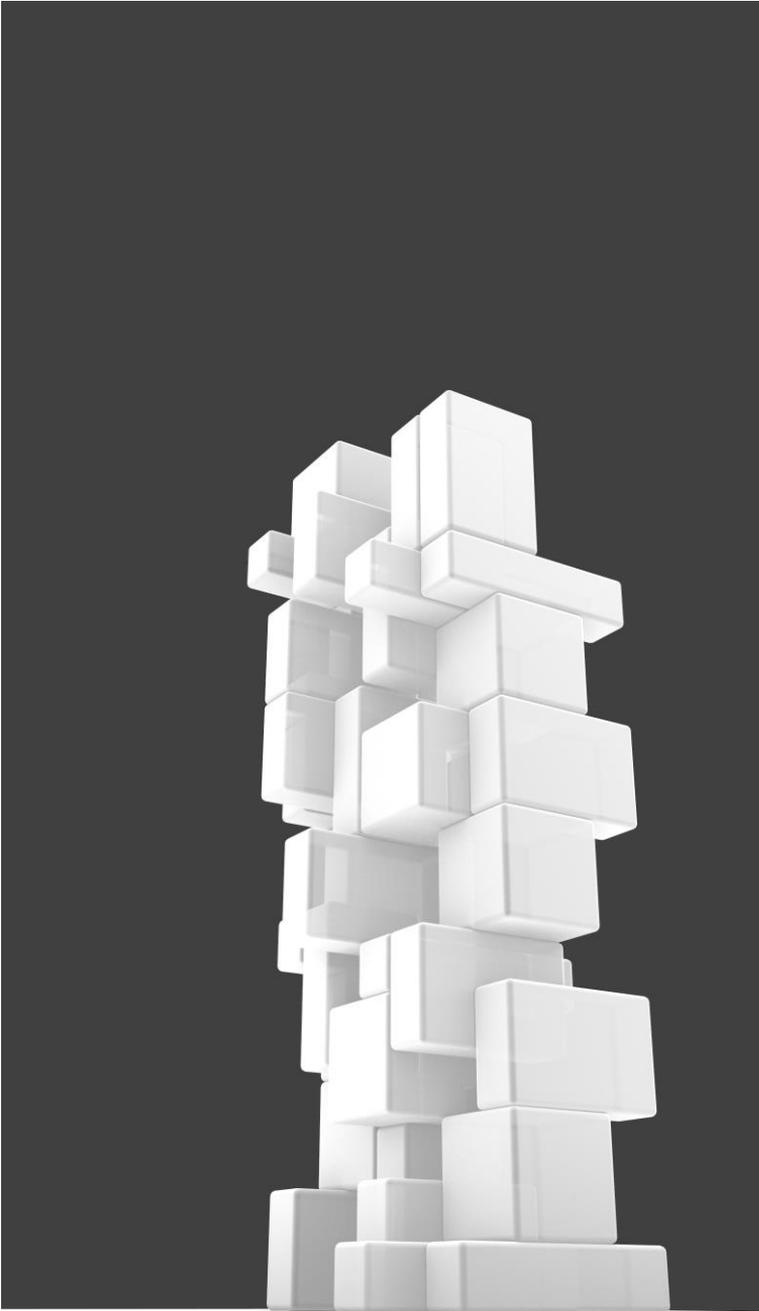
Applying the extended rules from Conwell’s Game of Life together with the performative evolutionary process through evaluation and discrimination the algorithm was able to create solutions which comply with the set building regulations - defined solar radiation for each residential unit - whilst increasing the density which is measured by the ratio of the footprint to usable area. Besides this, whilst complying with the set restrictions and requirements the evolutionary Cellular Automaton created solutions of architectural diversity and increases the efficiency of the respective land use [Fig. 10].



**Fig. 10.** Maximum Height tower in comparison with towers of multi-optimised genomes

For the moment the created cells are of equal dimensions but of different architectural functions which allow the accumulation of different functional cells into specific units such as residential units. The introduction of the “social condensers” the accumulation of different cells can be guided. The “social condenser” cells specified and placed by the designer will attract a certain group of cells respectively.

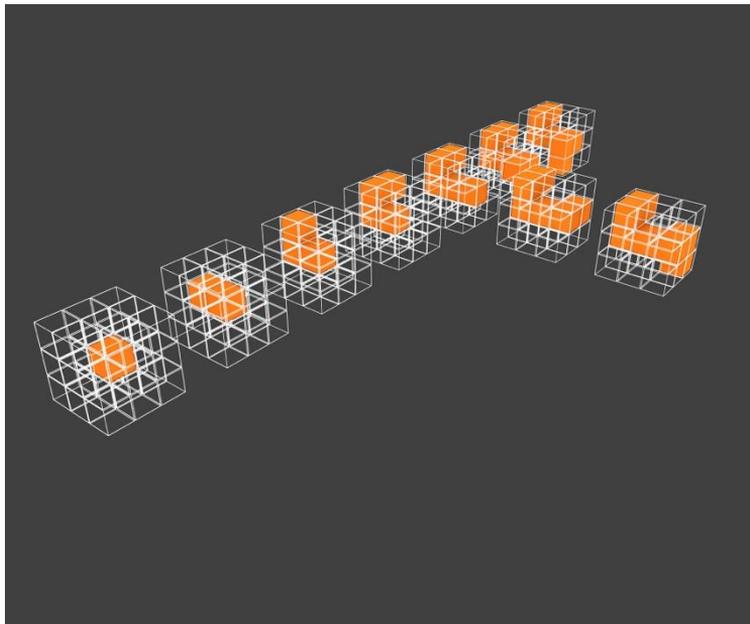
Architectural diversity in the global shape of the tower was achieved by the inclusion of the social condenser into the grid of the cellular automaton. Since the “social condenser” cells act as attractors adjacent cells with similar function around these cells are being melt into larger entities [Fig. 11].



**Fig. 11.** Social Condenser Schematic Result: The tower diversifies in three dimensions even more, while functions coalesce together.

Technically the implementation of the condenser cells was achieved through a python script generating the points in the grid for the social condensers. In future work we consider to incorporate the generation of the condensers in the cellular automata mechanism, requiring multiple types of cells incorporated into the morphogenetic mechanism.

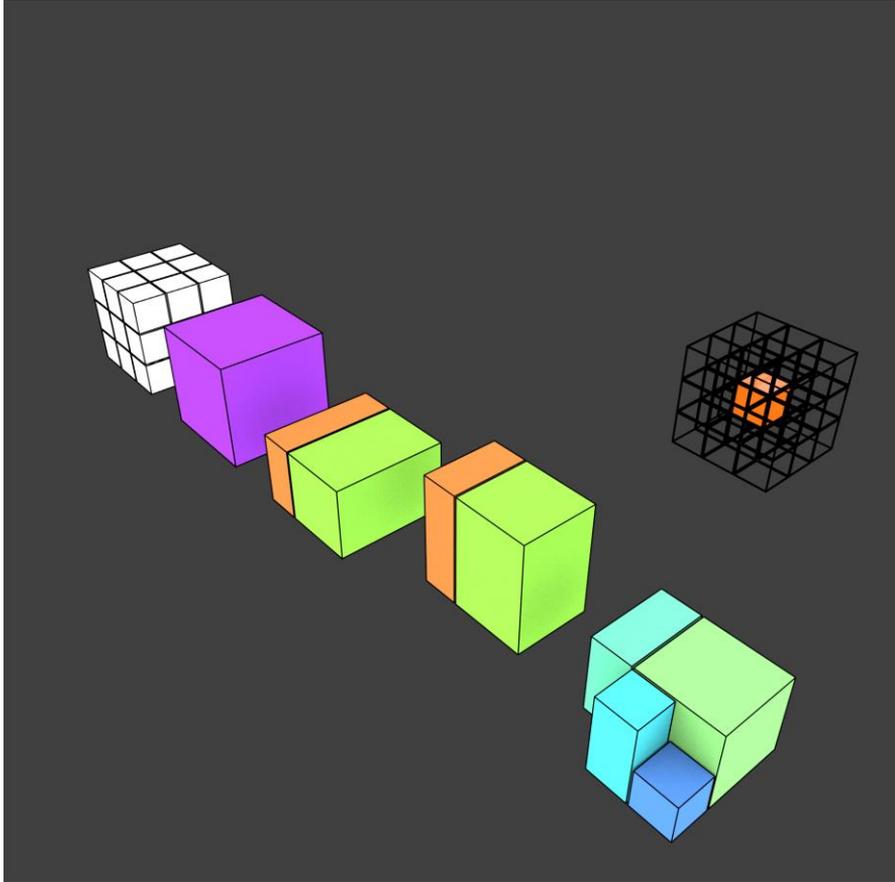
The introduction of types of cells according to functional activity is run in a parallel algorithm to the cellular automaton and transferred manually into the main model, importing them by hand rather than automatically. While this is an obvious weakness in the automation of the mechanism, nonetheless it allows for architectural intervention and authority within the system. It allows for developing rules of design where the cells do not just get deleted or created according to density, but in a more grammatical fashion get moved around to coalesce according to function and structural logic of the architectural design strategy. Thus the designer can create a living-room cell, a bedroom cell, kitchen cell, bathroom cell, circulation cell etc. The complexity of the algorithm grows exponentially as the type of cell needs to be taken into account. The social condenser cells act as centres of attraction around which the algorithm will accumulate cells preferably. For the coalescence of the cells we propose two main strategies. In the first strategy the accumulation of cells depends exclusively on the adjacency of cells to the condenser cells regardless of the similarity of their function [Fig. 11].



**Fig. 12.** Coalescence strategy without considering function but neighbourhood to social condenser cells.

The second strategy considers the similarity of the cell's function and accumulates cells of equal or similar function into larger cells. [Figure 12] By using the second style of aggregation, the algorithm proceeds in developing solution made out of the aggregated,

multi-cell boxes. For now the dispersal of different function happens as a percentage, however we would like to develop it to the stage where the algorithm designs apartments bottom-up from groups of functions.



**Fig.13.** Coalescence of cells around social condensers according to identical or similar functions.

## 5 Conclusions & Further Development

We have demonstrated that it is possible to design a generative and evolutionary parametric system, integrating programmatic function, floor area, and sunlight exposure along with a performative evaluation thereof. We proposed an automated system that is capable of developing large three-dimensional housing blocks, with functional and architectural diversity, increasing the density of the housing whilst retaining the size of a given footprint and the set requirements of sufficient sunlight exposure. The quality of the proposed design uses the available land more efficiently

whilst providing a diverse architecture with at least the same amount of sunlight exposure per day for each unit as the current implementation. We will continue to develop the system with the inclusion of basic structural and circulation evaluation functions, and we hope to expand and test the system using other building regulations, for example the UK's where lack of appropriate housing is a social issue. Further potential of the system lies also in developing a tool that evaluates the building's financial performance, from cost of construction to the price of sale or renting to make a profit in a specific time. The novelty of the method lies in the extension of the cellular automata mechanism with functions and types of cells, along with the three-dimensional dispersal of the social condensers. The introduction of an evaluation algorithm allows for discrimination of less performing individuals and enables an evolutionary development process within the rule based cellular automaton.

Further development is needed to integrate the allocation of the social condenser and the cellular automata into one single integrated algorithm. However, the implementation of an operational strategic architectural device such as the social condenser in three dimensions using computational tools contributes to the understanding of computational tools as a continuation of architectonic strategy; we argue for a strategic integration of performative tools as part of the genuine design process rather than a posteriori attained and measured performance. Thus we envision that a continuation of this system will lead into an integrated tool, combining the parametric generative system and a multi-parametric evaluation, helping architects and planners deliver competitive designs within fast developing environments.

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