

# Generative sub-division morphogenesis with Cellular Automata and Agent-Based Modelling

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**Abstract.** *This paper reports on some recent research carried out to develop computational generative urban design system that can be used as an alternative approach to master planning. The focus of the investigation is an 11 ha site located in the South-East edge of Auckland, New Zealand. The urban (or sub-urban) morphology is modelled as cellular automaton based on Hillier's (1984) x-y syntax in order to resemble the morphology of the existing village. An agent based system based on Reynolds' (1987) flocking algorithm evolves synchronously with the automaton and tests its ecological fitness. The emergent pattern of development therefore results from the mutual co-adaption of the cellular automaton and the agent based model. The outcomes are variety of spatial morphologies that connects well with adjacent existing village and at the same time take into account landscape and ecological peculiarities of the site.*

**Keywords.** *generative urban design; structural coupling; cellular automata; agent based modelling.*

## INTRODUCTION

Even though the shortcomings of the master plan are well known, it is still the main approach to urban design practice. The master plan is used to address both contextual and site issues through a formal layout and its inflexibility fails to respond to the evolving needs and complexities of the contemporary city.

This paper reports on research carried out to develop digital generative design systems in urban design that can be used as an alternative approach to master planning. The objective of this research project is twofold. Firstly, it attempts to model

various morphologies of a new sub-division as the emergent outcome of the dynamic co adaptation of two autonomous parallel computational systems coupled together. The modeling technologies used have been adopted and advanced by the young interdisciplinary field of Artificial Life and are known as Cellular Automata and Agent Based Modeling. Secondly, the project tries to take the digital generative design discourse out of its academic context and tests its applicability in the realm of industry's design briefs. The chosen site is located in peri-urban Auckland, New Zealand. A master plan for new mixed use

and residential sub-division has already received consent from the local authority. The research project takes on board the brief for the sub-division in order to set the constraints and to engender a generative approach on which the design experiments are based. The research project also seeks to discover at what stage of the design the brief will force us to weaken the integrity of the generative process.

The Cellular Automata and Agent Based Models were programmed using Netlogo [1] which is an agent based programming language and modeling environment developed as a parallel computation machine. It provides a powerful experimental tool for exploring and demonstrating the effects of massively parallel populations of interacting agents in biology, physics, geometry, social systems and ecology.

The input data for the models was created using ArcInfo and loaded into Netlogo with the help of Netlogo's GIS extension. The outputs of the models were exported back to ArcInfo and can be transferred to DWG files.

## SITE DESCRIPTION AND DESIGN BRIEF

The site is located within Whitford, on the fringe of Auckland City, New Zealand, approximately 20 kilometres South-East from Auckland's Central Business

District. It occupies an area of nearly 11 hectares, situated in the lower part of the Turanga stream catchment, and is within walking distance of Whitford village (see fig. 1). The site is near the edge of sprawling low density city and agriculturally productive peri-urban areas.

The design brief focuses on innovative residential development balanced with mixed use activities - retail and recreation. The proposed development should complement the existing village (see fig.2), both as spatial organization and as types of activities. The new development should acknowledge the landscape character and should be ecologically neutral. The ecological focus should be on hydrology and the interconnections between water, soil, flora and fauna.

## THEORETICAL UNDERPINNINGS OF THE PROJECT

### Urban Design and A-life

The young interdisciplinary field of "artificial life" (a-life) provides us with a new epistemology, a new way of understanding and exploring patterns and structures in the surrounding world as the emergent properties of iterative parallel actions of very simple autonomous and

Figure 1  
Site and context



Figure 2.  
Whitford village and site boundary



entirely local processes. The complex outcome emerges completely bottom-up, without any global controller, from the multiple interactions between these events.

This viewpoint provides a promising paradigm for architecture and urban design as the “emergent outcome of interconnected feedback loops, which replace top-down geometry and the reductionist tradition, with dynamic relations and emergent outcomes not defined in the underlying model” (Coates, 2010, p. 1). A-life has adopted and advanced an array of computational frameworks to apply this philosophy. Cellular Automata (CA) and Agent Based Modelling are amongst the key technologies used by a-life researchers (Whitelow, 2004).

### Cellular Automata and Alpha Syntax

Cellular automata are parallel, discrete and dynamic computational frameworks. They are composed of a large number of simple elements, called cells, arranged in a regular lattice. Every cell can have a finite number of states. Time is also discrete in CA and proceeds in iterative steps, i.e.  $t$ ,  $t+1$ ,  $t+2$ ,  $t+4$ , etc. The states of the cells are updated in a parallel manner according to a local rule, commonly concerning just the cell in question and the neighbouring cells, at every time step, i.e. the state of a cell at time ( $t$ ), depends on the state of the cell and the states of its neighbours at time ( $t-1$ ). All of the cells are updated synchronously and the state of the entire lattice advances in discrete time steps. In this way the local-global transition is purely formal, but it gives rise to emergent mobile formations that integrate, disintegrate and crawl across the array. This striking complexity and life-like dynamic generated by formal and local rules is frequently invoked in discussions for the merits of the a-life approach (Whitelow, 2004).

Bill Hillier’s alpha syntax model of space (Hillier et al., 1976), further developed in “The social logic of space” (Hillier and Hanson, 1984) can be considered one of the most fundamental contributions to generative architectural theory. The core idea is that a finite number of elementary generators or syntaxes can produce an infinite number of well-formed settlements morphologies. Syntax, according to Hillier, can

be defined as a “system of restrictions on an underlying random process.” (1984, p. 55) Later in his book, he (1984, p. 78) distinguishes three types of space: carrier space - nothing, or undeveloped space; x-space - closed, private or inside space; y-space - open, public or outside space. Using these spaces, he outlines eight elementary generators, or syntaxes, with varying degrees of flexibility. The one chosen for the experiments is called “clump” (1984, p. 78), or x-y. The underlying idea is that every bit of closed space is directly connected to a bit of open space and that every open space is connected to at least one other open space. The reasons for selecting x-y syntax are twofold. Firstly, it adheres to the morphology of the adjacent Whitford village and, secondly, x-y provides a high degree of flexibility (see fig.3).

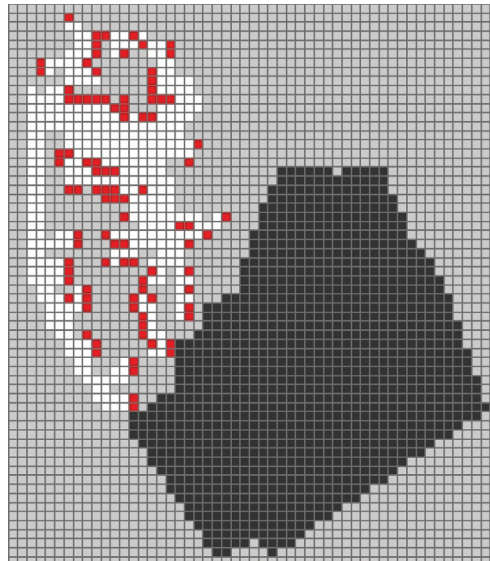


Figure 3  
Existing village morphology.

Hillier’s understanding of settlement’s spatial agglomerations are very close to Cellular Automata, and, according to Coates, they “can be seen as a method for describing spatial configurations and patterns of form as the emergent outcome of a discrete and temporal simulation” (2010, p. 139). The automaton modelled for the design experiments

generates patterns of land use and is described in detail in the next chapter.

### **Agent Based Modelling and Flocking**

Agent Based Modelling describes time and space using agents – autonomous little computers. Every agent has a strategy, usually defined in parameter space, and is aware of part of its surroundings. All of the agents try to implement their strategies synchronously and can alter their positions in metric space at discrete time steps. The actions of the agents are undertaken in Euclidian space and, therefore, distances, angles, and other metrics are significant. Agent Based Models are much more flexible, mobile and dynamic than the restricted topological tessellations of Cellular Automata.

Reynolds' (1987) flocking algorithm is among the most studied and employed Agent Based Models in A-life. This model is another canonical example of emergent collective intelligence based on local and simple stimulus reaction rules. There is no leader, i.e. no global control. The overall pattern emerges from the local interactions. Each agent reacts only to flock mates within a certain field of view. The basic flocking model consists of three kinds of simple steering behaviours:

- Separation gives an agent the ability to maintain a certain distance from others nearby. This prevents agents from crowding too closely together.
- Cohesion supplies an agent with the ability to cohere (approach and form a group) with other nearby agents. Steering for cohesion can be computed by finding all agents in the local neighbourhood and computing the average position of the nearby agents.
- Alignment gives an agent the ability to align with other nearby characters. Steering for alignment can be computed by finding all agents in the local neighbourhood and averaging together the 'heading' vectors of the nearby agents.

All the agents or turtles implement the

navigation rules simultaneously and iteratively. None of the rules say "form flocks". Yet flocks emerge, every time. Once a flock is together there is no guarantee that it will keep all of its members. Individual agents are constantly splitting away from their flock, joining another one, while more or less rearranging their flock mates.

Researchers from diverse fields have employed and interpreted flocking behaviours in attempting to study an impressive variety of phenomena. Flocks have been made to represent virtually every system of flow - from pedestrian, crowd dynamics and traffic to movement of animals and distribution of plant species in ecosystems (Arand and Lasch, 2006).

In this research, a learning, or exploratory flock, explained later, is utilized by means of testing the ecological fitness of the emergent subdivision morphology generated by the x-y cellular automaton.

### **Structural Coupling**

The theory of Autopoiesis pioneered by Maturana (1975) occupies central place in AL (Coates, 2010, p. 172). He introduced the concept of structural coupling which defines the dynamic relations between a system with either its environment or another system. Structural coupling describes dynamic mutual co-adaptation without allusion to a transfer of some ephemeral force or information across the boundaries of the engaged systems (Coates, 2010, p. 172). This notion allows scientists and designers to explore space, cognition and intelligence by building simple feedback systems between agents and their environments.

## **GENERATIVE URBAN DESIGN METHODOLOGY**

### **X-Y Cellular Automaton**

The CA serves to distribute the land use programme required by the brief and does not take into account ecological and topographic parameters and processes. It is based on Hillier's x-y syntax and is inspired by a similar model developed by Coates (2010). The site is divided into 10x10 metre grids, corresponding to

the minimal building unit and serves as a resolution for the CA. The cells that represent the site boundaries contain information for the contextual land uses - existing village, stream, and roads. These cells are static and their states can not evolve. They serve to determine the seeding conditions for the cellular automaton. The cells covering the site are set to a neutral state - carrier-space. There are two main types of land use - x-space (closed, built up space) and y-space (open-space). X and y-spaces are further divided into two subcategories each - closed space can be either retail or residential and the open space can be access (road) or 'square'. The 'squares' indicate widening of the open space configuration and are further used to locate retail closed spaces around them.

The concept that every open space should be connected to a closed space and every open space should be connected to at least one other open space can be expressed in a parallel manner, as suggested by Coates (2010, p. 141), in the following pseudo code:

- If I am a carrier space then
- If I have at least one neighbour that is a closed space, then I take my chance (variable named chance-closed that can be adjusted by the user and is expressed as percentage).
- If lucky I become an open space, otherwise I become a closed space.

The outputs of running the x-y automaton with low proportion of closed spaces are large amorphous spatial configurations with a lot of 'squares'

and retail closed spaces. When the proportion of closed spaces is increased the results are systems with many branches containing inaccessible islands of carrier space. If the percentage of closed spaces is increased to 40 or more the results are small spatial configurations with few branches, entirely surrounded by closed spaces. More detailed observations of the model reveal other emergent spatial phenomena: some of the islands of carrier space that have access to open space disappear, others become inaccessible; narrow passages of open space can lead to a cul-de-sac (see fig. 4).

Second and third order emergent open spaces can also be observed. For example, if an open space is completely surrounded by open spaces we can call it a second-order open space and if an open space is completely surrounded by second order open spaces we can call it a third order open space. These emergent agglomerations of open space allow us to further refine the land use matrix. If we have an open space that meets certain criteria, i.e. certain combination of neighbours in both Moore (eight neighbouring cells) and Von Neuman (four cardinal neighbouring cells) neighbourhoods that are open space we can call it 'square'. The emergent square-spaces can then influence the closed-space programme - if a closed space has certain access to a square-space, once again defined as a combination of the two neighbourhoods, it becomes a retail-closed space (see fig. 5).

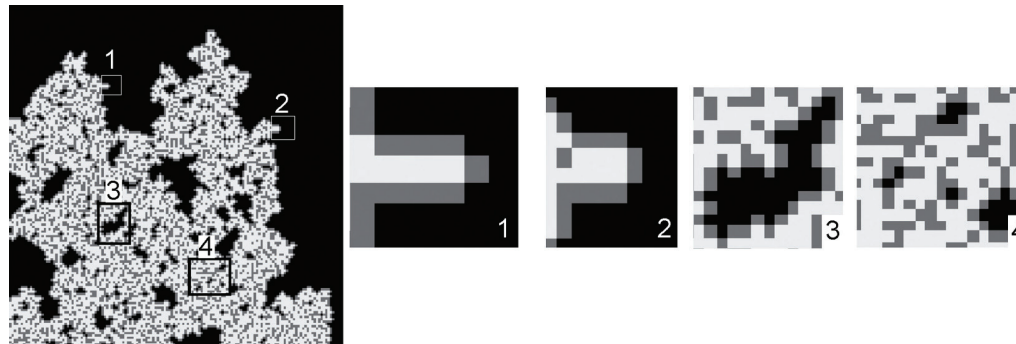


Figure 4  
Emergent spatial configurations. 1 and 2 - cul-de-sac, 3 and 4 - inaccessible islands of carrier space.

Figure 5  
Emergent urban morphologies. 1-'square' space, 2-retail space, 3-access space, residential space.



### Exploratory Flock and Mutual Coadaptation

As described previously, the cellular automaton, based on Hillier's x-y syntax, evolves locally and sets up patterns of land use. The transition rules that govern the growth of the automaton do not include information about ecological and landscape parameters and processes, so as not to overcomplicate the communications among the cells. A version of the flocking algorithm modeled as agent based system, as explained in chapter three, serves to communicate the ecological processes and tests the ecological fitness of the automaton. The flock is an equally parallel system and was programmed to be updated synchronously to the evolution of the CA. On the other hand the members of the flock are much more mobile and are capable of checking locations on the surface for the following gradients of ecological sensitivity:

- distance to riparian zones and overland flow-paths
- distance to existing patches of native vegetation
- slope (see fig.6)

This utilization of the canonical flocking algorithm as an ecological fitness function is based on the famous paper "The use of Flocks to drive a

Geographic Analysis Machine" by J. Macgill and S. Openshaw [2] and is inspired by Miranda & Coates' "The use of swarm intelligence to produce architectural form"(2000). These papers study how the emergent flocking behaviour might be used as an effective search strategy for performing exploratory geographical and landscape analyses. The methods rely on the parallel search mechanism of a flock, by which if a member of a flock discovers an interesting area, it will attract other members to explore that area in detail. This technique utilizes variable velocities and colours for all of the agents. Both velocity and colour have 'meaning' in regards to the success of an agent in finding an area of interest.

These properties of the algorithm render it a valuable technique for testing the ecological qualities of the emergent land use patterns. By being attracted to ecologically sensitive areas the flocking agents test the fitness of the subdivision morphology and can perturb the generated land use patterns. It is important to note that the flocking agents not only cluster on the ecologically sensitive areas, but also provide us with ways of connecting these areas. Although the format of this paper does not allow discussion of ecological connectivity in more detail, it will just be noted that the revegetation of steep slopes, riparian zones and preserving the existing patches of native vegetation have become a standard approaches in addressing ecological issues in peri-urban developments in New Zealand. What is often underestimated is the way of connecting these revegetated areas by means of providing a better habitat for wildlife.

The learning, or exploratory, flock is governed by the following rule set:

- Every agent assesses its current location and the number of other agents in its cone of vision. After that it changes its colour as described below:
- If there are other agents, but nothing interesting in the environment, then the agent turns yellow.
- If there are other agents and some interest in the environment then the agent turns green.



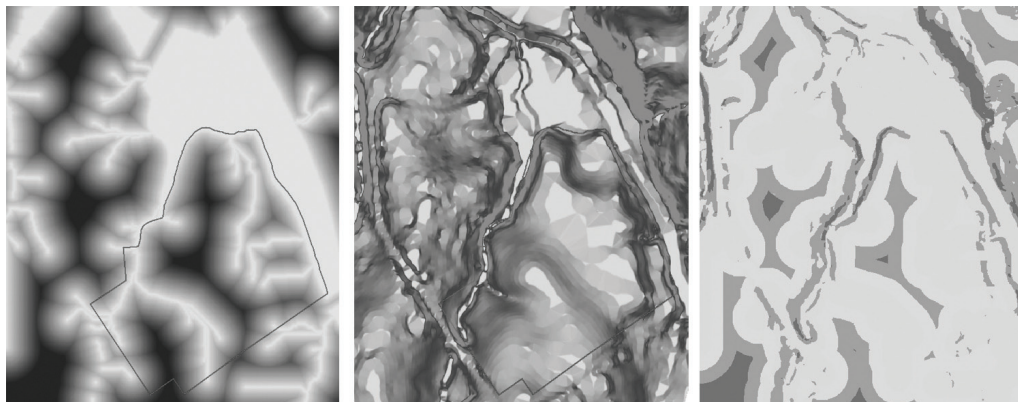


Figure 6 Areas of ecological sensitivity.

- If there are other agents and a significant interest in the environment then the agent turns blue.
- Then each agent adjusts its heading according to the following list of instructions:
- If the closest neighbour is too close then separate from it regardless of its colour.
- If the closest neighbour is green, disregard it.
- If the neighbour is blue, feel attracted.
- If neighbour is yellow, then avoid it.
- Every agent takes the weighted average of all target points generated above and moves towards that point with the following velocity rules:
- If I'm yellow move faster (This area is not interesting).
- If I'm green move at constant speed (There is some interest and I don't want to miss anything).
- If I'm blue, move slower.

This means that when agents find an ecologically sensitive area they will slow down and cluster in order to explore the area in more detail. This happens because their speed is low and they have the inertia to remain there. The agents in the neighbourhood that have not detected anything of interest will speed up and be attracted to heavier and slower agents. The idea is that the information is stored in the velocities of the agents. Speeding up corresponds to 'forgetting'

in the system. With this algorithm the flocks will move around, discovering ecologically significant areas. If the area does not have enough weight compared with another, it will not be able to attract enough agents. After iterating the algorithm numerous times, the flock will 'forget' the areas of low ecological significance. Not allowing the agents to stop ensures that some of them will leave the significant areas and may be attracted to a different area of interest. Hence, the learning, or exploratory, flock provides us with possible connections between these areas (see fig. 7).

To trigger structural coupling with the automaton, the flocking agents are further programmed to perturb the land use pattern. Only the green and blue agents, located on ecologically sensitive areas, can transform the evolving urban morphology. They can revert closed spaces and open spaces back to carrier space. In this way the emergent spatial morphology can both resemble and complement the spatial organisation of the existing village and at the same time take into account the existing landscape and ecological conditions (see fig.8).

## CONCLUSION AND FUTURE WORK

The discussed project is work in progress. One of the aims of the research was to model urban morphology as an emergent co-adaptation of two bottom-up

Figure 7 Learning (exploratory) flock.

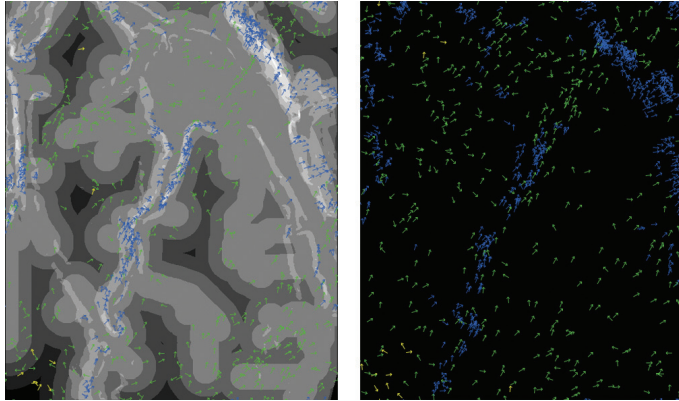
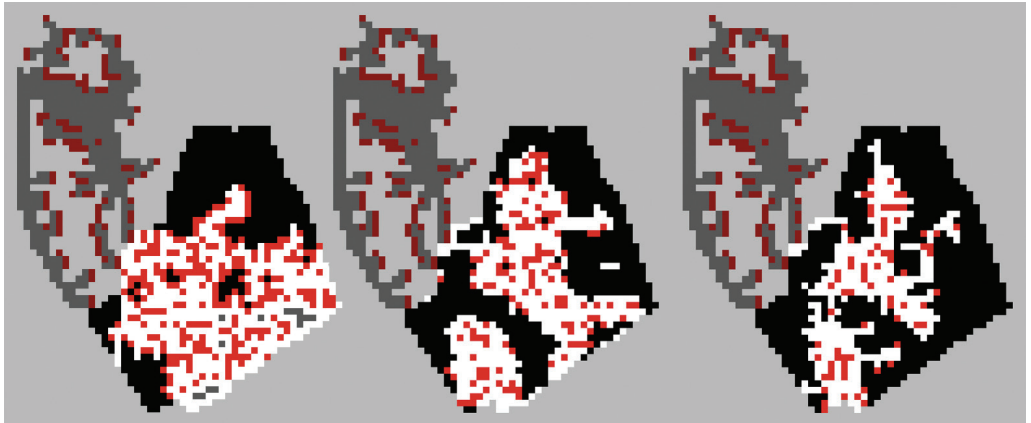


Figure 8 Emergent subdivision morphologies.



computational systems - Cellular Automaton and Agent Based Model. The outputs of the models reveal intriguing and unexpected spatial configurations. The simulations proved to be able to generate variety of well defined and syntactically correct urban morphologies.

The x-y automaton has an easy to understand structure, but the outputs are symbolic and abstract. These limitations are imposed by the gridded nature of Cellular Automata. Further research is needed in order to refine the rules for the subcategories of open and closed spaces. The flocking model proved to be an efficient way to explore landscape and context. The communication between the flocks and the x-y automaton needs some

refinement. The second aim of the project was to test the concept of generative design with real site and design brief. Some of the outputs of the models connect very well with the existing village in terms of spatial organization without disturbing ecologically sensitive areas.

This project did not attempt to develop beyond the morphological scale; the focus was on keeping the integrity of the generative design concept. The rules of the models were not overly specified and the outputs are produced entirely bottom-up.

One of the main difficulties of this type of modeling is the non linear relationship between the rules and the emergent overall pattern. Working with the



astronomical parameter space of CA and ABM can be difficult and challenging undertaking. Despite the challenges and difficulties, ABM and CA definitely have a future in urban design and architecture. They are one of the few computational frameworks that can be used to study complexities of the structures that we observe in the world.

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