Using Cellular Automata to Generate High-Density Building Form

HERR Christiane M. and KVAN Thomas
Department of Architecture, The University of Hong Kong, Pokfulam, Hong Kong

Keywords: cellular automata, high density architecture, urban morphology, generative design

Abstract: This paper presents an investigation into the use of cellular automata systems for the design of high-density architecture for Asian cities. In this architectural context, urban form is shaped by architectural solutions that are developed in a copy-and-paste manner. To this background, cellular automata are introduced and discussed with respect to the specific potential of cellular systems to support architectural design addressing large projects as well as cost and speed constraints. Previous applications of cellular automata to architectural design have been conceptual and are typically limited by the rigidity of classical automata systems as adopted from other fields. This paper examines the generative design potential of cellular automata by applying them to the re-modelling of an existing architectural project. From this application it is concluded that cellular automata systems for architectural design can benefit from challenging and adapting classic cellular automata features, such as uniform volumetric high-resolution models and globally consistent rule execution. A demonstration example is used to illustrate that dynamic, state-dependent geometries can support an architectural design process.

1 THE CHALLENGE OF VARIETY

Cities characterized by high density living conditions produce distinctive building forms in response to local conditions and needs. Asian cities, in particular, are subjected to ongoing rapid urban growth and increasing urban densities. This often results in mass-production of building form, particularly in the case of residential purposes. In response to high density and spatial limitations, building sizes have continued to grow during the past decades, often accommodating several thousand people per building and frequently more than 100,000 per housing estate. Increased development sizes are typically detrimental to architectural quality since building form is often designed highly repetitively and, under pressure of time and tight budgets, increasingly devoid of individual character. Once developed, building types are often standardised and reproduced in other cities without much architectural rethinking, such that context-insensitive design shortcomings are often also repeated. A building type designed for Hong Kong, for example, may be copied to Singapore, Shanghai or Guangzhou without acknowledgement of climatic, economic, contextual or social differences. While efficient in terms of space, the lack of variety in the standard building form leads to monotonous estates. Entire new towns are composed from rigid arrays of identical buildings, regardless of location or the cultural background of the inhabitants (Gutierrez and Portefaix 2004). Monotonous living environments are not only aesthetically challenged but can also have a negative impact on their inhabitants, limiting personal control of living space and forcing inhabitants into conformity with little opportunity for individual expression (Herrenkohl 1981, Evans 2003).

Architectural design for high density urbanism is typically determined by tight economic constraints and building regulations. The latter are typically of a highly prescriptive nature, rigidly determining all aspects of architectural expression from massing to window detailing. With ever-accelerating planning speed and developers’ pressure for quick financial return, architects face a design environment that has little concern for variety and architectural quality in the results of their work. Thus, high-density architecture in Asia is dominated by a limited set of building types that closely adhere to the site’s so-called *maximum development potential*. It describes the ideal building that will produce the greatest financial benefit to the developer, who in turn bears high economic pressure from competitors. To cope with these requirements, architectural design typically relies on simplified and repetitive standardised solutions, hindering the development of context-sensitive design alternatives and promoting copy-and-paste routines rather than responsive designs.

Figure 1 High-density suburbs of Hong Kong

To deal with the requirements of tight regulations and efficiency while at the same time exploring less rigid and more individual building morphologies, alternative approaches to the design of high-density building form are needed. In response to these demands, this paper proposes the use of cellular automata (CA) as a generative architectural design strategy in particular for high-density residential architecture.

CA can provide an automated approach to the complexity of designing with a large number of similar parts, reducing architects' investment of time and effort spent by architects by replacing top-down controlled design processes with a generative paradigm based on local control. CA also have the potential to assist designers in introducing variety to highly standardised building systems by providing efficient use of already established frameworks of design constraints as well as design and construction processes.

2 GENERATING VARIETY

Dealing with multiple constraints and complex geometrical configurations is a tedious task. To solve this type of design problem, architects need to devote a great deal of time to initially simple initial tasks, which rapidly increase in complexity as they interlink and repeat across large projects. In designing a high-density residential apartment block, architects might for example spend much time in reconciling the spatial layout of an apartment with the maximum permissible length of a fire escape route while considering minimum lighting requirements and restrictions to the site coverage. Once a solution is found, the designer copies this to every floor on the building rather than spending the time to find spatial and structural alternatives at different floor levels. This strategy does not necessarily manifest undesirable outcomes when applied at the scale of a single building, but it very likely results in overbearing monotony if it is applied to an array of 60-storey buildings comprising an entire city quarter or 'new town', as is often the case in recent urban developments in China (Figure 1).

Generative design approaches have emerged from the search for strategies to facilitate the exploration of alternative solutions in design, using computers as variance-producing engines to navigate large solution spaces and to come up with unexpected solutions (Negroponte 1970). In generative design, algorithms are often used to produce an array of alternative solutions based on predefined goals and constraints, which the designer then evaluates to select the most appropriate or interesting. A strength of the computer as a design tool stems from its capability to perform tasks that rely on numerically formalized dimensional or relational constraints. Design decisions that require a more holistic, context-based understanding and judgement are typically left to be decided upon by human designers (Cross 1977). The use of generative approaches in design is motivated in part by the need to manage and express increasing complexity of factors that determine the design processes. In designing contemporary urban environments, a multitude of requirements and constraints have to be observed, that can often overwhelm designers (Negroponte 1970). In this context, CA have received attention from architects as a generative strategy that is characterized by the simplicity of its mechanisms on one hand and the potential complexity of its outcomes on the other (Herr 2003). Driven by local communication between cells over time, behaviour in CA is based on simple rules followed individually by cells arranged within a larger grid. Relying on geometrical neighbourhoods to determine individual cell states, CA are inherently context-sensitive systems. Originally developed by the mathematicians Ulam and von Neumann, CA have been applied to a wide range of fields to study complex phenomena, ranging from Physics to Geography and have found some application in Architecture as described below. As a generative design tool, cellular CA are typically used in form of volumetric models that transcend traditional types of models in that individual volumetric units are capable of changing their properties according to predefined rules. As with evolutionary approaches to design, CA have been used mainly to explore variations of possible solutions resulting from the tempo-spatial development of initial setups over time. Design constraints are typically implemented in a bottom-up manner in form of simple rules that govern the local behaviour of each cell. The overall outcome of a CA system, however, is often complex and difficult to predict, which results in a design process that emphasises experimentation and exploration of solution spaces. Similarly to shape grammars, CA are characterised by deterministic transformation rules, but dependencies of cell states on adjacent cells provide localized evaluation mechanisms. This characteristic supports local instead of global control models, and is seen as a future opportunity to further generative architectural design (Koutamanis 2000). As a generative design strategy, CA are typically chosen for tasks that involve simple constraints operating on large numbers of elements, where differentiation and variety are sought (Watanabe 2002).

3 CELLULAR AUTOMATA FOR ARCHITECTURE

While CA have been explored in the context of architecture, previous approaches have tended to use existing systems like John H. Conway's *Game of Life*, experimenting with rule sets and interpreting complex spatial results as architectural form. This approach may yield interesting experimental results, but does not address specific requirements of architectural design, which generally involves responding to a design brief, design constraints and to an existing environment. Using CA in architecture further requires an understanding of which types of architectural design tasks can benefit from the application of CA, as opposed to design decisions that require human judgement. Both aspects of CA in design are discussed and illustrated in section 4. Automation of design processes with CA generally relies on numerical descriptions of design constraints or design approaches in which decisions are made according to systematic frameworks. Accordingly, the first architectural design project to bring together a generic understanding of useable space and microcontroller-enhanced building elements is Cedric Price's Generator project (Hardingham 2003). Price approaches architectural space much like a CA system, using volumetric units controlled by both the building's users and by a central computer. In Price's functionalist view of architecture, spaces within a building are generated by and for user needs rather than for their aesthetic values, and the building can change form during usage. A similar interest in form derived from function alone is expressed by Coates et al. (1996), who see their experiments with CA in architecture as the expression of an aesthetic of pure function. Extending Price's generic view of space evident in the Generator project to architectural form in general, Frazer (1995) and his students at the Architectural Association built the

Universal Constructor on an understanding of architecture as logic states in space and time. The system is implemented as a hardware CA system controlled by a host computer that functions also as a human-computer interface. Neither the electronic circuitry nor the cubic geometry of the *Universal Constructor*'s modelling units are designed to directly correspond to architectural concepts other than tempo-spatial logic states. As a generic system, applications of the *Universal Constructor* depend largely on software used in given applications, which maps cubes, their location, their 256 states and neighbouring relationships to built form. Looking for greater differentiation than that achievable with classical two-state automata in their experiments, Coates and his students have also increased the number of possible cell states and emphasise the role of environments and feedback in providing opportunities to develop greater diversity in CA models (Figure 2). Used as form generators without context, CA models tend to produce shapes that display fascinating three-dimensional form but are difficult to adapt to the functional requirements of buildings. Starting the design process with a three-dimensional CA system based on the rules of the *Game of Life*, Krawczyk (2002) deals with this problem by adopting enlarged cells to create contiguous areas in floor plans by overlapping and altering shape edges into curves and by providing vertical supports for cantilevered elements. Post-rationalisation measures of this kind demonstrate that a number of basic premises of classical CA systems may be changed in order to produce meaningful architectural form. While it is possible to use uniform voxel grids at high densities to approximate form, this is rarely useful in architectural design (Mitchell 1990). It can result in the CA system being used to generate form according to only few constraints regarding a particular architectural scale, and requires subsequent manual changes to respond to additional design constraints. This conflict is clearly visible in Watanabe's (2002) 'sun god city I' design, where units of a cellular automaton are arranged according to lighting criteria but many cells lack vertical support as would be required if the model is used for architectural purposes (Figure 2).

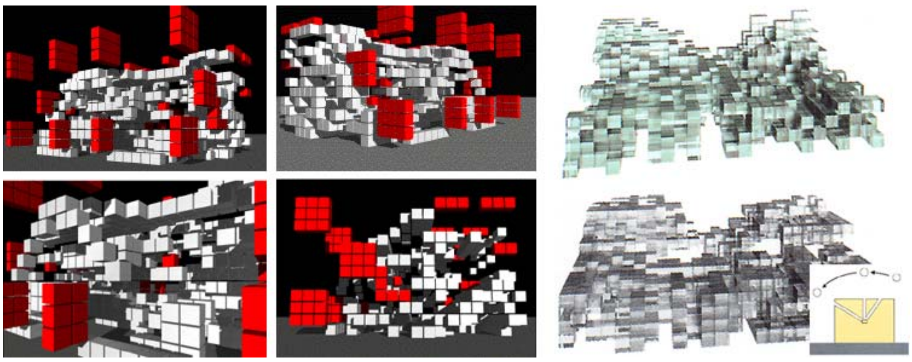

Figure 2 Architectural cellular automata by Coates and Watanabe

More design task specific CA systems could also improve computation performance, since CA models at high resolutions can require extensive calculation time, in particular if less simple rule sets are processed. Using generative CA systems for design tasks further entails the integration of cellular systems with a traditional CAAD environment. As Krawczyk (2002) observes, CA-generated form is likely to be used either in particular aspects or in particular stages of a design project, with the outcomes frequently modified during the design process on the basis of an architect's assessment. Attempting to design rule sets that are sufficiently specific to generate complete buildings defies the characteristic simplicity of rules in CA systems, which is one of the primary reasons to apply CA to design. In summary, CA offer ways to use simple rules in coping with quantifiable constraints, and can handle rather complex geometrical relationships due to transition rules operating according to local cell neighbourhoods. In a generative design tool, these features are well suited to tackle typical design problems in high-density architecture (Herr 2003). Previous research on the subject has tended to focus on developing an abstract and reductionist notion of architecture compatible with theoretical mathematical models. Frazer (1995), for example, has expressed the notion of architecture as 'logic in space'. Instead of attempting to bring architecture closer to mathematical abstraction, however, modifying mathematical paradigms to suit architectural design purposes promises results at a more immediate and practical level. Other generative paradigms have successfully demonstrated their architectural potential by remodelling design precedents, as for example shape grammars have been used to generate Chinese ice ray lattices, Palladian villas and buildings by Frank Lloyd Wright. In the case of CA, implementations have thus far been mainly conceptual studies. To illustrate the generative potential of CA in the context of high-density architecture, we have chosen to remodel an architectural design comprising a group of buildings proposed as a high-density city block in northern Japan (Figure 3).

Figure 3 High-density architecture for Aomori/Japan by Cero9

The implementation is primarily intended to give an example of how a flexible, modular and open-ended use of CA systems can be effective as generative tool in combination with manual design decisions.

4 DESIGNING WITH CELLULAR AUTOMATA: AN EXAMPLE IMPLEMENTATION

The competition entry chosen for remodelling was designed by the Spanish design team Cero9 in 2001. It proposes a high-density urban block for the city of Aomori in northern Japan, developing the given site as a high-density mixed use complex in form of an array of thin, 25-storey ‘micro-skyscrapers’. Architecturally, the design is based on a cellular understanding of building form where cells contain single living units and are easily identifiable visually, facilitating a rather straight-forward CA approach. For larger projects such as this one, Cero9 typically use a rationalised design process that aims at generating variety from simple rules, which are applied in successive design stages according to design constraints and project context. As three-dimensional modelling software, AutodeskVIZ was used, with additional scripts that provide CA functionality. To remodel Cero9’s design in a generic way, aspects and stages in the design dealing with quantifiable constraints were first identified according to Cero9’s (Diaz Moreno and Garcia Grinda 2004) own description. To accommodate both generative and traditional design procedures, the implemented cellular automata may be used in phases, with intermittent stages of manual design interventions. Cell behaviours can be assigned dynamically during the design process, such that elements within the modelling environment can change their behaviour over time. In contrast to classical CA, where cells are uniform and cell states do not affect cell geometry, CA functions can be assigned to any element in the modelling environment, with cells able to change their geometry in response to their states. Compared to a conventional generic high-resolution approach, this non-uniform solution greatly limits the number of cells required in modelling architectural geometries and avoids the restrictions imposed by the compulsory use of additive approximation based on homogeneous grids of elements. To accommodate flexible cell geometries and changing behaviours during the design process, cell neighbourhoods are identified dynamically, depending on the cells and functions in operation.

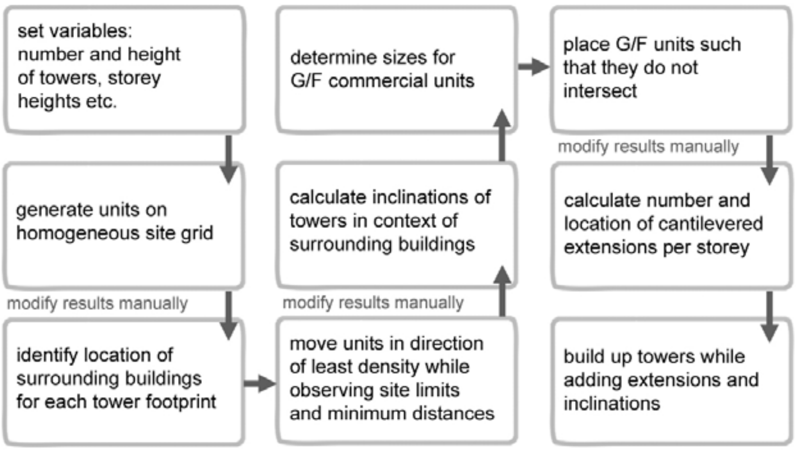

Figure 4 Rule-based sequence of generative design process

The generative sequence in this example begins with rearrangement of two-dimensional building footprints on the site, which grow into three-dimensional plant-like structures at a later stage. Following the design sequence described by Cero9, CA functions of elements in the digital model were found to be useful in a variety of tasks: The arrangement of towers on site constrained by available views and existing buildings surrounding the site, modifications of tower locations to accommodate tower inclinations, finding appropriate locations for commercial and community spaces connected to the towers, and the placement of local extensions to some of the living units (Figure 4). Design decisions not affected during CA execution include the cellular layout, which determines the characteristic tower footprint and the number of buildings on a site, while other variables and the assignment of rules to individual cells are decided upon during human intervention between CA execution phases. Elevated connections between individual towers, for example, were added manually at a later design stage. The modular character of the generative cellular design tool allows modification of the results during the design process without the need to change the design tool, as it would be necessary in a self-contained, deterministic CA environment. The generative functions implemented in this example operate mainly at the level of residential unit ‘cells’, but they could just as well be applied to similar problems on different levels of scale, depending on the modelling environment they are assigned to.

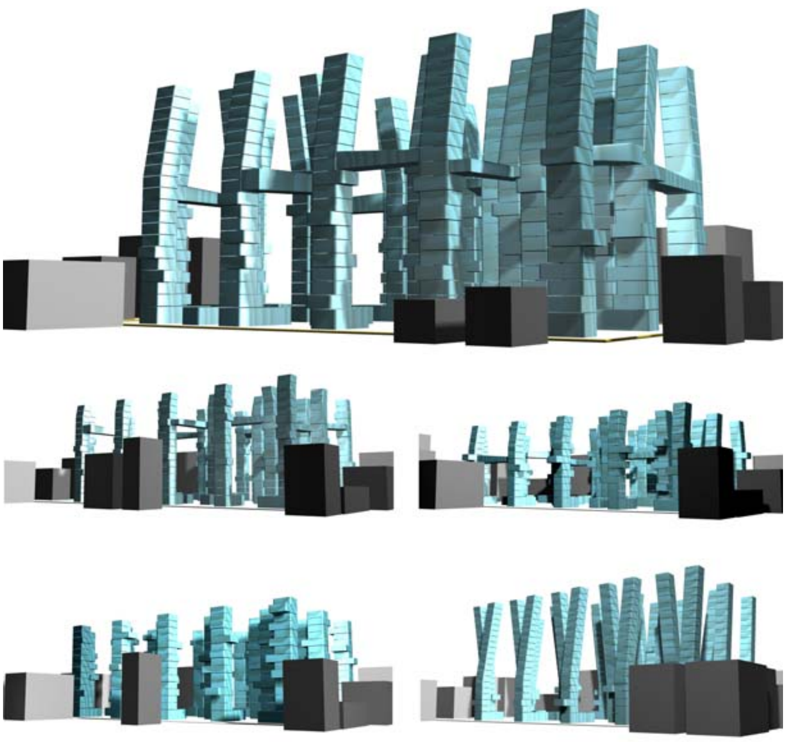

Figure 5 Alternative cellular automata-generated versions of Cero9’s design

For the purpose of a single project, developing a generative tool such as this example implementation will take longer than traditional design by hand. In the case of large high-density developments, however, repeated use for a variety of solutions (Figure 5) sustains additional time and energy spent in tool development.

5 CONCLUSION

As other authors have previously established, CA offer an effective generative method where architectural projects involve some degree of repetition amongst larger numbers of formal elements. Applying CA to the specific context of high-density housing as shown in the discussed example implementation has resulted in several observations that can be generalised within the context of architectural design. Particularly in the context of Asian high-density architecture, generative CA systems can offer design solutions to large-scale developments and simultaneously meet demands for high speed and efficiency in the design process. The development of a powerful CA system might easily require more resources than the application of traditional design methods to a given design project. Repeated application of a generic CA system to a class of projects, however, potentially yields great economic efficiency while individual designs will show context-sensitive variation. Architectural design projects benefit from looser, more paradigmatic interpretations of classical CA features. In this sense, pragmatic design considerations appear to increase the generative utility of CA systems much more than the strict adherence to features of classical CA systems in their ideal forms. To apply CA to specific problems, classical CA properties are often changed according to their intended use. Such modifiable features include the number of automaton states, the number of rule sets and their change over time. Other options exist, which seem specifically useful in adapting CA systems for increased usefulness in architectural design projects. These include the introduction of human intervention, atypical or dynamically changing definitions of neighbourhoods, variance or omissions in the sequence of automaton execution as well as automata arrangements beyond simple grids and more complex and dynamic cellular geometries. Making use of the latter (mapping automata states to dynamic cellular geometries) in the discussed project has effectively allowed geometric variation and might offer a general alternative to CA-based form finding using high-resolution systems at high computational efficiency.

REFERENCES

Coates, P., N. Healy, C. Lamb, and W.L. Voon. 1996. *The Use of Cellular Automata to Explore Bottom-Up Architectonic Rules*. Paper presented at Eurographics UK Chapter 14th Annual Conference held at Imperial College London, 1996.

Cross, Nigel. 1977. *The Automated Architect*. London: Pion.

Diaz Moreno, Cristina, and Efren Garcia Grinda. 2004. Soft Metropolitanism [Apartments in Micro-Skyscrapers]. In *EL CROQUIS 118: CERO 9, ABALOS & HERREROS, NO.MAD*, ed. F. Marquez Cecilia, and R. Levene: 140-1147. Madrid: El Croquis.

Evans, Gary W. 2003. The Built Environment and Mental Health. *Journal of Urban Health* 80(4): 536-555

Frazer, John Hamilton. 1995. *An Evolutionary Architecture*. London: Architectural Association.

Gutierrez, Laurent, and Valerie Portefaix. 2004. Houses for China. *Architectural Design: Property Development and Progressive Architecture: The New Alliance*, ed. D. Sokol: 81-87. Vol. 74 No. 1 January/February 2004. London: Academy.

Hardingham, Samantha (ed.). 2003. *Cedric Price: opera*. Chichester: Wiley-Academy.

Herr, Christiane M. 2003. Using Cellular Automata to Challenge Cookie-Cutter Architecture. In *The 6th International Conference on Generative Art 2003*, ed. C. Soddu: 72-81. Milano, Italy: Generative Design Lab, DiAP, Politectnico di Milano University.

Herrenkohl, R.C. (ed.). 1981. *Social Effects of the Environment.* Council on Tall Buildings and Urban Habitat: Volume PC Planning and Environmental Criteria Chapter 37.

Koutamanis, Alexander. 2000. Redirecting design generation in architecture. In *The 3rd International Conference on Generative Art 2000*, ed. C. Soddu. Milano, Italy: Generative Design Lab, DiAP, Politectnico di Milano University.

Krawcyk, Robert. 2002. Architectural Interpretation of Cellular Automata. In *The 5th International Conference on Generative Art 2002*, ed. C. Soddu: 7.1-7.8. Milano, Italy: Generative Design Lab, DiAP, Politecnico di Milano University.

Mitchell, William J. 1990. *The logic of architecture: Design, computation, and cognition*. Cambridge, Mass.: MIT Press.

Negroponte, Nicholas. 1970. *The architecture machine: Toward a more human environment*. Cambridge, Mass.: MIT Press.

Silver, Michael. 2003. Traces and Simulations. In *Mapping in the age of digital media: the Yale Symposium*, eds. M. Silver, and D. Balmori: 108-119. Chichester, Wiley-Academy.

Watanabe, Makoto Sei. S. 2002. *Induction design: a method for evolutionary design*. Basel, Birkhäuser.