Automation in Construction 49 (2015) 152–162

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Exploring cellular automata for high density residential building form generation

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ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form 23 August 2014
Accepted 21 October 2014
Available online 18 November 2014

Keywords:
Generative design
Computational design
Cellular automata
Design process
High density residential building

ABSTRACT

This paper presents an investigation into the integration of cellular automata in the architectural design process, specifically in the design of high density residential building forms. Addressing the complexity of cellular automata rule definition, we explore the potential of visual and diagrammatic descriptions to address density, accessibility and natural light in the architectural context. This paper reflects on the theoretical framework of cellular automata (CA) and what characterizes their application to architectural design. The intention is to develop a tool to support the adaptation of architectural requirements into CA principles. Focusing on the application of CA at the beginning of the design process, we outline the implementation of CA generating three-dimensional architectural form for a high density residential project in the Netherlands.

1. Introduction

The Randstad, a densely urbanized area in the west of the Netherlands, holds about 45% of the Dutch population. By 2040, it faces tremendous population growth, city expansion and employment developments; spatial planning policy documents indicate the necessity of additional infrastructure and the development of an enormous housing supply [1,2]. In any urbanized area, it is important to understand the way people inhabit cities socially, economically and environmentally and how dense city conditions can impact the quality of the built environment. Dense urbanized areas are often subjected to the supply of mass production housing. Perceiving the notion of efficiency as a key feature of a mass production strategy generally leads to the design of highly repetitive standard apartments. Due to the large amount of information involved in the design of high density housing, architects are commonly unable to design each dwelling individually and, instead, opt for standardized products that can be easily repeated based on the efficiency of the operational performances and economies of scale. Although mass production of high density housing promises operational performances and production efficiency, the designed forms typically demonstrate less variety, innovation and integration within the context. They are often limited to uniform building types, which meet neither customers' heterogeneity of demands nor social or contextual requirements. “While efficient in terms of space, the lack of variety in the standard building form leads to monotonous estates” ([3], p. 250).

The use of digital tools in design is growing rapidly. Adopting advanced digital design technologies, it is essential that we develop and expand our abilities to introduce variety in the design of building forms. Computational design incorporates different generative techniques that allow us to create designs that are characterized by formal and procedural complexities; by manipulating the relations between components one can control the properties of individual objects, evaluate the results and, correspondingly, customize the solutions. In generative design, computer algorithms can produce a vast number of solutions meeting specified constraints and requirements. However, the more realistic that the constraints are provided, the more complex the process generally becomes. Quantifiable requirements offer the architect less leeway, thereby making the design process more complex. However, simple generative mechanisms, when informed by the same quantitative requirements, can yield a significant, positive impact on the design process. The approach presented in this paper uses generative design techniques to create building morphologies with respect to architectural criteria and suggests strategies employed as customization methods to be considered within design decisions.

In particular, we explore the capability of the generative computational method of cellular automata (CA) as a design strategy to generate a variety of building forms for high density housing. We consider the question of how CA can be used as a computational form finding method to raise the effectiveness of the design of high density housing with

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http://dx.doi.org/10.1016/j.autcon.2014.10.007
0926-5805/

respect to variability and customization. The focus is on developing a computational design tool that can contribute at the early stages of the design process by addressing accessibility and lighting requirements. The final outcomes are the results of integrating generative and conventional design processes. While the potential of the CA method to generate diagrammatic forms is demonstrated, the post-processing of the generated results to meet the spatial requirements imposed by the program and context relies on manual manipulations that conform to the conventional design process. The following sections present cellular automata and some of their applications in architecture, the method of implementation, the characteristics of the implemented tool, descriptions of the generated results and their manipulations. Specifically, we examine the versatility of cell properties, that is, their ability to be adapted to different functions or requirements, in CA to the generation of architectural form for high density housing in the Netherlands. We focus on the implementation of a tool to develop a three-dimensional model that deals with architectural requirements by transcribing them into CA rules based on visual and diagrammatic architectural descriptions.

2. Cellular automata

Cellular automata, as a computational method, can be incorporated in both modeling and simulation contexts. Its capacity to model dynamical behavior employs mathematical properties consisting of rules, which update discrete variables of space, time and state synchronously. As simulation models, CA simulate the process of growth in a complex system consisting of discrete patterns and comprising simple rules.

The concept of CA in simulation growth is described by von Neumann [4,5], Schrandt and Ulam [6] and enhanced by Wolfram [7]. It can evolve over a number of dimensions including one, two and three, respectively introduced by Stephen Wolfram, John Horton Conway and Stanislaw Ulam. The process of growth is based on the state of individual cells, which is determined by local rules and changes over time. The local rules and, consequently, the state of a given cell depend on the states of its neighbors (which can be either directly or indirectly adjacent) at a previous time step. This model resulting from the interaction among adjacent cells can create a spatio-temporal system with emerging behaviors through time and space. In fact, each cell carries information, and the CA behavior determines the state of an object based on geometrical, spatial, functional, structural and environmental rule sets. For example, Conway's *Game of Life*, introduced by John Horton Conway in 1970, is based on three simple rules including survival, death and birth [8]. A live cell survives (into the next generation) if it has either two or three live neighbors, it dies if it has any other number of live neighbors. A dead cell comes to life if it is surrounded by exactly three live neighbors. Conway's *Game of Life* is a user-free process, meaning that the process of growth is determined by its initial state and there is no need for user inputs [9].

3. CA application

The application of CA covers a wide range of domains in structural engineering [10–13], mechanical engineering [14], physics [15] and architecture [9,16–22]. The major characteristic of a CA generative system is to produce a vast number of solutions and generate complex morphologies by applying simple rules to cope with the majority of constraints. Slotta [10] discusses the application of the CA technique to structural design. His CA system includes two sets of rules operating on cells based on the 8-cell *Moore* neighborhood. The first set of rules performs the structural analysis and determines the propagation of stresses and strains for each cell based on the displacement of its eight neighbors. The state of a cell is determined by its displacement value as a fraction or percentage of the maximum displacement within the structure. The second set of rules performs the design work. According to Slotta [10], the second set of rules deals with simultaneous analysis and design, in that depending on the analysis data, proper changes will be made into the connecting areas of beams to withstand the stresses.

In another example of CA application to structural design, Funes [13] proposes column construction based on the modular configuration of a single rectangular block. He incorporates shape rules as a complementary approach to help form-function identification of rectangular shapes, their position and decomposition to create stable forms. In mechanical engineering, Hajela and Kim [14] use a genetic algorithm technique to find CA rules for energy minimization in structural analysis. They test a cantilevered beam with a point load at its free end and a plate which has a hole in its center, and pull forces applied in all directions. Rothman and Zaleski [15] investigate CA rules in the behavior of gas–fluid dynamics using hexagonal patterns by employing a *Moore* neighborhood matrix for the particle collision behavior. They take advantage of the intuitive methodology of shape rules based on the physics of particle dynamics to illustrate the rules for particle motions. The rule sets are then converted into binary lists, which can be used as CA principles.

4. CA application in architecture

Perhaps Cedric Price's Generator project can be considered the first system similar to a CA system [16]. He uses volumetric cells controlled by users and a central computer, so that the building form can be changed according to their needs. Frazer [17] extends the view of Price in space by defining the notion of *Logic of Space*. Price and his students, at the Architectural Association, developed the universal constructor system as a CA system that is controlled by a central computer. The cells in this system respond to the tempo-spatial states, although they do not correspond to the architectural context.

Approaching CA applications in architecture, it is essential to understand which types of architectural design requirements can benefit from its usages. Krawczyk [18] adopts the rules of Conway's *Game of Life* in order to develop a three-dimensional architectural model that deals with functional requirements. He argues that unlike the parametric method, where parameters can be modified in order to achieve an anticipated result, the process of generation in the mathematical method of CA continues until a possible architectural pattern is reached [18]. While Conway's *Game of Life* does not deal with architectural requirements and constraints in an existing environment, Krawczyk proposes to address architectural considerations within the process by applying manual changes to respond to additional architectural constraints. Through manual changes, cells are scaled, edges overlap their neighbors and edges become curves in order to create the largest contiguous floor areas. Upon applying changes in horizontal connections, vertical supports are added to cantilevered elements. This concept generates several architectural results such that outcomes can be modified during the design process based on architectural requirements. In other words, modifying the mathematical paradigm of CA entails results with respect to more practical architectural purposes.

Addressing environmental parameters in architectural design can provide a new relationship between function and space. Considering major access to natural light from the south side, Coates et al. [19] implemented a CA system in order to bring light to each cell. They increase the diversity of the three-dimensional CA model by increasing the number of cell states and emphasizing environmental situations. Rather than limiting the rules to result in birth, death or survival based on the states of adjacent cells, they extend the rules to reflect on the spatial locations of neighbors and the complexity of relationships between cells by increasing the variety of states available for each cell. The process of growth occurs, firstly, in accordance with spatial locations of cells controlled by voting rules, and then, with birth, death and survival rules in the form of counting rules. By differentiating directions as bottom, below or next with respect to other cells, the voting rules allow a cell to overshadow others. However, the system does not properly address functional requirements such as vertical supports that could make the