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Original scientific paper

SELF-REPLICATING SYSTEMS IN SPATIAL FORM GENERATION - THE CONCEPT OF CELLULAR AUTOMATA[1]

Ljiljana Petruševski, Mirjana Devetaković, Bojan Mitrović

The self-replicating systems introduced theoretically by von Neumann, are widely examined in biology, computing, geometry, engineering sciences etc. In this study the authors are focused on the concept of cellular automata (CA) and its possible application in processes of spatial form generation. The study has been realized with participation of 60 senior architecture students, creating various spatial forms by using the CA concept, within the series of elective courses titled Generic Explorations. The experimental activity is supported by the software Fun3D, i.e. its CA module, which has been created at the University of Belgrade, Faculty of Architecture, to support generative processes in the field of architecture.

After introducing a general idea of the self-replicating systems, the authors explain the major principles of CA, particularly the issues of layered 2D automata, discussing possible approaches to spatial form creation. The study examines CA based on a cubic cell, evolving to a rectangular cuboid where width/height/length ratio can differ, as well as the gap between cells and some of the visual features, like color, transparency, texture etc. Creators of various spatial forms can set a pattern of initial cells, and define a rule for a self-reproduction of a single cell. Combinations of multiple CA systems have been introduced, as an entirely original approach to the problem of form generation in general.

A variety of approaches to the generation of spatial form, resulted from the experimental activity, indicate a significant potential of the CA concept application in many areas of spatial design. The authors suggest a range of interpretations of a resulted generic form, such as architectural, urban, product design, exhibition systems etc.

Key words: cellular automata, spatial, form, architecture, generic

INTRODUCTION

The self-replicating systems, introduced theoretically by von Neumann, are defined as systems in which a thing (cell, piece of software, machine…) can make a copy of itself[2]. In this research, the idea of self-replication has been represented by the cellular automata[3], popularized in John Conway's Game of Life in 70s, but widely investigated by Wolfram from mid 80s[4].

Examining this problem and its application in architectural design, the concept of cellular automata is used as a context in which a form can be, not just created, but finely tuned with the aim to achieve a controlled architectonics and spatial quality.

CELLULAR AUTOMATA

A cellular automaton is a discrete dynamical system. Space, time, and the states of the system are discrete. Each point in a regular spatial lattice, called a cell, can have any one of a finite number of states. The states of the cells in the lattice are updated according to a local rule. That is, the state of a cell at a given time depends only on its own state one time step previously, and the states of its nearby neighbors at the previous time step. All cells on the lattice are updated synchronously. Thus the state of the entire lattice advances in discrete time steps.

Conway's Game of Life - The GAME OF LIFE is a CELLULAR AUTOMATON devised by the British mathematician John Horton Conway in 1970. It is the best-known example of a

1 The paper is completed as a part of the project "Sustainable development and organisation of spa and tourist settlements in Serbia" which has been financed by the Serbian Ministry of Science and Technological Development.

2 Von Neumann, J.: The Theory of Self-reproducing Automata, A. Burks, ed., Univ. of Illinois Press, Urbana, 1966., (An online version available at: http://www.walenz.org/vonNeumann/index.html, accessed January 2009)

3 Frame, M.; Mandelbrot, B.; Neger, N.: Fractal geometry: Cellular Automata and Fractal Evolution, Yale University, 2009, http://classes.yale.edu/fractals/ (accessed January 2009)

4 Wolfram, S.: A New Kind of Science, Wolfram Media Press, Champaign, 2002

cellular automaton. The universe of the Game of Life is an infinite two-dimensional grid of cells, each of which is either ALIVE (populated) or DEAD (unpopulated or empty). Cells interact with their eight NEIGHBORS, the cells that are directly horizontally, vertically, or diagonally adjacent.

At each step in time, the following effects occur:

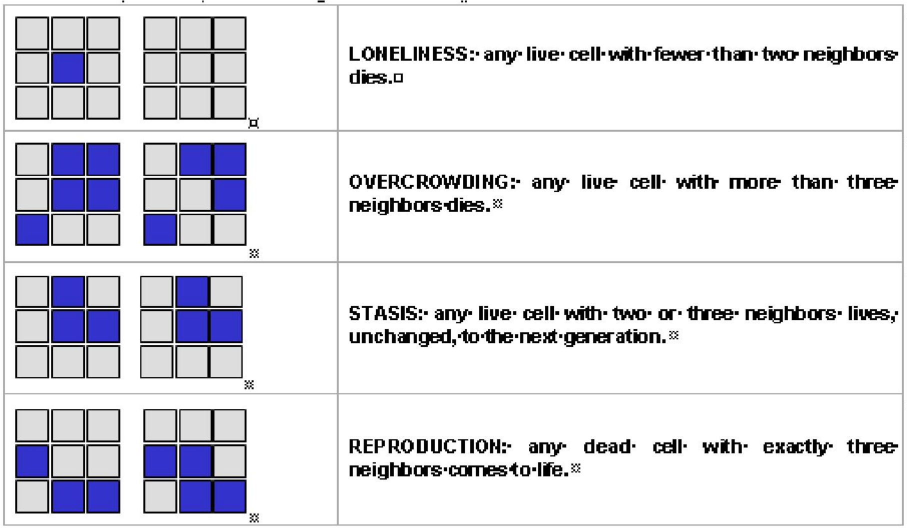

Figure 1 – The rules of the Game of Life, 2D

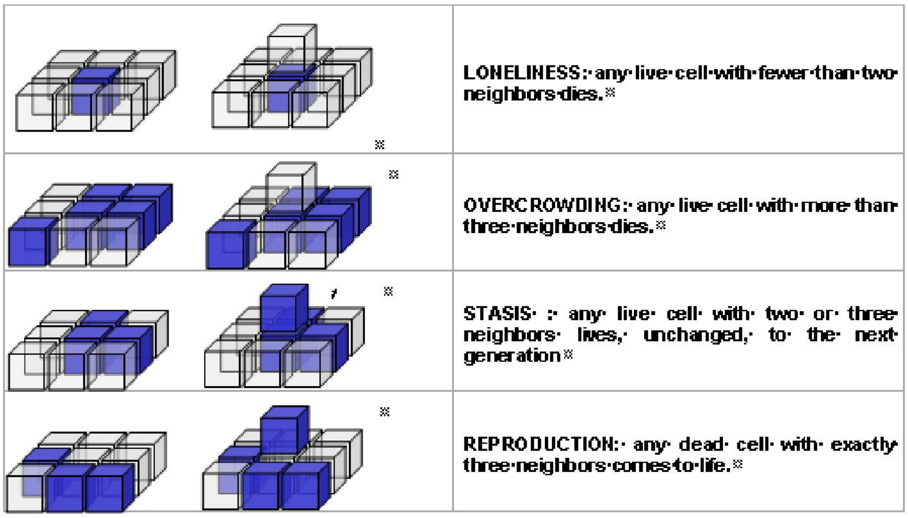

Figure 2 – The rules of the Game of Life, 3D Layers

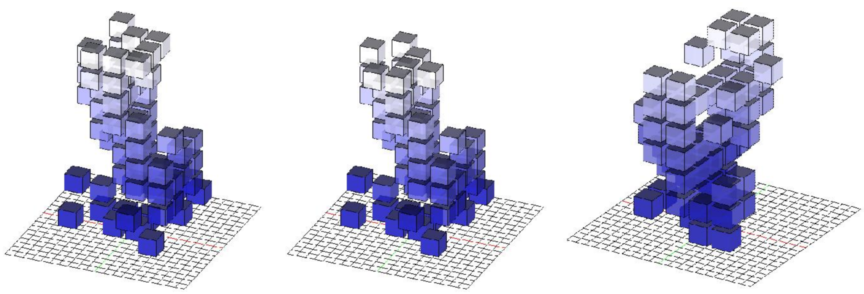

Figure 3 Typical CA spatial forms based on the rules of the Game of Life

The "game" is actually a zero-player game, meaning that its EVOLUTION is determined by its INITIAL STATE, needing no input from human players. One interacts with the Game of Life by creating an initial configuration and observing how it evolves.

The INITIAL PATTERN constitutes the first generation of the system. The second generation is created by applying the above rules simultaneously to every cell in the first generation -- births and deaths happen simultaneously, and the discrete moment at which this happens is called a TICK. The rules continue to be applied repeatedly to create further generations.

3D Layers Evolution View of the Game of Life - Considering a generative process as a set of layers instead of a change of a system single state, the flat cellular automata context becomes a spatial one, with a significant third dimension. The simple rectangular cell becomes a cubic block, reproducing itself in every following generation according to spatially interpreted rules of the Game of Life (Figure 2).

The layers of a single CA system, as shown on the Figure 3, define a spatial form that could be interpreted in different ways, depending of its own geometric characteristics and on a wider context.

PREVIOUS RESEARCH IN FORM GENERATION AND EXAMINING TOOLS

Distinguishing the CA computational method from other generative concepts, Krawczyk highlights its underlying recursive method that makes difficult to anticipate the future spatial form[5]. The series of spatial compositions (Figure 4) indicates a significant potential of the CA concept to be applied in early stages of architectural design.

Few years after Krawczyk's study, searching for efficient explorative tools, Martel has created the Form Generator based on Mathematica

[5] Krawczyk, R. J.: Architectural Interpretation of Cellular Automata, Generative Art Conference, Milano, 2002, http://www.iit.edu/~krawczyk/rjkga02.pdf (accessed January 2009)

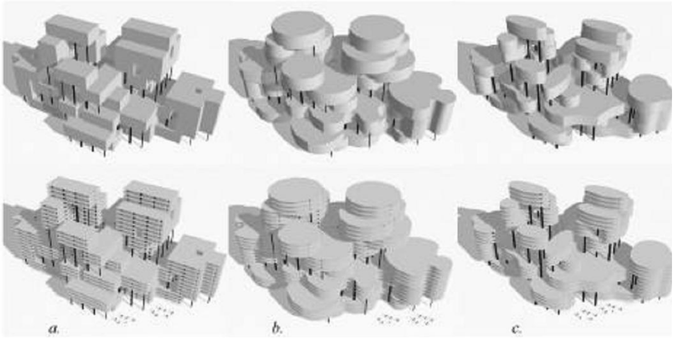

Figure 4 – The form series created by Krawczyk, 2002

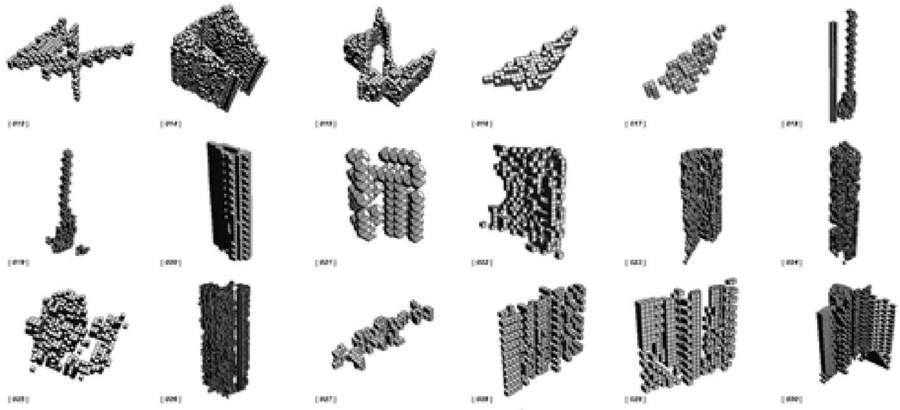

Figure 5 – The Form Generator by Maurice Martel, NKS Summer School 2007

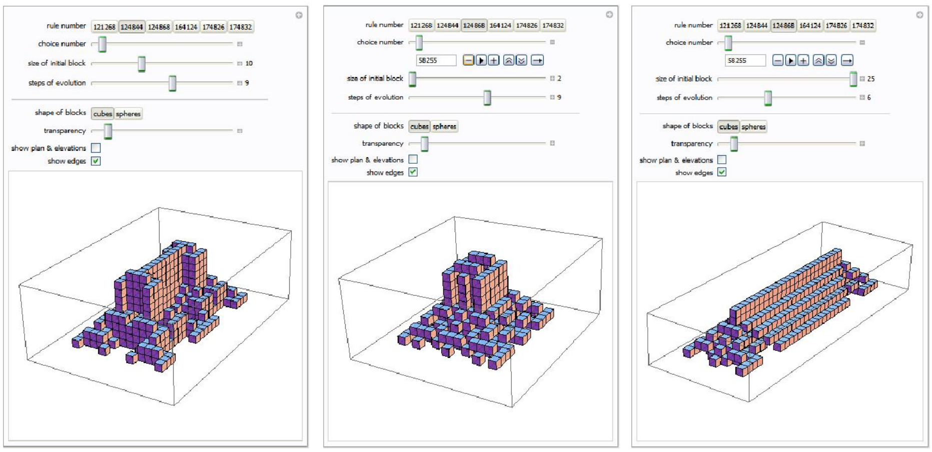

Figure 6 – A layered growth of spatial forms based on the CA concept; The Wolfram Demonstrations

software. The series of spatial forms on the Figure 5 represents his research within the NKS Summer School in 2007[6]. The generated spatial forms are based on a simple cubic cell, but the tool he proposes, seems to be more explorative in terms of the character of the resulting spatial forms.

None of the presented researches, however, offer a tool, that might be used for further examinations and research in other contexts.

Exploration of the CA concept has been supported by a range of stand-alone software, as well as Java based applets available online. The purpose of all these software is rather to visually explain the concept, than to produce some outputs, be it digital graphics, 3D model, or other kind of results.

One of the simplest and most inspiring tools that examine spatial growth of CA systems is certainly a freely accessible CA generator titled: Algorithmic Architecture with Cellular Automata[7], contributed by Jason Cawley and Stephen Wolfram within the Wolfram Demonstration project.

Within a range of educational demonstrations developed in Mathematica environment, there are examples of CA generators, visualizing spatial forms based on previously assigned rules. There's however a lack of software supporting generative process of 3D forms that could be exchanged with other CAD platforms, and therefore documented and fabricated.

The authors initiated creation of a software solution that could generate a spatial form.

THE SOFTWARE DEVELOPMENT

Fun3D (the name derived from "Function 3D") is a software developed by B. Mitrović, within the "Generic explorations" project. Its development begun with a module supporting creation of parametric curves and surfaces, continuing with another module aimed at creation of 3D L-systems.

The CA module of the software allows creation of CA based spatial form, as well as control of the following CA elements:

- Initial configuration (controlled by a graphic interface)
- Rule definition (totalistic)
- Total number of layers
- Position of a system (x, y and z coordinates)
- Rotation of the system (along x, y and z axes)
- Proportion of the cell (height, width and length)
- Color range of the cell layers
- Transparency
- Gap between cells of the system
- Lighting

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6 Meinberg, F.: A New Kind of Building, The Wolfram Blog, July 26, 2007, http://blog.wolfram.com/2007/07/ (accessed January 2009)

7 The demonstration is available at: http://demonstrations.wolfram.com/AlgorithmicArchitectureWithCellularAutomata/ (accessed January 2009). The title Algorithmic Architecture with Cellular Automata relates to the famous title by Kostas Terzidis

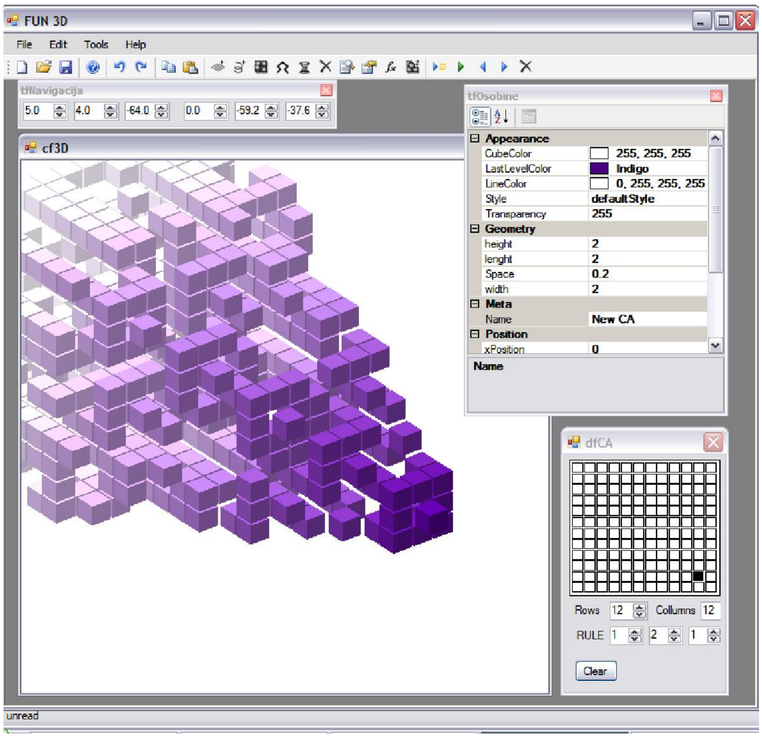

Figure 7 – Fun3D (created by B. Mitrovic, within the "Generic Explorations" project)

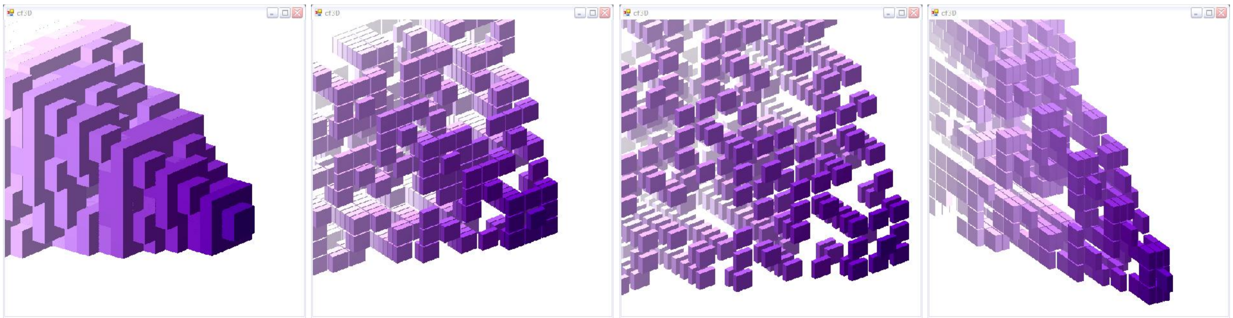

Figure 8 - Variations of the CA system based on the same rules

• Shadows

Variation of mentioned parameters, especially the ones affecting geometry, results in a range of spatial forms. A sequence on the Figure 8 represents variations of the CA system based on the same generative rule. As resulted forms have surprisingly different spatial characteristics, the Authors suggest a need for deep exploration in the field of geometry of 3D cellular automata.

The presented module can generate and visualize several CA systems within the same scene, each with different geometric parameters, and based on different rules. It also permits copying of an entire system and pasting it within the scene. Combination of various CA systems within the same scene, results in a spatial form of a significant complexity that needs to be additionally examined and interpreted.

One of the most important features of the CA module is export of dxf[8] file formats that makes the software fully compatible with a range of CAD programs.

Further development of the CA module, within the Fun3D software, includes some additional features both geometric and explorative. The geometric features that need to be improved are related to definition of a basic cell . The additional explorative features presume a possibility to chose particular segments of a CA space (universe), both vertically (along generations) and horizontally (in the initial cell layout).

The Fun3D software is protected by the Creative Commons license[9], which means that it could be freely used and redistributed, with mentioning its author (B. Mitrović) and the context in which it has been developed (Generic Explorations project, Faculty of Architecture, University of Belgrade).

THE EXPERIMENT

The CA module of the Fun3D software was experimentally offered to the group of 60 students of architecture, within the elective course "Generic Explorations". After being introduced with a theoretical basis of the CA concept, the students used the Fun3D software to examine possibilities of a spatial form creation. The main methodology in this experimental activity was the so called "research by design", the common methodology in architectural research[10].

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[8] dxf – data exchange format also known as drawing exchange format , widely used for exchange of 3D vector graphics.

[9] The Creative Commons Attribution license - this license lets others distribute, remix, tweak, and build upon a licensed work, even commercially, as long as they credit the author for the original creation. This is the most accommodating of licenses offered, in terms of what others can do with works licensed under Attribution. http://creativecommons.org/ (accessed January 2009)

[10] Foque, R.: Research in Design Sciences, in ADSC, No. 10-11, Department of Design Sciences, University

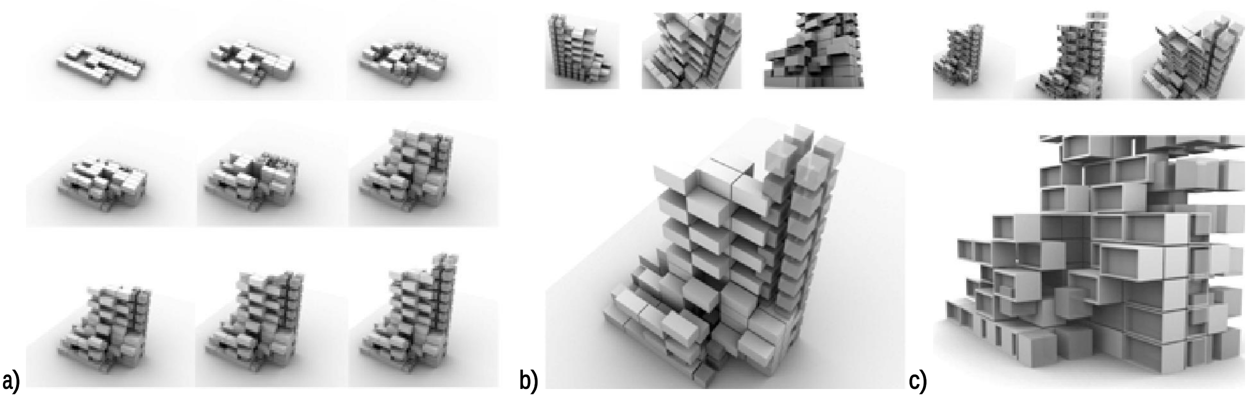

Figure 9 – Genesis of a CA based spatial form (Generic explorations 01/02, student Stanislava Predojević)

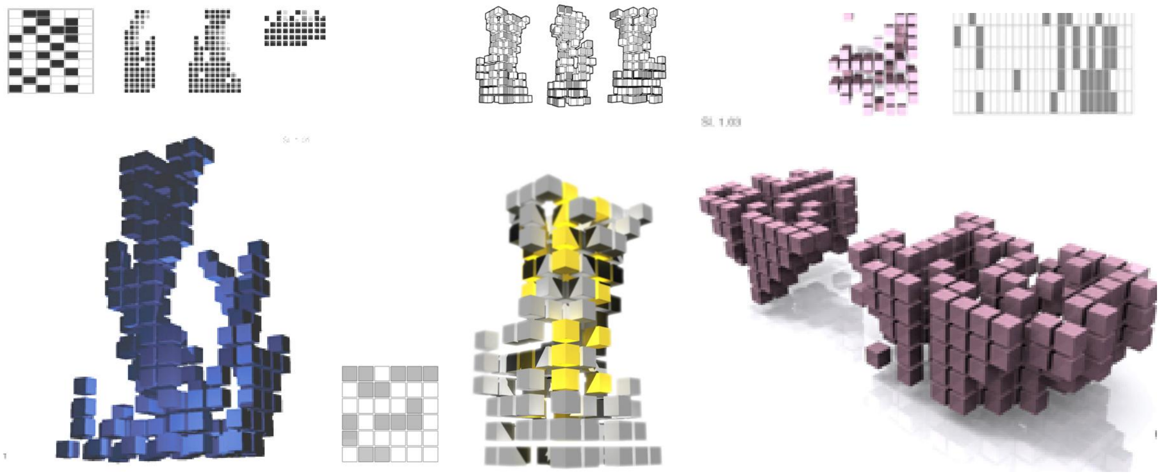

Figure 10 – Spatial forms generated with a simple cubic cell

The presented experiment consisted of three stages:

- The basic generation
- Combination of CA systems
- Contextualization

In each stage the students were asked to create an original spatial form or a composition, and to briefly present the main issues that occurred. Results from each stage are systematized and analyzed, according to some regularity that has been noticed.

The basic generation stage

The basic generation stage was the exploratory one, in which the participating students acquired the basic understanding of the potential of spatial form generation, based on a layered generations of planar (2D) cellular automata. Figure 9, a) illustrates this stage with a sequence of generative steps consisting of layers of cells, growing from the ground level.

This stage resulted in a variety of spatial forms which could be systematized in two characteristic groups. The groups are distinguished by the basic system cell which reproduces itself according to the rule of the chosen automatism.

The first group is created with a simple cubic cell and has an easily recognizable cellular structure (Figure 10). Spatial forms of this group are similar to the results of Maurice Martel (Figure 5). Their architectural interpretation would lead towards skyscraper structures or mega-blocks.

The second group of results in the basic generation stage consists of more sophisticated results (Figure 11). In the examples of this group some additional features of the software were applied, as well as some modifications in other visualization programs.

The combination stage

An original feature of the Fun3D software, allowing combination of multiple CA systems, resulted in the stage of the experiment, where students were asked to create a spatial composition consisting of several different systems.

The results from this stage (Figure 12) could be divided in two groups, the ones resembling mega-complexes, and the others indicating structural complexity of a single form. While the first group of the results appears in majority of cases, based on contrasts between the skyscraper-like systems and flat structures (Figure 12, a, b, c), the second group is incomparably more interesting. The second group of results combines multiple CA systems within a single complex form,

College Antwerp, Antwerp 2003; according to Savić, M.: Istrazivanje pristupa reformi visokoskolskih kurikuluma, u kontekstu stvaranja Evropskog prostora visokog obrazovanja,(Research on approach to reforms of the high school curriculum in context of creating the European space for high education), PhD thesis, Faculty of Architecture, University of Belgrade, Belgrade 2007

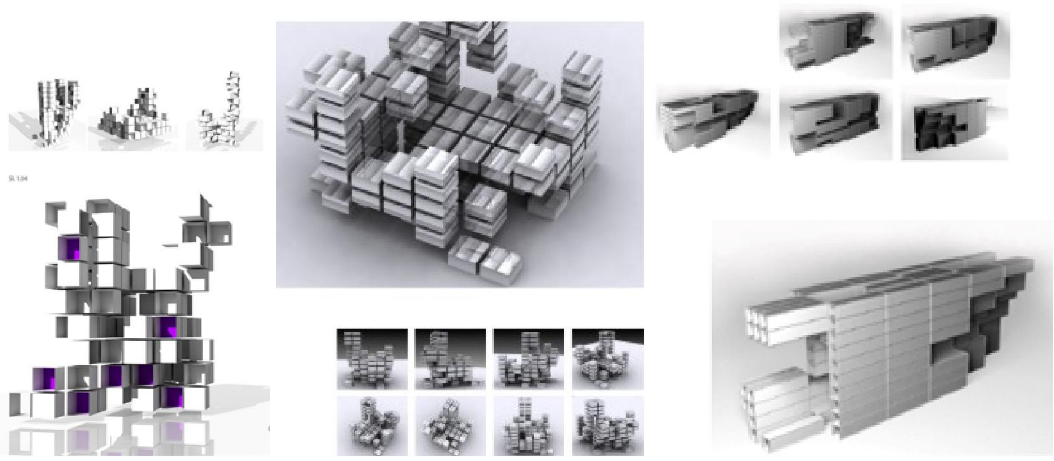

Figure 11 – Spatial forms generated with a modified cell

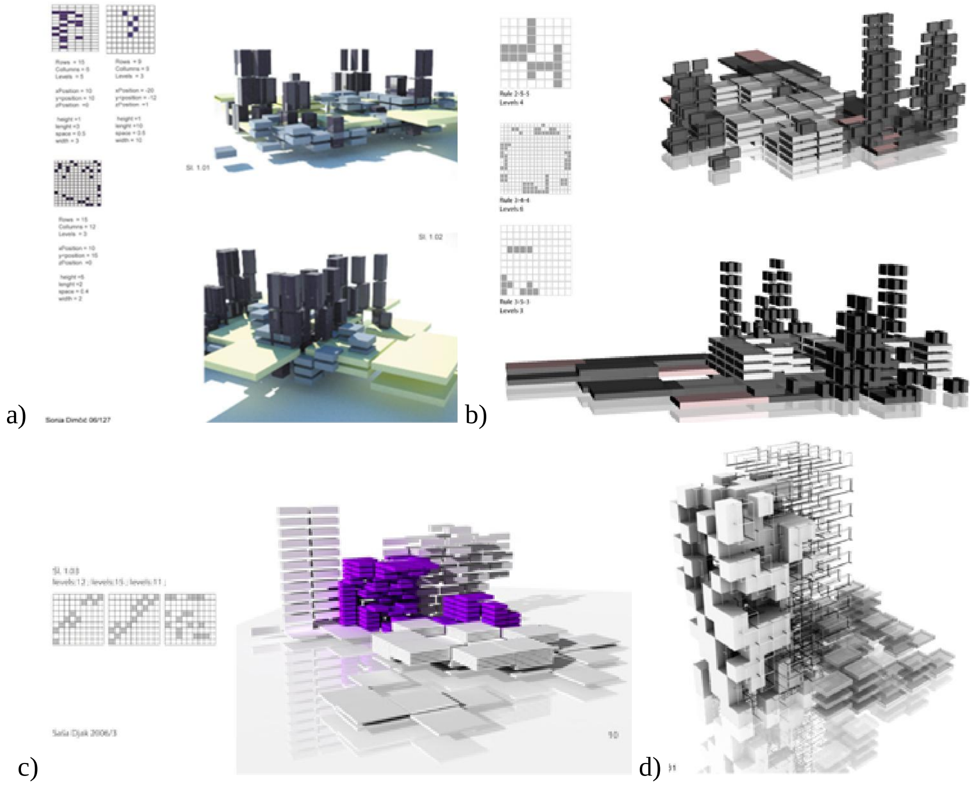

Figure 12 – Spatial compositions based on combinations of CA systems

indicating a possibility of structural interpretation of architectural form using the CA concept. The Authors here suggest that certain CA systems might be treated as a system of structural elements (such as slabs, columns, walls, etc.).

The contextualization stage and the major contextual references

Despite a remarkable architectonics of a spatial form based on the CA concept, some contextual references are needed to explain it scale, a possible function, a further signification in the wider environment etc., so that the form could be interpreted architecturally.

The final stage of the presented experiment is dedicated to the contextualization of a generated form, i.e. to the consideration of a context during the generative process. The context of interest in this study was a balneal touristic area, with its functional, social, geomorphologic, climatic, aesthetic and other characteristics.

The contextual references that have appeared in the presented experimental results could be systematized in the following groups:

- Human figure
- Greenery (various trees, plants, etc.)
- Landscape references
- Functional indications
- Built environment

While the physical references (i.e. human body, plant, other buildings etc.) explain the scale of the object, its monumentality and formal character, the function needs to be

Figure 13 – Contextualization of spatial compositions based on the CA concept

pointed out more explicitly, indicated by color, assigned material or textually explained.

Examples on the Figure 13 represent the CA based spatial compositions in an imaginary balneal context: a playground structure, a leisure area and a hotel complex, respectively. For each of the examples, and every single CA system, it is possible to make an architectural interpretation of the main elements such as the basic cell, the generative rule, and the generative structure.

CONCLUSION

The self-replication as a generative principle, represented in this research with the CA concept, could efficiently be applied in early stages of spatial form creation. Results of previous research activity in the field, obtained both theoretically and as a "research by design", indicate the significant potential that requires deeper explorations from a variety of view points. The presented research integrates mathematical basis related to the CA concept with an architectural point of view, offering some original approaches to the problem.

Creation of the software supporting the CA based spatial form generation, allows control of a range of geometric parameters within a single system, a combination of multiple CA systems, as well as data exchange with the CAD platforms. These features, together with its availability to the academic and professional community, make it a valuable exploration tool in the field of cellular automata applied in architecture. Its experimental use within the elective course "Generic Explorations", with participation of 60 senior students of architecture at the Belgrade University, resulted in a variety of approaches divided into the stages of initial generation, combination of CA systems and contextualization of the CA based spatial compositions.

The results presented in this paper are the base for some additional examinations of a possible architectural interpretation of all the elements of a CA system. Among the issues for further research, the authors also recognize the issues of prototyping of the CA based spatial form that should considerably differ from the fabrication of the spatial systems created with other generic concepts.

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References

Bogdanov, A., Manić, B., Petrić, J.: An approach to study of methods for urban analysis and urban fabric renewal in observation of a city as a multiple fractal structure. Arhitektura i urbanizam, (20-21), 51-60., 2007

Coates, P.; Healy, N.; Lamb, C.; Voon, W.L.: The use of Cellular Automata to explore bottom up architectonic rules, Eurographics UK Chapter 14th Annual Conference, Imperial College London UK, 1996 (http://uelceca.net/research/other/eurographics1996.pdf, accessed January 2009)

Frame, M.; Mandelbrot, B.; Neger, N.: Fractal geometry: Cellular Automata and Fractal Evolution, Yale University, 2009, http://classes.yale.edu/fractals/ (accessed January 2009)

Krawczyk, R. J.: Architectural Interpretation of Cellular Automata, Generative Art Conference, Milano, 2002, http://www.iit.edu/~krawczyk/rjkga02.pdf (accessed January 2009)

Maeng, D., & Nedović-Budić, Z.; Urban form and planning in the information age: Lessons from literature. Spatium, (17-18), 1-12., 2008

Meinberg, F.: A New Kind of Building, Wolfram Blog, 2007; http://blog.wolfram.com/2007/07/ (accessed January 2009)

Terzidis, K.: Algorithmic Architecture, Architectural Press, 2006

Von Neumann, J.: The Theory of Self-reproducing Automata, A. Burks, ed., Univ. of Illinois Press, Urbana, 1966. (An online version available at: http://www.walenz.org/vonNeumann/index.html, accessed January 2009)

Wolfram, S.: A New Kind of Science, Wolfram Media Press, Champaign, 2002

Other resources

Creative Commons licensing organization; http://creativecommons.org/ (accessed January 2009)

Fun3D software - http://code.google.com/p/fun3d/ (accessed January 2009)