Parametric Modeling for Advanced Architecture

M. Stavric[1] and O. Marina[2]

Abstract—Computer simulation of evolutionary processes is already well established technique for the study of environmental, biological and economic dynamics. Use of algorithms for generation of virtual entities that will develop its functional and formal properties within the non-linear process of adaptation of complex system is a foundation for new point of view in understanding architecture and urban environment. This paper describes parametric approach in architectural design through elaboration of shift in paradigms in architecture that has brought to the idea of use of parametric modeling with emphasis on two different groups of parametric software and presents the possibilities of generative algorithms in modeling architectural form and development of cities and urban design.

Keywords—geometry, parametric design, generative algorithms urbanism, architectural design.

I. Introduction

Description and explanation of a natural phenomenon within abstract mathematical framework has become very successful with introduction of calculus in 17th century. Physical phenomena of world around us have become reproducible without direct reference to physical reality. It was achieved with use of codes and equitation that represent the underlying order and regularities of represented phenomena.

The use of code in architecture as a formal and design convention has a long tradition. The transformations of those codes and constraints have determined development of architecture throughout history. With introduction of computation, codes in architecture could be understood as a set of instructions determining certain attributes of the formal entity or instructing a process of manipulation of the same.

The formalization of the design process and use of computation has opened an endless range of generative power of algorithms. This has enabled architects of today to create new environments with a system of codes that is coherent with the nature of the phenomena and in the same time to be creative. It is a moment of revelation in a sense of newly released power of codes and algorithms that contemporary architect can use to breed new forms rather than to specifically design them.

Digital modeling and visualization of architectural buildings has become the benchmark in the work of architects and is unavoidable in architectural education [19][24]. From the original 2-D programs used for drawing architectural designs, the software used for computer-aided design has now turned into intelligent 3-D software packages based on parametric modeling. These new possibilities have led to new movements in architecture and defined the field of non-standard architecture.

Judging by the latest trends, the development of digital design did not end with simple parametric modeling; it has taken a step ahead by using generative algorithms. Several software packages offer graphical algorithm editors (e.g. Coffee, Grasshopper), which are directly linked to 3-D modeling tools and allow interactive parametric modeling. These editors do not require any previous knowledge of programming or scripting, and yet they make it possible for designers to generate a broad range of non-standard designs that can be changed interactively. This new parametrically based approach in architectural design enables architect to search for a completely new level in form generating process. It is possible with design of non-standard objects that can be dynamically transformed to achieve a strong interaction and integration of design process with fabrication of architectural elements, or in the scale of urban plans with development of semantically enriched elements.

This paper gives a brief overview of parametric design using two distinct types of parametric software packages and presents the possibilities of applying of generative algorithms in modeling architectural form and development of cities and urban design.

II. Shift in Paradigms in Architecture

Dominant typologies that have served to legitimized the production of architectural and urban form since 18th century were either based on the idea of return of architecture to its natural origins – a model of primitive shelter as an imitation of the order of Nature, or emerging as a result of Industrial era – architecture as a process of production of functional parts [26]. In these concepts urban form is just an inert receptor of

M. Stavic is a researcher at the Graz University of Technology, Faculty of Architecture, Institut of Architecture and Media, Austria. Inffeldgasse 10/2, 8010 Graz, Austria (phone: +43-316-873-4738, e-mail: mstavric@tugraz.at).

O. Marina is Assistant Professor at Faculty of Architecture, University “Ss. Cyril and Methodius”- Skopje, Republic of Macedonia, blvd. Partizanski odredi 24, 1000 Skopje, Macedonia (phone: +389 2 3116367, e-mail: ognenmarina@gmail.com)

externally imposed order and therefore its form is predetermined by fixed typologies [4].

The order in classical architecture has been determined by formal tools or *techne* of composition connected with order and distribution of matter. The form is predetermined by formal typology organized and transferred in reality through canonical system of formal conventions and is encoded by social conventions through which building obtains social relevance within the built and social environment. The idea of architecture and urban form as an inert receptor of predetermined form originates in part from the dominant concepts of representation. Formal elements of architectural form represented in Cartesian three-dimensional space are determined by fixed coordinates of their points within the system. With this, elements of architecture are nothing more than a copy of ideal, platonic forms liberated of any trace of inherent order [5].

Most of the paradigms were delegitimized with the fact that the origin of the order of urban form was positioned outside the system instead to acknowledge the inherent order of the system as fundamental for form generating process.

With process of revision of Modernism dominant concepts in architecture are based on phenomenology directly confronting with functionalism and universal positivistic models of Modernism [9]. With this shift in paradigms and transcendence of concepts in architecture the interdependence of the inherent nature of phenomena of architecture and the process of its creation has become a new challenge. The nature of the architecture and urban form is inherently dynamic and cannot be determined by fixed types regardless of the vastness of the number of types. Therefore, the existing concepts in theory of architecture and urban form based on fixed typologies do not provide solid ground for understanding the process of creation of form and the phenomenon of urbanity in general. Solution of this situation can be reach only by radical change in the viewpoint: the architecture and urban form not to be conceived as a static system of predetermined ideal forms but rather as a dynamic system of changes that will generate a complex result.

The concepts of instability and de-centralization of identity [7] will be used in architecture to exclude existence of an ideal form [4] and to determine that the shape is a unique result of process of morphogenesis. As a result of this, the idea of form in architecture will shift from a fixed typology toward a historically convergent result of a form generating process in time, shaping unique and historic result that is coherent to the nature of the phenomena that we recognize as architecture. The emerging form will be a result of a process of morphogenesis as a historically embedded process of creation and adaptation [11].

With this shift in paradigms a theoretical ground for novel design tools and methods in architecture has been established. Within this theoretical framework the creation of a form can be understood as a process of *individualization* where every particular property of a distinctive element is a result of accumulation and interaction of different influences, conditions and restrictions, a process that is completely dependent on specific and historically contingent details.

Adjacent to this concept is the *topological paradigm* where identity and position of each of the elements or parts of it within the system are determined exclusively through its relation with all other elements within the system. Since there is no centre to dictate the predetermined form of elements of the architectural and urban form, formal order is established only by locally defined relations between the elements. This decentralized order generating process is distributed within, and in the same time dependant on a *population of elements*. So, instead of thinking in terms of a form defining centre the system should be understand in terms of population of elements. This *multiplicity* [6] of elements and local relations that create the order of the system are the source of a morphogenesis process. In a situation where a system of architectural forms is defined as a population of elements, we always have to specify the process of creation first, in order to have the idea of the overall form of the system. This process is inherently historic and it is based on the existence of differences between the elements. Without the existence of these *productive differences* that raise the process of adaptation and differences leveling within the system and the diffusion of novel and creative solutions within the population of formal elements there would be no morphogenesis.

These are the new paradigms and new concepts that should help us to construct a model of dynamic development of architectural and urban form. Therefore, in the next chapter we will introduce some of the concepts and softwares that are enabling the creation of form as a dynamic and parametrically determined non-linear process.

III. Parametric Design

During the past fifteen years digital media in architecture was used in different ways and influenced the whole field of construction and design. At the beginning digital media was applied only as a representational tool. With emerging digital technology architecture has found a new tool for conceptual design in digital media [22].

On the one hand architectural design was inspired by the various possibilities of digital technology itself. On the other hand many topics from different fields influenced the design. Former "invisible" mathematical and geometrical algorithms, forms and structures are now visible and spatial understandable for architects and, therefore, usable. Using new technique architectural design has established computational concepts such as: topological space (topological architectures), isomorphic surfaces (isomorphic architectures), motion kinematics and dynamics (animate architectures), keyshape animation (metamorphic architectures), parametric design (parametric architectures), genetic algorithms (evolutionary architectures) or fractal geometry (fractal architecture) as discussed in Kolarevic [14].

Generally in parametric design form is shaped by values of parameters and equations are used to describe the relationships between the forms. Hence, interdependencies between forms can be established and their behavior under transformation can be defined (mathematically and geometrically). Since about 1990 parametric design has influenced the development of digital architectural design, where we can distinguish between:

- architectural CONCEPTUAL parametric design and
- architectural CONSTRUCTIVE parametric design.

IV. Conceptual Parametric Design

In conceptual parametric design, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters different objects or configurations can be easily created. Rosenman and Gero, Prousalidou [18] analyze parametric and generative representations of buildings, whether based on orthogonal or curvilinear geometry (DeCOi [3]). They are powerful owing to their ability to capture a high degree of variation in a few numerical values. Software like Maya or Rhinoceros (with Mel or Rhino Script) offers such script editors for parametric design. Maya is software developed for film industry (primarily for animation and capturing) but lately many architects (Fig. 1) have used it for conceptual design.

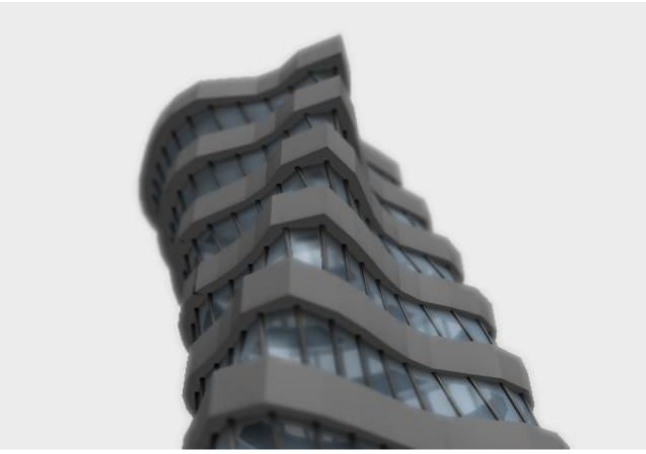

Fig. 1 Mel scripting, student Martin Schnabel, Institute of Architecture and Media, Course DM2

This design method requires knowledge of programming or scripting and it is inherent of the mathematical algorithms whereby interactive design is not possible.

V. Constructive Parametric Design

Constructive parametric design refers to data embedded within a predetermined 3D object. This parametric concept is realized in various CAD packages like Autodesk Revit, Soft Plan, Nemetschek, ArchiCAD or Chief Architect. Instead of drawing lines, arcs, etc. designers can insert pre-drawn components, doors, windows, load elements, stairs or roofs etc.

This results in 3D models instead of 2D drawings, which is already standard in ship-building industry. The objective of such technology is to reduce the drafting time and corrections to 2D drawings. We detected some limitations in such software tools. First, it is not possible to consider a wide range of different building materials to make one standard for all manufactures of building materials and components with the aim to provide an “intelligent” model. Second, these software tools are originally designed for standard building elements, whereas non-standard elements of contemporary digital architecture cannot be implemented [15].

In contemporary architectural practice there are some successful examples of using parametric design and we will discuss some of the projects.

Nicholas Grimshaw & Partners used parametric design for the arched roof of the train shed at the international terminal at Waterloo Station in 1993. Each arch and its related cladding are different as the roof width changes along the curved track. In this project only a single parametric model of one arch is modelled and different parametric controlled variations define the whole roof.

A bigger-scale project is the Hessing Cockpit Building within the alliance of the Acoustic Barrier in Utrecht, Holland (Fig. 2).

Fig. 2 Oosterhuis/Boer, Hessing Cockpit Building, Utrecht 2005

Kas Oosterhuis and Sander Boer proposed one parameterized universal detail for the whole structure, One Building – One Detail [2]. Oosterhuis/Boer provided a digital control model to the contractors, which allowed them to build all constructive details on top of this control structure. All steps are described as an Autolisp routine. The Swiss Federal Institute of Technology has realized three projects of complex forms: Swissbau Pavilion, Inventioneering Architecture, Libeskind’s Futuropolis (Fig. 3) in timber by implementing parametric design as early as at the beginning of the design process [21].

Fig. 3 Libeskind’s Futuropolis

Frank O. Gehry went one step further using fully parametric support for a whole building – from design to manufacturing. Frank Gehry and Associates formed 2002 Gehry Technologies (GT) [9] to provide integrated, digitally driven constructions and methodologies for the building industries. Frank Gehry starts projects by sketching and manipulating physical models. Using inverse engineering physical models are translated into Catia and projects are controlled and manufactured using computer-generated construction plans. At GT it is known what it will be, how it will be made and who will build it right from the beginning of the project. Teams of architects, engineers, and consultants work together in the same Catia database. The accuracy of the information and the elimination of middlemen reduce everyone's cost and risk, and make non-standard objects buildable. Gehry Technology is serviceable for big project teams working with the same database. This oversized technology is not useful in the case of standard architectural practice.

The whole projects were geometrically well elaborated and this enabled their realization within a digital chain process (from CAD to CAM). All three of them are very different in design and building strategies but they show the advantages of using parametric design methods.

VI. Generative Algorithms

Generative programming is a style of computer programming that uses automated source code creation through generic frames, classes, prototypes, templates, aspects, and code generators to improve programmer productivity. It is often related to code-reuse topics such as component-based software engineering and product family engineering. In the field of architecture such editors are tightly integrated with modeling tools that require no knowledge of programming or scripting, but still allow designers to build form generators from the simple to the awe-inspiring [12].

In order to explain the concept of generative algorithms in architecture, let us remind ourselves of the conventional method of digital design. Digital modeling involves the definition of spatial elements (solid or plane/surface), their transformation and modification. Each change in the design leads to modifications in the geometry, making it extremely complicated to intervene on every single element, which is directly interdependent with the other elements. With any such changes it is necessary to adapt, scale and reorient each individual element, which is very time consuming.

Generally speaking, two basic principles may be singled out when it comes to this type of design process. The first principle is associated modeling, i.e. the synthetic building of a structure based on the hierarchical functioning of objects and their interdependencies. The second is the generative principle, where one solution is selected out of many 3-D spatial configurations offered representing the optimal configuration. The selection criterion for the optimal configuration may be technical or aesthetic.

It is precisely these two basic principles of conceptual design that may be described by means of mathematical models and are contained in associated and generative modeling.

A. *Associated modeling*

Associated modeling refers to a method where elements are connected in a fixed order, which produces a result creating a basis for building a new order. Let us draw a curve and quadrilaterals at its beginning and end whose dimensions will depend on the curvature of the line at its initial and final points. If we change the form and position of the curve, the associated quadrilaterals will change their positions and sizes. This method of design extracts the required parameters from the designed structures and manipulates them using the right algorithms.

B. *Generative modeling*

Instead of drawing a structure, generative modeling uses numbers as the input data. Designs are generated by means of mathematical operations, dependencies and functions. Any structure designed in this way contains a great number of variables within its internal structure, which may be used as the next step in the design process. This kind of modeling allows maneuvering in the development and generation of the design which is not possible when using standard 3-D modeling tools.

For example, let us take the range of integers 1-10 and use a random number configurator to generate three different numbers representing the spatial coordinates of three distinct points in space. The generated spatial points define a NURBS geometry. Every time the spatial coordinates of any of the input points x, y or z change, the generated surface automatically changes its geometry and adapts to the new variables.

C. *Generative algorithms in architectural design*

Modeling which uses associated and generative modeling is called generative algorithm modeling. This process has the term algorithm in its name because objects are generated using algorithms in this type of design and their output for the further stages of design is also generated by means of algorithms. When it comes to architectural design, Grasshopper is one of the most commonly used generative design editors [13][16]. This editor is connected to Rhino 3-D objects and offers a range of mathematical tools for generative modeling such as operators, conditional statements, functions and trigonometric curves (Fig 4).

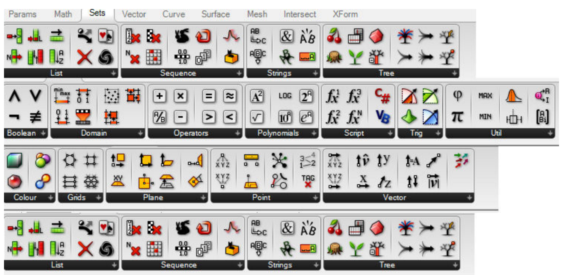

Fig.4 Grasshopper mathematical operators

There are operators from the branch of analytic geometry for vectors, points and planes. The list and data management is a very important segment as it allows extensive database manipulation. In terms of advanced modeling options, it is possible to use scripting in VB.NET, rhino. NET SDK (it allows access to OpenNURBS geometry) and C#.

The operations and analysis of associated elements make it possible to select from a number of options for NURBS geometry and somewhat fewer options for mesh objects.

D. Parametric urbanism

Contemporary urbanism tends to embrace a dynamics of the material and social process that are shaping contemporary cities [8][23]. It is based on form finding process organized by networks of interrelated systems. This novel paradigm and theoretical ground determines the city form as dynamic, non-linear and mostly parametric phenomena. However, the ramification of these new paradigms and concepts and their application in novel design and production tools for urbanism have widely remained untheorised and have not been exercised in practice.

The foundation for application of general theory of computing in urbanism is in the effort to formalize the dynamics of development of urban form as a procedure, a sequence of logical steps. By shifting the focus from the matter toward the organization of the system of urban form in general, the essence of this process will be determined as a set of rules regardles of materiality of the phenomenon. This abstraction of the phenomena to a level of abstract organizational structure enables us to think of it as a complex system based on simple, locally determined rules.

Parametric approach to urbanism addresses the ways in which associative design systems can control local dynamic information to effect and adjust larger urban life-processes by embedding intelligence into the formation, organization and performance of urban spaces, uses, activities, interfaces, structures and infrastructures [25]. Built environment is the biggest and most complex creation of mankind. Its complexity and vastness comes from a process of continous creation of urban form not only as a physical objects but as a proces of creation of spatial, social an cultural relations. Dependance of form creation process on these configurational aspects of urban form determines the importance of understanding the same. By this proces of transformation of preexisting condition and creation of new order within the physical reality and new configurations of space social meaning and relevance is added to an act of construction and form creation. With this architecture becomes socially relevant and meaningful. With this system of architectural form becomes the spatio temporal manifestations of configurational order realised througs physical elements.

With creation of a basic element of architectural form – spatial cell the elementary configurationally relation between inside and outside is created. Through process of addition more discreet elements are created that generates complex configurations of physical and spatial structures.

These elements and their spatial relations and configuration of the system in general are represented through system of cellular automata (Fig.5).

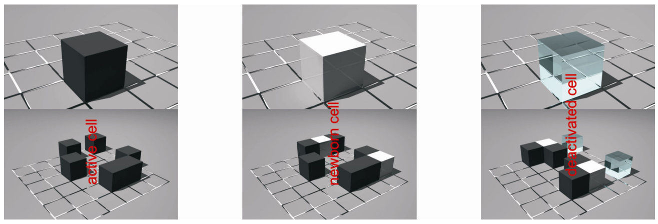

Fig. 5 Cellular automata model

The condition of each of the cells will be determined as result of interaction and accumulation of different locally embedded rules rather than by an exterior, order imposing centre. In this model use of cellular automata is additionally justified with spatial and representational similarity between elements of urban form (buildings, lots, streets, squares and others) and discrete cells as elements of the model [17]. Furthermore condition of each of the elements of urban form that is beyond its formal aspect (property rights, legal status and others) can be represented with binary determined condition of the system of cells (Fig.6).

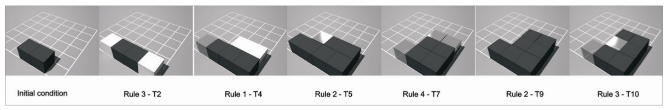

Fig. 6 Cellular automata model of development of architectural form

The complexity of the system comes from a locally driven set of simple rules that induce continuous adaptations and changes on local level, but with an impact on the overall condition of the system. It enables us to generate complex and novel shapes and configurations as a result of a dynamic, nonlinear and locally driven morphogenetic process (Fig. 7).

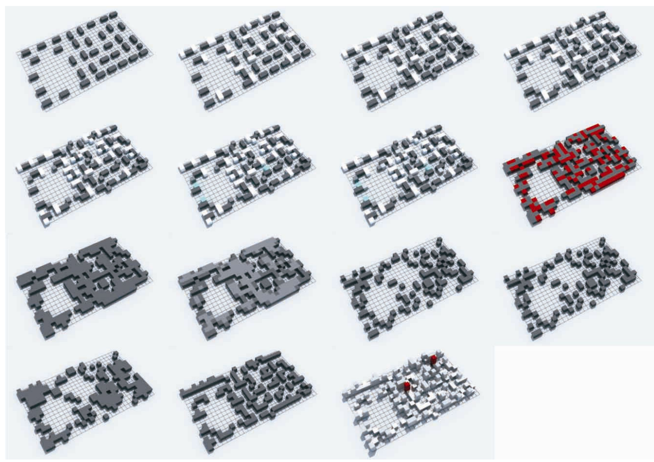

Fig. 7 Cellular automata model of development of urban form in residential area in Skopje

These new structures are more than a sum of their parts and are not predetermined or preconceived by any means. They are a result of a historically embedded process of creation, which is driven by locally conditioned simple rules and constrains. To breed new designs of the city form these rules need to be manipulated and to contain principles of growth [1]. These rules reflect a genetic code in that they orchestrate the response of the parameters and elements of the system (lines, surfaces, objects, cells or even a single attribute determined entity) to the influence of diverse agents and conditions within the system, creating an emergent order. The result is surprising in the way that final shape is a result of a bottom-up emerging order and is dependent on sequences of random, interrelated and local interactions.

The digital tools used to model cities with parametric approach and to generate different urban forms are widely available as packages that use cellular automata, agent-based models, associated or generative modeling and other systems in digital urbanism. These are the tools that give us the potential to understand, update and improve the process of creation of cities where non-standard methods coherent with the nature of the phenomena of city can be conceived to confront the banality of repetitive, arbitrary and pre-determined form production on the city scale.

The following case may serve as a quick explanation of how to use the generative algorithm method in urbanisms.

Task definition: Generate a surface based on the given topological coordinates and determine the optimal conditions for the location of the principal thoroughfare (the conditions are technical: inclination and curvature by means of osculating circles). Based on the results define areas of different housing quality (conditions: proximity to thoroughfare, terrain topology). The urban structure was generated using the graphical algorithm editor Grasshopper. The first step in the modeling process involved generating the topological coordinates (x,y,z) which were used to create a NURBS geometry of the terrain (Fig. 8).

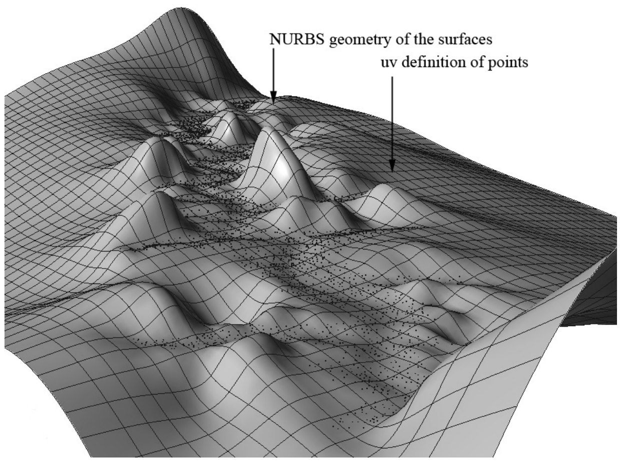

Fig.8 Surface definition with u,v parametar

The advantage of using the NURBS geometry in comparison with the mesh geometry lies in the fact that significantly less data is used and the modification of the existent geometry is simpler as uv parameters are used. At Fig. 9, NURBS surface is defined with the set of points and uv value is extracted from the final form.

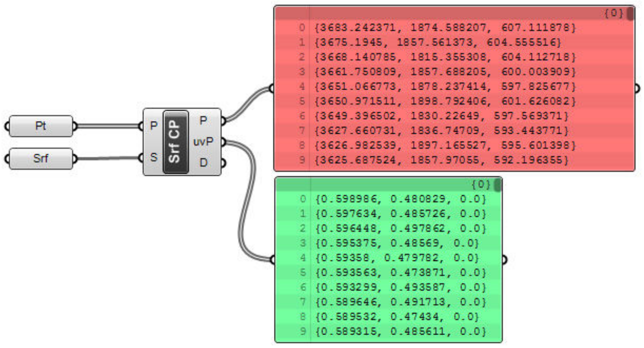

Fig.9 Space coordinates and uv values of the points

This is possible because spatial coordinates are reduced to parameters located in the 0-1 domain- uv domain. Note: The z coordinates of the points are scaled for the purpose of better visualization of the terrain morphology.

The next step involves generating the horizontal contours. These contours are obtained as the given surface intersects the planes running parallel to the xy plane. Depending on the complexity and intricacy of details in the terrain generated in the further stages, various horizontal distances between the contours are also defined by means of parameters. All the contours are generated as a 3rd-order spline curve (Fig.10).

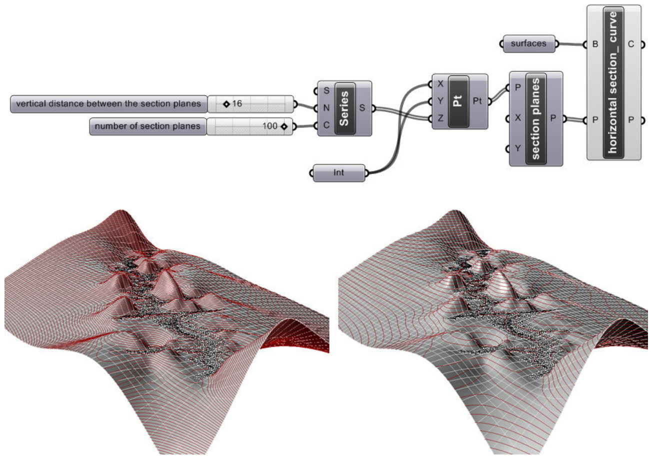

Fig.10 Parametric definition of intersection plane and results for two intersection distances

The generated horizontal contours are used to determine the optimal route location in relation to the position of the selected coordinates. All coordinates are associated to Rhino geometry and the proximity to the principal thoroughfare is analyzed, used to differentiate between different housing quality zones (Fig. 11 and Fig. 12).

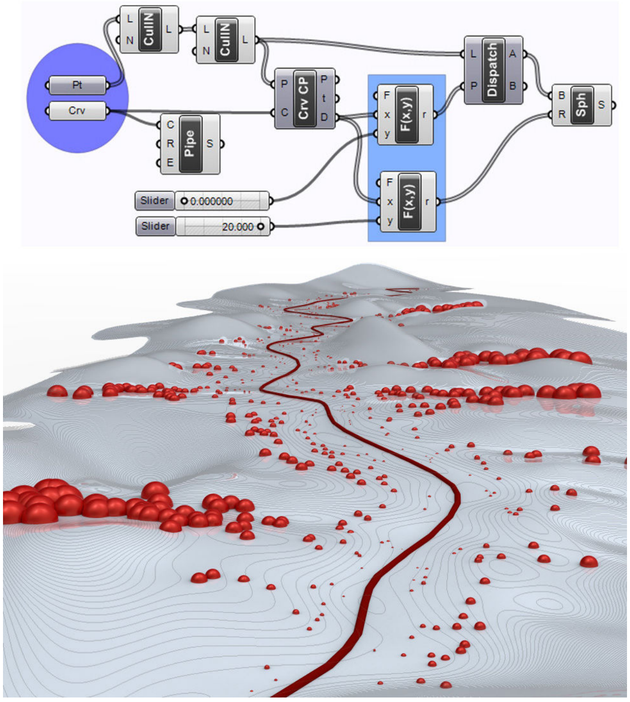

Fig. 11 Visualization location of urban elements based on housing quality standards; parametrical and virtual model

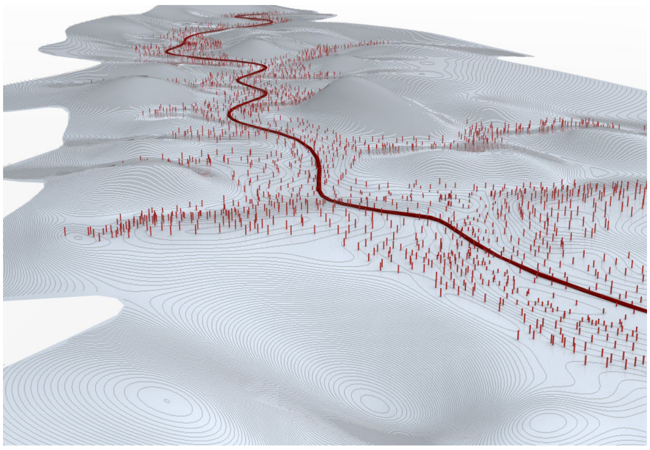

Fig. 12 One of the infinite options in generating parametric design

VII. Conclusion

In the age of digital parametric non-standard architecture, mathematics and geometry represent the core of the architectural design process. It has a central role from the initial stage of finding form, shaping form, generating form, to the process of manufacturing architectural elements. Contemporary computer technology allows the application of a number of tools for the design, analysis, simulation and manufacturing of complex architectural forms. In the process of design, today's leading architects as well as leading schools of architecture use different software packages and digital technologies, thus contributing to the formation of a new aesthetics of digital architecture. On the one hand, technical possibilities open up new horizons in architecture, while on the other, they give rise to new issues related to the disciplines of mathematics and geometry.

Acknowledgment

This work is supported by the Austrian Science Fond under grand T440-N13 and COST Action TU0801.

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Milena Stavric,born in Belgrad (1969), BA in Architecture and Urbanism, (1993), MSci in Architecture and Urbanism (2000), PhD in Architecture and Urbanism (2002) at Faculty of Architecture, University in Belgrada, Serbia. 2006, PhD nostification at the Graz University of Technology, Austria
She holds position of Researcher at the Graz University of Technology, Faculty of Architecture, Institut of Architecture and Media, Austria. She is lecturer at the Faculty of Applied Science Johanneum, Graz, Austria and visiting professor at the Faculty of Architecture and Civil Engineering in Banja Luka, Bosnia. She is involves in several scientific researches: Austria Scientific Fond (WFW), "Non-standard architecture using ornaments and plane elements"(2009-2012) and „Geometric Processing in Architectural Education"(2010-2013). She had a scholarship from BMWK (Austrian Federal Ministry for Science and Research) for projects: "Comparative Analysis of Education of technical Students in Field of Geometry at TU Graz and University of Belgrade"(2003) and Generation of Surfaces of Higher Orders in CAD-systems and its Applications in Engineering Practice" (2004) - Mach Grand Grant.
Milena Stavric is active participant of COST TU0801 Action: Semantic Enrichment of 3D City Models for Sustainable Development and she has participated with her work at several scientific conferences (Bremen, Sydney, Taipei, Montreal, München, Dresden, Zürich, Chaing Mai, Dresden, Vienna, Faro…).

Ognen Marina, born in Skopje (1972). BA in Architecture and Urbanism, (1997), MSci in Architecture and Urbanism (2006), PhD in Architecture and Urbanism (2010) at Faculty of Architecture University "Ss. Cyril and Methodius"-Skopje, Republic of Macedonia.
He holds the position of Assistant Professor at Faculty of Architecture, University "Ss. Cyril and Methodius"-Skopje, Republic of Macedonia. Faculty Research Associate at College of Architectural and Environmental Design at Arizona State University, Arizona, USA, for a period of 2002-2003.
Dr. Ognen Marina is a memeber of AAM-EAAE (1997) and ENHR (2010) and has participate with his work at several scientific conferences and meetings ENHR2010 in Istanbul, IABSE 2010 in Venice, PBE 2010 in Brno, WSEAS 2010 in Faro and others. He is active participant of COST TU0801 Action: Semantic Enrichment of 3D City Models for Sustainable Development. His core interest is in development of dynamic models of developemt of urban form, use of digital tools for better understanding the urban phenomena and interdependance of process, form and materials in architectural design.
Ognen Marina, besides its research work is active in architectural design and competitions and has received many awards in the field of architectural design. He has participated in architectural exhibitions at BIMAS (2000-2008) Skopje, Belgrade and at the XXII UIA Conference of Architecture in Istanbul.