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SHAPE GRAMMAR IN CONTEMPORARY ARCHITECTURAL THEORY AND DESIGN*

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Abstract. *In the past decade, digital technologies had a great impact on contemporary architectural practice, design and theory. CAD/CAM technologies opened up new opportunities by allowing design and production of complex geometric shapes. One of the first applications of computational process in architecture was based on using shape grammars, a rule-based expert systems in artificial intelligence generating geometric shapes. Early applications of shape grammars in art and architecture started shortly after its invention during the 70ies and 80ies of the XX century, however, their potential as a generative design tool still has not been fully exploited in practice. Despite their popularity in academic circles, shape grammars have not found a widespread place/usage in computer aided architectural design.*
Role of shape grammar as a generative design and analysis tool and their influence on contemporary architectural design and theory are examined in this paper. Also, new and ongoing issues concerning shape grammars are discussed in order to indicate further directions of their usage.

Key words: *shape grammar, rule-based systems, computational design, procedural modeling.*

1. INTRODUCTION

Most architects today use computers as an efficient representation tool for modelling and drafting architectural forms. One of the first applications of digital technologies in architectural practice was related to writing scripts, which is a set of instructions assembled in order to solve complex design problems providing *help* with the *decision-making* process.

During the second half of the 20th century, a number of architects recognized computation as a powerful tool for solving certain architectural problems. In the 60ies Allen

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Bernholtz and Edward Bierstone utilised computational algorithms in order to decompose complex design problems into simple sub-problems and then to recompose a solution [1]. At the same time, computational algorithms were used in calculation of tensile structures for the first time. One of the first attempts of using computational approach in art and architecture started with work of George Stiny and James Gips. In their seminal article published in 1971, they founded Shape grammar, first design-oriented generative system [2]. Five years later another Stiny's text "Two exercises in formal composition" became the foundation for many applications of shape grammars in architecture [3]. Up until today there exists practical concern for shape grammar in architecture, but it has not been fully implemented in conventional CAD applications.

An overview of the roles of shape grammar applications in architectural design, practice and ongoing issues are presented in this work. The objective of this paper is to describe, analyze and evaluate different approaches as well as to reveal new directions in usage of shape grammar in the future.

2. SHAPE GRAMMAR IN COMPUTATIONAL DESIGN AND CONTEMPORARY ARCHITECTURAL THEORY

The term shape grammar may be described and considered on two levels - computational and visual-spatial.

In computational theory, shape grammars are specific classes of rule-based expert systems in artificial intelligence which generate geometric shapes. A shape grammar consists of shape rules and a generation engine that selects and processes rules recursively, starting from an initial shape. Rules are used to specify a way of replacing particular shapes and to describe the manner of replacing. Underlying the rules are geometric transformations i.e. translation, scale, rotation, reflection, that permit one shape to be a part of another [4]. A distinctive feature of shape grammar is that a set of finite number of rules and shapes may generate an indefinite number of design solutions. Moreover, it can be used as an analysis tool, for decomposition of complex shapes and as a synthesis tool, generating complicated forms starting from a simple shape [4].

Shape grammar can also be defined as a formalism to represent visual, or even spatial, thinking. The phrase 'shape grammars' more literally refers to visual design grammars. In that sense, shape grammar represents the philosophy of looking at the world that is not through learnt or imposed decompositions, but through those that have a practical meaning at that point in time [5]. It is important to emphasize that spatial aspect of shape grammars was crucial for its implementation in contemporary architectural theory and design framework. Application of shape grammar in architectural theory and design had a history four decades long. In the academic circles of architects, shape grammar was adopted long before conventional drafting CAAD (Computer-aided architectural design) tools were developed.

Generative grammars is a notion originally coined to describe natural languages, but found other multiple applications very soon. It was introduced in theoretical linguistics by Noam Chomsky in the late 1950s, and it was very important in creating and development of formal grammar and rule-based systems in computer science theory. Relying on logic of Chomskyan generative grammar, shape grammar is also based on usage of formal language semantics and formation rules. Differing from classical rewriting grammar, shape grammar

symbols are rewritten to represent geometric entities. In other words, rule-based system relying on shape grammar became a framework for computational theory of design.

One of the key concepts in architectural theory in the second half of the 20th century was the concern for architectural elements. Analogy between traditional grammar in linguistics on one side, and language of geometric transformation and architectural elements on the other, was very influential among certain circles of architects in the 1970s. Peter Eisenman was among the first architects who explored application of generative grammar in architecture inspired by Chomskyan linguistics theory. Generative grammar was a theoretical framework for the series of his housing projects in 1960s.

Unlike Eisenman's approach, shape grammar has also been used in exploring new aesthetics generated by computational algorithms. The "essence of the architectural type" that relied on the new computational medium quickly became an interesting subject matter in design education [6].

In the late 1980s, Harvard Graduate School of Design introduced the first programming course obligatory for architects. TopDown software suitable for architects, was written mainly at UCLA by Robin Liggett and William Mitchell and it partly dealt with shape grammars logic. The course did not achieve expected success because students were asked to engage in the actual coding process [6]. However, many shape grammar related projects of that time, including the previously described example, imply great potential in the field of architectural heritage, design and theory. In architecture shape grammar applications have been used for the purposes of synthesis and analysis and as a combination of both approaches. Evolution of shape grammar in the context of computational design and contemporary architectural theory is given in Fig 1. This organization chart is designed to summarize the development of the key ideas that lead from the foundations of the shape grammar in architecture to the recent investigations. To estimate future tendencies of the shape grammar applicability in architecture, understanding of this transformation process is crucial.

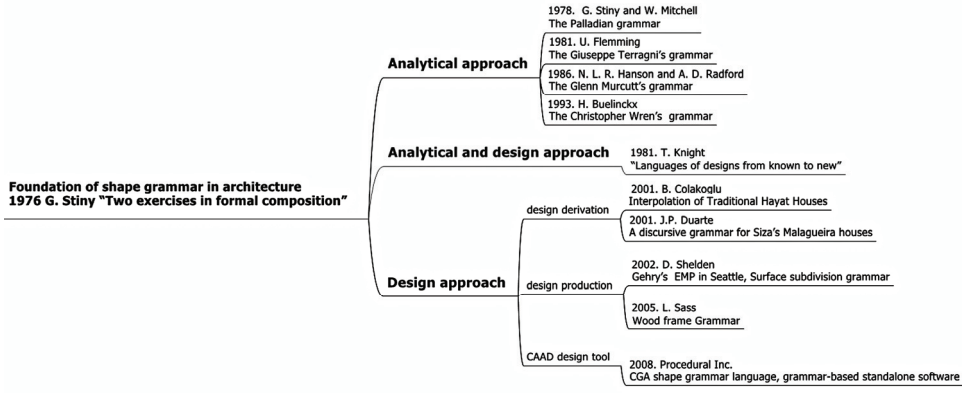

Fig. 1. Evolution tree of the shape grammar application in architecture.

Described analysis of the shape grammar development and sequential transformations in the means of applicability improvement, provides evidence that many architects recognised great advantages of this approach. Use of a shape grammar as an analytical tool and

as a design tool in the area of architecture and urbanism is given in the following sections. The most influential examples are evaluated in order to reveal expected directions of future development.

3. SHAPE GRAMMAR AS AN ANALYTICAL TOOL

Until the last decade of the twentieth century, application of shape grammar was developing as a tool for analysis. Through its first applications, shape grammars became an established paradigm in the theory of computational design.

The first analytic study with shape grammars was given by Stiny in his 1977 paper, "Ice-ray: a note on the generation of Chinese lattice designs", setting the layout for the shape grammar application standards in further research [3]. In the next year, Stiny and Mitchell published the work "The Palladian grammar" that initiated an ambitious and influential research on how shape grammar can be used in a study of an architectural style [7]. They proposed a method based on parametric shape grammar for generating ground plans of Palladio's villas as a definition of the Palladian style. Specifying the shape grammar rules, they recast parts of Palladio's system of proportion and "architectural language" in a modern, "generative form".

Rules defined in "Palladian Grammar" were based on examples of villa plans drawn in the Quattro Libri dell'Architettura by Andrea Palladio in 1570. Mitchell and Stiny followed Wittkower's opinion about ground plans as the most distinguishing feature of Palladio's villa, and that is why other aspects of Palladio's architectural system, such as decorative elements or villa facades, are not considered in their work [7, 8]. As Stiny and Mitchell noted, the definition of Palladian style by use of the parametric shape grammar, initiated other issues and questions of aesthetics and historical interest to be investigated. Grammar, for example, can be used to distinguish stylistic features in neo-Palladian movements that are canonical in Palladian sense from those that diverge from Palladio's standard architectural usage [7].

In the following years, analytic grammar has been extensively used in numerous works, revealing general strategies and creating a knowledge base for understanding particular architect's composition. During the 80's and 90's, shape grammar was used to analyse works of Giuseppe Terragni, Frank Lloyd Wright, Glenn Murcutt and Christopher Wren [9-12] as well as for the vernacular styles of Japanese tearooms, Taiwanese traditional houses and for the landscape architecture of Mughul gardens [13-15]. Among these works, the Koning's and Eisenberg's grammar written for the Frank Lloyd Wright's prairie houses are notable for being the first three-dimensional architectural grammar, inspired partly by Stiny's earlier work on kindergarten grammars and the alleged influence of Froebel on Wright's architecture [3,10].

Compositional forms for Wright's prairie-style houses are derived from shape rule schemata. Establishing the location for a fireplace was crucial, since it takes the central place in Wright's prairie-style houses design [10]. Once a fireplace is established, living zone and service zone can be added by schemata 3-7 (fig. 2). The basic compositions enumerated in Figure 2 can be further refined through the design process.

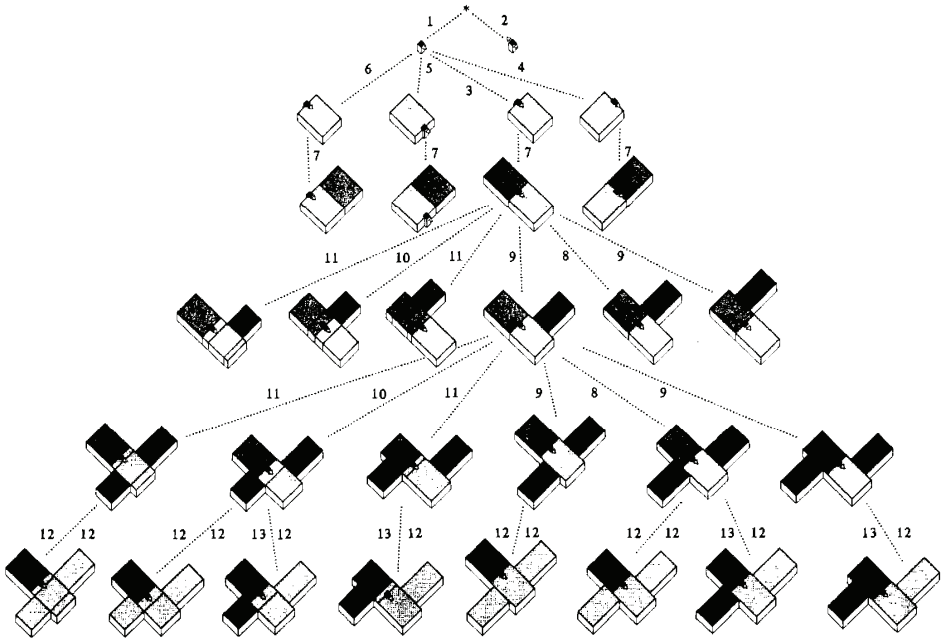

Fig. 2. Koning's and Eisenberg's compositional forms for Wright's prairie-style houses.

Implementation of shape grammar as an analytical tool was even more broadened in past decade. According to the presented development of the shape grammar that was used for the analysis of architectural objects, we conclude that shape grammar as an analytical tool has an important role in previous and future researches in the area of architecture. Expansion of digital technologies and constant refinement of its practical use in the studies of architecture provides a necessary base for a high potential new approach.

The main issue is not based on modelling geometrically and historically accurate buildings, but based on qualitatively correct model that define complex dependencies between architectural elements. In that sense, analytic grammar can serve as the platform for studying architectural typology on more complex levels that cannot be carried out without the appropriate computational background.

4. SHAPE GRAMMAR AS A DESIGN TOOL

Developing new, original designs by using shape grammars emerged from analytic approach and combining existing rules and grammar language. In 1981, Knight proposed a method for creating new grammar language and design based on the existing one [3,16]. Starting from a known style, its spatial relations and underlying grammars, she transformed rules in order to create a basis for the new grammar and style. As Knight noted, it can be used to characterize the historical evolution of known styles into

succeeding ones as well as to develop new designs [3]. Therefore, this approach to shape grammar is both analytical and synthetic.

In the early 90ies shape grammars were used for teaching architectural composition. Students of architecture at MIT, Harvard, UCLA and Yale used the shape grammars to learn about the architectural design language of certain buildings and apply various modifications in order to generate their own new languages.

In the following years, shape grammar was more developed as a generative design tool within research projects in the Design and Computation PhD program at MIT. Within their PhD studies and further scientific research, Birgul Colakoglu, Jose Duarte and Lawrence Sass gave a noticeable contribution to the utilisation of shape grammars as a generative design tool.

Birgul Colakoglu explored the application of an informal shape grammar in order to form new house designs that carry stylistic characteristics of an existing traditional "Hayat" houses designed in the Ottoman style in 18^{th} and 19^{th} century in Sarajevo. New house forms were intended to be used to generate "interpolations" of the existing type in a given architectural context [17].

Jose Duarte developed shape grammar system based on Alvaro Siza Vieira's Malagueira housing projects. Duarte's grammar based system was able to derivate houses based on the work on housing projects for living that were still being designed and constructed. Duarte's shape grammar was based on the corpus of the thirty-five houses designed by Alvaro Siza at Malagueira, near Evora in Portugal, between 1977 and 1996. The Malagueira grammar was developed with Siza's support and therefore it could be perceived as a natural extension of Siza's work at Malagueira [18]. According to Crisman, even Siza himself, could not accurately discern between houses that he designed and those that were derived by computer programs [19]. The work of Jose Duarte was significant because he proposed a successful model with the ability for generating diverse non repetitive mass housing.

Another significant contribution of shape grammar application in architectural design is given by Lawrence Sass. In his research projects in the past several years, Sass introduces a novel method to generate house designs completely from 3/4" plywood sheet using a shape grammar routine and CNC fabrication process [20]. Shape grammar routine is used to subdivide initial solid shape into constructible components for digital fabrication on CNC cutting machine. Sass' approach is addressed to the fast and transportable housing production based on changing needs for a digital fabrication that are low cost and custom designed [5]. According to Sass, his approach provided an efficient solution for the improvement of low quality connections between panels of current wood frame housing construction, that are usually caused by manually driven construction tools [20]. He proposes a novel approach to design and construction that combines friction fit assembly and CAD representation [21]. In contrast to conventional construction, this method does not need special fasteners at connections between panels. It can be made by one material type with integral attachments. Shape grammar is used to define assembly methods and tool cuts for the elements that are held together by friction only.

Shape Grammar algorithms have been applied on several projects designed by Gehry Partners. These applications are directed toward rationalization of the surface forms to address specific constructability requirements [22]. In Gehry Partners office, surface fabrication strategy driven by shape grammar logic was conducted for the first time on

Experience Music Project in Seattle. Shape grammar approach in Gehry's design projects based on assumption that surface forms on any curvature can be constructed from flat sheets, deformed within some limited range. In addition, it is presumed that the dimension of surface sheets is determined from values of Gaussian curvature [22]. The design surface was initially decomposed by subdivision surface algorithm derived from Mitchel and Stiny Mughul garden grammar [15]. The basic grammar production rule subdivides a square into four smaller squares. Depending on local surface curvature, basic rule may be recursively re-applied in order to get smaller, flat square regions of various sizes. There are limitations of the initial grammar based algorithm that produce more subdivisions than necessary in a relatively predictable pattern of equal sized regions. This rule-based algorithm is then improved and more efficient results are obtained in the following design phases. Rather than simply splitting the region in the middle, grammar algorithm is improved in searching for the optimal layout of subdivision surface (Fig. 3).

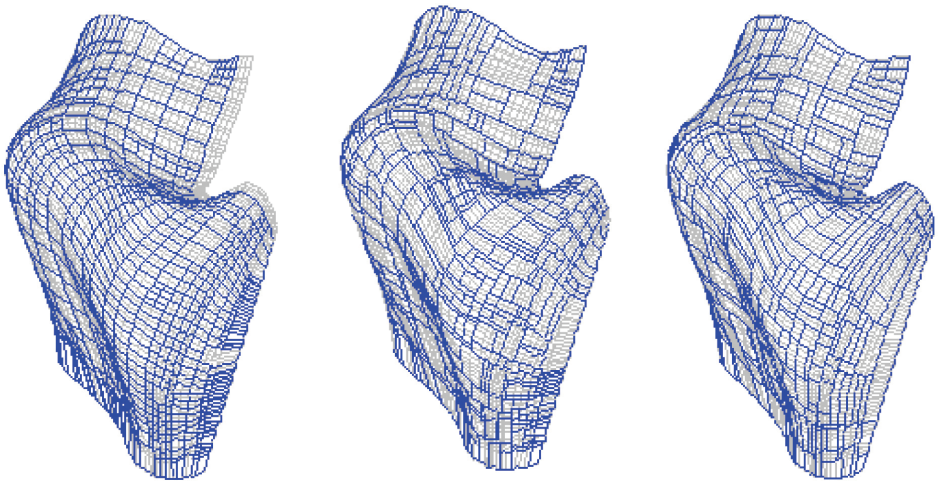

Fig. 3. Subdivision grammar results applied to Gehry's Experience Music Project in Seattle.

First commercial 3D modelling application with procedural modelling approach based on a novel shape grammar language (CGA shape), CityEngine, was released by the Swiss company Procedural Inc. in 2008 CityEngine was developed at ETH Zurich by Pascal Müller during his PhD research at ETH Computer Vision Lab. CityEngine uses procedural modelling approach, which means that it automatically generates models through a set of rules that iteratively refine a design by creating more and more details. In the context of buildings, by applying a CGA shape grammar, rough volume model of a building facade is generated and finally details that retain flexibility to future changes are added. Model of a building has a hierarchical structure and contains semantic information important for reusing design rules for creating procedural variations [23].

CGA shape grammar for procedural modelling was developed in order to allow creation of virtual cities using the two dimensional street networks [24]. Its further application in procedural modelling allows buildings to be modelled with high visual

quality and level of detail [23] as well as automated image-based modelling from single facade images of arbitrary resolutions [25].

Fig. 4. Various (hypothetical) views of the ancient Pompeii, based on real building footprints modelled with CGA shape grammars.

Procedural modelling with CGA shape grammar has been already extensively used in urban planning, architecture, archaeology and digital cultural heritage. It was used for real-world 3D reconstruction of the centre of the Munich, Rotterdam, and Marseille as well as for master plan design of sustainable city Masdar and Nanjing [26]. Also procedural modelling with CGA grammars was used to visualize and reconstruct uncertainty of ancient cities and devastated buildings. Procedural 3D reconstruction of Puuc-style buildings in Mexico is a prime example of expressing uncertainty of devastated buildings. CityEngine has been used for procedural reconstruction of Puuc-style building in Kuiuic, Mexico. In this 3D reconstruction shape grammar rules use "control parameters", which are the set of shape attributes to control the overall result of a grammar rule set and it can be read from the GIS database. By "control parameters", range of possible values for each building type is expressed. By simple modification of "control parameters" of the grammar rule set, each building type can be generated in about 5 to 10 minutes [27,28]. Another example that utilizes CGA shape grammar tools in 3D procedural reconstruction cultural heritage is virtual reconstruction of Ancient Pompeii. In collaboration with archaeologists who provided ground plans and drawings/sketches of building types in ancient Pompeii, Haegler, Müller and van Gool created 190 design rules to model complete city including the streets and placement of trees [28]. The resulting model has about 1.4 billion polygons at its highest level of detail (fig 4).

Despite the popularity of the researches of shape grammar in academic circles, application in architectural practice remains limited. Decisive reason for its limited usage in architectural practice is a lack of commercial 3D software application that contains shape grammar tools. A key point that influences a future role of shape grammar in the domain of architecture is the

release of a first commercial version of software that utilizes shape grammar logic. This opens a new perspective for its further usage in architecture and urban design.

5. CONCLUSION

Designing with grammars is deeply rooted in contemporary architectural theory and design. Analogous to traditional grammar, language of architecture has its own grammatical rules that govern the process of analysing, designing and creating buildings. Any kind of architectural form can be interpreted as a formal grammar system with its own set of formation rules, syntax and semantics of grammars. Among other rule-based systems, shape grammars take an important place in contemporary architectural theory and design. Shape grammars were successfully used as a computational design tool over period of four decades. As it is shown in the paper, shape grammar found its usage in many fields of architectural design, urban planning and cultural heritage.

Despite their applicability in many aspects of architectural design, shape grammar has not yet exploited its full potential. Shape grammar system used in the XX century has not been designed to operate automatically. Also, design with classical grammars demands people with high computer programming skills.

Development of a software package with a high level of automation and visual editing tools for designing a grammar, such as CityEngine, makes the shape grammar more applicable to common users among architectural professionals. Numerous interesting examples of procedural modelling with CGA grammars confirm that shape grammar has a significant role in the future as a computational tool in architectural design. Vast expansion of such design approaches in such a short time period, initiates the conclusion that close future development will drastically improve shape grammar usability in the area of architectural design. Hence, the presented analyses and evaluation of previously described architectural projects are very important for understanding the future value of the shape grammar logic.

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GRAMATIKA OBLIKA U SAVREMENOJ ARHITEKTONSKOJ TEORIJI I PRAKSI

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U poslednjih deset godina, digitalne tehnologije imale su ogroman uticaj na process arhitektonskog projektovanja, građenja i teoriju savremene arhitekture. CAD/CAM tehnologije pružile su nove mogućnosti u projektovanju i izgradnji objekata kompleksnih geometrijskih formi. Najraniji primeri primene računarskih algoritama u arhitekturi koristili su se gramatikom oblika, ekspertskom sistemu veštačke inteligencije baziranom na pravilima koji generiše geometrijske oblike.

Prvi primeri primene gramatike oblika u umetnosti i arhitekturi nastali su odmah nakon njihovog nastanka tokom 70-tih i 80-tih godina XX veka, ali njihov potencijal kao generativnog projektantskog alata, ni do danas nije u potpunosti iskorišten u praksi. Uprkos svojoj popularnosti u naučno-akademskim krugovima, gramatika oblika se nije postao uobičajena alatka u računarski podržanom arhitektonskom projektovanju.

U ovom radu je istražena uloga gramatike oblika kao generativnog i analitičkog alata i njenog uticaja na savremenu arhitektonsku teoriju i praksu. Takođe, prikazane sui nove tendencije u primeni gramatike oblika u cilju definisanje daljih pravaca njenog razvoja.

Ključne reči: *gramatika oblika, sistemi bazirani na pravilima, dizajn računarskim algoritmima, proceduralno modelovanje.*