Automation in Construction 35 (2013) 329–337

Contents lists available at ScienceDirect

Automation in Construction

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

Procedural modeling in architecture based on statistical and fuzzy inference

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ARTICLE INFO

Article history:
Accepted 18 May 2013
Available online 14 June 2013

Keywords:
Procedural modeling
Shape grammar
Fuzzy logic
Probability
Architecture
Cultural heritage

ABSTRACT

In this research, we propose a novel method for automated simulation of the characteristics of a group of architectural buildings that share similar typological features. The procedural modeling algorithm for 3D simulation is based on shape grammar rules and a mathematical model that combines statistical analysis and fuzzy logic.
In this research, we used a group of sacral buildings on the territory of Vojvodina. 3D mass models that are similar to the real world buildings are automatically generated via CGA Shape Grammar programming rules. The results demonstrate that coupling procedural modeling with fuzzy and statistical analysis enables generation of infinite number of buildings representing the typical appearance of an architectural type and their variations, which is a reliable reproduction of characteristics of the real world buildings. We also demonstrate the application of this approach in the simulation of architectural heritage appearance.

1. Introduction

Creation of visually compelling 3D models is one of the most important tasks in various fields of architecture, including architectural design, historic preservation and town planning. Modeling of complex 3D architectural environments is a very expensive and time-consuming process and various digital tools and modeling approaches have been developed in order to enhance productivity.

Procedural modeling was proven as an efficient method for automatic generation of specific classes of objects such as buildings, truss structures, plants, urban environments or natural landscapes. In procedural modeling, automated generation of 3D building models is mostly based on production systems (e.g. L-systems, shape grammars and graph grammars) and it is based on selecting a set of parameters and rules that iteratively evolve a design by creating a more complex scene [1–3].

Probability theory and fuzzy logic are the principal components of an array of methodologies for dealing with problems like uncertainty and imprecision, and they are complementary rather than competitive [4,5]. Complementarity of fuzzy logic and probability theory is rooted in the fact that probability theory is concerned with partial certainty, whereas fuzzy logic is mainly concerned with partial possibility and partial truth. In this paper, both theories are used in synergy, together, for mutual benefit. Fuzzy theory is used instead of subjective or personal interpretation of probability. In this case, a hybrid approach combining two theories is the best, particularly when characterizing different kinds of uncertainties that plague complex problems, such as architectural studies.

This research of procedural modeling in architecture is based on an assumption about architectural styles and building typology. Statistical and fuzzy analyses of the real world building characteristics are used in order to deal with the possibility and uncertainty in the study of an architectural type. The term architectural style commonly refers to a way of classifying architecture, emphasizing the characteristic features of a design. Similarly, the term 'type' in architecture presents the idea of an element which ought itself to serve as a rule for the model [6]. Consequently, grammar based design strategies became a foundation in teaching and analysis of building typologies and architectural styles, since they can be described as a set of parameters and rules.

According to the predefined architectural style or typology, specific rules can be used in order to generate buildings. Considering the vast diversity of buildings with the same architectural style, there are series of buildings that could be described using the same grammar rules, but there are also buildings that share stylistic characteristics with other groups of buildings. Those buildings actually keep variability of architectural forms due to artistic intentions, regional characteristics, different construction and materials, or for some other reason. Such similarities between buildings of the same architectural style are often neglected and difficult to define.

Procedural modeling algorithms are based on repetitive patterns of regular facades [7,8], efficient optimization methods for style description [9], or statistical compositions of basic elements [1]. Procedural modeling is already used in 3D simulation of historical buildings [2,10,11], but without consideration of adequate correction factors based on statistical and fuzzy inference that are applied in this paper.

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0926-5805/$ – see front matter
http://dx.doi.org/10.1016/j.autcon.2013.05.015

The objective of this paper is to design a procedure that can generate an infinite number of 3D models, considering the variations that are similar to a selected group of real world architectural buildings. A procedural modeling approach that leads towards modeling efficiency is combined with statistical and fuzzy analyses that are used to reproduce characteristics of the real world buildings. Statistics and fuzzy logic are used to define properties of the real world buildings, and procedural modeling is used to create variations of the 3D model, according to the calculated probabilities.

In this research, we used a group of sacral buildings on the territory of Vojvodina. A statistical model is used to analyze the characteristics of these buildings and, furthermore, a subgroup of Neo-Gothic chapels was extracted and defined as a fuzzy set. Based on these calculations, 3D mass models that are similar to real world buildings are automatically generated via *CGA Shape Grammar* programming rules.

2. Methods and materials

The subject of this research is an architectural building, more precisely, a group of buildings. Two representative groups of buildings (Group A and Group B) were selected for this research.

A wider group of selected buildings used in this research (Group A) is limited by geographic area, purpose of the building, and the building period. A group of similar public buildings built in the recent past is selected. This group is defined as sacral Roman Catholic buildings (churches and chapels) in the Danube area of Vojvodina, built in the period from the early 18th to mid-20th century. The number of buildings belonging to the group is 86.

A subgroup of buildings (Group B) was selected from Group A and defined as the fuzzy set of Neo-Gothic chapels that were built around the year 1900. The total number of buildings belonging to the group is 20.

This research is divided into several steps that rely on different scientific methods:

i) Statistical analysis of the shape characteristics of sacral buildings located in the Danube area of Vojvodina, built between the beginning of 18th to the middle of 20th century. Analysis of variance and Kruskal–Wallis test were used to compare variability through time. Multiple comparison method (Fisher's LSD method, Tukey's test, orthogonal contrasts and graphical methods) was used to identify specific differences between the tests.
ii) Results of the previous statistical analysis were used to select a subgroup of buildings (Neo-Gothic chapels that were built around the year 1900) and to segregate shape properties that are typical for these chapels, and to calculate a grade for each element of the fuzzy set.
iii) Probabilities were calculated for each shape property of Neo-Gothic chapels. Fuzzy logic was used.
iv) Procedural modeling algorithms have been designed based on the previously calculated probabilities. *CGA Shape Grammar* programming language was used to design a procedural model.
v) Generation of virtual models that are similar to the real world buildings (in the group of Neo-Gothic chapels) has been done by CityEngine application.

3. Statistical analysis

A built environment is the product of a complex variety of human operations, such as social, economic, cultural and other influences. In spite of significant differences among buildings, some characteristics signify certain periods, areas and purposes. Architectural styles and types can be defined by layering and comparison of buildings and their parts. Facilities that were built for similar needs often use similar patterns, especially in historical periods, when the use of traditional materials and limited possibilities of loading tolerance also caused the similarity of most of the buildings. Therefore, it is possible to find an identical basic concept regarding the analysis of the shape. Similar functionality adds to that.

Probability models and statistical methods for analyzing data are often used in engineering studies [12–14], but it is not a common practice in the studies of architectural typologies. However, statistical procedures are very useful tools because they provide the investigator with both descriptive and analytical methods for dealing with variability in observed data. Statistical techniques can be used as a powerful aid in designing new models and systems in architectural studies.

For this research, statistical analysis was first used for segregation of a representative group of buildings (Group A). It deals with characteristics of buildings:

- purpose,
- location,
- building period,
- shape characteristics:
  - size of the building,
  - plan shape,
  - proportion of nave,
  - shape of the apsis,
  - number and shape of sacristies,
  - number of towers,
  - position and shape of the tower,
  - type of vertical wall elements,
  - shape of the portal and shape of the front door opening and
  - shape of the front and side openings.

These characteristics are represented numerically to describe real world buildings and provide an adequate base for statistical analysis.

We compared variability of sacral building characteristics built in the area of Vojvodina between 1704 and 1938 (Group A). In order to derive characteristics that depend on building period/style/type, properties of the buildings were compared as well. Based on the observed variations, it was possible to segregate groups of buildings according to similarity of their properties.

For example, recognizable characteristics of Neo-Gothic chapels built around the year 1900 were identified in this statistical model. A group of buildings, used for the second phase of this research (Group B), was isolated according to these specifics. Limits of the group are set to include all chapels built between 1870 and 1930. It is of great importance to introduce fuzzy logic in the following analysis of this set, since the same grade cannot be assigned to a chapel, which is under strong influence of the previous or next period or other concepts of shaping, as it can be given to a typical Neo-Gothic chapel of the analyzed period.

4. Shape rules based on fuzzy inference

Studies in architecture use methodologies mainly based on human intuition and assumptions. One of the main deficiencies of commonly used intuitive approaches is that it is very hard to define explicitly which building (according to its shape properties) belongs to a certain group. For the majority of architectural buildings, their characteristics are highly diverse.

In architectural researches, when a specific group of buildings is detected, a common practice is to include (or exclude) buildings in the group by verbal description (such as ‘typical’, ‘partly’, ‘atypical’, etc.). In reality, there are much fewer buildings which are typical representatives of one typological group, than many others, which have several characteristics of two or more different types and belong somewhere between the groups. In architectural practice, buildings are often excluded from researches due to this problem of simple classification. To overcome these problems, we converted the intuitive architectural approach to mathematical approach and we introduced fuzzy sets in order to acquire explicit and accurate results [15–18].