ARCHITECTURAL SHAPE GENERATING, THROUGH ENVIRONMENTAL FORCES

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ABSTRACT: In this paper we present a new parametric approach based on environmental constraints, in order to generate digital models of architectural shape, directly within a three-dimensional geo-referenced environment. Those constraints may be regarded as force fields with a specific spatial dimension. The system allows user, through implementation of specific generative procedures, to manage interactive architectural design processes. The designer is able to explore all possible infinite scenarios and the various possible design alternatives, by changing the parameters values and verifying in real time the results of the changes. Two experiments are presented.

KEYWORDS: Architectural generative design, city modeling, procedural modeling, visual analytics

RÉSUMÉ : *Cet article présente une nouvelle approche paramétrique basée sur des contraintes de l'environnement, proposée dans le but de générer des modèles numériques de formes architecturales directement dans un environnement tridimensionnel et géoréférencé. Ces contraintes peuvent être considérées comme des champs de forces dans une dimension spatiale spécifique. Par des procédures génératives spécifiques, le système permet à l'usager de gérer des processus interactifs de conception architecturale. En modifiant les valeurs des paramètres, le concepteur peut explorer une multitude de scénarios possibles, ainsi que des variations infinies de solutions. Les résultats des changements peuvent être vérifiés en temps réel. Deux expérimentations sont présentées.*

MOTS-CLÉS : *Conception architecturale générative, modélisation de la ville, modélisation procédurale, analyse visuelle*

1. INTRODUCTION

New generative design tools enable architects and engineers to manage an interactive architectural design process to generate one building (architectural design) or a very large urban context (city modeling). Two aspects can be observed in the relevant literature:

- The complexity of all spatial relations between architectural shape and the realm of environmental constraints produces very interesting morphogenesis processes.
- New opportunities offered by GIS systems allow designers both to access spatial information made available from the public administration, which is particularly useful for urban design, and use the GIS environment as three-dimensional space modeling.

Our research focuses on a generative design system which allows designers to link the architectural shape with the various constraints emerging from the environment. The goal of the work is to generate three-dimensional models of buildings, directly within a three-dimensional geo-referenced environment, by using environmental constraints. We have analyzed and encoded some environmental constraints belong to building and urban planning regulations, in order to achieve the generative rules.

2. LITERATURE SURVEY: THE GENERATIVE TOOLS IN ARCHITECTURAL ENVELOPE DESIGN

In this section we will describe the most relevant generative design tools that are used in the early stages of architectural envelope design. In this stage take place the creation and analysis of the theoretical volume and the final shape of architectural envelope. We will divide the generative design tools in two categories:

- Architectural design; those category includes the digital tools that are used in order to design one building.
- City modeling; it consist of digital tools that allows designer to generate many buildings, neighborhoods and cities.

2.1. Architectural design

The morphogenesis of architectural shape could be performed by using climatic or physical elements, such as solar radiation (Caldas 2005) and solar passive evaluation (Marin *et al.* 2008), the latter being based on a Unified day (UDD) method. They lead to the optimization of architectural envelopes through a genetic algorithm to minimize HVAC and lighting energy respectively, in the first case, and solar passive qualities in the second case.

Particularly interesting are those systems which implement a generative process based on constraints derived from urban regulations and city zoning planning. Donath and Lobos (2008) implement a methodology based on following zoning planning regulations: site size, buildable coefficient, site coverage coefficient, setback requirements, sky exposure plane, maximum building height, storey height, underground levels. They obtain a Decision Support Systems tool based on the platform of a BIM software, that allows to simulate several options for building envelope according to the parameters required by the city zoning planning.

Biao (Biao *et al.* 2008) use the Floor Area Ratio in order to achieve a generative architectural process based on a Multi-Agent-System.

Mellantoni (2006) realizes Parametric Envelope; this tool allows designers to create prototypes in REVIT. The urban code is turned into computable data and theoretical volume is shown in real time.

2.2. City modeling

One of the most important examples is CityZoom (Turkienicz *et al.* 2006). It is a decision support system for urban planning: buildings are generated by applying urban regulations on plot geometry, according to input parameters. It determines the building characteristics which are to be assessed or optimized, such as number of floors, front or size width, and plot occupation. It is a powerful tool to evaluate the impact of urban regulations.

CityCAD is a new system for the automatic generation of buildings. By allowing analysis of urban master plans in the early design stages, it can improve productivity on city design, planning and development projects. It calculates floor areas, densities, costs, car parking requirements and spaces and a wide range of other planning, environmental and financial data. Müller (Müller *et al.* 2006) use a technique called Split Grammars derived from shape grammar, which generates many configuration alternatives for the building façade. A tool based on the CGA Shape, CityEngine (Parish and Müller 2001) was developed to enable designers to generate many digital models of buildings and cities by changing a set of specific rules that can be managed by designers themselves.

New opportunities offered by more innovative GIS systems allow designers both to access spatial information made available from the public administration, which is particularly useful for land planning and urban design, and use the GIS environment as three-dimensional space modelling.

Larive and Gaildrat (2006) use Wall Grammar in order to automatically generate building exteriors. The system imports building footprints defined by polygons and building heights. The building outlines and heights can be either obtained automatically or defined by the user in a GIS environment. Subsequently, the system uses such data to create 3D building models.

3. THE AIM OF OUR RESEARCH

Our research is aimed at developing an application that combines the modelling ability of CAD systems with the numerous opportunities offered by geo-referenced systems. Therefore, designers can generate three-dimensional models of buildings inside a three-dimensional geo-browser. The system allows users to produce an interactive design of the architectural shape. Users can change geometric features of architectural shape in order to optimize specific formal requirements, or generate building models according to urban and seismic constraints linked to the specific environment. As a result, designers are enabled to interactively operate in the generative design process: they can explore unlimited scenarios and various possible alternatives by changing the value of selected parameters and verify the results of such changes in real time.

Furthermore, the development of this system entails the following significant results:

- Optimization of the architectural envelope shape and volume.
- Optimization of façade configuration, based on the most important local architectural features.
- Interoperable access to planning and, more generally, to geographical information available at the public administration level.
- Access to processing functionalities which are necessary for land management and urban design.

4. FRAMEWORK OF THE SYSTEM

We formalized the concept of Force field in order to implement the generative process of the architectural envelopes. Its formal framework consists of four classes: Urban Constraints, Seismic Constraints, Generic Constraints and Architectural Constraints.

The Urban Constraints class is a list of the most important and useful parameters established in compliance with urban planning regulations, such as:

- Building ratio index (BRI). It is the ratio between the maximum theoretical volume of the building and the area of the site (building plot).
- Site coverage coefficient (SCR). It is the ratio between area of building plot and area of the site.
- Maximum building height (HB max) allowed by the natural ground level.
- Maximum building storey number (SN max) allowed by the natural ground level.
- Minimum distance between building plot boundaries and building footprint (DB min).

- Minimum distance (D min) between the building and generic elements of urban landscape, as roads, parks or other buildings.
  The Seismic Constraints class contains some parameters established by seismic regulations. This class does not take into account the structural aspects and all elements related to mass distribution of the building. The Seismic Constraints take into account element related to the geometry of the architectural envelope, such us:
- Maximum building height. This parameter depends on the type of building structure (skeleton, walls), materials (steel, concrete, wood) and width of the roads.
- Minimum distance between building plot boundaries and other buildings.

The Architectural Constraints class is a list of geometric parameters that are used to generate the architectural envelope and to locate it in the three-dimensional geo-referenced environment. General regulations (urban, seismic) do not impose specific values for those parameters. They are:

- Minimum (hs max) and maximum (hs min) storey height.
- Minimum windows height (ho min) and minimum windows length (hL min).
- Type of windows and doors.
- Building footprint.
- Vertex angles (ai) of the building plot and building footprint,
- Theoretical volume of the building.
- Area (A) and perimeter (P) of building plot and building footprint.

The formulation of Generic Constraints class is still in progress. This class was intended to include some particular environmental factors within the generative architectural design process, such as type of urban zone, presence of significant architectural works, elements of natural landscape, vehicles, people and information flux.

4.1. Implementation of the generative rules

The parameters of four classes are linked to each other, through geometric, topological and algebraic relations. These relations duly translated in java code, become generative rules; they are the engine of the developed system. The generative rules allow users to automatically generate and transform architectural shape. The architecture of the whole client-server system developed is based on a Java Enterprise Edition Environment. The client has been developed on top of NASA World Wind libraries while each component at the server side is developed as an Enterprise JavaBeans in line with component-based distributed business applications. Enterprise JavaBeans are scalable, transactional, and multi-user secure. These applications may be written once, and then deployed on any server platform that supports the Enterprise JavaBeans specifications.

5. THE GENERATIVE PROCESS OF ARCHITECTURAL SHAPE

The system allows designers to explore any possible scenarios. The process implemented consists of three stages (Figure 1- top, left):

- INPUT
- DATA PROCESSING
- OUTPUT

INPUT – The first step is managed by the user, who sets the Force field. The Force field is the focus of the whole generative process. The user sets all the parameters in the Urban Constraints, Seismic Constraints, Generic Constraints classes and some in the Architectural Constraints class, as shown below:

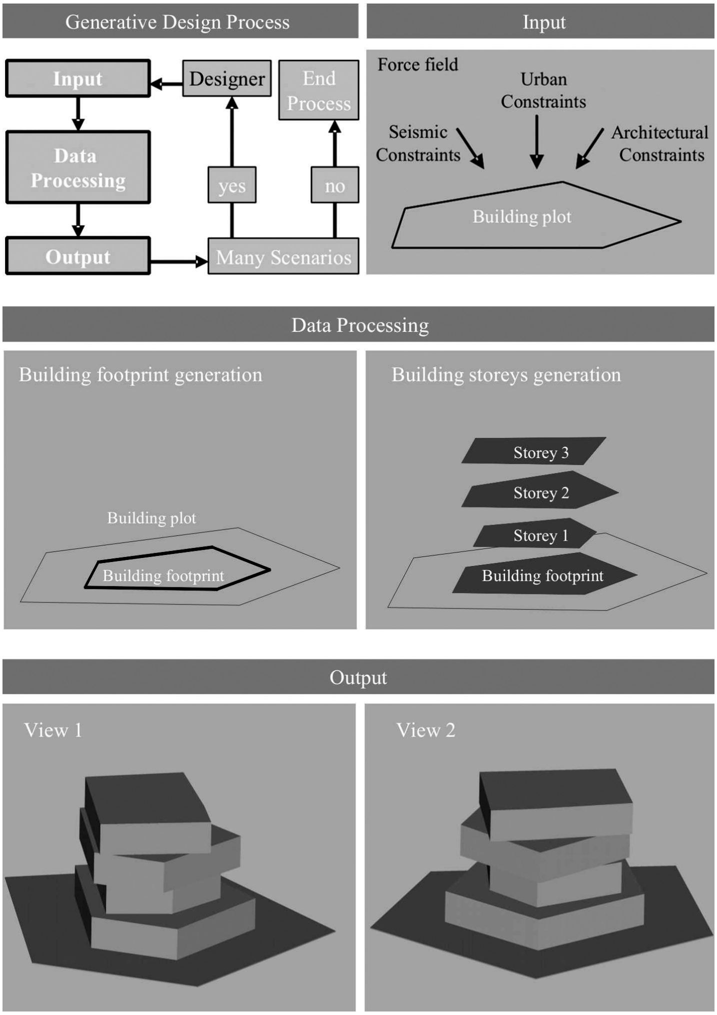
- Minimum and maximum storey height.
- Window type and size.
- Building plot. It is the site where a three-dimensional model of the building will be generated. The user defines a building plot by using the coordinates of the vertices. Coordinates are referred to a Cartesian system with origin at the centre of earth. The building plot may be any type of polygon, such as a convex, concave, regular or irregular one.

DATA PROCESSING – From this stage onwards, the control of the process is shifted from the user to the system. Through generative rules, the Force field shapes all architectural objects within the urban context. This is a computational stage, during which all generative parameters of the architectural envelope are calculated, as explained below:

- Building footprints. The system converts the coordinates of the building plots from meter to longitude and latitude values, and the vertices of building footprints are calculated. At this point, the building footprint coordinates can be displayed within the three-dimensional geo-referenced environment.
- Architectural envelope. The system works out the values of other parameters in the Architectural Constraints class: more specifically, building height, number of storeys, storeys height, number of windows and distance between windows. Those values are combined with the Generic Constraints ones so as to establish the generative parameters.

OUTPUT – The three-dimensional building models are automatically generated by the system, through extrusion process, and they are shown on geo-referenced environment. After the main elements of the buildings are laid off, the system works on texture mapping. As a result, a multi-pass texture creation process produces the optimal texture, which represents the most suitable material combination according to the Force field applied to the area.

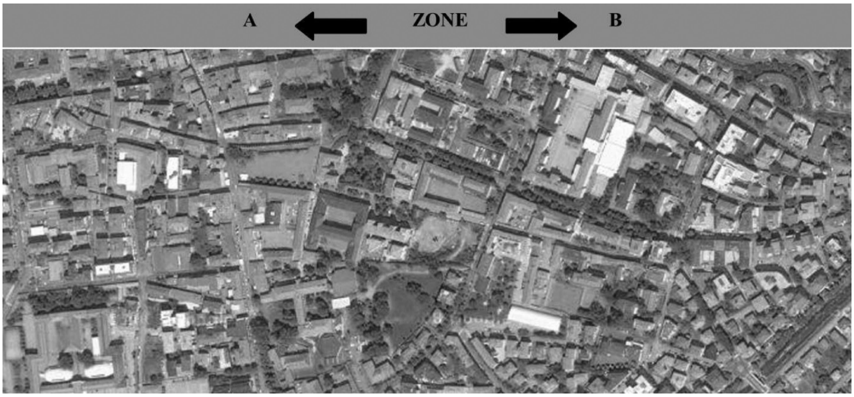
FIGURE 1. *THE GENERATIVE PROCESS OF THE ARCHITECTURAL ENVELOPE.*



6. TWO CASE STUDIES: AN EXPERIMENT IN NASA WORLD WIND

Two examples show how the system allows users to manage shape and external configuration of the architectural envelope. The test will help us verify the impact of the Urban Constraints class on an existing zone within the territory of Trento (Italy). The area under examination includes two zones, defined zone A and zone B (Figures 2). For each of them, specific values for the Urban Constraints and Seismic Constraints parameters were established in compliance with local regulations. Their value was changed so as to obtain two different Force fields (Figures 3 and 4, right).

FIGURE 2. *ARIAL PHOTO ILLUSTRATES AN AREA OF TRENTO (ITALY).*



6.1. Generating scenarios

The designer can generate various scenarios by changing the building plots and/or the constraints of Force field. We defined two scenarios for the zone A (Figure 3) and zone B (Figure 4), according to the process described in Figure 1, section 5.

Scenario 1: digital models of buildings appear in NASA World Wind through an interaction between the Forces field and all the building plots (Figures 3 and 4, top).

Scenario 2: we focus on the architectural shapes that have been previously generated. We modify the configuration of buildings and of the whole neighbourhood, by changing the Field of forces parameters (Figures 3 and 4, bottom). The vertices coordinates of the building plots have the same value in all scenarios. The value of the Generic Constraints parameters is 1.

Other scenarios can be generated, until the architectural shape satisfies specific formal requirements. Hence, the user can analyse both the theoretical volume and final shape of the architectural envelope through the scenarios generated.

FIGURE 3. *ZONE A: VISUALIZATION OF TWO SCENARIOS IN 3D GEO-REFERENCED ENVIRONMENT.*

SCENARIO: 1 — Zone: A — Force field

Urban Constraints:	
- BRI = 2.20	m^3/m^2
- SCR = 0.35	m^2/m^2
- DBmin = 5	m
- D min = No limits	m
- HBmax = 10	m
- SN max = 4	-
Architectural Constraints:	
- hsmin = 2.90	m
- hsmax = 3.00	m
- homin = 1.60	m
- hLmin = 1.20	m

SCENARIO: 2 — Zone: A — Force field

Urban Constraints:	
- BRI = 1.50	m^3/m^2
- SCR = 0.40	m^2/m^2
- DBmin = 5	m
- D min = No limits	m
- HBmax = 16,5	m
- SN max = 6	-
Architectural Constraints:	
- hsmin = 3.00	m
- hsmax = 3.40	m
- homin = 1.60	m
- hLmin = 1.20	m

FIGURE 4. *ZONE B: VISUALIZATION OF TWO SCENARIOS IN 3D GEO-REFERENCED ENVIRONMENT.*

SCENARIO: 1	Zone: B	Force field

Urban Constraints:	
- BRI = 2.20	m^3/m^2
- SCR = 0.35	m^2/m^2
- DBmin = 5	m
- D min = No limits	m
- HBmax = 10	m
- SN max = 4	-
Architectural Constraints:	
- hsmin = 2.90	m
- hsmax = 3.00	m
- homin = 1.60	m
- hLmin = 1.20	m

SCENARIO: 2	Zone: B	Force field

Urban Constraints:	
- BRI = 1.50	m^3/m^2
- SCR = 0.40	m^2/m^2
- DBmin = 5	m
- D min = No limits	m
- HBmax = 16,5	m
- SN max = 6	-
Architectural Constraints:	
- hsmin = 3.00	m
- hsmax = 3.40	m
- homin = 1.60	m
- hLmin = 1.20	m

7. FUTURE DEVELOPMENTS

As to our next goals, these entail:

- Improving the algorithm so as to increase the efficiency of the application and, consequently, manage more and more complex architectural shapes.
- Besides, other environmental elements will be added to the Force field to better enable the system to simulate the effects of the context. For instance, physical and climatic factors such as solar radiation, intensity and direction of dominant winds may be included in the generative process.

- Finally, a study is being carried out to automate the generative process of the scenarios by means of evolutionary algorithms. To date, we have analysed genetics algorithms (GAs) and the bee colony optimization algorithm.

8. CONCLUSIONS

The development of architectural morphology and city configuration may be considered as the result of a complex process involving all environmental constraints. Hence, knowledge of the action exerted on the architectural envelope by those constraints is essential to set the early stages of the generative process.

Many difficulties have arisen when collecting information. The most complex problem is the difficulty in finding the relations between the elements that are often of different nature, defining significant variables that characterize the urban context. Some environmental elements can be easily identified and encoded: geometric components as height, floor number, area of building footprint and other aspects derived from general regulations to name but a few. However, other types of environmental factors, such as social codes, economic factors and psychological aspects, are very often difficult to translate into generative rules.

More specifically, the most complex issues dealt with finding and implementing the relations between various types of elements, as well as defining significant parameters that characterise the architectural shape and environmental context. Many of the actions which limit the shape derive from considerations that can not be immediately translated and represented according to pre-defined codes, therefore giving origin to qualitative nature evaluations. These difficulties, aside from the complexity itself bound to concepts that rules a planning process, sometimes also force to a partial behavior in coping with the planning aspects, leaving out some that may be, at times, necessary, in order to research simplifications that the complexity of the system requires.

ACKNOWLEDGEMENTS

We would like to thank Nicolò Tosi for their enriching contribution to the research.

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T. Tidafi and T. Dorta (eds)
Joining Languages, Cultures and Visions: CAADFutures 2009