A Grammar-Based Generative Urban Design Tool Considering Topographic Constraints

The Case for American Urban Planning

Mina Rahimian[1], José Nuno Beirão[2], José Pinto Duarte[3], Lisa Domenica Iulo[4]
[1]Department of Architecture, The Pennsylvania State University, State College, PA, USA [2]Faculdade de Arquitectura, Universidade de Lisboa, Lisbon, Portugal [3]The Stuckeman Center for Design Computing, The Pennsylvania State University, State College, PA, USA [4]The Hamer Center for Community Design The Pennsylvania State University State College, PA, USA
[1,3,4]{mxr446|jxp400|ldi1}@psu.edu [2]jnb@fa.ulisboa.pt

This paper explains the development of a generative urban design tool based on shape grammars. The novelty of this tool lies in considering the topographic constraints of the site and generating various alternatives of urban design scenarios accordingly. For the purposes of this research, San Diego has been chosen as an example of a steep city with varied topography that, in consequence, has created distinct urban typologies within the city. With the use of shape grammars, the rules and patterns forming the urban structure of each typology have been decodified. The extracted urban shape grammar is then used as the basis for a generative design tool producing various urban design scenarios considering the limitations and potential of the site's topology. This paper describes the extracted urban shape grammars and how that informs the development of the presented generative urban design tool.

Keywords: *Generative Design, Urban Shape Grammars, Topography, American Urban Planning*

INTRODUCTION

This paper presents the grammar-based model underlying a generative urban design tool, built upon the principles of urban planning in American cities. The tool is written as an extension to CItyMaker (CIM - developed at University of Lisbon) and is part of a larger research project. The larger research uses artificial neural networks (ANN) to explore the complex relational pattern between the many dimensions of urban form and energy performance in communities, leading to a framework for designing high energy performance solar-powered community microgrids well before their construction. Urban form in the larger research is identified and measured by nine-

teen energy-relevant spatial indices for the specified unit of spatial analysis (i.e. zip code). Selecting the spatial unit of analysis, the ANN needs to be ran on a large dataset with measurements of urban form as its predictor variable, and monthly measures of net energy performance (energy consumption and on-site PV energy production) as its response variable. In an ideal situation, the required dataset will be prepared by measuring the identified indices of urban form in thousands of existing solar community microgrids along with monthly rates of community-wide energy performance. Since accessing real-world data is not feasible, a generative urban design tool with energy simulation properties is developed in this research which (1) repeatedly produces numerous alternatives of community urban configurations supported by a rule-based system, (2) for each design alternative measures its urban form, and (3) simulates its energy performance to obtain numerical results. This paper discusses the development of the generative urban design tool which is primarily used for synthesizing the spatial data required for the larger research project. The simulation features added to the generative system are not discussed in this paper and will be explored in future publications.

The uniqueness of the presented generative urban design tool, in comparison with other similar ones, lies in generating alternative urban design scenarios for any given regional boundary while considering the limitations and potential of its topography. This paper describes the generative technique behind the development of this tool and details on its operation. Section 2 gives a brief explanation on the use of shape grammars in urban planning and section 3 describes the grammar behind San Diego's urban planning which could be generalizable to other American cities. Section 4 delves deeper in the creation of the generative design tool and its operation as part of CItyMaker. Discussions on the contribution of this tool to the field and potential for further research and implementation are explored in the last section of the paper.

GENERATIVE RULE-BASED DESIGN AND URBAN PLANNING

In a generative design framework, design automation techniques are employed ranging from basic rule-based systems to advanced AI-based procedures (Gu, Singh, & Merrick, 2010). Different subcategories of generative design algorithms exist with a common procedure towards design: they all start with a set of design goals - often stemmed from designer's past experiences and the environment where the design is situated - and then innumerable possible permutations of a solution are explored. Although overlaps and similarities exist among the different generative design techniques some appear to be more suitable for certain design and automation tasks (Gu, Singh, & Merrick, 2010). For example, rule-based systems like shape grammars tend to be used when there is a strong domain knowledge, and stochastic systems like genetic algorithms are used when there's a weaker domain knowledge.

The use of shape grammars has gained popularity in design of various scales ranging from urban design (Beirão J. N., 2012) to housing (Benros, Duarte, & Hanna, 2015) and product design (Garcia & Barros, 2015). The reason for shape grammars' popularity is conceivably for its fourfold benefits as stated by Beirão and Duarte (2018): (1) analytical purposes where design rules and processes are understood, (2) synthetic purposes where new design alternatives are generated, (3) regulatory purposes where the limitations of new design alternatives are controlled, and (4) prediction purposes where simulation algorithms are developed accordingly.

A rich body of literature has used shape grammars for unveiling patterns of urban design. The first urban grammar was proposed by Catherine Teeling (1996) for describing the generation of urban form in the docklands of Friedrischafen, Germany. Duarte et al. (2007) presented an urban grammar for the Marrakesh Medina, an ancient fabric that grew spontaneously over time, resulting in a complex urban form that expressed social conventions and physical conditions. Following these analytical grammars, Duarte

and Beirão (2011) proposed the use of shape grammars for supporting flexible urban planning. Then, in 2013, Barros et al. presented a grammar for describing a Mozambican slum, Cidade dos Caniços, an informal settlement where land is divided prior to occupation. More recently, Verniz and Duarte (2017) developed a grammar to describe the spontaneous growth of favelas in steep terrains and Ena (2018) proposed a shape grammar to describe the development of favelas in flat terrains, both in Rio.

This paper adds to the current conversation on urban grammars by capturing planning rules that take topographic constraints into consideration. In the work of previous researchers, the site's topography did not play a pivotal role in the development of the urban grammar. The only precedent which explores the role of topography is the work of Verniz and Duarte (2017) in which topography acts as the main stimulus for shaping the form of urban structure in informal settlements. However, unlike the work of Verniz and Duarte, this paper does not see topography as the primary force impacting urban structures but investigates the different ways topography distorts and changes the formal stream of planned urban structures.

Figure 1
A portion of San Diego's map from 1979. By closely examining the map the three urban typologies are visible. Source: www.sunnycv.com

THE URBAN GRAMMAR

Analysis of San Diego's Urban Typologies

Concentrating on American urban planning, this paper takes San Diego county in California as a case study. The reason for choosing San Diego is due to its varied topography which has caused the emergence of different urban typologies throughout the region (Figure 1). By closely examining the aerial maps of San Diego three different urban typologies are identified (Figure 2):

Figure 2
Samples of the identified three urban typologies, from left to right: organic grid, mixed grid, and orthogonal grid.

1. Organic grids: are often created where the topology fluctuates considerably within the region limits and close-to-narrow ridges and alleys are observed. In organic grids, buildings are constructed on the ridges and alleys where minimum construction standards are met.
2. Orthogonal grids: are normally planned and constructed where a massive area of the site is flat or has a limited steepness. According to San Diego's GIS data, a flat area is where the slope is less than 15%. An orthogonal grid is made of a series of parallel streets which run at right angles to each other forming a grid.
3. Mixed grids: are the combination of the previous two typologies. Mixed grids emerge where the orthogonal grid meets the edge of a steep slope and gets distorted, organically, in consequence.

Development of an Urban Grammar for San Diego

Rather than recommending a separate set of grammars for each one of the urban typologies, one general set of grammars is introduced that covers the un-

derlying pattern of all three. This unified urban grammar follows the principle that any region in San Diego tends to follow an orthogonal grid pattern until the pattern gets distorted due to topography resulting in an organic or a mixed grid arrangement. This principle and the derived urban grammar can be generalizable to most cities in the US since orthogonal grids form the structural core of the majority of American cities and towns (Southworth & Owens, 1993). The popularity of orthogonal grid plans lies in creating an efficient pattern for maximum land use where the emerging square or rectangular blocks build an interconnected variety of routes that are readily expandable for potential urban growth scenarios. The New York City grid is perhaps the most recognized grid plan in the American history. Houston, Texas, is an example of a city constituted of several grids oriented in different directions. Other cities, such as Chicago, Salt Lake City, San Francisco, and Charlotte to name a few, follow the same principle of an orthogonal grid plan.

Following the lines of the above-mentioned principle, the urban grammar introduced in this study is divided into two parts: the first part is the grammar for generating orthogonal grids, and the second part is the grammars explaining the logic behind grid distortions when reaching the edge of steeped slopes. Note that the grammar is developed in an abstract way such that the underlying design procedure is not strictly specific to San Diego and could be used for recurrent design purposes fitting many urban design scenarios in American contexts.

- Urban shape grammar part I: Orthogonal grid

The proposed grammar for orthogonal grids has been adopted from the underlying grammar of CIty-Maker with minor changes. CItyMaker is a rule-based parametric urban design tool based on shape and description grammars (Beirão J. N., 2012). CItyMaker was developed as the generative component of the City Induction project which integrates various design support tools for the formulation, generation, and evaluation of urban design scenarios (Duarte, Beirão, Montenegro, & Gil, 2012). The adopted urban grammar generates the compositional axes of the urban plan leading to the generation of orthogonal grids, and patterns to generate urban blocks.

The design of an orthogonal grid starts with creating the main perpendicular axes (*av*=main vertical axis, *ah*=main horizontal axis) directed towards the identified major viewsheds or major gateways of the region. Before starting the generation process the initial attributes of the shapes need to be labeled: site limitations as *Ls* and references as *Ref*. The intervention site limit is always a closed polyline and references are elements inside *Ls* which have been either selected by the designer or contextualized inside *Ls* as regional landmarks (Figure 3).

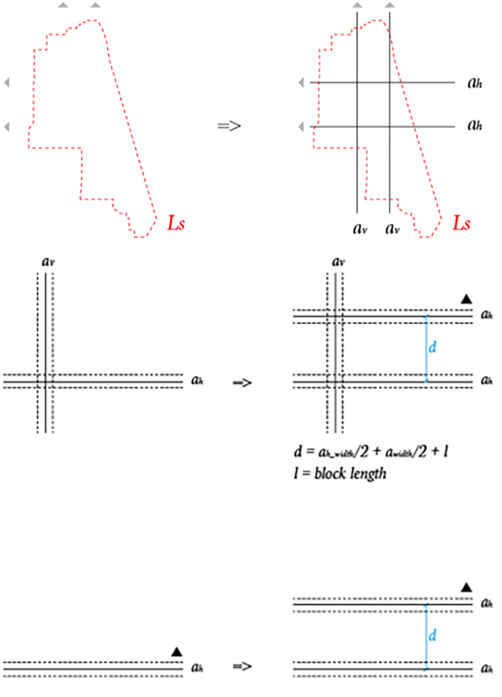


Figure 3
Drawing av and ah axis in the direction of viewsheds.

Figure 4
Rules for generating the compositional structure of the street grid.

Figure 5
The width of the streets depends on the location of Ref.

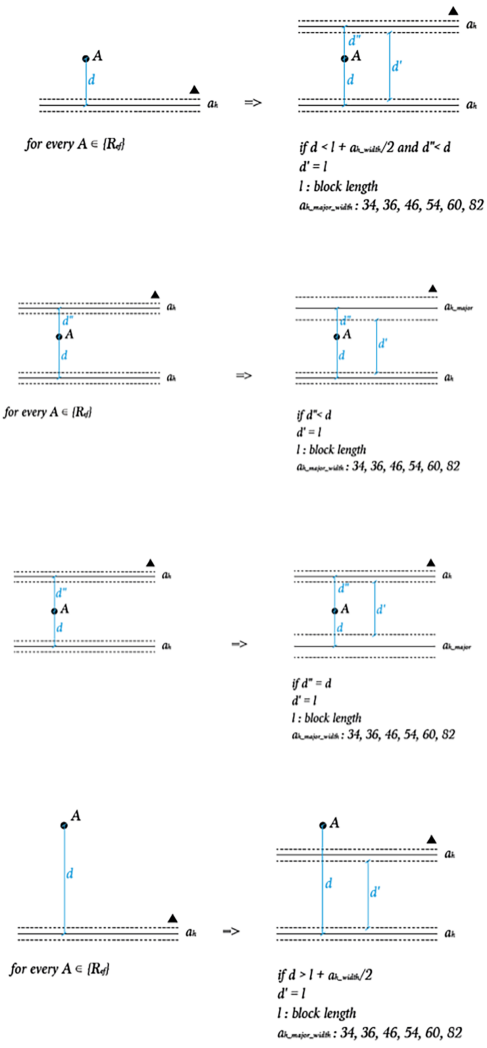
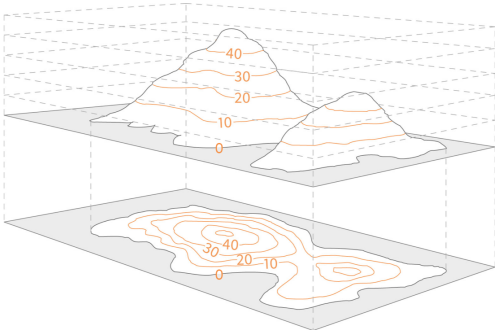


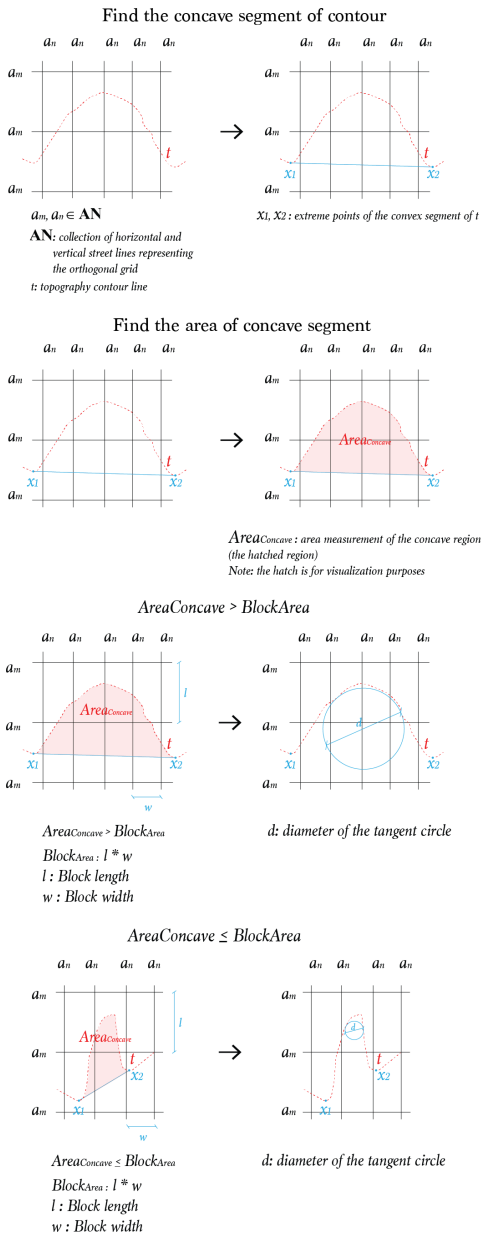
Figure 6
Contour code 0 representing edge of a stepped slope. Source: getoutside.ordnancesurvey.co.uk

The rest of the streets, responsible for the compositional structure of the grid, are generated in parallel to av and ah. The default distances between the set of horizontal and vertical streets are the size of the predefined block length and width. In the case of San Diego and according to the city's planning framework, block sizes diverse spanning from 200-300 (approx. 60 - 80m) in width to 300-750ft (approx. 90 - 230m) in length. The rule application can be better understood in Figure 4. The upward and downward arros labels are used for the recursive application of rules and indicate the direction for applying the rule. The rule applies recursively until it falls outside Ls. The width of the streets depends on the proximity of a *Ref* point to it. For instance, if the distance of *Ref* point from the generated street equals the sum of block length and half of the reference street's width then the generated street becomes a major street by changing its width to the width of a major street. The widths of major and minor streets are specified according to the city's street design guideline. When the *Ref* is in between two streets depending if its closer to either one of the streets, rules illustrated in Figure 5 apply (Beirão, Duarte, & Stouffs, 2009). Due to space constraints the complete rule derivations for the orthogonal grid is not included in this paper.



- Urban shape grammar part II: Grid distortions

Hills, slopes and mountains are represented on a topographic map using contour lines. Contours close together indicates that the slope is steeper; when the contour lines are further apart the slope is shallower. According to San Diego's topographic map, construction is done in areas where the steepness is less than 15%. Accordingly, the urban grid follows orthogo-



nal arrangements in such areas and distorts when it reaches the edge of a steep slope where the incline exceeds 15%. The contours of interest for developing the grammars of grid distortions are the contours representing the edge of a steep slope, labeled as *t* (contour with elevation code 0 in Figure 6).

Findings show that patterns of grid distortions vary depending on: (1) the size of the concave areas created by the t contour line, as well as (2) the narrowness of the concave segments of the *t* contour line itself. The size of the concave area is compared against the area of one urban block and the narrowness of the concave segment is measured by the diameter of a circle inscribed in the concave segment of *t* and compared against the length of an urban lot. Therefore, the distortion grammars are categorized into four classes representing four different regional conditions that trigger change in the orthogonal grid: 1. Large concave area with wide concave segment: AreaConcave > BlockArea AND d > w, 2.Large concave area with narrow concave segment: AreaConcave > BlockArea AND d ≤ w, 3. Small concave area with wide concave segment: AreaConcave ≤ BlockArea AND d > w, 4. Small concave area with narrow concave segment: AreaConcave ≤ BlockArea AND d ≤ w.

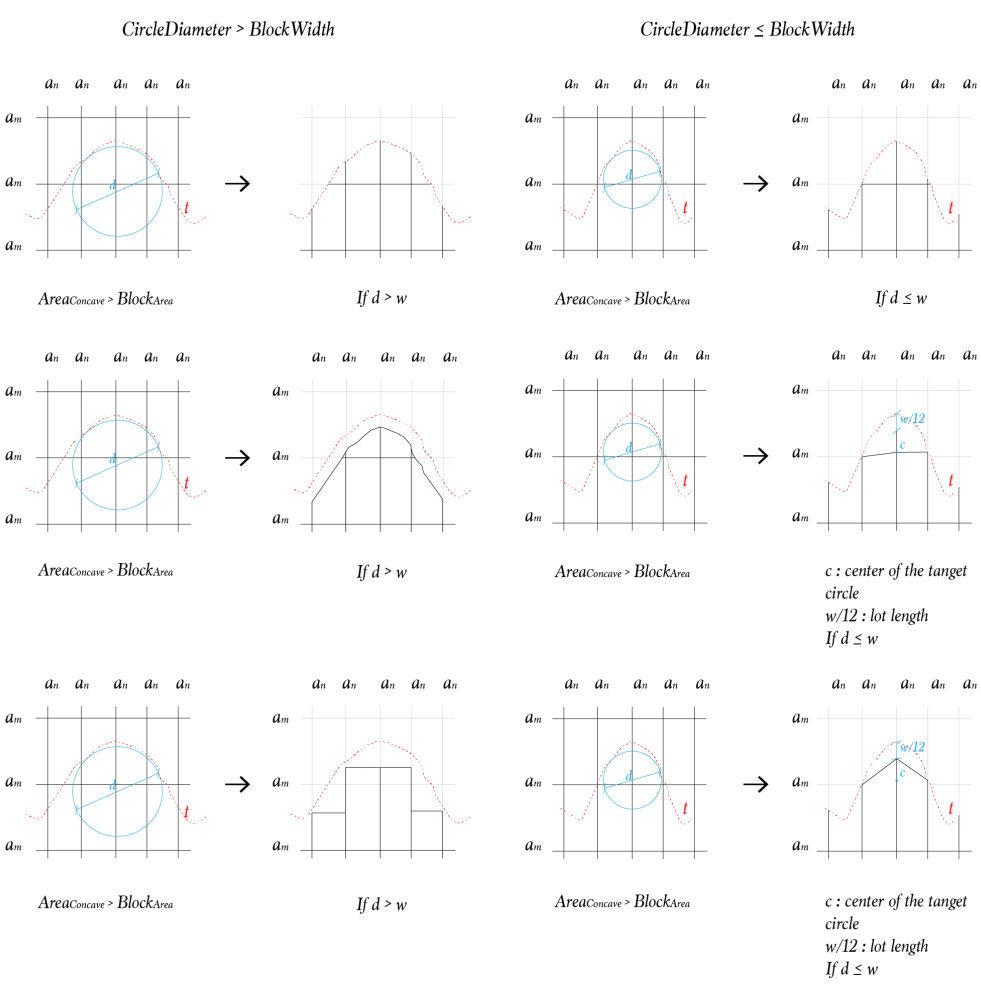
Where AreaConcave = area of concave region, BlockArea = area of one block, d = diameter of the inscribed circle c, and w = distance between two consecutive street lines or block width. Thus, when given any area of interest that includes the *t* contour line, first the orthogonal grid is created using the grammar described previously; then, for creating the grid distortions, the grammars in Figure 7 - 9 are applied.

DEVELOPING THE GENERATIVE URBAN DESIGN TOOL

After extracting the shape grammars of the urban grid, the next step is to translate the grammars into code. Grasshopper (a visual programming tool built on top of Rhinoceros®) and Python is used for codifying the grammars in this research. The developed tool takes the following steps for

Figure 7
First grammar from top is for finding the concave segment of the t contour line; second grammar is for finding and measuring the concave area; the bottom two grammars are used for comparing the size of the concave area to the area of one urban block

Figure 8
Grammar for comparing the size of the inscribed circle to the width of one urban block, when AreaConcave > BlockArea.



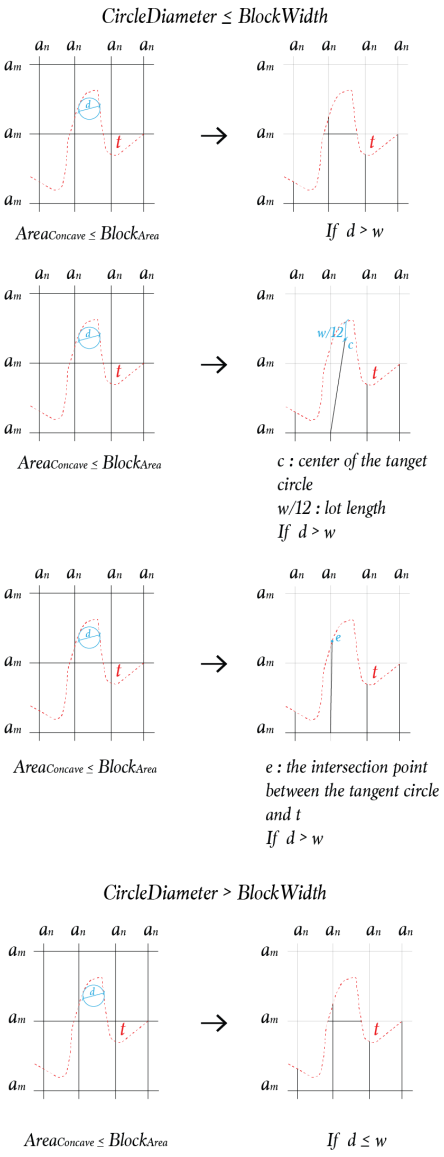


Figure 9
Grammar for comparing the size of the inscribed circle to the width of one urban block, when AreaConcave ≤ BlockArea

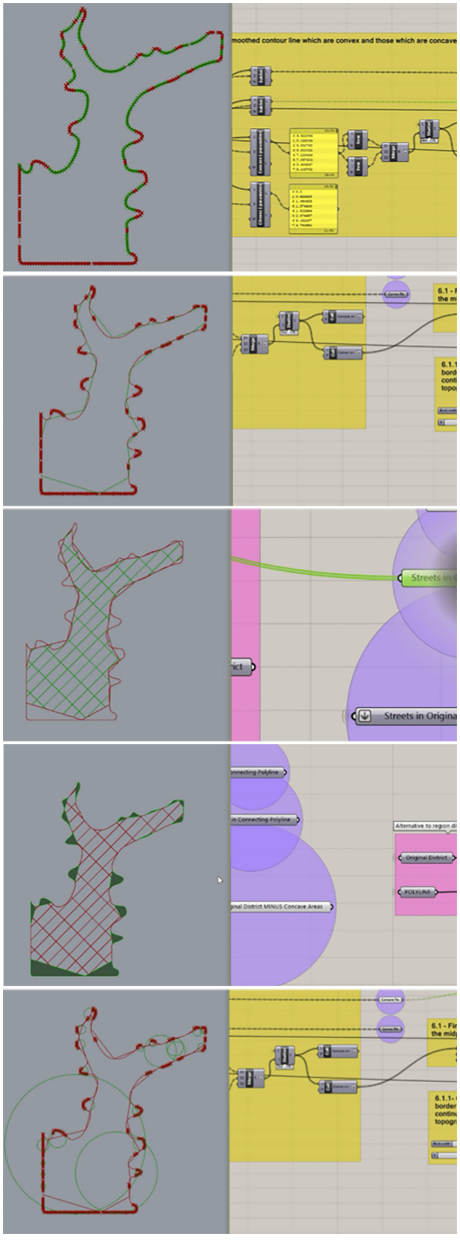
any given region that includes a closed polygon representing the t contour line. The algorithm takes the following steps for evaluating the *t* contour lines, creating the urban grid, and then distorting it where needed (Figure 10):

- Smoothening the contour line: the first step is to make sure the imported or drawn contour line is not a connected sequence of line segments and is a closed planar curve. An algorithm was developed to smoothen any given boundary and convert it to a closed planar curve.
- Finding the concave and convex segments of the contour: after the smoothening process, the next algorithm places numerous points on the curve and evaluates the concavity and convexity of the curve at each of those points. By identifying all consequent series of points that have the same curvature, the algorithm outputs segments of the curve which are concave and segments that are convex. In the top image of Figure 10, the green segments are convex and the red ones are the concave segments of the contour.
- Finding the boundaries of the orthogonal grid: the next step is to find the boundary limits of which the orthogonal grid will extend up till. For this the extreme points of the convex segments of the curve are identified and connected to create the boundary polyline.
- Using CItyMaker to create the orthogonal grid: CItyMaker is used at this stage to generate the orthogonal grid that will be drawn in the limits of the boundary polyline. For this, CItyMaker inputs the overall orientation of the grid, dimensions of width and length of the urban block. These inputs can be altered at any time in the design generation process.
- Evaluating the concave areas and concave segments of the contour: by finding the region difference between the original smoothened curve and the connecting polylines, the concave areas can be selected. At

Figure 10
Several screenshots of the urban grid generation process.

this stage the concave areas are categorized into two groups; larger than a block size and smaller than a block size. For each group a circle is inscribed into the concave segment of the curve to further categorize the areas into ones with narrow concavity and wide concavity. The narrowness of the curvature is measured by its inscribed circle and is compared against d' as described in the grammars.

- Implementing the topography grammar: in the previous step, the concave areas were divided into two, and each of the groups were also divided into two. For each of the four groups certain grammars are allocated. In this step, the grammar explained in the previous section is codified and converted into a generative system.
- Implementing grammar for creating blocks: all steps until now have been generating the street pattern of the district. At this stage urban blocks are inserted in between the streets and using the specified block grammar, algorithms are developed to connect block to create a larger one or divide block to create smaller ones.
- Generating urban lots and populating them with buildings: after populating the streets with urban blocks, an algorithm is used to create lots within the blocks and populate them with building geometries with different areas, heights, and different assigned building types in the context of building codes and zoning of the city.



CLOSURE

The described generative design system is not the main objective of the broader research, but it's significantly important for synthesizing the required spatial dataset by generating alternative community design scenarios for any given district boundaries. At this point, for any input region the tool finds the boundary limits of which an orthogonal grid can exceed up to, identifies the concave areas created by the edge

of a steep slope in the topology, and based on one of the four categories which each of the concave areas fit in, the system assigns one of the prescribed grammars and populates it with urban blocks and buildings. Moreover, in the broader research a list of all spatial attributes of urban form with energy relevance were identified, their importance in a community microgrid context were described, and a metric for measuring them were specified. At this stage of the process where 3D models of communities have been generated, the algorithm measures all the predefined indices of urban form and aggregates them in a .csv file, prepared for machine learning purposes.

The shape grammars obtained herein are based on a case-study which is admitted to be an urban representative of most American cities. Since the inferred design language has generative properties, it's important to note that the tool generates urban design scenarios within the same design language but for different topological contexts. By this, the tool is not purposed towards generating urban design scenarios with high energy performance and the future added simulation properties are for analytical purposes only. The study presented in this paper contributes to the field of shape grammars by creating a set of rules that take topography into account. By implementing the rules into a tool, it also is extending CItyMaker and is pushing forward existing research.

ACKNOWLEDGMENTS

This work and the works to follow are supported by Penn State Department of Architecture, the Stuckeman Center for Design Computing (SCDC), the Hamer Center for Community Design, and the Design Computing Group (DCG) at ULisboa.

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