Optimizing the "characteristic structure"

Combining shape grammars and genetic algorithms to generate urban patterns

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Abstract. *The present paper is part of an undergoing research that aims at developing software that can generate urban plans, based on contemporary urban design concepts, in an optimized way. As a design method, the project proposes the use of the trilogy formulation/generation/evaluation, which starts with an outline of the design requirements, proceeds with the definition of generative procedures that can result in these requirements, and follows with the evaluation of the generated designs.*
The paper describes the development of a computer program that implements some of Marshall's evaluation methods, and further elaborates them to define generative criteria and to optimize the resulting designs with GA techniques. The program aims at generating what Marshall calls a "characteristic structure", a type of urban fabric that is usually found in vernacular urban fabrics.
Keywords. *Generative design; urban design; genetic algorithms; shape grammars.*

INTRODUCTION

The present paper describes part of an undergoing research that aims at developing software to generate urban plans, based on contemporary urban design concepts, in an optimized way. As a design method, the project proposes the use of the trilogy formulation/generation/evaluation, which starts with an outline of the

design requirements, proceeds with the definition of generative procedures needed to achieve these requirements, and follows with the evaluation of the generated designs. The process does not end here. The result of the evaluation process must retrofit the generative phase, adjusting its parameters for further elaboration and optimization until an optimal solution is obtained.

Although this type of procedure has been often applied to architecture and industrial design, it is not commonly seen in the field of urban design. This field has developed several evaluation methods, most of which generate objective data, but its generative methods are often simplistic and still based on early functionalist precepts. Little effort has been applied to describe urban structures in terms of an underlying logic that can be used to systematically generate new patterns based on successful existing urban areas.

The part of the project presented here shows the use of parametric subdivision rules and genetic algorithms to create certain types of urban fabric, based on concepts discussed by Marshall (2005). This strategy is then compared to the use of simple parameterization.

BACKGROUND

The 1960's saw a strong reaction against modern architecture and urban design, which resulted in spaces often more adapted to cars than to people. Christopher Alexander, for example, criticized the hierarchical route structure of planned towns and suggested that a city should look more like a semi-lattice than like a tree. Moreover, modern architecture methods of design were considered too subjective, making it difficult – if not impossible -- to take advantage of the new power of the computer. The reaction against modernism in architecture started with the Design Methods Movement and continued as a series of systematic studies that aimed at helping architects design in a more objective and well-grounded way, usually taking advantage of automation for analysis and synthesis.

In the late 1970's Alexander proposed a set of verbal rules for designing successful urban spaces based on traditional city patterns. In the early 1980's Hillier and Hanson developed at Bartlett-UCL a set of tools for analyzing the social effects of urban design. In the 1990's, at the same university, Batty used fractal geometry for urban analysis and simulation. More recently, Marshall (2005), also from UCL, has extended these concepts, proposing new strategies for generating and evaluating street patterns, with the aim of helping designers create better urban environments not just in terms of efficiency from the circulation and density points of view, but mainly in terms of creating opportunities for social interaction.

Even though Marshall does not mention in the book the use of geometric rules for generating the street patterns he describes, it is possible to imagine the use of parametric shape grammars to describe and create some of them. The shape grammar formalism was developed in the 1970's by Stiny and Gips to generate rule-based designs. It has been used initially to create original abstract compositions, but its applications soon evolved to architecture in both synthesis and analysis, and incorporated the concept of parameterization.

Marshall's analytical method is very objective and systematic. He developed concepts and a precise mathematical model that permits an objective assessment of the street fabric. Through a set of case studies he establishes the values within which the optimal street structures should fall. For this reason, his theories can be used for directing the generative process towards optimized urban fabrics. However, the number of possible parameters is very large, so the search for an optimized solution means that an enormous amount of possibilities must be considered. For this reason, we propose, in the present work, the combination of his analytical methods with optimization methods, such as genetic algorithms (GA).

The concept of GA has been developed since the 1950's in the field of Artificial Intelligence to deal with problems that incorporate a large number of parameters. It is based on Darwin's theory of evolution and mimics the process of mating and natural selection through the recombination of parameters and the application of an evaluation ("fitness") function. The combined use of shape grammars and GA has been proposed by Gero since the late 1980's. In this technique the order of application of the rules is considered as one of the parameters that can be changed and recombined to result in optimized designs.

OBJECTIVES

The present paper describes the development of a computer program that implements some of Marshall's evaluation methods, and further elaborates them to define generative criteria. More specifically, the program aims at generating what Marshall calls a "characteristic structure", a type of urban fabric that is usually found in vernacular urban fabrics.

The objective of this work is twofold: on the one hand to develop a set of automated tools that could be easily used in urban planning education, and on the other hand to create a meaningful example of the application of an optimization technique - a genetic algorithm - in urban design. Marshall's descriptions of good street patterns, combined with a rule-based system, provided the framework for the generative system, and his objective evaluation methods were used as fitness functions.

IMPLEMENTATION

The design strategy implemented is essentially top down, and can be used to fill up delimited areas that require the characteristics of a typical mixed-used, traditional neighborhood with spaces that have unique qualities and a variety of scenes, perspectives and scale. The program being developed will allow for the generation of street patterns, quickly analyzing them, and finding optimized solutions in terms of the selected criteria. Unlike in typical Genetic Algorithm implementations, we plan to develop it in such a way that it can be used independently for generating and analyzing urban plans (designed automatically or "step by step"). The GA function will allow the user to choose which analytical tools will be used as the fitness function, so that the result of different types of optimizations can be compared. In other words, the GA will not be a complete black box, as it permits the user a certain level of interaction.

Also, differently from most automated design software, the program will generate and analyze schemes made of simple lines, which is much quicker and looks more like a possible alternative in a work in progress than a final solution. Differently from many automated design implementations, it does not have the pretension to be the sole means of design; it recognizes the fact that the use of computer programs in the design process cannot overshadow the designer's intentions. This can encourage users to apply further changes to the results "manually", trying more alternatives, and maybe even using the analytical tools again to test new alternatives, adapted from the automatically-generated ones.

GENERATIVE ALGORITHM

The development of the algorithm started with the deconstruction of a small patch of a traditional urban pattern, similar to what Marshall call a "characteristic structure" (Figure 1). The patch was extracted

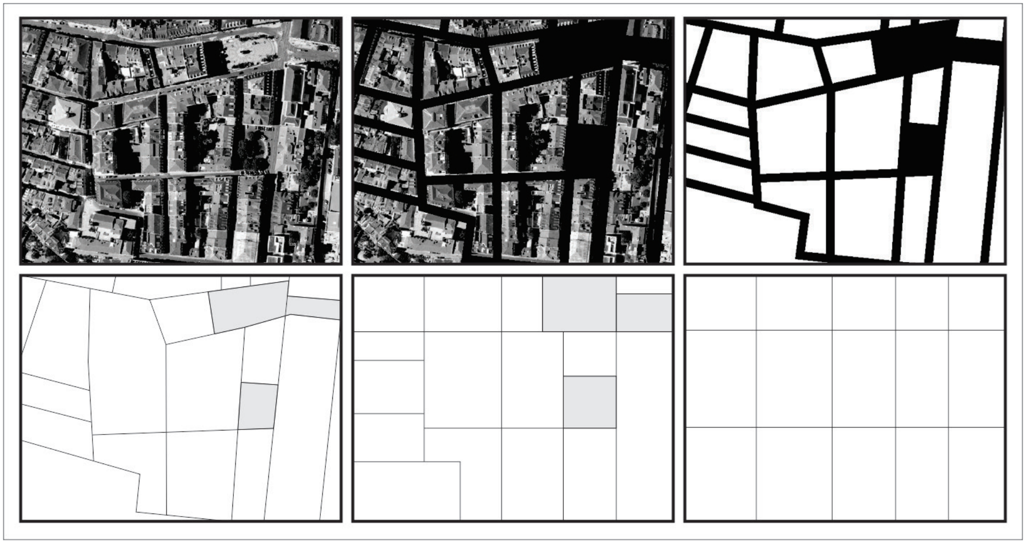


Figure 1
Deconstruction of a traditional urban structure.

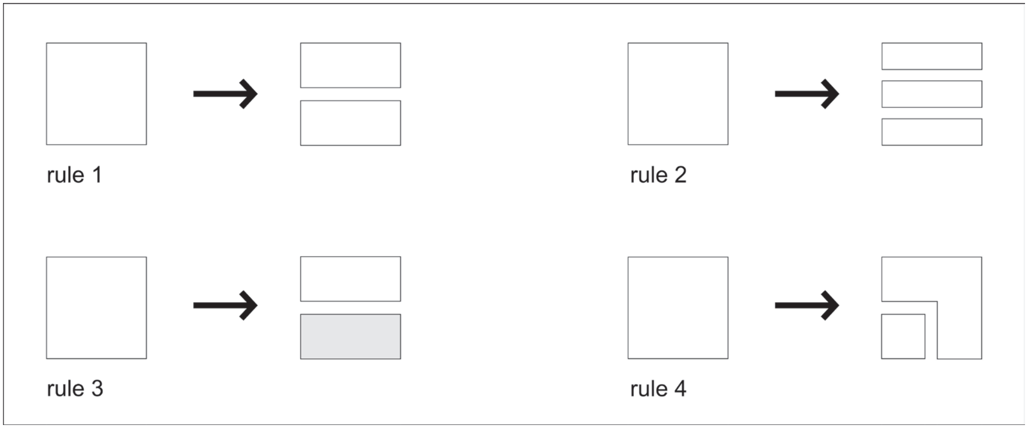


Figure 2
The four rules inspired by the analysis.

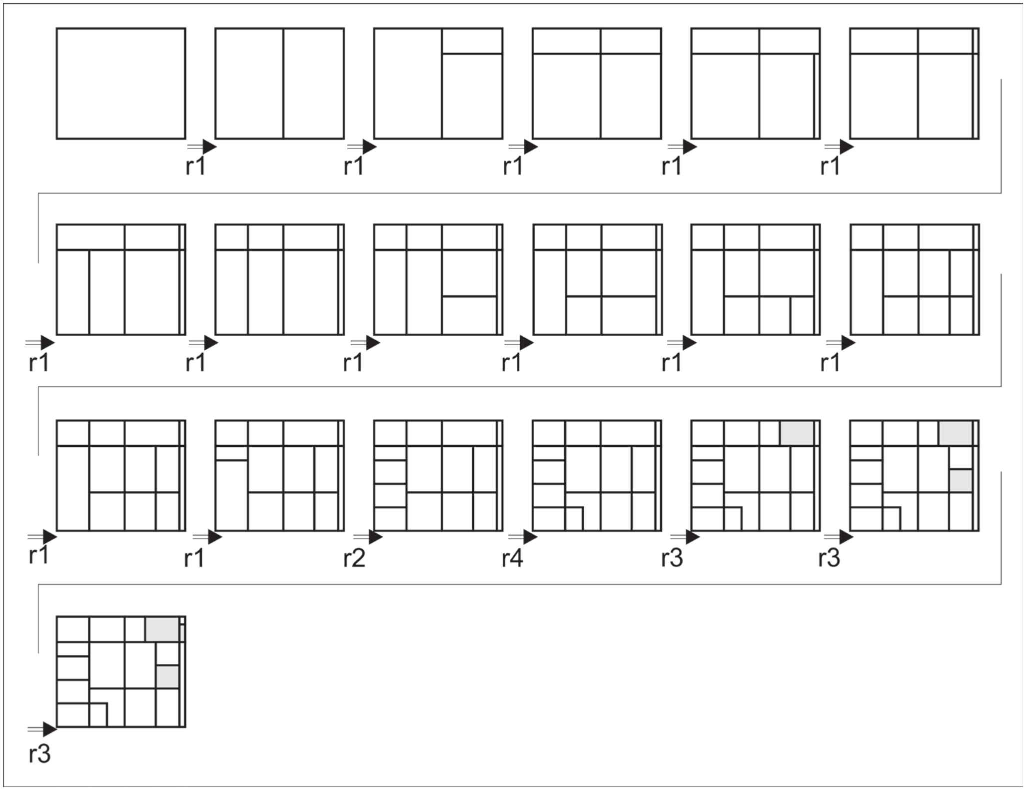
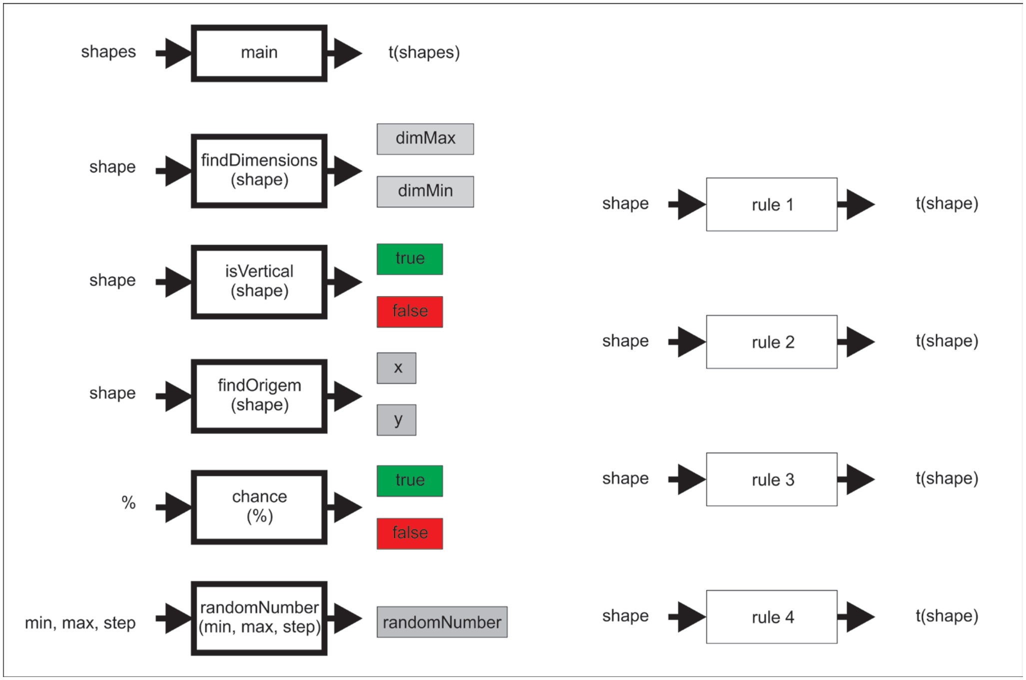


Figure 3
The application of the five rules to generate the patch.

from Lisbon´s Bairro Alto, an area that was initially planned in the XVI century and was transformed after the XVIII century earthquake. The analysis of the patch revealed certain typical patterns that were translated into four basic shape rules (Figure 2), which allow for a recursive splitting of blocks, for the introduction of a loop, and for the insertion of a square. Figure 3 shows the application of rules 1 to 4 in the generation of the original patch. Interestingly enough, these rules capture the generative nature of many vernacular grids of similar morphological types. The street networks developed in such fashion generate structures that fit in Marshall's definition of a route structure. He describes characteristic structures as being "semi-griddy", typically having short and long routes and some differentiation in depth. The street structure should contain a relatively great amount of 'T' junctions, some crossroads and eventually some few tributary or stemming streets (cul-de-sacs and dead ends). All the street networks generated by the four rules fall in street morphological types that correspond to Marshall's generic description of a characteristic route structure. The recursive application of additive rules guarantees that the generated network is a route structure. Routes in Marshall's definition are linear paths "which may be continuous through junctions with other routes".

The next step consisted in establishing possible ranges of parameters for each rule and implementing them computationally (Figure 4). Next, an overall diagram of the part of the program that generates characteristic structures was outlined (Figure 5). The input element for this part of the program is a rectangular grid with unequal block dimensions in x and y. The algorithm analyzes the dimensions of each rectangular block and decides which rules can be applied. Parameters are considered and applied in a modular fashion, for instance, modules of 10 meters.

Figure 4
Definition of functions. The transformation functions are on the right column.



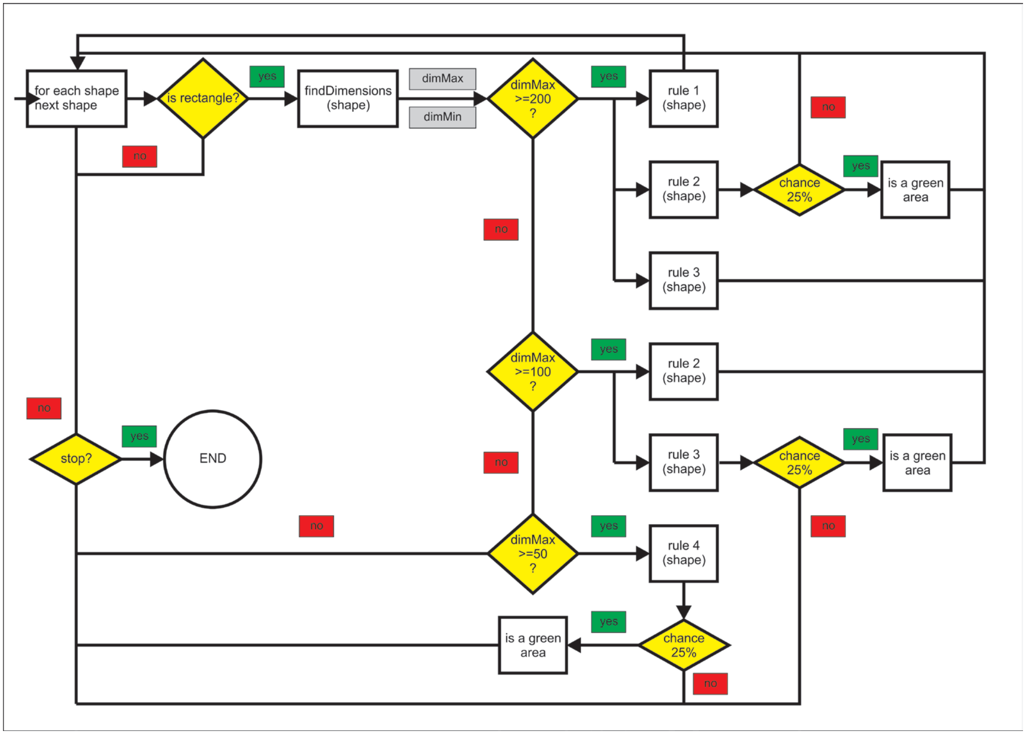


Figure 5
Program general diagram.

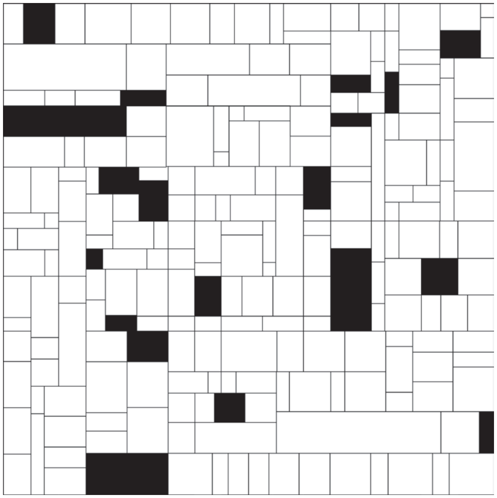


Figure 6
An example of an urban pattern generated with the algorithm developed.

The size of the module will determine the chance of generating coincident crossroads (X crossroads). The larger the module, the higher the chances of generating X crossroads, and the smaller the module, the higher the chances of generating T crossroads.

The user has a chance to bias the generation by defining the likelihood with which certain rules may be applied. For example, one can decide how often Rule 2, which introduces a green area, will be applied after a block has been subdivided. Figure 6 shows an example of a pattern generated by this recursive subdivision process, which is combined with conditional statements. The program was implemented in AutoCAD VBA. Rule application is partially constrained by the area of the rectangle to which it applies. Area is also used to define the stopping condition in the algorithm.

GENETIC ALGORITHM

The next step of this work will consist in developing a genetic algorithm that uses the generative function above and combines it with a fitness function. The quality of urban spaces is a subjective issue, thus difficult to evaluate through objective values. For this reason, we will base our fitness function on the three desirable characteristics of an urban pattern proposed by Marshall, some of which are based on Hillier's spatial syntax: relative connectivity between 0.35 and 0.45, limited depth (but some differentiation), and complexity level between 0.35 and 0.6. Depth is the number of turns that one has to do to get from a given street to the main road. Connectivity is the number of routes with which a given route connects. Continuity is the number of links that forms a route. Relative connectivity and complexity are measures of the street network. The sums of depth, connectivity and continuity of all routes each divided by the summation of their sums provide the network relative ratios for these three properties. In other words, these ratios provide the network's relative depth; relative connectivity and relative continuity which are properties of the network. Complexity is a ratio which evaluates the degree of intermixture between regularity and recursivity of the network which is the number of distinct route types above the maximum depth level divided by the number of routes. A distinct route type corresponds to a route with a distinct combination of depth, continuity and connectivity.

The way the generation algorithm draws the network enforces the definition of a route structure. At each rule application a route is defined. However, the amount of calculations required to yield the network values of relative connectivity and complexity are rather complex. It involves the registration on a table of the three main properties of routes: continuity, connectivity, and depth. Connectivity and continuity can only be filled in the table at the end of the route structure generation. Depth is automatically registered in the table at each step of the generation. A route code is simultaneously registered, which will help finding the connectivity and continuity values for each route. Once the three route properties are filled up, the route type column can also be filled and their summations can be computed. These tasks end the calculation of the properties of routes. From this point on, an algorithm computes the properties of the network, in particular, the ratios corresponding to relative connectivity and complexity. These are purely mathematical calculations following Marshall's concepts. With these two values the network can be ranked and compared with the characteristic values of the characteristic structure of street patterns. If fulfilled, the generation process has achieved its goals. If not, it loops back and regenerates the grid.

Here we need an optimization algorithm, in this case a genetic algorithm. In order to do so, we need to register the genetic code of the route structure as a tree by keeping track of all steps of the generation and registering the corresponding genotype. At each step two or three rectangles are produced through the application of one of the rules 1-4. The genetic code of a particular route structure is, therefore, given by the tree of rules applied until the end of the generation and the value of the modular size being used. The reader should note that the size of modules influences the number of crossroads and, therefore, it also influences the characteristics of the street network. In short, the genotype encodes the order in which rules were applied at each step of the generation.

At this point, we should discuss the tangible meaning of manipulating the genetic code. As just stated, the modular size influences the number of generated crossroads. If the module size is bigger, chances are that we will get a higher number of crossroads. Marshall states in the definition that a characteristic structure contains a majority of 'T' junctions. As such, by comparing the number of crossroads with 'T' junctions, we will know if the module's size should be raised or diminished in the following generation. In the case of deciding which rule to apply there are two factors that influence the results: (1) the rule chosen to be applied and (2) the likelihood set for the application of each rule. For instance, Rule 3, which creates a small square, if used too many times, the network will tend to have two many green spaces. In the case of Rule 2, the network will tend to form more sets of parallel streets of the same size forming a slightly different visual pattern. The genetic code can be manipulated in two different ways: (1) simply by changing the rule to apply or (2) by changing the likelihood with which rules are applied. The latter seems to define a more meaningful way of controlling the results as it takes into consideration the meaning of influencing the occurrence of particular kinds of morphological types. It is also the option used by Marshall in a recent work (2009).

For this purpose, we are currently developing algorithms that evaluate each condition, based on a graphic analysis of the urban patterns that will have been previously drawn by the generative algorithm. A graphically enhanced interface will improve the designer's interpretation of the network being generated. For example, by drawing the blocks of each subdivision with a progressively narrower line, it is easy to retrieve the information about the depth of each route (Figure 7). Besides simplifying the computational process, this strategy also allows the user to visually understand the reason why a possible solution was ranked lower than another one. A similar strategy will be used for coding the other characteristics. The level of connectivity of each route, for example, will be color-coded.

Finally, we plan to develop an interface in which the user can set up certain initial parameters, such as the grid's overall dimension and the blocks' mean area, and the desirable values for the fitness function (within the ranges of values proposed by Marshall). The program will then show, step by step, the generation of families of solutions, the evaluation of each solution according to the three criteria, the selection of the two best options, the combination of their genes (parameters and sequence of rules), and so on.

DISCUSSION

In a recent publication Marshall (2009) shows a network simulation tool called NetStoat. The generative formalism of this tool is also based on

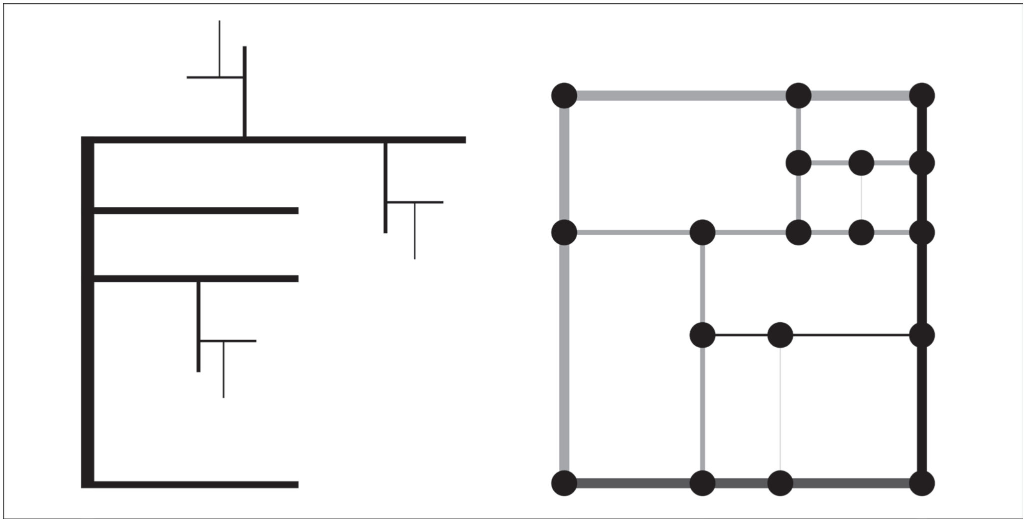


Figure 7
Drawing recursively subdivided streets in progressively narrower lines helps perceiving depth information. Color coding can also be used for representing connectivity.

shape grammars. It was developed to allow for testing four types of generative rules which may be used individually or together, by setting the likelihood of the occurrence of certain rules of. The four generative patterns are called tree, span, T-span and grid. Tree is based on a stemming fractal rule. Span is based in our rule 1. T-span constrains the rectangular subdivision by drawing a new, perpendicular street to the largest side of rectangular blocks. Grid divides rectangles into four parts with an orthogonal cross. NetStoat is used as an analytical instrument to understand and evaluate the properties of street patterns generated with these basic rules.

Our approach is design-oriented. However, the information extracted from Marshall's analytical work could be used to set heuristics to improve our genetic search. In generic terms, additional propositions from Marshall's work could be encoded to improve our proposed model. For instance, Marshall's rules also allow the generation of route structures and they could easily be added to our generative algorithm. As long as rules are defined as route additions a route structure is always built.

CONCLUSION

We have described ongoing research developed with the goal of coupling optimization algorithms with shape grammar-based generative tools for urban design. The ultimate goal is to constrain the generation of street network patterns towards solutions with characteristics set a priori, namely, depth, connectivity, continuity, and complexity as defined by Marshall. This work complements the City Induction project, which is aimed at developing an urban design support tool, by adding optimization to its formulation, generation, and evaluation capabilities. (Duarte et al., 2011)

We expect that this work can help evidencing three important concepts in contemporary urban design: (1) the combined use of rules and parameters can be much more powerful in design than the use of parameterization alone, (2) it is possible to use objective evaluation methods to guide the generation of urban fabrics, and (3) it is possible to combine the automated generation of optimized solutions with an active participation of the designer in the process (in other words, GA does not necessarily need to be used as a black box).

The expected application of this work is twofold. In urban design practice, integrated in urban design support tools, for generating urban environments with certain, desired features, thereby helping to gain an increased control over the outcome. And in education, to enhance the students awareness regarding the topological properties of urban fabrics; to provide methods to objectively analyze and evaluate properties of street patterns and relate them with their expected performance; and to provide greater awareness of the advantages of using a dynamic approach to urban design supported by parametric design and objective analytical methods.Future work consists of further developing the implementation and testing it in workshops. The application will have a potential for teaching urban design along with generative systems, including parametric design, shape grammars and genetic algorithms.

An interesting future development of this work would consist in defining an algorithm for interpreting the route structure of existing urban fabrics. This would allow analyzing any fabric, existent or generated, including a generated network in an existent context. Such approach would extend the usability of the tool and is regarded as fundamental research for future work.

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