PARAMETRIC 'ROUTE STRUCTURE' GENERATION AND ANALYSIS

AN INTERACTIVE DESIGN SYSTEM APPLICATION FOR URBAN DESIGN

José Nuno Beirão,
TU Delft; TU Lisbon.
J.N.Beirao@tudelft.nl; jnb@fa.utl.pt

Pirouz Nourian,
TU Delft.
P.NourianGhadiKolaee-1@tudelft.nl

Bart van Walderveen,
TU Delft.
bartvanwalderveen@gmail.com

ABSTRACT

Marshall (2005) developed the concept of characteristic structure of a street network as a characteristic set of indicators extracted from the street network through a process which he called "route structure analysis". In this paper we propose an integrated process for street network generation and route structure analysis embedded in a parametric urban design process. The street generator is compatible with a larger system aiming at the production of parametric urban designs. The system has been built in a parametric CAD environment and encompasses a method for interactive urban design allowing for dynamic visual responsiveness to morphological change and data change. The street network generator, presented in this paper, is based on a recursive rule which subdivides rectangles within the bounding box of a site area. For each set of goal inputs a street network is generated and "complexity" and "relative connectivity" are calculated through a semi-automatic procedure.

Keywords: parametric urban design, route structure analysis, design methods.

INTRODUCTION

Designing street networks, especially on a large scale, is a difficult task and involves large degree of responsibility because the street network is the most resilient component of the urban environment and once laid down it tends to stay almost unchanged. In 'Streets and Patterns' Marshall (2005) develops the concept of *characteristic structure* of a street network, which is supposed to be the typical structure of a potentially successful street structure. Marshall uses the topological features of a street network to assess the two main indicators of a *characteristic structure*: *complexity* and *relative connectivity*. In his study, Marshall has analysed a large set of street structures corresponding to different morphological types taken from several different urban contexts and analysed all of them calculating the two main indicators. Marshall observed that certain types of street networks perceived by most people as pleasant urban spaces produce measurements of complexity and relative connectivity always within particular ranges of values. The hidden claim is that using this knowledge, urban designers can design street networks which are more likely to develop the most praised qualities of urban spaces, at least those directly related with the topological characteristics of the street network. The question lies on understanding how to assess such characteristic of the urban space while designing it.
In the research presented in this paper we developed a recursive street network generator on a parametric

design platform providing a real time calculation of the network complexity and relative connectivity measures. Such tool allows the designer to grasp the hidden characteristics of a street network expressed in these topological indicators and therefore enhances the designer's perception of the proposed environments. In the next section we explain the structure of the parametric design system supporting the implementation of our recursive street network generator. In the following section we introduce a brief review of Marshall's concepts and a discussion about its meaning in urban design. At this point we focus on the core of the research: the purpose of the recursive street generator, its structure, the method to use it and how it can be plugged in to a larger parametric urban design system. In the discussion we analyse and evaluate the first results obtained from the use of the recursive generator indicating its achievements and shortcomings.

PROBLEM STATEMENT

Laying down a particular street network in any urban context is a serious decision, if not just for its specific properties, especially for the fact that once a street network is implemented little can be done to change its morphology. In a city buildings can be replaced and changed. Even a block can be entirely changed without much trouble. However, the street network is highly resilient and tends to stay unchanged along time, with its intrinsic properties, either bad or good. Designing them correctly before any implementation becomes a sensible issue which involves the responsibility of providing urban developments with structures that can evolve into positive and successful urban environments.
In Marshall's properties of complexity and relative connectivity there is underlying information about the expectations that one can figure from particular route structures. Although limited, the set of case studies presented in 'Streets and Patterns' allows us to use the above referred properties as indicators of the potential success of a street network.
A question arises: how can we be informed about the properties of a street network at very early stages of the design process? Is it possible to obtain information on the street network properties every time a designer explores a new move?
However reserved Marshall's statements may be regarding assumptions about the quality of street networks, there seems to be at least some evidence that certain structures produce potentially better results.
The hypothesis underlying this research is that we can define route structures and calculate their properties, using Marshall's method, almost in real time and each time a move changes some state or arrangement of properties in the design. This paper shows a parametric urban design system that we developed, a reference to its density measurements calculator and a recursive street network generator, a plug-in for designing route structures which is able to simultaneously perform a route structure analysis of the generated network. A concept model for a route network analyser is proposed.
The main concept underlying this research is that by developing parametric design systems which are able to retrieve real time data on the properties of the generated designs allows the designers or design team to enhance their awareness on the potential qualities of the proposed design.

PARAMETRIC URBAN DESIGN SYSTEM

The recursive generator described in this paper is a plug-in component of a larger parametric urban design system built in a CAD environment using a visual programming interface. The CAD environment used in this work was Rhinoceros and the programming interface was Grasshopper. This system was defined to be used as an urban design exploration tool for district scale allowing the manipulation of goal inputs for which a set of block scale parameters and urban indicators are output. The system is described in detail in a recent paper (Beirão et al. 2011).
The urban indicators used in the mentioned system follow the conventions defined in Berghauser-Pont and Haupt (2010). Some of the parameters are manipulated as desired inputs at district level whilst the model delivers the consequent outputs at block level through bounded distribution methods. The flowchart in Figure 1 shows the main processes integrated in that system. There are 3 main types of inputs: geometrical inputs, programmatic inputs and distribution factors.

The geometrical inputs constitute the starting point for using the system in an urban design process. The geometrical inputs are basically a set of polygons, a set of points and a set of lines/curves. The polygons represent a set of bounded areas for intervention. The points can represent focal points, a main square, and locations for local squares or public buildings. The curves represent the main streets in the area. The designer is therefore able of specifying and designing the main components needed to compose a district. Different street networks can be assigned to the bounded areas allowing the designer to develop different plan layouts for the overall area. Each network is defined by means of two parameters or variables and the street width. The design system at the present stage offers three different morphological street types: rectangular, radial and the recursive type explained in this paper. However the system was developed in such a way that allows continuous extension by plugging in new network type generators to the core of the programme. The street network changes by using a switch to explore solutions through the available set of street generators. An extra geometric parameter allows the designer to control the maximum allowed number of floors in the plan. The programmatic goal inputs are a desired goal density expressed as building intensity (FSI) and a desired spaciousness for the plan (OSR). The programmatic inputs are defined at district level. The scale is considered adequate for designing large neighbourhoods. The system also allows the control of a set of distribution factors that influence the distribution of the building intensity over the district. The distribution is basically controlled by the exceptional geometric components (main street, squares and the city centre) for which weights are defined individually by the designer according to the attraction value he or she recognizes in each component according to the context.

The design exploration tool provides data calculations to the designer in real time updating each time s/he changes some part of the geometry or a parameter. The constant updates of data according to geometry make the design system responsive and encompassing what is regarded to be a typical consistent design process in terms like those defined in Lawson (2006), that is, that design is a negotiation process between problem and solution by means of analysis, synthesis and evaluation. At each move the designer is able to assess it not just in visual terms but also on the consequent measurements of that particular design state being therefore able to reflect on several levels of its meaning and especially relating morphology with its measurements.

The calculations provided by the design system inform the designer on urban indicators calculated both at district and block level. Table 1 shows the information provided per block at block level and at district level. Such information in the model can be stored in a database and eventually accessed in a GIS platform for further analysis, using an 'object-oriented' data-storage protocol as a geo-referenced location plus its various attributes. Integrated analysis with the design context can therefore be performed in the GIS environment. The shaded set of indicators in Table 1 is used to define a building code per block that is consistent with the goals of the overall plan.

The parametric urban design system is able to provide continuous update of data regarding density based urban indicators allowing for continuous assessment of the design states move after move. The whole system is organized following the concept of 'design patterns' (Woodbury 2010) - recurrent sets of algorithmic operations compacted or clustered into components performing generic operations. As an example, certain design operations, like filtering parcels of design geometry components from the main set of geometry components, for instance, functions filtering excessively small blocks, were compacted into similar design patterns. We called them geometry filters.

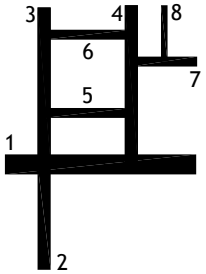
ROUTE STRUCTURE ANALYSIS

In his book Marshall establishes a set of conventions and provides them with a set of mathematical models to calculate what he calls the *characteristic structure* of a route network which he claims to be the structure of street networks of towns which are perceived as pleasant urban environments. The characteristic structure is recognized when two main indicators, complexity and relative connectivity, reach medium to high levels (page 154).

Marshall's conventions are summarized in this section. The analytical process is called *route structure analysis*.

A route is a linear aggregation of links where the points connecting links are called joints. Each joint has one 'through route' formed by conjoining two links. At each joint the number of links exceeds the number of routes by one. For the whole network, the number of links exceeds the number of routes by the number of joints.

There is no single 'correct' route structural representation of a graph of nodes and links and the set of routes formed from it. The specification of elements for analysis relies on the contextual interpretation. Only after being subjectively abstracted from the context, topology and network can be clearly and objectively analysed. However, the main criterion for interpretation is to consider the most continuous paths of movement through a junction. The subjectivity lies in the fact that continuity of movement does not necessarily depend on the morphological hierarchy of the street but rather on its topological position within the network. Interpretation is needed for disambiguation. In any case Figure 1 shows an illustration of the main concepts involved in a route structure.



Route numbers	Depth
1	1 (datum)
2	2
3	2
4	2
5	3
6	3
7	3
8	4

Figure 1 - Route representation following Marshall's conventions and respective depth.

Route structure analysis is based on 3 basic properties: Continuity, Connectivity and Depth.

Continuity (l) – is the number of links that a route is made of, or, the length of a route measured in links. Reflects how many junctions the route is continuous through.

Connectivity (c) is the number of routes with which a given route connects and reflects the number and nodality of joints along a route.

Depth (d) measures how distant a route is from a particular main route (the 'datum') measured in number of steps of adjacency. The datum has the depth of 1. Routes connecting the datum have depth 2 and so on.

Street networks can be regular (e.g.: iron grid), recursive (fractal) or complex.

Recursivity is the number of depths (= maximum depth) divided by the number of routes.

Complexity is the number of distinct types present less the value of maximum depth all divided by the total number of routes.

Summarizing:

Network properties

L	number of links in a network	
	= network sum continuity	$=\sum l$
C	network sum connectivity	$=\sum c$
D	network sum depth	$=\sum d$
S	sum value of a network	$= L+C+D$
R	number of routes	
Y	number of types of route	
D'	maximum depth value of network	

Netgram properties

Λ	relative continuity	$=L/S$
X	relative connectivity	$=C/S$
Δ	relative depth	$=D/S$

$\Lambda+\Omega+\Delta=1$

Hetgram properties

Ψ	irregularity	$=Y/R$
Φ	regularity	$=1-\Psi$
Θ	recursivity	$=D'/R$
Ω	complexity	$=(Y-D')/R$

$\Phi+\Theta+\Omega=1$

The *characteristic structure* of a street network is defined as falling within the following values (p. 154):

- Relative connectivity (X) around 0.35 – 0.45
- Not too great a depth (but some differentiation)
- Complexity (Ω) 0.35 – 0.6

Route structure analysis' calculations follow three steps. The first step defines the route structure according to the principles stated above and is subject to context interpretation. The second step involves the calculation of the route structure properties until relative connectivity and complexity can be calculated. The third step evaluates the meaning of the measured values by comparing them

with the characteristic structure values. The interpretation of all calculations is still an issue for experts.

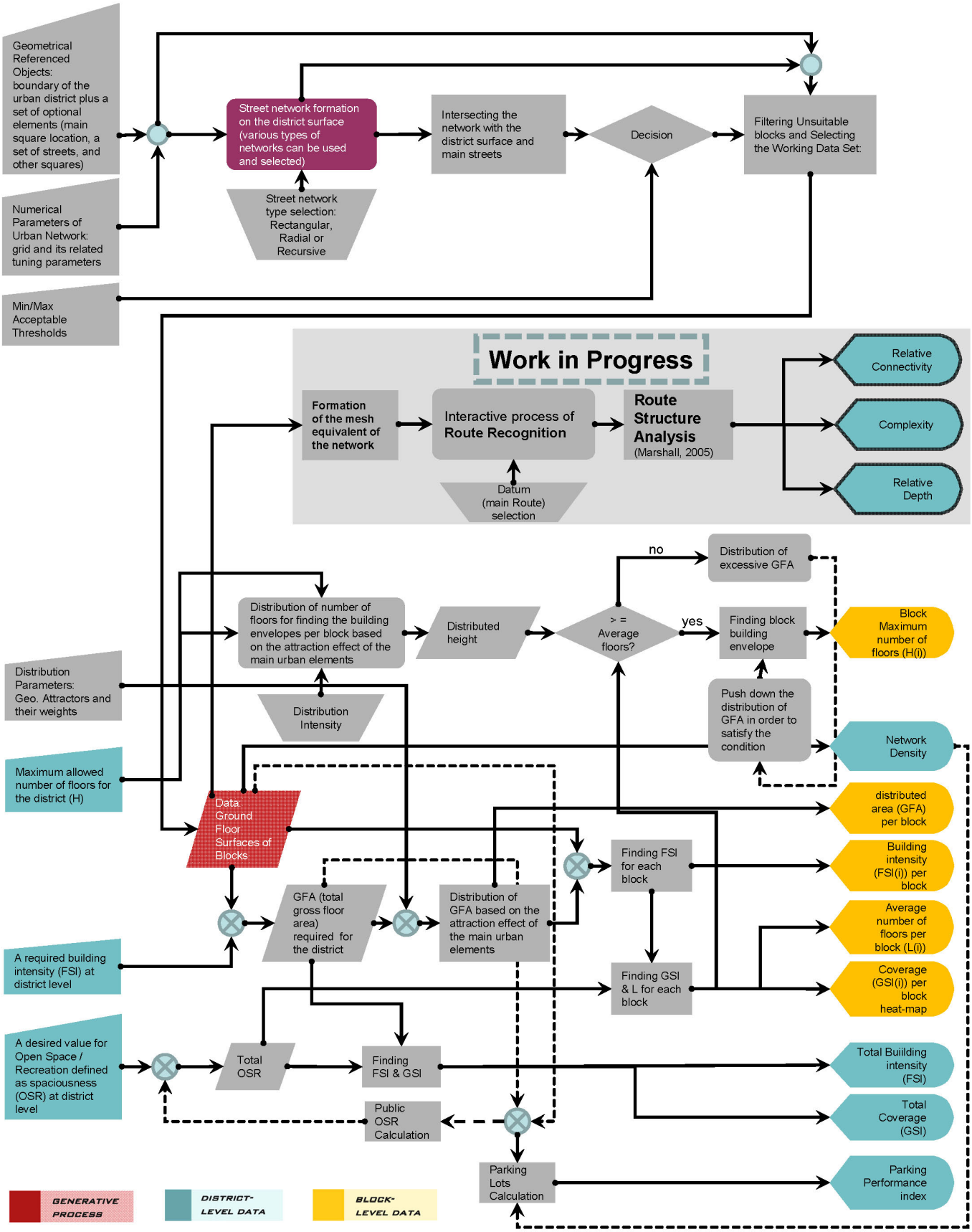


Figure 2- Flowchart of the parametric design system.

THE RECURSIVE PATTERN

In the definition of a characteristic structure Marshall describes it as being "semi-griddy", typically having short and long routes and some differentiation in depth. Along the examples and descriptions it becomes clear that 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). In a recent publication (Marshall 2009) he shows a few images of computer generated street networks where a mixture of 'T' junctions, cul-de-sacs and crossroads are randomly generated according to some rules. This was the main motivation for developing the street network generator shown in this paper.

We considered an added value developing a street network generator capable of designing route structures and simultaneously deliver the calculations that allow the identification of characteristic structures. In other words, the goal was to define a design system application that generates the route network and simultaneously performs route network analysis.

Our street network generator is based on a recursive parametric rule that subdivides rectangles. The rule is shown in Figure 2. The rule applies always if the area (A) of the rectangle is bigger than a user predefined area (A') and the parameter *u* is constrained to a minimum value (*u'*) corresponding to a user defined number of pixels. The pixel size is also predefined by the designer. The pixel size has a meaningful impact in terms of the morphological characteristics of the street network and also influences some results, namely the ratio between crossroads and 'T' junctions. The finer the pixel the higher the number of 'T' junctions. Typical values for the pixel size are 5m, 10m and 20m and they influence the modularity of the network. The first constraint works as the stopping condition of the recursion. The parameter *s* corresponds to the user defined value for the street width.

The two constraints of the grid generation behave as controllers allowing the designer to manage the size and proportion of urban blocks. In that sense, the recursive generator guarantees the generation of certain qualities in a network: (a) the network is essentially generated following Marshall's description of a characteristic route structure; (b) the block size and proportion can be controlled by the designer allowing the generation of blocks within the boundaries based on local or theoretical evidence either supporting the use of small or large blocks. The system randomizes some of the decision but constrains the results within acceptable design solutions. The qualitative meaning is a matter for contextual interpretation. A proper application would be to use this system for filling the vacant urban districts, given the main access routes.

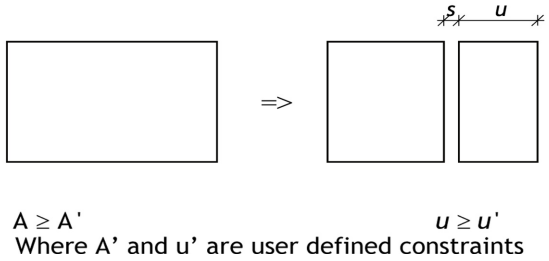


Figure 2 - Recursive rule

Parametric programming interfaces such as Generative Components and Grasshopper are feed forward systems which do not allow for looping back the linear flow of data. In order to solve this problem we had to devise a system that could allow for looping back the information we needed. The main concept works by breaking the information flow into discrete moments, store the data in a data tree of strings or an excel sheet and feed it back in the next recursion. This was done as an alternative to a previous solution where the recursion is obtained using Chatzikonstantinou's 'hoopsnake' component (2011).

While using the urban design system, when a designer chooses to use the recursive street network generator, s/he follows an interactive process of generation as explained below (see also flowchart in Figure 4):

1- Input of starting geometry, consisting out of two surfaces (the main route – datum - is the street defined between the two surfaces – rectangles – and it is defined by the system user).
2- Press a button to start the recursion loop. Alternatively, s/he can choose the step-by-step recursion process to have more control on the way pattern grows namely by manipulating at each step the above mentioned parameters.

3- There is a data exchange interface, which converts geometric data into matrices. This is a necessary step in order to make the recursion technically possible, since looping is only possible with numerical variable parameters.

The recursive division then evolves through a set of states following the algorithm:

4- A 'matrix-to-geometry' converter interface decodes the initial set of surfaces.
5- Subdivider (Kernel) – splits the geometry and outputs the new sub-surfaces.
6- Display visualization of the new geometry.
7- Feed the new surfaces back into the recursive process.
8- Determines the dimensions of each surface and filters out surfaces that are too small.
9- Determines the direction of the split for each surface. Split is always made along the short edge.
10- Creates the split proportions based on random numbers with a certain threshold. It gives each surface the percentage where it should be split. With a threshold of 10% this will be between 10% and 90%. With a threshold of 40% it will be between 40% and 60%.
11- Visualizes the new set of surfaces.
12- Checkpoint for interruption: user sees the new split. If s/he is not satisfied with the proportions, s/he can refresh the split with a new proportion within the acceptable range.
13- Converting geometries to matrices.
14- Loop prerequisite: whenever a step is made, the data is passed on and loops back to step 4.

This set of steps ends when the split conditions are no longer satisfied. Each of the above points corresponds to a particular function defined by a set of code components in the programming interface. The network generation is ended but some extra procedures are still needed to get a route structure able to be analysed according to a typical route structure analysis.

In Figure 3 we show the appearance of the street network generated with the recursive generator already integrated in the main design system shown in the flowchart in Figure 2.

STORING ROUTE STRUCTURE DATA

The recursive formation of the street network provided by the recursive street network generator produces a new route at each iteration allowing the formation of a topologically consistent route structure where the datum is the widest street resulting from the first subdivision avoiding anymore problems regarding interpretation. All other streets will have a modular width increased by their progression in the recursive process (as it is visible in Figure 3).

Outputs at block level		
		Unit
Identifier		
	Block number – index	Integer
Attributes / urban indicators		
code	FSI – building intensity	m^2/m^2
code	GSI – coverage (block)	m^2/m^2
	GFA – gross floor area (per block)	Square meters or hectares
code	OSR – spaciousness	m^2/m^2
	L – average height (block)	Number of floors
code	max H – maximum height	Number of floors
	A – block area	Square meters or hectares
Distributed function / use		
	Function	String
	Function intensity in block (%)	Percentage
	Area per function	Square meters
Geographical location		
	Centroid of block polygon	Point coordinates
	Polygon corner points	List of point coordinates
Outputs at district level		
	l - Network length	M
	N - Network density	m/ m^2
	GFA – gross floor area (district)	Square meters or hectares
	GSI – coverage (district)	m^2/m^2
	L – average height (district)	Number of floors
	PPI – parking performance index	If ppi>1 parking capacity is insuficient
	DPI – daylight performance index	% of floor space exposed to sunlight

Table 1 - Outputs of the design system

However, although the recursive street generator is capable of generating from scratch a route structure, the insertion of the network in the main parametric model changes the structure for two main reasons: (1) set of main streets inserted manually change the structure and probably should contain the datum, and (2) the adaptation of the network to the site cuts parts of the network changing its structure.

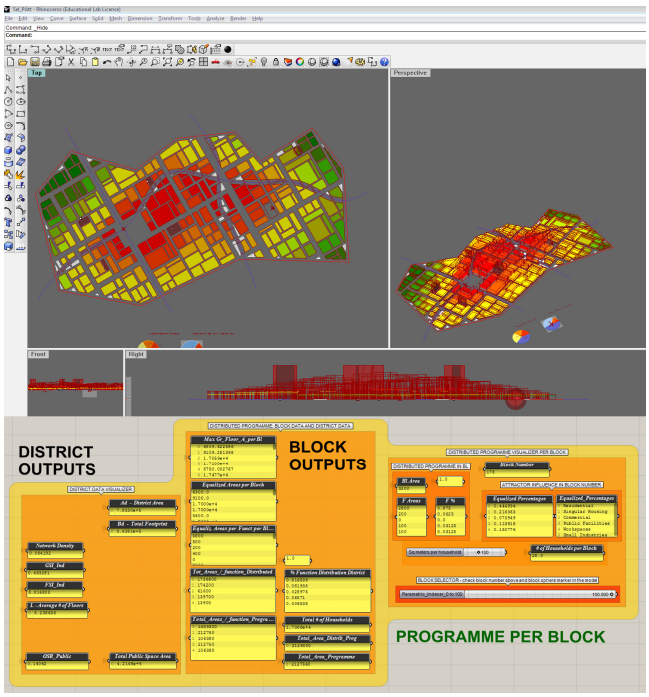


Figure 3 - The street network generated with the recursive generator. The heat map from red to green indicates the building intensity. The pie charts indicate the distribution of functional programme. This subject is addressed in another paper. Below there is a sample of the output interface available in the programming environment. The interface indicates the numeric values of the density indicators.

To deal with this we developed a route structure analyser. The route structure analyser starts by converting a copy of the network. The datum is then selected manually by the user to avoid the need for interpretation algorithms. The user is allowed to select the first routes again to avoid problems regarding interpretation. In order to define the route network structure an algorithm starts from the datum, recognizing/identifying the routes and storing all the information associated with each route's depth. At each step the algorithm stores the continuity and connectivity of the previous route and the depth of the routes. At the end, all the route structure data is stored in a table allowing for the calculation of the other parameters needed to assess the complexity and relative connectivity measures.

The table is necessary essentially for the identification of route types. A route type corresponds to a single combination of depth, continuity and connectivity and this can be clearly identified in the table.

The first manual steps allow overriding most questions regarding the interpretation of the network. In this way, the route structure obtained in the end is likely to correspond to an acceptable interpretation of the street network. The calculation of complexity and relative connectivity is automatic. This information is immediately presented in the data interface augmenting the designer's perception about his/her design decisions.

The outputs are numerical calculations of relative connectivity and complexity. The designer simply needs to confront these values with the accepted ranges identified by Marshall as the characteristic structure for evaluating the street network's fitness within this concept. This calculation specifically enhances the designer's perception on the topological qualities of the network.

DISCUSSION

The main principles explored in this research are:

1- Creation of a parametric urban design system providing a high degree of interactivity between design decisions and data dynamics and flow (either goals or outputs).

2- Enhancing the designer's awareness on the consequences of proposed design moves by providing consequent measurements on urban density indicators or network properties. The idea is to keep track of urban indicators in a dynamic process allowing designers to get an immediate overview of data changes as a response to changes in the design.

The two developed characteristics allow for the development of urban plans in such a way that the designer is able to reflect on each design decision made along the design process considering not just morphological composition but also what such morphology means in terms of urban indicators and network properties. Information and design are provided simultaneously offering the possibility for a continuous reflective attitude towards design moves, while interactivity maintains the reflective

characteristics of design process as identified by Donald Schön in his work (1983).
All the indicators and properties provided as output by the parametric urban design system are measurements calculated accurately following Berghauser-Pont and Haupt and Marshall's mathematical models. These methods help to measure complex built environments with numerical measures objectively calculated from the relations among urban elements. The computational design tool presented in this paper incorporates these analytical models improving the designer's evaluation of deisgn alternatives. The tangible meaning of the measurements is left for the designer's interpretation and depends on the context. The interpretation is supposed to be an expert's task.
Setting out the street network in a new large urban development is a serious decision which usually lacks reliable information regarding future consequences in terms of the qualities of the urban environment. The subject is reasonably difficult to tackle because scientific studies regarding relations between urban morphology and the success of the urban space itself are far from producing decisive answers concerning objective qualitative criteria.
Most design decisions at this level are made basically following simple rules, basically rules of thumb, eventually taken from urban design manuals (Barton et al. 2003) (Steiner & Butler 2007) which in most circumstances accumulate valid but essentially empirical knowledge taken from the large amount of empirical existing studies on urban morphology. Our system provides an interesting platform for future studies regarding the relations of urban morphological types with their performance.
More fundamental studies on urban spatial analysis following more accurate scientific methods such as *space syntax* (Hillier & Tzortzi 1976) (Hillier & Hanson 1984) or *place syntax* (Stahle et al. 2005) are essentially post design techniques used for urban analysis rather than methods integrated in the urban design process. Although we understand that they play a fundamental complementary role, they can

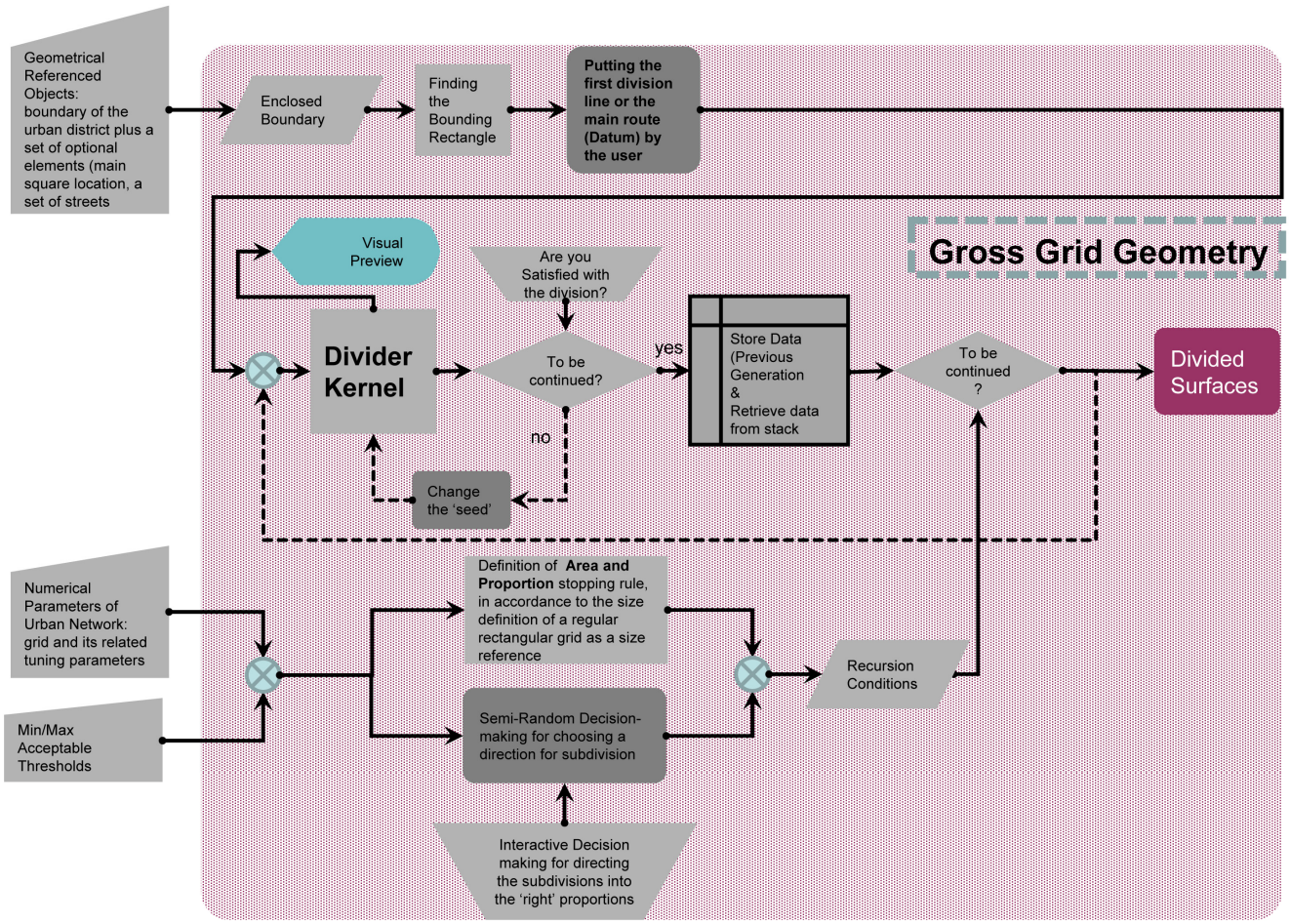


Figure 4 - Flowchart of the recursive street network generator.

only be applied after at least a reasonably frozen solution is achieved.
The parametric urban design system that we are developing, aims at giving some additional insight regarding preliminary design decisions at district scale. Berghauser-Pont and Haupt's indicators and Marshall's route structure analysis provide additional information for urban designers that can point towards the definition of better street networks by trying to capture the best possible output indicators while designing. The definitions of what is a better or worse decision are not addressed here because it will always be context dependent. Our argument simply states that the access to indicators and other related data, in real time and at each move, all along an urban design process, is in itself an improvement on the information available for supporting a designer's decision. As such, we can say that our system is simultaneously a design system and a design support system.
Our route structure analyser is still in a preliminary format and needs to be further debugged. It started simply by generating the route structure and respective analysis using the recursive street network generator simultaneously as network generator but also for storing and calculating the network properties as defined in Marshall's method. The recursive generator itself by using the above referred rule is likely to produce street structures within the range of characteristic structures or at least very close to it. The addition of the other composition elements of the plan - main streets and squares – and integration in the main model tends to add extra complexity to the network improving the expected qualities of the network.
However, the route structure analyser, according to the proposed concept-model, aims at analysing any available street network and not just the ones generated by the recursive generator. Some problems regarding contextual interpretation still stand as a difficulty in the implementation of an algorithm for defining the route structure. Nevertheless, the problems of interpretation can all be solved manually allowing the analyser to measure a route structure according to Marshall's principals. In any case, the provided analytical system integrates in the design process a tool capable of giving some feedback on the topological relations underlying the spatial configurations being proposed and opens an extensive field for studying the existent knowledge on spatial analysis (Hillier 1996) and its application in the design process.
Finally, we think that our parametric urban design system provides means for design exploration which are consistent with most updated ideas concerning the main elements composing the urban space (Duany & Plater-Zyberk 1993) (Jacobs & Appleyard 1987), namely concerning the use of the concepts of district, block and a qualitative set of traditional urban elements without forcing particular configurations at building level.

CONCLUSION

Parametric design system applications allow building up interactive urban design systems which provide not just for morphological exploration but also for exploring through the consequent data variation on urban indicators and network properties. Such data exploration provides our design tool with the characteristics of a design decision support tool because decision support and design exploration are integrated in the same design environment. The proposed systems are capable of dealing with morphology, data and topological relations providing interactive information at these three levels and therefore enhancing designers' awareness about the *qualities* of each design decision.

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