CIM-St

A Design Grammar for Street Cross Sections

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The design of streets plays an essential role in shaping the quality of our cities. In particular, the design of a street's cross section determines in many aspects the realm of its use, enhancing or reducing its ability for being walkable streets or traffic oriented streets. This paper shows a street cross section design interface where designs are controlled by an ontology and a parametric design system supported by a shape grammar. The ontology provides a semantically ordered vocabulary of shapes, symbols and descriptions upon which the grammar is defined. This paper focuses on the grammar definitions and its translation into a design oriented interface.

Keywords: Parametric Design, Ontologies, Compound Grammars, Street Cross Section, Urban Design Systems

1 INTRODUCTION

CIM-St is an extension to a City Information Modelling (CIM) tool, dedicated to the (semi-)automatic generation of street cross sections of street types selected by the designer.

The design system combines computational ontologies (Gruber, 1995) with a compound grammar (Knight, 2003), an extension of the shape grammar formalism (Stiny & Gips, 1972). The former describes and structures knowledge about a specific knowledge domain (in this case, the city) and are used to inform and control the design generation process, ensuring the semantic accuracy of the final design. The compound grammar, on the other hand, combines generic shape rules (Beirão et al., 2009) enhanced with description functions (Stiny, 1981) that, informed by the ontologies, select which rule to apply and provide meaning to the designs. The compound grammar follows a procedural structure and is composed of two parallel grammars, one that generates the street section and another that generates the corresponding plan view.

The combination of shape grammars with ontologies results in a generative design system with analytical capabilities, ensuring the production of valid design solutions at the end of the generative process (Grobler et al., 2008). The knowledge base of our system was built from part of the Networks ontology, itself a sub-ontology of the City ontology (Beirão, 2012), and provides a taxonomic structure of the concepts of the street system and transportation networks.

In this paper, we will show that the semantics of the design system is supported essentially by the ontology structure which also controls the sequence of procedures through its hierarchic structure, while
shape rules are very simple ones, essentially additions of parametric quadrilaterals where the parametric variation is provided by the ontology depending on the specifications of the shape class.

2 THE NETWORKS ONTOLOGY
The networks ontology describes networks within the City domain. The most representative one is the streets’ network, not just because it describes one of the strongest morphological factors in urban morphology, but also because it is the physical support of most of other networks - public transportation; bicycle network; infrastructural networks, etc.

The street network is composed of several sub-ontologies (Figure 1), a set of street names (SN - Street Nomenclature), a set of descriptions defined in terms of the role of the street as part of the Transportation Network (TN), a set of street descriptions (SD) describing the partial components of a street section for each basic street type, and a set of street parametric components (SC) that combined according to the provided descriptions will generate a street section in two types of Euclidian representations - plan view and section.

Conceptually, as a design interface, the system was developed considering that a designer soon after laying out the main ideas for a master plan will design the streets considering as input the width of the street section. Therefore, the initial shape in a street section design generation will be an abstract section composed of two opposite facades on opposite sides of the street at a distance corresponding to the street width. Technically, in terms of shape generation the initial shape is the center point of the street section. However, the generation process starts with the generation of a street description by means of a description grammar. The outcome of the description grammar will then inform the compound shape grammar which will, in turn, be responsible for generating the representation of the street profile. A parallel shape grammar generates the plan view of the same street profile.

3 GENERATIVE PROCESS
The street section design starts from a raw profile inherited from a plan design (not addressed in this paper). This raw profile contains the following information: building section on both sides of the street, a center point half distance between them and a hierarchic value which constrains the association possibilities with the street types in the sub-ontology SN (Figure 2). This hierarchic value is obtained from a basic axial representation of streets by means of their centerlines which should have been already generated as a rough urban plan. This axial representation simply classifies four types of street axes (from a1 to a4) each admitting a consequent transformation to a limited subset of the total set of SN and TN street types. The transformation of each raw profile into a coherent and valid street profile is done in four steps: the selection of the type of street to be designed (limited to the previously mentioned subset); the definition of the components present in the final street profile; the specification and generation of each component’s geometrical representation and, finally, the assembly of the final representation of the street profile and its evaluation.

Figure 1
Structure of the sub-ontologies used in the CIM-St.
Figure 2
Raw profile of the street, where coordinate $x_0$ is equal to half the width of the street. The hierarchic value was omitted because TN ontology is not yet implemented.

3.1 Street Type Selection
SN provides a vocabulary of street types: Street (st), Avenue (av), Boulevard (bv), Main Street (ms), Promenade (pr), Grove (gr), Lane (la), Alley (al), Cul-de-Sac (cs) and Ring Roads (rr). In a first step, a description rule replaces the hierarchic information given as label associated with the street centre by a street type, for instance, Street, and associates the label “st” with the street center. Technically, it erases the hierarchic label (any between $a1$ and $a4$) and adds “st”. The hierarchic label restricts the list of admissible street types for a given raw profile based on its width, setting it as a ceiling for the minimum possible width of the minimum description of each street type. In terms of the design interface, all the user is required to do is select one of the possible street type options from a pull-down menu in the interface.

TN is an additional classification given in terms of the role of the street as part of the transportation network. Adds a second classification given from another semantic viewpoint. This classification allows a user to define the role of the street while defining the role of the street from a transportation oriented viewpoint. Transportation Network (TN) as is defined in Beirão (2012) is a five-level hierarchic classification of car oriented streets that should be combined with SN street types in order to have a full street classification.

Considering that the classification provided by TN is essentially transit oriented while the classification given by SN is essentially based on a cultural description of a street that expresses its qualities in a name given in a particular language, we can say that TN provides a transit oriented structure while SN provides a human oriented viewpoint. The idea is that by giving different weights to the classifications the system may privilege one or the other approach. However, till now, none of the TN options have been yet implemented, so we will omit more information about this sub-ontology. The reason for omitting this part of the ontology was to skip some computational complexity that would only be focusing on car oriented planning, factor that is nowadays criticized as being responsible for destroying public space quality since the advent of modernist planning. However, this implementation has not been forgotten as we will argue in the discussion section.

3.2 Street Description
At a second step, a description rule establishes the minimum description of street components for each street type. For instance, a Street (st) is composed at least by two sidewalks and a car lane in the middle. Street Components (SC) is a set of street profile components such as the ones defined in Table 2. Note that in Table 2 street components are ordered as follows: 1 - street parking; 2 - sidewalks; 3 - bicycle lanes; 4 - bus lanes; 5 - car lanes; 6 - green stripes; 7 - noise protection; 8 - tree alignments; 9 - tram lanes; 10 - canal; 11 - leisure walkway; 12 - protection rails. The integer numbers associated to the street components will be used as indices in the descriptions.

The rule can be written as:

$$D1 : \text{st} \rightarrow < 2|5|2 >$$

Street descriptions are composed of four main elements: symbols “<” and “>” marking the boundaries (beginning and end, respectively) of the street description; a sequence of integer numbers like “2” and “5” (as in the description rule D1) representing different street components and their order in the street profile; and the symbol “|” working as a splitter of the description, marking a separation between street components. If a street is composed of a single component, as in the case of a narrow pedestrian street, no splitters are required in the description.

The minimum street description can then be extended by adding other street components. For instance, in a Street (st) we may add a bicycle lane (D2) or a parking lane (D3) at the side of each sidewalk.

$$D2 : 2|5 \rightarrow 2|3|5$$

$$D3 : 2|5 \rightarrow 2|1|5$$
**D4 : 5 → 5|5**

Rules D2 and D3 can be applied only once on each side of the street while rule D4 can be applied many times until a total street width is “filled up”, adding as many car lanes as required. By applying such rules, we may obtain variations of the street type Street (st) with formats like < 2 | 3 | 5 | 1 | 2 >; < 2 | 3 | 5 | 3 | 2 > or < 2 | 3 | 5 | 2 >. Other options can be obtained. Note that rules D2 and D3 can be applied symmetrically as follows:

- **D2 : 5|2 → 5|3|2**
- **D3 : 5|2 → 5|1|2**

The Street Descriptions (SD) column in Table 1 prescribe which adjacent components are admissible, according to the profile schemas of Table 2, therefore specifying which are the valid adjacencies accepted in a street description. So, the rules shown above produce street descriptions which are always symmetric and define what will be the components of the street cross section to be generated. In order to develop non-symmetrical street layouts we added a rule that allows overriding the predefined street descriptions at any point:

- **D5 : |→|x** where x is a variable representing any street component that respects the adjacency constraints mentioned above.

The reader should keep in mind that we do not show the complete set of street description rules and therefore should imagine possible additional rules available for applying other street components not mentioned in the examples above.

<table>
<thead>
<tr>
<th>Street Nomenclature (SN)</th>
<th>Minimum Street Description (SD)</th>
<th>Possible relations to Transportation Network (TN)</th>
<th>Stratification by speed (after Marshall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>st - street</td>
<td>&lt; 2</td>
<td>5</td>
<td>2 &gt;</td>
</tr>
<tr>
<td>av - avenue</td>
<td>&lt; 2.8</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>bv - boulevard</td>
<td>&lt; 2</td>
<td>5</td>
<td>2*</td>
</tr>
<tr>
<td>ms - main street</td>
<td>&lt; 2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>pr - promenade</td>
<td>(S2 + (11) + S2); (S3 + (13) + S3)</td>
<td>(S2 + (11) + S2); (S3 + (13) + S3)</td>
<td>S2.5 - S2 With horizontal stratification</td>
</tr>
<tr>
<td>gr - grove</td>
<td>(S2 or S3 + (11) + S2 or S3); (S2 or S3 + (13))</td>
<td>(S2 or S3 + (11) + S2 or S3); (S2 or S3 + (13))</td>
<td>idem</td>
</tr>
<tr>
<td>la - lane</td>
<td>&lt; 2</td>
<td>5</td>
<td>2 &gt;</td>
</tr>
<tr>
<td>al - alley</td>
<td>&lt; 2 &gt;; &lt; 2</td>
<td>5</td>
<td>2 &gt;</td>
</tr>
<tr>
<td>cs - cul-de-sac or impasse</td>
<td>&lt; 2 &gt;; &lt; 2</td>
<td>5</td>
<td>2 &gt;</td>
</tr>
<tr>
<td>rr - ring roads</td>
<td>&lt; 7</td>
<td>12</td>
<td>4x5</td>
</tr>
</tbody>
</table>

*with tree alignment or green stripe

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Table 1
Partial representation of the SN object class
Parallel to the generation of street descriptions, the system generates a detailed description of each component’s parameters. Table 1 shows a column indicating profile parameters which are user input variables constrained within a range of accepted standard values taken from well-established urban design standards (the reader may find additional information on this topic in Beirão (2012); for the purpose of this paper the used values are the same as found this latter reference, mostly taken from Pedro (2002)). For instance, sidewalks are composed by the following set of parameters: \( \{ w, e, d, h \} \) where the total sidewalk width is equal to \( e + w \), and \( w = s + d \) including a tree alignment at \( d \) distance from the sidewalk border. The parameter \( w \) which may be considered the usable sidewalk width can variate between 1.25 and 5 meters. In the computer implementation, the maximum limit was actually made flexible to accommodate automated adjustments because the sidewalk width is actually liable to be the most flexible parameter. The value \( e \), is particularly important in terms of street performance because it is the value that provides a space for activities developed inside the buildings to ‘drool over’ the sidewalk contaminating the public space with the activities found inside the private spaces; for instance, a fruit stand or a Cafe’s esplanade (Gehl, 2011; Barton, Grant, & Guise, 2010; Higueras, 2006). So, parallel to the street description rules for any situation where, for instance, a sidewalk (“2”) is generated we will have a description rule generating the description of the sidewalk:

\[
C1 : 2 \leftarrow \{ w, e, d, h \} \quad \text{where the parameters } w, e, d \text{ and } h \text{ are all user input.}
\]

Additional description rules for other street components can easily be defined following Table 2.

Through this example, the reader can understand that the total width of the street can be easily checked automatically while generating the street description providing information whether the street cross section is already fitting the total street width or not. Until this point it is also obvious that the whole procedure is strictly symbolic.

3.3 Component Specification and Representation

At a third step, Street Component labels are replaced by their representations. First, the components are specified as one of their sub-types (when they have one), as in the differentiation between “lateral” and “central” sidewalks. These specifications are the result of the component’s position in the description, options introduced by the designer or restrictions defined in the ontologies, such as admissible adjacent components. Lateral sidewalks, for instance, appear in the street description immediately after or immediately before a description boundary symbol (i.e. “< 2 |” or “| 2 >”, respectively), while central sidewalks always appear between description splitters (“| 2 |”). Some street components (2 - sidewalks; 6 - green stripes; 7 - noise protection) still allow a further level of specification through their combination with other components, as in the case of sidewalks with tree alignments. These levels of specification correspond to user input and may be considered as part of the platform’s design flexibility.

To avoid ambiguity, the “_” symbol was introduced to link associated components’ indices. If we consider the following partial description “| 2_8 | 6 |”, we can undoubtedly state that the tree alignment (“8”) is part of the central sidewalk (“2”), despite being placed next to a green stripe (“6”). Adding tree alignments to sidewalks, therefore, is as simple using the following description rule:

\[
D6 : 2| \rightarrow 2 - 8|
\]

, while adding tree alignments to green stripes and noise protections follow similar rules:

\[
D7 : 6| \rightarrow 6 - 8|
\]
\[
D8 : 7| \rightarrow 7 - 8|
\]

Description rules D6, D7 and D8 could be generalized as a production system (Gips & Stiny, 1980) with variable \( a \) and a single rule, where: \( a | \rightarrow a_8 | \) and \( a \) is a component that has no restrictions regarding the addition of trees.

After the specification of the street components, the system is ready to generate their representations accordingly, following a tree derivation of the com-
<table>
<thead>
<tr>
<th>Street Components (SC)</th>
<th>Profile Schema</th>
<th>Profile Parameters</th>
<th>Transportation Network (TN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1- Street Parking</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Lateral Sidewalks**

- \( 1.25 \leq w \leq 5.0 \)
- \( s \geq 1.2 \)
- \( w = s + 0.3 \cdot \text{width} + d \)
- \( 0.3 \leq d \leq 0.75 \)
- \( c \) is an extra space for additional purposes. E.g.: esplanade, benches, telephone booth, commercial activities, etc.
- \( 0 \leq e \leq 2.5 \)
- \( e \) can also be used also as tolerance. The \( w \) value is further restricted depending on the street type to which it belongs. The values indicated here encompass all possibilities in the case of central sidewalks.
- For central sidewalks:
  - \( 1.25 \leq w \leq 2.0 \)
  - \( w = s + 0 \cdot \text{width} + d \)
  - \( 0 \leq e \leq 0.2 \)
  - \( h = 0 \) in the case of \( 6, 7, 8 \) or \( 10 \)

**Central Sidewalks**

- \( 1.0 \leq w \leq 3.75 \)
- Variations depending on street type:
  - \( 7 \) and \( 12 \) apply only to R1
  - \( 0 \leq h \leq 0.2 \)
  - \( h = 0 \) when next to \( 1, 4 \) or \( 5 \)

**2- Sidewalks**

**3- Bicycle Lanes**

**4- Bus Lanes**

**5- Car Lanes**

**6- Green Stripes**

**7- Noise Protection**

**8- Tree Alignments**

**9- Train Lanes**

**10- Canal**

**11- Leisure Walkway**

**12- Protection Rails**

---

Table 2
Partial representation of the SC object class.
pound grammar using a simple set of parametric shape rules. Street components’ shape stem from the center point of the street which, as we will see in the next step, will be moved to its final position according to the street descriptions generated in the previous steps.

The shape rules applied in this process are of two kinds:

(1) An addition rule adds an insertion point and respective label for each description; the placement coordinates of the point correspond to a translation given from the street center point.

(2) A rule erases the label and replaces it with the correspondent street component.

3.4 Profile Assembly and Evaluation

The global representation of the street cross section comes with the verification of the total width of the street together with the semantic accuracy of the profile, which is ensured by the ontologies during the generation process.

The last step mentioned in the previous section, distributes the representations of the street components along the profile of the street, according to the final description including already all the options given by the user. In fact, due to the semantic structure given by the ontology the generated cross section contains in addition to all the morphologic description any further qualitative information associated with the options that might be considered useful for analytical purposes. Furthermore, the relationships between the street components and the cross section as a whole define spatial relations within the street space that might be evaluated differently according to the purpose of the street within the plan or simply as a definition of public space quality. Therefore, we added a set of analytical tools that provide additional information about the generated profile that could express some of its qualities.

The analysis implemented until now are simply based on morphologic information and are composed of two simple graphics summarize in two pie charts. The first graphic gives a chart on street component impact. The color code gives an immediate overview of the distribution of component types differentiating those dedicated to people (in greenish tones) from those dedicated to traffic (in reddish tones). This gives some information to the designer about whether the street is essentially a pedestrian or a car oriented street. The second pie chart indicates a rough measure of how much trees cover sidewalks. This value is calculated considering both the tree width inputs in the user interface and the total width of sidewalks. The obtained chart is a very rough representation of a relation of tree coverage and available sidewalk space which might be argued to lack important information such as tree type or distance between trees. Still, the chart provides a first impression to the designer about a possible effect of tree coverage along a street.

4 USER INTERFACE AND OUTPUTS

CIM-St interface for street profile design was meant to be as simple and intuitive as possible, posing simple and direct questions to the users that will generate their designs and providing the necessary parameters in order to edit them. It was also meant to provide enough flexibility for users to compose their own street descriptions at will, in a simple and expedite fashion, through the direct manipulation of the symbols in the street description. (Klerk & Beirão, forthcoming)

Working mostly at the symbolic level, using production rules to define and manipulate descriptions and set components’ parameters, allowed us to sim-
not only information processing but also user interaction with the generative system. Simple, objective questions that can be mapped to Boolean or enumeration answers became the primary design mechanisms, allowing users to design at a semantic level using natural language. Answers to these questions target different levels of the ontology maintaining semantic relations and controlling the application of the compound grammar’s rules.

Should the user desire a more direct approach to the generation of the design, or if the street profile required is not standard, the option to override the description enables users to directly specify the type of street components to use and where they will be placed in the profile. This translates into controlling the procedures of the grammar. In the interface, the user simply introduces the street component index where it is considered necessary.

The system was implemented with Grasshopper 3D mainly for educational purposes, so that architecture and urban design students willing to understand the inner workings of the application could easily “take a look under the bonnet” and even modify or extend the application at will. Ontologies were represented using XML format and stored in external files which are fed into the system using a custom XML parser (refer to Klerk & Beirão (forthcoming) for more information). As for the user interface itself, we decided to implement it using Andrew Heumann’s Human UI [1] add-on for Grasshopper 3D, giving it a clean and responsive look with dynamic updates and a dedicated pop-up window with visual analytics (Figure 4, right). The resulting design is displayed in Rhinoceros front viewport (Figure 4, left) and can be “baked” into the CAD application for further editing.

Users control the generation of the design through CIM-St’s main window, starting with the selection of the type of street they desire and its total width. A series of simple, pre-defined questions and parameter sliders will allow them to quickly customize their design. The questions posed to the users are related with the existence of street parking and its type, if there are any bicycle lanes (one or two-way), if there is a canal, if the system should use Green Stripes to adapt any remaining space of the street and if it should automatically add Tree Alignments to Sidewalks larger than 5 meters. A tab with sliders to control specific components’ parameters is also available in the interface. Still in the “Definition” menu, users may override the given street description as mentioned above; on the “Extras” menu, they will find the controls for secondary elements (trees, acoustic panel, buildings) and visualization options. Additionally, CIM-St provides a pop-up window with visual analytics, providing real time information to aid the design decision process, as mentioned above.

A preliminary study with graduate and undergraduate students taking the course of Parametric Urban Design at the Faculty of Architecture, University of Lisbon (2016-2017), showed the interface to be “clear and intuitive”, “user friendly and understandable”, with a “concise” and “visually appealing layout” that “can be used easily” (user feedback).

5 DISCUSSION AND FUTURE WORK

The generative system behind CIM-St allows it to support designers in the rapid creation of large quantities of street profiles, relieving them from repetitive tasks and promoting the test and comparison of many different solutions, leading to more qualified design solutions.

CIM-St was thought to be a design tool containing additional information to support design decision during the ideation phase. During the development of the tool as is presented here and even during the writing of this article, we were able to raise our...
awareness on possible improvements or additional features that can be easily introduced while providing additional information to support the users. As such, in this section we provide an extended discussion on these topics.

As mentioned in section 3.1 the implementation of the TN sub-ontology is still missing. The implementation of this sub-ontology will allow introducing better evaluation criteria while distinguishing or balancing information between traffic oriented streets and pedestrian oriented streets. This addition will introduce the interesting topic of deciding how to weigh the two different vocations which cannot be treated linearly because the topic is essentially network oriented. As such, this particular topic, although stressing its underlying interest, should be carefully treated including the development of appropriate methods to approach it which should certainly include topologic analysis as part of the method.

At a representation level, it is evident that the system would profit from having the generation of the street cross section together with a partial plan representation, let’s say, an extension in plan about 10 meters in length, which could provide the user also a plan view of the street produced by that cross section. The use of the plan has not been implemented yet but is foreseen to provide further possibilities in terms of design information.

The design interface already considers relatively abstract information about the buildings containing the street. Such information might be added to the representation model and used for analytical purposes. So, more evident and probably easier to implement than the previously mentioned issues, there are topics of analysis that can be promptly added to the system. Here is a list of already planned work:

- A street parking indicator inspired on the Parking Performance Index (PPI) of Berghauser-Pont and Haupt (2010), using the information gathered from the use of the street parking component (“1” in Table 2). At least, our street profile can set the assumptions regarding the street’s parking capacity need to calculate PPI.
- Evaluating the potential of the sidewalks to support street life based on its width and already mentioned supporting theory. This topic could be evaluated just roughly from the morphological properties of the sidewalk but more accurately by adding information about qualities of the ground floor such as transparency and building porosity. In fact, the tools shown here could be easily crossed with the tools found in Beirão and Koltsova (2015) providing positive inputs in both research approaches.
- Evaluating the canyon effect of the street profile together with the tree coverage. The reader should understand that the system developed until now allows the user to input the measures of trees - trunk and canopy - which although not indicative of a particular tree type, allows the designer to set the ideas about the kind of tree form planned for a space providing evidence that might support such decisions.
- Introducing street components with hybrid functions. Presently, it is not possible to [explicitly] create street profiles with areas sharing different functions, such as a predominantly walkable street that allows a reduced level of traffic to pass through it. This happens because current street components are function-oriented and there is no option available to inform the system that a certain component may share some properties from another.

The system might also be improved by establishing a connection between the generated representations (which are low detail representations of street profiles) and BIM providing constructive detail and hence including the detail design phase in the design flow. As this intention can be easily obtained by simply connecting this representation with already existent IFC objects available in commercial software
we decided that it could be interesting to add a kind of pre-detailing sub-ontology where schematic constructive intentions could be added to the design; for instance, setting permeability characteristics of pavements which may allow the calculation of additional quality indicators like the street’s surface permeability index, information that may contribute towards the design of more sustainable streets.

As a conclusive statement in this section, we would like to stress that many of these features are so easy to implement that we plan to have them ready before the end of the year. After concluding such tasks, the research will focus on the relations between street morpho-types and building morphotypes to try to measure their mutual positive synergies.

6 CONCLUSIONS
The design interface described in this paper was implemented on a parametric visual interface following a compound grammar mostly composed of symbolic rules operating on ontology descriptions. The semantic control over the design generation is obtained through the ontology which controls the relationships between the components of street profiles. The result is an elegant grammar composed of a few description rules and two parallel shape rules replacing a description with an equivalent shape, one generating the cross section representation and the other the respective plan representation. The implementation follows the simplicity of the grammar and puts its efforts on the interactivity of the design interface.

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