Advanced Tools and Workflows for Urban Designers

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I. Introduction

The medium of formal city making is both physical and representational. That is, the physical stuff of cities – brick, stone, mortar, steel, rubber, glass and asphalt – is represented in drawings, models and specifications, before it is put in place. This disciplinary common sense has long since underpinned the work of architects, urban designers, planners and engineers. As Robin Evans famously pointed out, ‘architects do not make buildings, they make drawings of buildings’ (Evans, 1989). We need drawings – maps, plans, sketches, designs, models and blueprints – to study the possible arrangements of materials in advance of the usually expensive, time-consuming and often dangerous concerted act of building.

The relationship between the physical stuff of buildings and their representations is never fixed nor stable. Materials and drawings are regularly misaligned. This is due to many factors, including inadequate drawings, lack of data, the inherent resistance of the materials, bad workmanship or merely error. There are many different ways to manage such misalignments. Some aspire to make representations ever more accurate and construction systems ever more controlled to better determine the physical outcome. Others accept the misalignment for pragmatic reasons, or exploit it for aesthetic and social ones. Those in engineering disciplines manage the inevitability of such misalignments through the concepts of tolerance and structural redundancy.

Architectural, urban planning and design mediums were, as we know, enhanced by powerful digital technologies since the last decades of the twentieth century. But the more recent rise of predictive modelling, big data and urban science may profoundly restructure these mediums. Procedural- and agent-based modelling software have particularly important roles in such a restructuring. Both substantially expand what can be represented in urban planning and design, supplementing conventional form- and material-based information, with information on ecology, land-use, land-value, property ownership, and the mobility patterns of people, goods and traffic. But beyond expansion of the representational palette, these kinds of software have the potential to change the relationship between design, planning and everyday urban experience. Allied with newly abundant geospatial and socio-economic data – from such sources as real-time sensors, smart phones, intelligent buildings and smart city systems – procedural- and agent-based modelling take their place in hybrid cyber-physical cities. In this scenario representations are not merely materialised, but are in a constant and circular exchange with the physical stocks and flows of the city.

Despite the far-reaching possibilities of this emergent medium for city making, the contemporary situation is fractured and cluttered. Many different software, platforms and computer-aided design tools are promoted by different manufacturers and compete for attention. This chapter examines the possibilities for this new medium for city making by proposing pathways through this shifting software environment for the urban design process. It focuses on procedural modelling, as distinct from mere three-dimensional modelling, and its effects on urban design practice, and how it can effectively support the work of architects, planners and engineers.

We first look at how newly available data can be organized and managed at the scale of a city and in 3D (Section 2). The so called *City Information Models* are developing quickly and are increasingly put into operation to serve as data back ends in administration and planning offices. We will highlight a prominent example and show how it integrates with GIS, and provide a general overview of the most important properties of a 3DCIM. Then, we will provide a brief introduction to procedural modelling (in Section 3), based on the CGA (Computer Generated Architecture) Shape Grammar, which is implemented in Esri's CityEngine, ArcGIS 10.x, ArcGIS Pro and available as a library for 3rd party applications. We will show how a procedural model can be used to integrate urban design knowledge. Finally, we will present how the techniques can be used to work with land use and building function planning in 3D, how to work with street networks and block subdivisions. The chapter concludes with an outlook and final remarks.

II. The 3D City Information Model

An urban planning project takes place within an existing context of built structures, legal requirements and the natural surroundings. In contrast to traditional 2D GIS, these environments are inherently 3D especially within a city where the third dimension is often the only option for growth. There are, therefore, increasing needs to model the planning context with rich information in 3D.

Whereas earlier 3D city models were almost exclusively used for visualization and had in turn relaxed requirements regarding accuracy and semantics, today's applications ask for spatial information models that are general enough to serve a wide range of use cases beyond visualization. Several standardization efforts are under the way such as CityGML (Kolbe et al. 2005), INSPIRE (Perego et al. 2012), FGDC-STD-003 (Halfawy et al. 2006) or Esri's 3DCIM which specify semantic-rich information models. They not only cover the 3D representation of constructions and their spatial attributes but also the natural environment and sub-surface structures.

Here we take a closer look at Esri's 3DCIM as an example of such an information model. The 3DCIM is complementary to Esri's well-established Local Government Information Model (Crothers 2011) and the Building Information Model BISDM (McCabe and Young 2011).

A 3D city is in general a vast a collection of features, networks and surfaces, and there are many approaches how to model it for purposes of processing, analysis and visualization. The approach chosen by the 3DCIM is driven by use cases that specifically benefit from 3D GIS. A design goal of the 3DCIM is to be compact and simple in its structure, making the core of the model easy to understand and to populate with data.

Content-wise, the 3DCIM is organized into three basic themes: the built environment, the legal environment, and the natural environment. Each of these themes shares some common attributes and traits, which are described below.

A. The Built Environment

The built environment is comprised of features and networks that are created or actively managed by humans. These features include: structures (buildings, bridges, tunnels), utility networks, multimodal transportation networks (interior and exterior), installations (e.g. street furniture and sensors), and street trees.

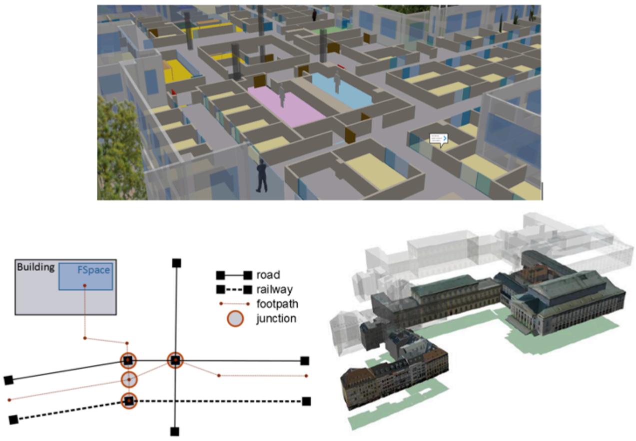


Figure 1: Examples of built environment: interiors (top); transportation networks (left); structures (right)

B. The Legal Environment

Features in the legal environment define land use plans and regulations, and property ownership boundaries. These include land use zones, which can have a nested structure (zones that are within and override the regulations of larger zones), and may have both 2D and 3D dimensional attributes, like maximum buildable heights. These regulations are typically stored as tables and may also apply to parcel (ownership) boundaries.

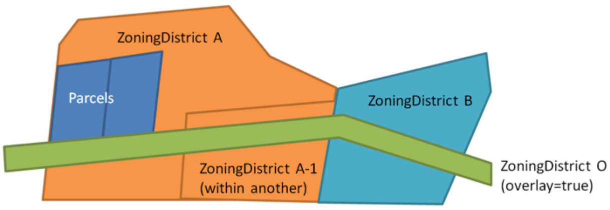


Figure 2: Example of overlapping zoning regulations in the legal environment

C. The Natural Environment

The natural environment is comprised of all naturally occurring features on, above, or below the earth's surface. This can include the land cover (wilderness areas, biomes and water bodies), but also surface/subsurface geologic structure and above-earth atmosphere, climate, and weather.

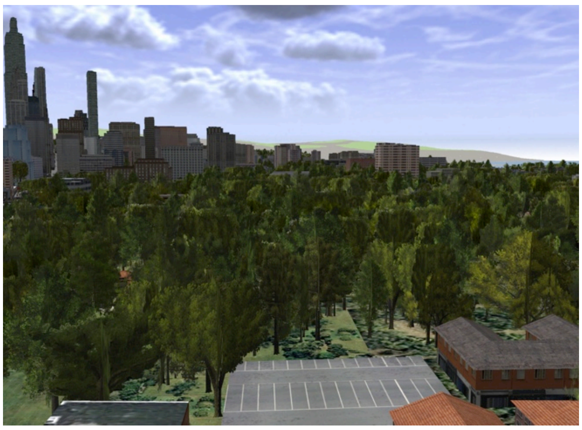


Figure 3: Example of the natural environment in a city scape

D. 3D City Information Model Structure

Within these three themes a set of 'Feature Classes' (FC) and 'Object Classes' (OC) describe the model in detail, as summarized in Figure 4.

In order to considerably shorten design iterations and evaluation, a 3D city information model is typically combined with a rule based system such as CGA which is presented in the next sections. Off-the-shelf rule libraries shorten the design cycle even more since they directly integrate with the underlying information model and need little or no customization.

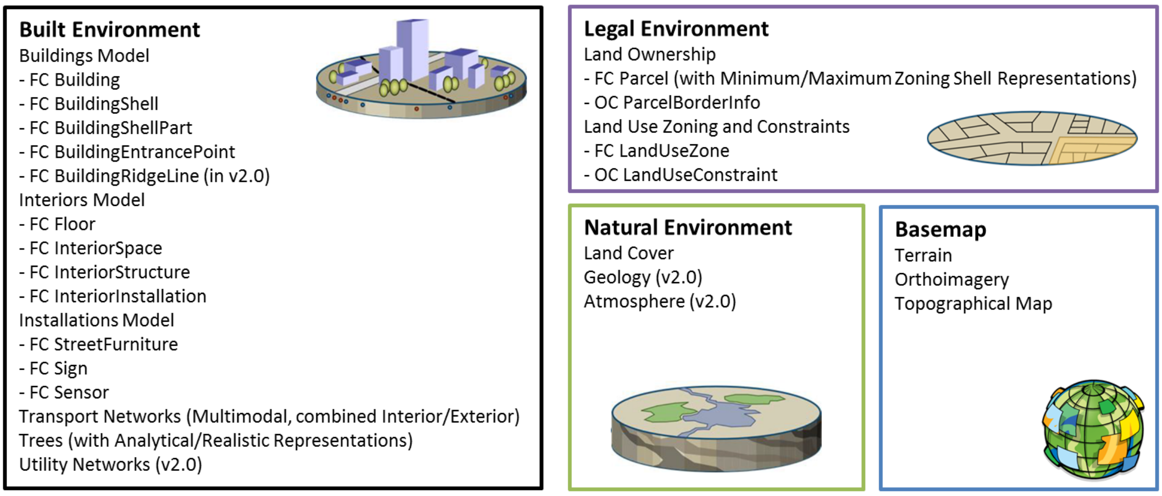


Figure 4: The data models for the built environment data, the legal and the natural environments in addition to the GIS basemap

III. Procedural City Modelling Workflows

A. Rule Based Systems

The design and modelling of urban structures with classical, polygon-based methods is very time consuming. Everybody who worked on a large-scale planning project knows the limits of 3D tools in terms of scalability and maintainability. Furthermore, adapting and modifying a planning project to changing constraints is difficult due to the enormous number of edit operations required on a polygonal model. Design iterations are in consequence very expensive and thus kept to a minimum, which often limits a systematic exploration of the design space.

Rule based – or procedural – modelling solves the time and quality challenge with a completely different modelling approach, which are generated based on spatial rules. A prominent example of such a rule system is CGA (Computer Generated Architecture), implemented in Esri's CityEngine, ArcGIS 10.x and ArcGIS Pro software. Procedural models are descriptions of spatial structures (e.g. an architectural style) encoded with CGA rules that are parameterized. These rules can be easily applied to large areas and the corresponding 3D models are generated by the software instead of hand-modelled by architects or designers. Because of the rule-based nature, every design change immediately results in a newly generated 3D representation and shortens iterations from days or weeks to a few seconds or minutes. This enables new workflows where hundreds of design variants can be explored, analysed and optimized together with stakeholders while respecting all regulatory and other constraints encoded in the rules.

B. A Simple Procedural Model

The following CGA example will show how procedural modelling is different from the classical polygon based modelling (e.g. with CAD software). The goal is to model a simple multi-story building and extracting the Gross Floor Area (GFA) for different floor usages in an urban planning project.

The first step in a procedural model is the translation of the spatial structure of the building into a set of rules. Although this example focuses on a building, the same principles can be applied for other purposes such as street networks or vegetation.

A CGA rule tells the system how an input *shape* is transformed through *operations* into a number of resulting *shapes*. For our example here, we take the building footprint as the input shape for our rule, extrude it vertically along the y-axis and the result of this extrusion is the building massing:

```
attr height = 30
Footprint --> extrude(height) Massing
```

This rule reads as “take the input shape *Footprint*, extrude it by *height* and apply the *Massing* rule”. You may have noticed that the *Massing* rule is undefined. Undefined rules automatically result in the creation of a 3D shape so *Massing* actually stands for the result of the extrusion of the input shape. This very simple rule shows already two advantages of a procedural model over a fixed CAD model: the rule can be controlled geometrically – depending on the input shape (the building footprint) – a massing will be generated which follows the outline of the footprint. Furthermore, the rule is parameterized by the *height* attribute, which controls the extent of the extrusion. The *height* attribute as well as the footprint geometry can be interactively changed by the designer in the modelling tool or linked to GIS data and thus be driven by an external data source.

The next step is the subdivision of our massing into multiple floors. For that purpose, we split the massing along the y-axis into a ground floor, some intermediate floors and a roof:

```
attr roofHeight        = 1
attr floorHeight       = 3
attr groundFloorHeight = 4

Massing-->split(y) {
       groundFloorHeight:Floor |
    { ~floorHeight:      Floor }* |
       roofHeight:       Floor }
```

This Massing rule reads as: “Take the input shape and split it upwards along the y-axis. For splitting, apply the following pattern: create a ground floor with height *groundFloorHeight*, create as many floors as possible with approximately *floorHeight* height and finally add a roof with *roofHeight*.” Again, the attributes *groundFloorHeight*, *floorHeight*, and *roofHeight* allow easy parameterization of the resulting 3D model and enable the evaluation of different designs.

The last step in this example is the calculation of the GFA for the use types “retail”, “office”, and “apartment”. For visualization purposes, the use types will be colour coded by a simple mapping function between use types and RGB colours:

```
col(useType) =
      case useType == "retail":    "#ff0000"
      case useType == "office":    "#00ff00"
      case useType == "apartment": "#0000ff"
      else:                        "#888888"
```

For our GFA calculation we will replace the Massing rule by writing something slightly more complex. Its main purpose is to take into account a ratio between office and apartment space. This is expressed in the *Floors* rule consisting of the subdivision into the two use types by a *split* operation and a *ratio* attribute. The *ratio* attribute allows the designer to explore different floor space distributions while getting an immediate visual as well as analytical feedback as we will see below.

```
attr ratio = 0.5
```

```
Massing-->split(y) {
        groundFloorHeight:Floor("retail") |
        Floors |
        roofHeight:Floor("roof")}

Floors-->split(y){
          'ratio    :{~floorHeight:Floor("office")}* |
          '(1-ratio):{~floorHeight:Floor("apartment")}*}

Floor(useType) -->
      color(col(useType))
      report("GFA." + useType, geometry.area(bottom))
```

In this *Floor* rule, the *color* operation sets the *color* of the shape and *report* evaluates an expression (in this case the bottom area of the shape) and stores the result under the given key "GFA." + *useType* where *useType* gets replaced with the actual use type value ("retail", "office", "apartment"). This reporting capability is the source for all analytical processes that may follow and its results can be stored e.g. directly in a geodatabase.

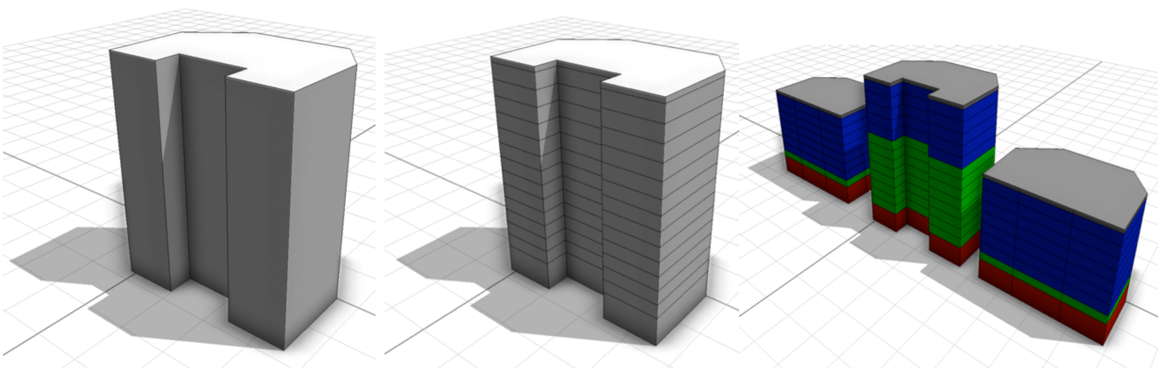
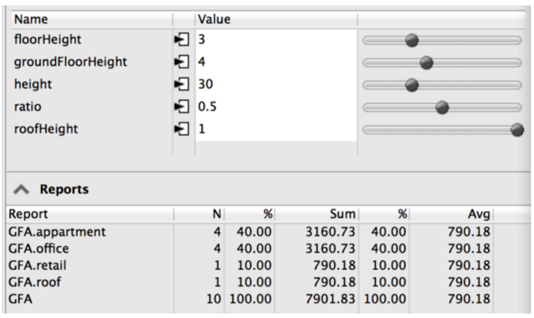


Figure 5: An example of procedural model: left) an extruded massing, middle) the massing subdivided into floors, and right) a planning proposal with colour-coded use types.

Obviously, this example is a very crude approximation because we ignore the fact that some space will be needed for service structures such as elevators, stairways, ventilation, utilities and so on. But it shows the basic principle and the very powerful mechanism generating at the same time a visual representation as well as an analytical result. **Error! Reference source not found.**shows the interactive controls for the attributes defined in the rule file as well as the results of the GFA calculations.



Name	Value
floorHeight	3
groundFloorHeight	4
height	30
ratio	0.5
roofHeight	1

Reports

Report	N	%	Sum	%	Avg
GFA.appartment	4	40.00	3160.73	40.00	790.18
GFA.office	4	40.00	3160.73	40.00	790.18
GFA.retail	1	10.00	790.18	10.00	790.18
GFA.roof	1	10.00	790.18	10.00	790.18
GFA	10	100.00	7901.83	100.00	790.18

Figure 6：Interactive control of the rule attributes and rule-based GFA calculations

Procedural modelling is successfully applied in large-scale urban environments ranging from complex zoning and planning scenarios (Singapore Urban Redevelopment Authority 2014) up to cityscapes for Hollywood block buster movies such as "Cars 2", "Total Recall", or "Man of

Steel". Besides Esri, other companies provide ready-to-use CGA rule libraries, thereby reducing the time required for rule writing considerably.

Once a parametric model is created for a given area of interest, it will be available to specific design workflows, such as dealing with land use, street network design and analysis or evaluation as highlighted in the coming sections.

IV. Case Studies

A. Land Use

The topic of land use is about the human use of space, which defines planned functions of urban areas. It involves the management and the modifications of a natural environment or wilderness into a built environment such as fields, pastures, and settlements (Watson et al. 2000). Land use planning is considered as one of the most crucial subjects in urban planning, and of course, an indispensable factor in all kinds of urban simulation application (Waddell 2002).

In this section we present a possible workflow that illustrates the transformation of 2D GIS data to smart 3D city models. The workflow was realized using ArcGIS and CityEngine with its powerful 3D geometry modelling and visualization capabilities.

Shapefiles, which are used to store land-use information, can be imported directly into the tool. Based on the attributes in a planning map, CGA rules can be derived to constrain the layout and functions of building environments. CGA can therefore be seen as a medium to transform such attributes and rules into a procedural modelling process that result in an intuitive 3D scenario. Moreover, as a general advantage of procedural modelling techniques, empirical knowledge can be used to enrich the 3D scenario and bring it one step closer to the reality.

Error! Reference source not found. is an example of a simplified 3D scenario generated from a 2D land-use map. We use this example to demonstrate one of the very concerned urban issues called mixed-use urban space, which has been addressed in related work such as (Zhong et al. 2014). The land use plan provides the constraints of dominating functions in one area. However, not specified in the land use plan are specific building functions, which define how a building is used in reality. Thus, building function refers to information at a smaller spatial scale and includes specifications for multiple floors (i.e. requires building volumes) and is thus not fully compliant with land use. Therefore, a 3D scenario is required to give full details of building functions and to depict compact urban space. As shown in **Error! Reference source not found.**(a) refers to the original land use plan. (b) shows 2D building footprints that strictly follow the land use plan. (c) shows a 3D scenario generated by procedural modeling which takes the land use planning as a base but adds more local/contextual information about the real usage of buildings. In this scenario, two simple rules were applied: (1) the number of floors is proportional to the area of a building footprint; (2) the buildings may have multiple use types distributed at different floors. Based on investigated information, the possible combinations could be "commercial + residential" or "commercial + storage + office", which are demonstrated in **Error! Reference source not found.**(c) with different colour codes.

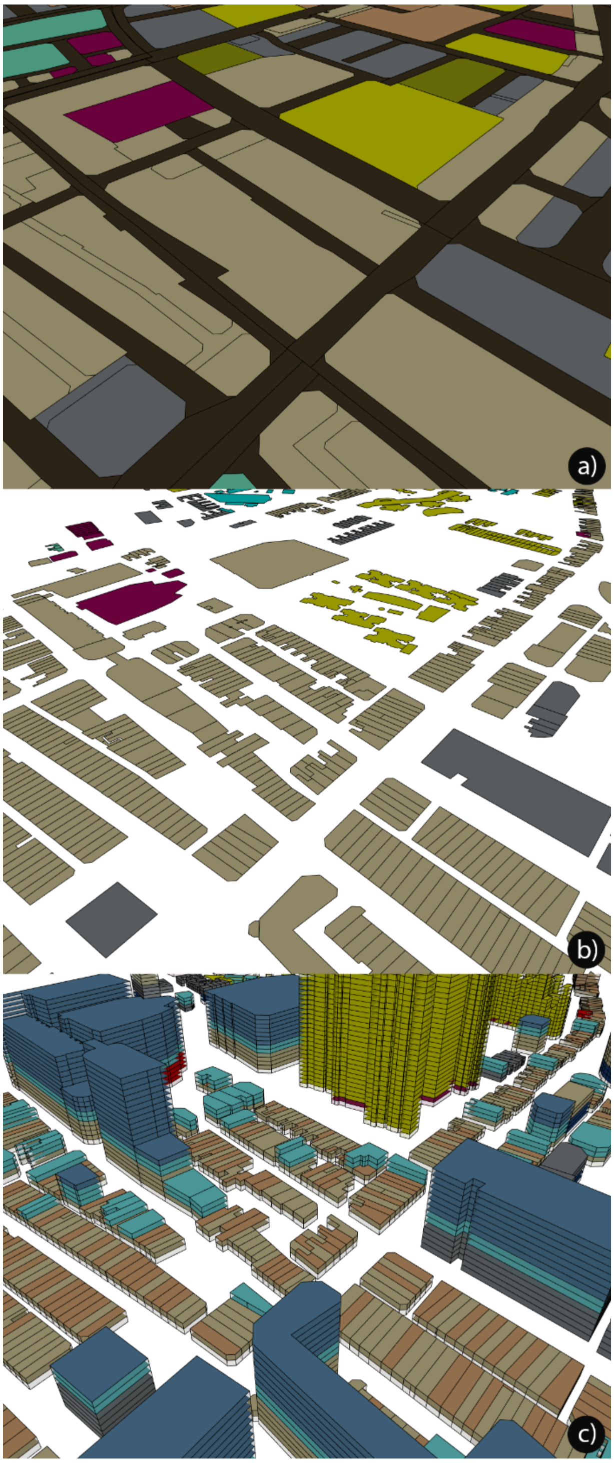


Figure 7: Generating a 3D mixed-used scenario from a 2D land-use map.

B. Street Networks and Block Subdivision

Street networks represent the arteries of a city and define the formal shape and structure through enclosed blocks, building lots and spaces in between. Creating and manipulating street networks has seen increasing tool support over the past years. Software like Autodesk's Civil 3D (Autodesk 2012) extend parametric design beyond street networks and can be applied to almost any network-like structure including the related civil engineering tasks such as cut and fill of the existing terrain. Esri's CityEngine gives the urban designer tools for interactively changing the network structure while maintain block subdivision constraints like minimal/maximal areas and street access. Furthermore, space syntax (Hillier et al. 1976) based integration and centrality calculations of a street network can be directly translated to street attributes e.g. for providing the necessary transport capacity.

Thanks to the parametric nature of these software products, the urban designer can concentrate on the high level network layout tasks and let the software create the dependent spaces, shapes and structures. The tools play hand in hand with procedural building and street models and result in a fully integrated and interactive workflow where network changes are immediately reflected in the block subdivision and in turn affect the footprints of procedural buildings. For analysis and visualization, CGA rules can be applied equally to streets and result in a seamless procedural modelling environment for buildings, streets and vegetation covering a wide range of the urban designer's needs while transforming the way a designer works within the urban space (Jeffries 2014).

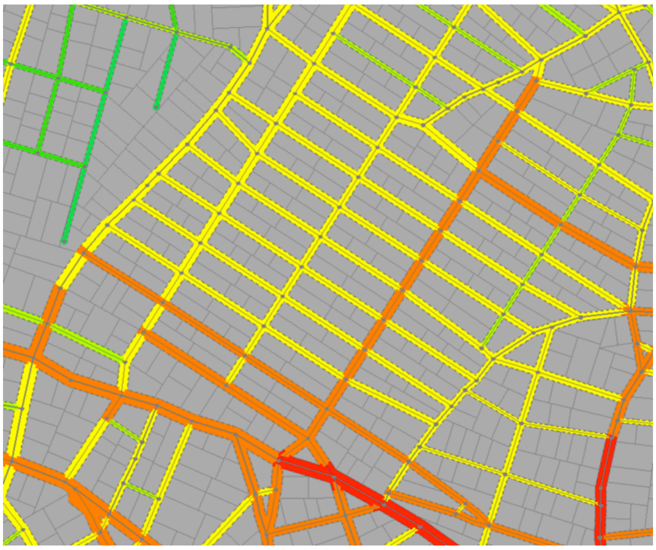


Figure 8: Visualization of street analysis results, automatic street width calculation and constraint based block subdivision

V. Conclusion

Although modern software tools enable new workflows and a completely new way in which urban designer can interact with their planning proposals, they also come at a price. Learning and deploying new tools and especially a completely different way of 3D modelling such as CGA is a major investment in software licenses, infrastructure and training.

Despite all the efforts done by the different vendors to provide interoperability of their tools and adhere to common exchange standards, small mismatches in the data may still require careful manual steps as part of a workflow.

Every urban designer has thus to decide on a project-by-project basis if the investment in training and the necessary changes to established processes outweigh the closer interaction with stakeholders and the design space exploration. Designers doing so praise the increase in flexibility and swiftness of design changes while reducing tedious calculation tasks and the management of the legal environment. Or to say it with the words of Elliot Hartley (Garsdale Design): "It used to take ages to change one parameter. Now you can do it at the click of a mouse." (Jeffries, 2014) We strongly believe that these mouse-clicks done by great designers empowered with new tools will shape a better urban future.

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