Towards a modular design strategy for urban masterplanning

Experiences from a parametric urban design studio on emerging cities in Ethiopia

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In emerging countries there is a need for rapid urban planning, since they are confronted by unprecedented wave of urbanization. This need is even bigger since usually there is no adequate number of professional educated urban planners in these countries. Therefore, we investigate in this paper how to develop a set of methods that allow to generate urban fabric semi-automatically. The challenge is to come up with a generative planning model that adapts to multiple boundary conditions. Through a modular design strategy generative methods are applied by students in an urban design studio in order to combine them into more complex planning strategies for small cities in the emerging country of Ethiopia. The modular approach allows to break down planning into sub-issues to better deal with the overarching problem. For testing the implemented generative urban design strategies various cities are generated at different locations in Ethiopia with various topographic situations. Their underlying design strategies and modular approach are discussed in this paper.

Keywords: Urban Design, Planning Systems, Modules, Teaching, Emerging Country

INTRODUCTION

The design of a city is a complex task, involving the definition of numerous elements and the consideration of many performance criteria. Especially in emerging countries facing rapid population growth and urbanisation it is a challenge for urban planners to continuously envision new neighbourhoods or entire cities in a minimum of time while ensuring max-
imum quality. Computational methods can therefore offer valuable support, either regarding the rapid generation of variants (see e.g. Weber et al., 2009; Beiaro, 2012; Duarte & Beiaro, 2011) of the evaluation of variants by analysing different criteria, such as accessibility (see e.g. Karimi, 2012; Sevtsuk & Mekonnen, 2012), visibility (see e.g. Czyńska & Rubinowicz, 2015; Yang et al., 2007) or energy demand (see e.g. Ratti et al., 2005; Robinson et al., 2009).

To efficiently design sustainable spatial structures it is necessary to equip urban planners with the skills to use these methods effectively. Educating students of architecture and urbanism we set up a course (urban design studio with accompanying seminars) that enables them not only to use, but also to adapt and develop such methods and to apply them on a case study in Ethiopia.

Ethiopia is currently trying to adapt to its rapid urban growth by fostering the development of thousands of new small cities (with approximately 10,000 inhabitants) in the coming years (GTP-II, 2015)[1]. This challenging task served as the background for our design studio, namely to develop a method for rapidly creating plans for the sustainable development of these small cities. The focus therefore has been the spatial morphology of the city. This refers to the physical overground elements of a city, such as streets, plots, public spaces and buildings. These elements are of greatest importance in planning, since they - once built - persist over long periods of time and greatly influence the behaviour of the urban user.

The goal of the course was to develop a computer-based design strategy, which rapidly creates solutions that are adapted to varying environmental parameters (such as topography or existing streets and buildings) and which integrates the perspective of the urban users (movement patterns and land use). The students should learn how to approach the high challenges of urbanisation through new planning methods while considering quality of urban space, resources and limited amount of time. To get an understanding for relevant criteria of emerging cities the students got to know the context through an excursion to Ethiopia, discussion with local people, lectures and literature. Beside, the students got equipped with basic skills for parametric modeling and computational urban analysis. The former served for the rapid generation of urban models. The latter focuses on methods how to analyse a city quantitatively (e.g. density, walkability, centrality). With this knowledge they then had to conceptualize and implement a computationally supported city planning method and apply it to different cases.

In this paper, we put special focus on the design strategy, that the students developed. This strategy is based on modular thinking, helping to handle the complexity of urban planning. In the following we briefly discuss the modular approach, present exemplarily three students works and finally briefly discuss the challenges and potentials of this approach in education as well as for the practice of urban design.

**MODULAR DESIGN STRATEGY**

The challenge for designing a city stems from the high number elements it is made of (such as streets and buildings). Between these elements there are many relations (such as adjacency or walking distance). Both, the form of these elements and the relation between them are influencing the performance of a city in terms of social, economic and ecological criteria (such as lively, costs or energy consumption). Although a city can be evaluated only by taking into account all elements (“the whole is more than the sum of its parts”), during design considering all elements at once is hardly possible, due to human’s cognitive capacity and the fact that elements are often highly interdependent. Thus a certain structure for simplifying the problem needs to be introduced. This structure often is referred to as a design strategy and can take several forms (see e.g. Lawson, 2006). One strategy, that is rarely used in design, well known in the field of programming, is “Divide & Conquer” (D&C). In D&C one divides a problem into several subproblems until they are solvable. By solving all subproblems the original problem becomes solved.
However, this causes problems in the case of design, since solutions that one created for solving subproblems might not be compatible to each other on a higher level. For example, the requirements for an urban neighborhood are to promote social interaction and ensure privacy. The former can be achieved by a well connected street network, the latter by a cul-de-sac street network. The contradiction in this example occurs by the fact that the design variable that was used to solve the two problems (requirements) was the same (the street network). This lead to two different ways for defining the design variable. In order to combine both solutions a new solution needs to be created. (see Figure 1)

In order to make the D&C-strategy applicable for design Bertel, Freksa and Vrachliotis (2004) introduced an adapted version of D&C, namely “Aspectualize & Conquer” (A&C). Thereby the decomposition is not into disjoint parts, but is based on the notion of a problem’s aspects, whereby aspects “provide criteria for the making the selection, and choosing the right aspects must thus be seen as a key factor for successful solving of design processes” (ibid., p. 273). If we take the example from before, we would define the design variable “street network” as an aspect. This aspect is then processed in order to promote social interaction and ensurance of privacy. Thus, in synthesis both problems are regarded at the same time with no need for changing the design variable.

The idea of dividing the task of designing a city into several aspects was the starting point for our design studio. We asked the students to identify certain aspects and create computational modules for each. These modules shall be capable of generating a certain outcome (such as a street network) by certain requirements. Therefore, the students had to define (1) which input is needed for each aspect, (2) how it processes these inputs and (3) how the aspects relate to each other. Regarding the first issue, they had to clarify what are essential boundary conditions for an aspect and what are performance criteria that are applicable to that aspect. For example, a street network is based on existing streets and topography and shall ensure high accessibility. The second issue is about the algorithm for creating a solution. Therefore, each module can consist of generative and evaluative parts as well as of optimization procedures. For example, a simple module for creating a street network can consist of a grid-generator, an accessibility analysis (e.g. space syntax) and an evolutionary algorithm for varying the grid dimensions in order to achieve a high accessibility. Regarding the third issue, the students had to define a sequence in which these modules are processed. For example, the definition of land use can be based on the street network (e.g. locate commercial land use in highly central locations) or the street network can be based on an afore defined land use plan (e.g. main streets are passing through commercial land use zones). In the following the strategies that the students developed are presented.

IMPLEMENTATION AND EXAMPLES
The generative algorithms for the cities presented in the following were made by a group of students during a one semester urban design studio. The students were introduced to urban analysis methods for understanding the performance criteria used for the evaluation of the designs, to programming in C#, as well as to parametric design by using the software
Grasshopper for Rhino3D and our self-developed DecodingSpaces components (Schneider, Bielik & König, 2011; König, 2015). The latter provide a set of methods for generating and analysing street networks, street blocks, plot subdivisions.

The groups of students (3 students each) had to think in abstract systems to create a parametric, modular city design. They had to set their own priorities and goals in the boundaries of the course outline. The creation of their generative strategies started by defining the performance criteria and the relationships to each of the three aspects (street network, street blocks, land use). By iteratively improving the design strategy they developed and arranged the modules.

The outcome of this process was different in every group. In the following the work of three student groups is described with particular focus on the modular design strategy. All student projects can be accessed in an online documentation [2] and on demonstration videos explaining the functionality of their concept [3].

To compare the strategies, they are visualised as shown in figure 2. Input A is data that is transferred from other modules. Input B is data that is applied through other contextual or manually added data to influence the procedure of the module. The module itself generates and/or evaluates the spatial organisation of an aspect in relation to the given performance criteria like walkability or density. It then outputs new data like geometries of streets or buildings.

**Group 1 - Vector-field approach**

The focus of this group was to establish a street network that relates to the topography and useful allocation of functions such as schools, churches or hospitals. The group developed four different modules, namely Boundary, Street Network, Street Blocks and Land Use (see Figure 3). They used a linear design strategy, starting from the boundary of the city, followed by the generation of the street network, the analysis of street blocks and lastly the assignment of functions. As a base to generate their city they chose to use vector fields that contain information about the topography and existing road network. The approach to generate the streets is comparable to the work of Chen et al. (2008).

The module “Boundary” defines the border of the city, which limits the area in which it shall grow. Its input data is the topography, existing streets, the needed area as well as manually added data such as location and weighting factors for the strength of the influence of existing streets and/or topography on the shape of the city. Its output is a curve that defines the boundary. The calculation is done by growing the boundary on a vector field in the direction with the least threshold until the needed area is reached.

The module “Street Network” requires the city boundary as input and makes use of the topography, existing streets and manually added streets to define a vector field. New artery streets grow then on top of this vector field and divide the city into several parts. This process was optimised by the group to get equally sized subareas. The output is a list of curves defining the main street network.

The module “Street Blocks” creates the remaining streets inside of the main street network that define the city blocks. Its inputs are the street network and manually defined densities and block sizes. The algorithm again uses the vector field to distribute points that are connected through a Delaunay-Triangulation. The triangulated street seg-

Figure 2
Scheme showing how to read the visualised modular design strategies of the student groups.
Figure 3
Modules and their sequential order of
Group 1 - Vector-field approach

The last module “Land Use” allocates functions such as schools, churches, commerce, hospitals or public buildings on site. It needs a street network and topography as input and can be manually adjusted by the group. Since this component defines greatly the social structure of the city it needs a well defined street network. The group therefore had to iterate and improve on the aforementioned modules. The streets and the street blocks are then analysed regarding several criteria (block size, altitude, accessibility, centrality). Based on these criteria certain uses are located on specific blocks (such as a church on the highest point of the city, or the municipality on the most central street block). The module’s output is a map with land-use labels for each street block and placeholder geometries of the respective buildings.

**Group 2 - Force-based approach**

The priorities of this group were equally distributed on land use and the main street network. Both modules can be independently developed. Afterwards a module for creating secondary street grid follows. Lastly a second land use-module defines the detailed allocation of uses. The generation of the city is mainly done with force-based algorithms. Forces can be slope of topography or the location and connectivity of certain land uses. Each force has an objective like keeping a certain area, staying close to a point or keeping lines in a certain angle. They have different strengths and try to pull the geometry towards their objective. In competition with other forces they either reach their objective or they pull as much as they have strength. In this way the geometry is deformed until all forces find a state of equilibrium. In Figure 4 the sequence of modules is displayed. The group developed five modules, namely Boundary, Land Use, Street Network, Street Blocks and Land Use 2.

Similar to Group 1, the module “Boundary” generates a curve as an output that defines the limits of the city. It does so by applying forces on it such as occupying a defined area of square meters and flatness of the topography.

The module “Land Use” requires the city boundary as input as well as required land uses with their respective sizes and adjacencies between each other. Furthermore they can have preferred locations such as high places, sloped or flat terrain or the center of the city. These connections are forces and work like springs trying to bring interconnected functions close to each other. When the forces do not have enough strength anymore to pull and the functions do not move anymore, their locations can be used as an output.

Module “Street Network” generates a primary street grid based on the city boundary. Additional inputs are topography and existing streets. Streets are created by forcing the street lines to adapt to the topography, keeping them as horizontal as possible.
while leaving enough space between border and existing streets of the city for buildings. The output are curves in form of a deformed street grid.

The module “Street Blocks” combines the modules “Street Network” and “Land Use”. It creates grids inside of the main street structure that serve as street blocks. If certain land uses need more space then blocks will be merged into a bigger one. The output are curves defining the whole street network.

Lastly, module “Land Use 2” allocates commercial land use and residential densities. The group decided that these land uses are more dependent on the street network than others, since they need to be at highly integrated (frequented) locations in the case of commercial use and rather unfrequented locations in the case of residential use. Therefore the module analyses the street network through Space Syntax methods and allocates the functions.

**Group 3 - Watershed approach**
The third group decided to put main emphasis on water infrastructure as a necessary resource for the development of the city. They created four modules: Street Network, Street Blocks, Land Use 1 and Land Use 2 that sequentially build up on each other (figure 5).

The input of the module “Street Network” are topography, existing roads, a manually specified location and the water rundown. Compared to the other groups this module gets along without having a specified city boundary and solves it in this module. The priority clearly lies on the resource of water by using the water rundown to define street locations. This affects all other modules in the sequence.

Module “Street Blocks” takes the water street network as input. Since those streets follow the water running down the hills, horizontal street networks are missing. Therefore they are added parallel to the existing street in a distance of 60m to subdivide the street network into blocks (in order to have lots on both sides with a depth of 30m). If these blocks are longer than 200m they are again subdivided, to ensure walkability (see Sevtsuk et al., 2016).

The module “Land Use 1” uses the whole street network as input. Since those streets follow the water running down the hills, horizontal street networks are missing. Therefore they are added parallel to the existing street in a distance of 60m to subdivide the street network into blocks (in order to have lots on both sides with a depth of 30m). If these blocks are longer than 200m they are again subdivided, to ensure walkability (see Sevtsuk et al., 2016).
sure (Integration at Radius 400m, referring to locally well accessible places). Afterwards module “Land Use 2” adds more functions to the city by finding locations around the subcenters for a list of land-uses with certain sizes, adjacencies and distances to each other.

**Application to different cases**

After each group developed their design strategy they were able to generate cities not only on one specific site but on many. For the course they had to create plans for three different sites in Ethiopia namely Haro Welabu, Fefa Dildiy, Anko Golma. The results can be seen as figure-ground plans in figure 6. The comparison shows how the design adapts to different contexts like the topography while inheriting the logics of the strategy.

**DISCUSSION**

Bertel et al. (2004) point out that A&C relies on well chosen aspects and their sequential order needs clear prioritization. The designer needs to decide what information is most important and which aspect should have more influence than another. By defining the generative strategy in relation to their performance criteria each of the student groups developed a different approach. All groups considered with various weightings that the street network is highly influenced by the environment especially the topography, that the properties of street blocks depend on the street network and that land use distribution needs most information from other aspects. The street network was prioritized by nearly all of the groups as a base for the allocation of functions. Only group two has calculated the land use at the same time as streets. The geometries however differ greatly and were produced either through a vector field, forces or water rundown or simple rectangular grids.

With the introduction of the aforementioned aspects in our course we saw the advantage of defining the scope of our computer-based modules: one module would deal with only one aspect making it exchangeable with other modules of the same. As expected, the information that the produced modules handle and need as input and give as output are similar. It would be therefore possible to exchange the modules of street network and block in a group, since they both need boundaries and then create their streets. But even in between groups modules could be shared. For example force-based generation of geometries could be combined with modules that use vector fields or water rundown. This shows us that the flexibility and exchangeability of modules can also be advantageous in urban planning, but with the demand of a planner to prioritize the sequence of modules. On the other hand we also realized that not all modules are exchangeable, since they need different information and are dependent on other modules. Group two therefore tried to run land use calculation and street network independently from each other, preferring flexibility, but
Figure 6
Design Strategy applied to different villages. From left to right: Haro Welabu, Fefa Dildiy and Anko Golma.
reducing information for the allocation of functions. The issue of parallel and sequential modules is shown in figure 7. Modules can be arranged independently from each other running parallel which allows to flexibly exchange them, but with the need to combine their information later, or modules can be arranged in sequential dependency with one gaining information from the other.

CONCLUSION
The group results show the possibilities for educating architecture and urbanism students without prior knowledge in programming or computational design in one semester. The division of the main problem into sub-aspects helped the students to understand and grasp the complexity of a city better. It also assisted in the development of a design strategy, since the aspects could be easily translated into modules that generate the cities. By creating a computer-based method the strategies can be applied to not one but many locations in Ethiopia, and through the flexibility of modules the design strategy can be easily adapted to different contexts. The designer automates repetitive design tasks by translating them into modules. The exchangeability of the modules lets the designer try out different procedures in a fast pace. Simply said, a module is outsourcing repetitive tasks of the designer to give him more time to plan, design and explore the solution space. This automation capacitates one with more time to iterate over many designs, making the process itself semi-automated. The course therefore made the students understand, how important such a rapid generation of cities can assist planning processes in emerging countries like Ethiopia.

An interesting observation was that the parameterized but closed components prepared by the supervisors for special purposes like generation of street networks, parcels and buildings were usually replaced by the students own algorithms. There was obviously a need for understanding and adapting the procedures in detail in contrast to using black box parameterized generative models. This demand for keeping the control over the generative process conflicts with the inherent logic of generative design methods, since more sophisticated algorithms may create urban designs more automatically and eventually lead to another level of control as expressed by Kelly (1995).

OUTLOOK
Modules have certain advantages like the exchangeability, automation of tasks and straightforward application on planning aspects. They need clear attention on ordering their sequence and the compatibility between each other. Linearly computed, they can produce results fast and could iterate over many solutions fast. However after setting up the sequence there is no iteration in the sequence itself. Modules stay in a fixed information of flow and do not communicate backwards. Parallel computing could show alternatives, like for example Carl Hewitt’s Actor Model (1973), which would let the aspects communicate and influence each other.

Furtheron an analysis and comparison of performance of the generated designs could quantitatively
characterise the effectiveness of the design strategies. It would assist the iteration of design solutions and would add the analysis to the framework of formulation and generation of design as described by Duarte, Montenegro and Gil (2012).

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