Procedural modeling of urban green space pattern designs taking into account ecological parameters

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Abstract. Cities all over the world are challenged by increasing the quality of life of urban citizens in order to ensure sustainable urban development. However, a lot of policies and planning fail in integrating environmental aspects in a way that makes them applicable for design leading to rather unsustainable developments. This paper presents an approach to integrate ecological parameters into urban design using a procedural, shape grammar driven modeling and visualization system. Design specifications and ecological goals given in the Masterplan of MASDAR City derived as an application example for the workflow. We used the concept of ecosystem services to break down the ecological process knowledge to design rules and meaningful, quantifiable spatial indicators. Our results demonstrate the application of the proposed approach covering different planning scales (district and building level). The integrated model suits as an assessment tool that can be used to test urban design alternatives on the ecological functioning as a starting point for architects.

Keywords. City modeling; shape grammar; ecological indicators; urban ecosystem services; sustainable urban patterns.

1. Introduction

Sustainable urban development is a major challenge cities are facing all over the world. Especially the consideration of natural urban ecosystem contribution to public health and increasing the quality of life of urban citizens is becoming increasingly difficult under growing development pressure. UN-HABITAT [1] points out inappropriate policies and ineffective planning neglecting environmental aspects and supporting rather environmental degradation than sustainable urban development. Although scientific ecological process knowledge has grown considerably, applications in sustainable urban development are missing (Opdam, 2007). A main reason is the missing transfer of the relevant information to decision-makers in a credible and comprehensible manner. Further, there is a lack of taking into account stakeholders' values (Nassauer and Opdam, 2008; Wissen et al., 2008). In this study, we present an approach to integrate ecological parameters into urban design using a procedural, shape grammar driven modeling and visualization system.

2. Related work

In landscape and urban planning, new approaches have been suggested integrating ecological aspects into decision-making processes using the concept of ecosystem services (Grêt-Regamey et al., 2008). Ecosystem services are “the benefits people obtain from ecosystems”, such as recreational opportunities, air filtering, micro-climate regulation, habitat for species, nutrient retention, water filtration, or a sense of place to name a few (MEA, 2005). Major advantage of using these natural resource units is that these are comprehensible indicators that can be quantified and thus enable a trade-off against socio-economical indicators (Grêt-Regamey et al., 2008).

As one type of urban design can usually not fulfill all quality requirements, knowledge about urban services must be in a form that can be used in creative design-driven processes developing and assessing various alternatives. In this context, procedural modeling approaches using shape grammars offer powerful city modeling and visualization tools enabling quick visualization of complex city models, evaluation of alternatives and iterative design workflows (Halatsch et al., 2008; Ulmer et al., 2007). Also in the field of plant ecosystem modeling parameterized procedural plant models were successfully used for simulating complex scenes with thousands of plants (Deussen et al., 1998).

In the article we will show application examples of operationalizing ecological knowledge, coded into shape grammar rules for generating alternative green space pattern designs for the Swiss Village Abu Dhabi in MASDAR City, an ecocity of the future.

This paper is organized as follows: Chapter 3 gives a short overview on the case study site. In chapter 4, we describe the approach of integrating ecological process knowledge into procedural modeling of urban open spaces. Application examples of the proposed approach are given in chapter 5. Finally, in chapter 6, we draw conclusions from our application examples and give an outlook on future work.

3. Case study site

MASDAR City is a new urban district of Abu Dhabi designed from scratch, comprising an area of 650 ha and a target population density of approx. 135 people per ha. It shall become an ecocity of the future that will be only dependent on renewable energy. Located in the core zone of MASDAR, a Swiss Village with a size of 12 ha is planned, in which Swiss companies shall promote Swiss technology, design and quality (SVA, 2009). Although explicit targets for environmental aspects, such as numbers of indigenous species nesting on site, are given in the guidelines for MASDAR city, directly relating applicable rules for appropriate urban green space design are missing. In order to support the Swiss Village Abu Dhabi Association in the design process of the Swiss Village, environmental rules shall be made applicable by encoding environmental rules and integrating natural resource indicators into the urban design process.

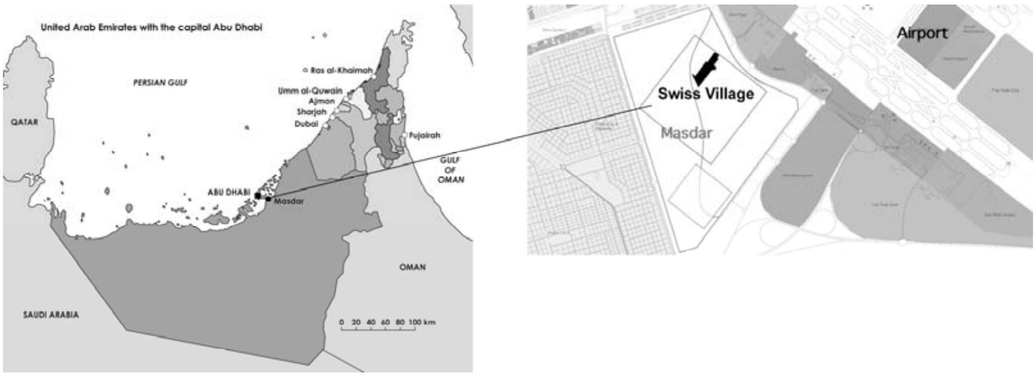


Figure 1
Location of the Swiss Village in Masdar City, Abu Dhabi, United Arab Emirates (map source: SVA, 2009)

4. Applying generalized ecological knowledge in procedural modeling of urban green space pattern design

We draw upon novel approaches for automatically generating designs using shape grammars (e.g. Beirão et al., 2008; Halatsch et al., 2008; Ulmer et al. 2007) and expand them with ecological parameters. Our workflow comprises four main modules (Figure 1): (1) Architectural guidelines, (2) Ecological knowledge generalization, (3) Procedural modeling, and (4) Iterative development of alternatives.

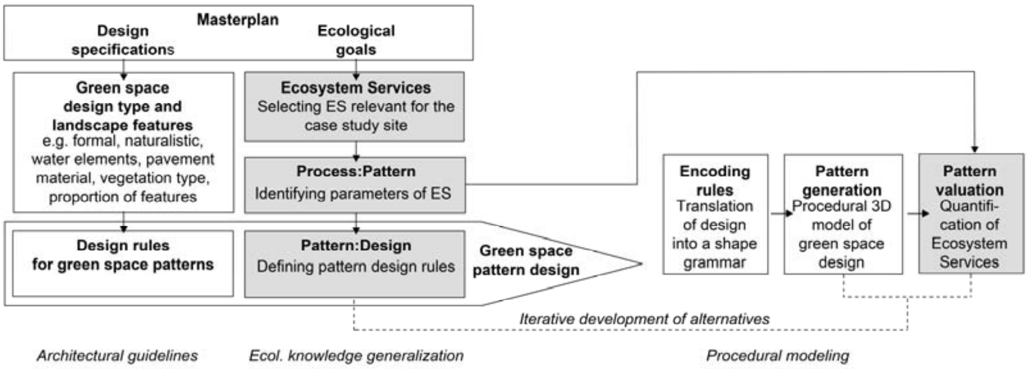


Figure 2
Workflow for integrating ecological knowledge into procedural modeling of urban green space pattern design alternatives using shape grammars.

4.1 Architectural guidelines and ecological goals

In a first step, we reviewed the specifications given by the Masterplan of MASDAR City. These can be divided into green space design specifications instructing the general layout of different urban green space types and ecological goals, e.g. targets regarding water and energy consumption, climatic conditions to be achieved, or target plant and animal species on site. However, whereas the architectural design rules could be directly applied for pattern design, design rules to achieve the ecological goals were not that obvious.

Generalized knowledge on ecosystems processes had to be applied for the derivation of credible ecological design rules.

4.2 Ecological knowledge generalization

For the generalization of the ecological knowledge, we followed the logic of Nassauer and Opdam (2008), who propose to link the scientific knowledge on landscape ecological pattern-process relations with the design of landscape patterns (process:pattern:design). Further, we used the concept of ecosystem services in order to break down the ecological process knowledge to meaningful, quantifiable spatial indicators.

According to the goals of the Masterplan, we choose two ecosystem services relevant for MASDAR City, i.e. the vegetations' possibility of enhancing the urban micro-climate (cooling service) and the provision of habitat (habitat service) of urban green spaces. Then parameters, i.e. landscape features ensuring the quality of each ecosystem service, were identified based on ecological process models (e.g. Mörtberg et al., 2007; Grêt-Regamey et al., 2008). These landscape features, i.e., required size, structures such as mature trees or hedges, vegetation types and species, connectivity to other patterns etc. (Mayall and Hall, 2005), are the basis for defining ecological green space pattern design rules.

Finally, by applying the combined architectural and ecological green space pattern design rules, the determined landscape features were organized to basic design patterns that define major design solutions (Beirão et al., 2008; Ulmer et al., 2007).

4.3 Procedural modeling

The basic design patterns formed the required input for the procedural modeling. The patterns were encoded to rule sets structured in shape grammars. We used CGA shape grammars that are implemented in the CityEngine system [2] for urban green space generation (see Ulmer et al., 2007; Halatsch et al., 2008). The main advantage of this system is that it can quickly produce and visualize in a three-dimensional view urban environments of any size based on the CGA shapes. The latter are grammars producing patterns by sequentially applying rules for spatial distribution of features (Halatsch et al., 2008).

4.4 Iterative development of alternatives

The resulting green space patterns can be analyzed and evaluated either by visual assessment or additionally by again applying ecological process knowledge. Thus the potential quality of the patterns' provision of the selected ecosystem services is expressed in quantitative indicators, such as the potential amount of target species or the green spaces' cooling capacity. Changing the design rules based on the findings leads to the procedural production of alternative green space patterns in an iterative way.

5. Application example

We present two examples of applying the procedural modeling approach on the district or building block level as well as on the building level in the Swiss Village Abu Dhabi in MASDAR City. In chapter 5.1 we show on the larger scale how ecological parameters are integrated into the CGA shape grammar rule in order to define the location and size of green space areas within the built-up area required for providing suitable habitat for selected focal species. In chapter 5.2 we demonstrate on the building scale how the distribution of trees around a building can be modeled parametrically taking into account the cooling function of the vegetation and tree species requirements.

5.1 Ensuring the habitat function of urban green spaces

Designing suitable habitat configuration in urban areas must acknowledge a broad spectrum of different species' requirements. Ecological profiles that comprise simple landscape indicators based on similarities between requirements of different focal species (i.e., species representing landscape characteristics that will encompass the needs of many other species (Mörtberg et al., 2007)) are suitable for generating rules for designing sustainable landscapes for these profiles (Opdam et al., 2002). Important parameters determining the habitat suitability of a landscape are, e.g.: (1) Land cover type reflecting the habitat of each species during its yearly activity, (2) patch size required for a pair or social unit, and (3) habitat proportion giving the threshold for the minimum proportion of habitat on a landscape scale (Angelstam et al., 2004). The quality of the foraging habitat is assumed to be limited by the proportion of the species' home range, which are overlapping for both focal species (Angelstam et al., 2004; Flux and Angermann, 1990).

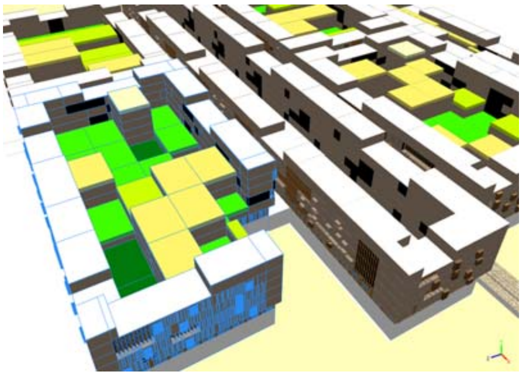
Representative focal species were already given by the targets of the MASDAR Masterplan, which aims at a population size of 30 desert hares (*Lepus capensis*) and 10 bird species such as the European Roller (*Coracias garrulus*) nesting on site. Table 1 provides quantitative and qualitative habitat characteristics for defining suitable green pattern designs for these two focal species.

Focal species	**Land cover type**	**Patch size**	**Home range (min.)**	**Habitat proportion**
European Roller (*Coracias garrulus*)	Forest (e.g., Mediterranean); Shrubland (Mediterranean/Sub-tropical/Tropical Dry), Grass-land, Pastureland	300 ha	300 m from the nest; network of patches	75'000 ha "pure habitat" for 100 breeding females
Desert Hare (*Lepus capensis*)	Shrubland (Mediterranean/Sub-tropical/Tropical Dry), Grass-land, Pastureland	5-20 ha	10 ha as a continuous area	2'000 ha "pure habitat" for 100-500 hares

Table 1
Habitat parameters of selected focal species (sources: Angelstam et al., 2004; BirdLife International, 2008; Drew et al., 2008; Flux and Angermann, 1990).

For both focal species it is obvious that MASDAR City with an area of 650 ha can only contribute to the totally required proportion of sufficiently large habitat patches at the landscape scale. Urban open spaces in MASDAR City are organized on different floor levels and categorized in different types. In the residential environment these types are e.g. small public gardens, small semi-private courtyards or private courtyards. According to the different types the Masterplan specifies the general type and percentage of vegetation. Whereas small public gardens may comprise up to 60 percent vegetation of indigenous or Mediterranean plants, private courtyards should be predominantly hard paved complemented with xerophytic and endemic lower storey planting.

Desert Hares are relying on habitats on the ground level, whereas birds can also make use of habitats on the other levels if trees or hedges are provided. As the habitat quality depends on both, the floor level and the vegetation cover and type, it is necessary to know how much open space area is available on which floor level (assuming that the upper floors are more private). Therefore, we integrated into the existing CGA shape grammar of the architectural building design rule a "split shape attribute" describing the number of total floor levels and the index of the current shape. Thus we were able to assign different colors on the top floor level and report the roof area (= possible open space) available on each floor level. Figure 3 shows a resulting 3D visualization of the floor level patterns generated with the CityEngine and the reporting results of the available roof area.



Report	Number of Area types	Area type %	Sum Area (m^2)
Area	24	100.0	10685
Area.Level 0	4	16.6	1576
Area.Level 1	11	45.8	5112
Area.Level 2	2	8.3	658
Area.Level 3	6	25.0	2862
Area.Level 4	1	5.1	477

Figure 3
Distribution (left) and reported size (right) of urban green space patterns on the ground floor level and different roof levels of a building block (highlighted in blue) relevant for taking into account habitat function parameters.

The reporting results show that the pattern of the highlighted building block can provide for a pair of Desert Hares about 3.2 percent (Area.Level 0) and for a pair of European Rollers about 11.3 percent (Area.Level 0 - 3) of the required patch size area. In order to add further detail, rules can be applied on the roof areas generating open green space patterns according to the given open space types. This will also allow for an analysis of the habitat quality on the building scale using the procedural urban model. However, on the larger scale the procedural model must allow for querying of neighborhood relationships in order to model and analyze network dependencies.

5.2 Enhancing the urban micro-climate

Climate is one of the most important topics in MASDAR City, whose subtropical climate is characterized by high temperatures regularly exceeding 40°C up to 50°C in the summers (May-October). Thus the vegetation's evaporation and/or shadowing are relevant ecosystem services for cooling and a pleasant micro-climate. Trees are efficient air cooler. Air can be cooled down up to 2°C in a combination of shade trees over grass lawns (Shashua-Bar et al., 2009). Important parameters of the trees' cooling efficiency are shape (Kotzen, 2003), size and age (Gomez-Munoz, 2010), and composition (Raeissi, 1999). Trees should be planted at the eastern and western building side. Further, tree height and distance between tree and house should be in a ratio of 1:3 up to 1:4 (Raeissi, 1999). However, plant species that alter the micro-climate might have high water consumption such as palm trees or need a layer of sweet sand due to low salt tolerance, which leads to ecological and economic costs.

To take advantage of vegetation effects on micro-climate like air cooling it is essential to know the required structures, modes of functioning and conditions of the ecological system. We demonstrate on a small scale modeling example how this knowledge can be generalized and integrated into rules for procedural urban green space generation. The example comprises only some lots with houses of 1-3 stories and two tree species: Mediterranean Pine (*Pinus pinaster*), and Date palm (*Phoenix dactylifera*). We integrated relevant parameters of these tree objects in our model. The Date palm that can get 30-35 m high, is adapted to the region, and offers a wide crown (6-12 m), but has comparatively high water consumption (180l/day). The Mediterranean Pine is significantly smaller (15-20m), with a smaller crown width (6-8 m), and consumes less water (90l/day). Optimal would be a mixture of both trees to get maximal cooling service with minimal water consumption. The attributes given above were defined in the code of the CGA shape grammar rule as "attr" (an example is given in Listing 1). Thus, they can be called and individually changed for iterative generation of alternative tree species selection and distribution patterns. Further relevant attributes for tree plantation in MASDAR could be salt tolerance, needed soil volume or soil composition.

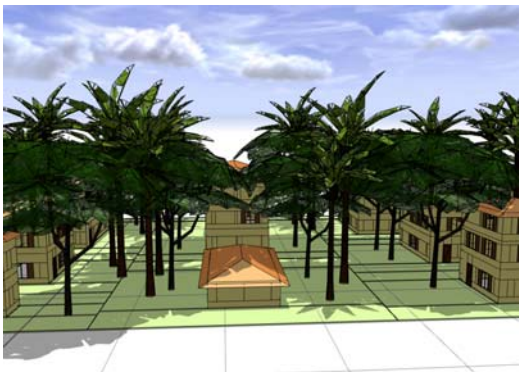
```
attr buildingdepth = rand (6,10)
attr buildingheight = rand(8,12)
attr dist = 4                          # distance house to lot border
attr treedist = rand (6,10)            # distance between trees
attr ext = 0.1                         # expansion of grass
phoenix = "phoenix.obj"
phoenix_height = rand(20,30)           # height
phoenix_width = rand(6,12)             # crown width
phoenix_water = 180                    # water use [m^3] /day   (approximation)
phoenix_crown = phoenix_width*phoenix_width     # shadow area [m^2]
```

Listing 1: Example of defined attributes in the "CGA shape" source code.

Applying CGA shape grammars, each lot (parcel) is assigned a shape grammar rule set. This set of production rules is transforming the lot based on shape operations and query statements. These were set up in order to select and distribute the chosen tree species along building facades. The reporting function offers the possibility to report defined attributes as output figures for a selection of lots, e.g. total water consumption or shadow area (simplified as the square of the crown diameter). These are interesting indicators regarding the consumption or provision of limited goods such as water and shadow in hot and arid zones where houses need to be cooled and water is rare like in MASDAR. The demonstrated approach is suitable to quickly generate and compare scenarios of alternative green space designs according to the visual output as well as basic quantitative indicators. Listing 2 contains a small example rule set and Figure 4 shows a possible resulting pattern's 3D visualization as well as the associated reporting table.

```
Lot -->
        alignScopeToAxes()                    # align all lots
        split (z) {dist : garden(ext) | ~0.5 : part | dist : garden(ext)} # split north-south
part -->
        split (x) {~1 : garden(ext) | 0.01 : TreeArea(-1)| buildingdepth :
        Building(buildingheight) | 0.01 : TreeArea(1) | ~1 : garden(ext)}
                                              # split east-west; plant trees along the houses
Building(h)-->
        extrude (h)
        color(building)
TreeArea(tr) -->
        split (z) {~treedist:  Tree(tr) garden(ext)}*
garden(h)-->
        extrude (h)
        color(soil)
Tree(tr) -->
        30%:  t(tr*rand(phoenix_height/4,phoenix_height/3),0,treedist/2+rand(-1,1))
                                              # translate trees
              s(0,phoenix_height,0)           # height
              r(0,rand(0,90),0)               # random rotation
              i(phoenix)                      # insert object
              report("Phoenix dactylifera", 1)
              report("Water usage", phoenix_water)
              report("Shadow area", phoenix_crown)
        else: NIL
```

Listing 2: This "CGA shape" source code distributes trees along building facades according to tree species' parameters. Some parts have been omitted for simplicity.



Report	Number of instances	Sum
Phoenix dactylifera	16	16
Pinus pinaster	9	9
Shadow area (m^2)	25	1941.2
Water usage (m^3)	25	3690.0

Figure 4
Tree distribution along building facades taking into account cooling function and tree species requirements (left). Reporting of the instances per tree species, sum of total shadow area and water usage (right).

6. Conclusion and future work

We showed a procedural modeling approach to integrate natural resource aspects into urban green space pattern design. In our examples, we demonstrated how far habitat suitability criteria as well as cooling services can be fulfilled by modeled urban green space patterns. In addition to a solely visual assessment, the evaluation of resulting patterns using meaningful, quantitative indicators on the corresponding potential quality of ecosystem services allows for altering the design rules and producing alternative patterns. In this way, optimized patterns meeting ecological needs can be designed in a computerized manner. Whereas the general approach is transferable to other cities (also in the European context), the generated rules are specific to the conditions in MASDAR City.

MASDAR City offered a suitable case study for developing the procedural modeling approach because of the controlled conditions (planner can influence the design without taking into account existing structures). As urban development takes place in more complex conditions, the next step will be to alter existing structures by procedural modeling. How to enhance current urban quality by integrating ecological aspects into the procedural pattern design process?

As demonstrated in chapter 5.2, addressing one need (cooling), can affect the fulfillment of others (low water consumption) and a balancing of interests in an interdisciplinary collaboration process is needed (Matsuoka and Kaplan, 2008). A trade-off of different services of the landscape and urban system is necessary. The further integration of indicators and applicability of the model for the weighting of services is the task of future research.

The values of the ecosystem services indicate how far important ecological requirements of the local natural environment are taken into account in the urban design. These requirements are by far not all and other needs such as socio-economic requirements have to be integrated into the procedural modeling approach in order to design sustainable urban patterns. Thus the approach has to be open for integrating the particular concerns of various stakeholders.

In a relating project the design rules for the building massing and facade structures were elaborated as procedural model accordingly. Thus, a procedural model comprising both, the building structure and a layout of the open spaces according to the specifications of the Masterplan can be generated. This allows for direct visual evaluation of the outcomes and is a valuable support tool for informing architects responsible for developing more detailed housing and landscaping typologies. Linking quantitative indicators to the 3D visualization more directly will make it a powerful tool for assessment purposes that can provide indicators of both, socio-economic and ecological aspects. Getting the urban open areas there where they are actually needed makes the tool a valuable negotiation basis for architects and planners.

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