Shape Grammars for Architectural Heritage

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ABSTRACT

Shape grammars have been introduced in architectural theory some decades ago. They have been applied to architectural construction methods (e.g. Chinese traditional wooden buildings) or for analyzing the design patterns of well-known architects (e.g. Palladio, Frank Lloyd-Wright).

These examples demonstrated that complex geometrical shapes could be generated by a set of replacement rules out of a start symbol, usually a simple geometric shape. With the advent of powerful tools like the CityEngine an interesting field for practical applications of these grammars arose opening a whole range of new possibilities for architectural heritage.

On the one hand, a description of ancient building principles in the formalized way of a shape grammar can aid the understanding and preservation of cultural heritage. With the possibility to actually construct digital 3D models out of shape grammars, they became even more interesting. Furthermore, this approach allows for a large scale creation of 3D models of entire settlements and cities.

On the other hand, shape grammars allow for structured approaches to virtual 3D reconstruction as has been demonstrated for e.g. Mayan or Roman architecture. Besides that, the possibility to specify parameterized variations of the models proves to be an extremely helpful feature.

In this paper we reconsider shape grammars in architecture and examine influences onto procedural modelling. Then we argue for state-of-the-art tools like the CityEngine that apply shape grammars and procedural modelling in architectural contexts and exemplify their power and potential by reconstructing traditional Balinese settlements.

INTRODUCTION

In Architectural Heritage one aims at the conservation of built heritage, where a combination of artistic, contextual, and informational values is usually considered. This includes intangible culture in the form of traditions and knowledge, as well, which is more difficult to preserve than physical objects. Nevertheless, an accurate preservation of physical objects involves in-depth knowledge about the architectural principles and techniques of the respective period.

Another important aspect of architectural heritage is virtual 3D reconstruction of buildings that often exist only in remains or in literature. For this task the same profound knowledge is indispensable.

The conservation of this profound knowledge in digitally processable form is of crucial importance. Beside the digital representation of plans and 3D models, the traditional knowledge should be conserved in digital form, as well.

Knowledge can be preserved in digital media (text, images, audio) for easy distribution and wide access such as Wikipedia or purpose-built platforms. To make this knowledge functional, it needs to be interpreted. This can be done partially automatically with the aid of shape grammars.

In this article we present an evaluation of shape grammars as a means for digital preservation of architectural heritage and exemplify it trough the virtual reconstruction of traditional Balinese settlements.

The section on shape grammars gives a brief introduction into this topic and explores them in architectural contexts. With the increasing immersion of computer technology into architecture, digital design became more flexible, which is discussed in the subsequent section. The section "Implementation and Tools" reflects the algorithmic nature of shape grammars and introduces the tool CityEngine which was used to implement our examples. In the main section we introduce a grammar for Balinese traditional architecture and demonstrate the achieved results, including the automatically generated 3D models. We conclude with a discussion of this approach.

SHAPE GRAMMARS IN ARCHITECTURE

Shape grammars in architectural theory have existed a while before their implementation in digital machines. (March, 2011) provides a good overview of the use of shape grammars in architecture. An excellent introduction into shape grammars in general with a particular focus on their use in architecture can be found in (Özkar & Stiny, 2009).

Shape grammars in architecture are a production system that generates 2D or 3D shapes and consist of rules and a generation process. A rule defines how an existing shape (or part thereof) is transformed into another. A start rule activates the generation, a termination rule ends it.

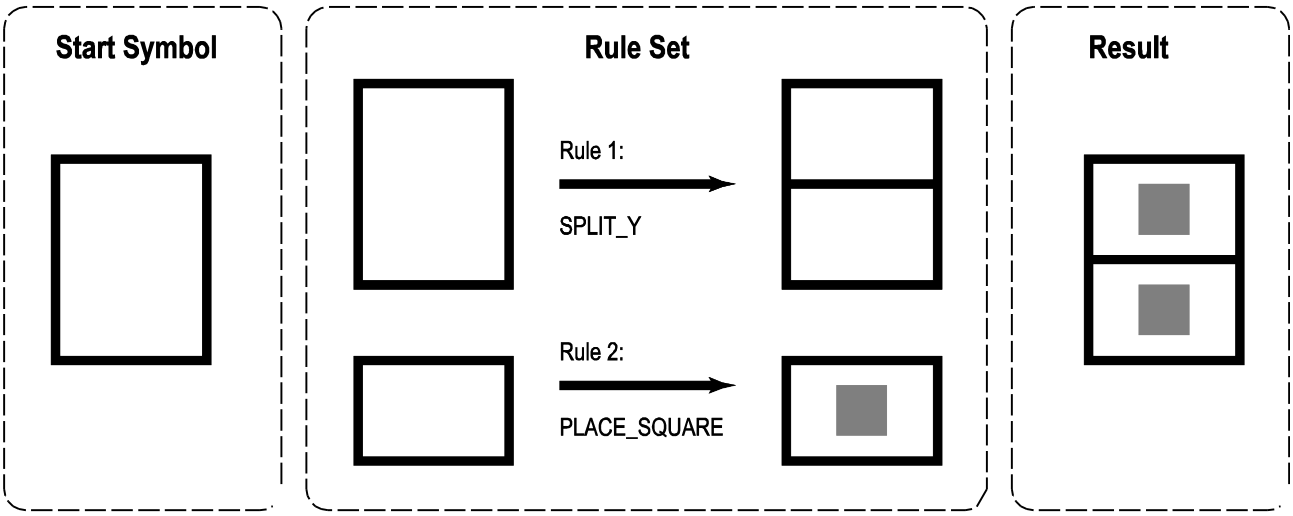

Fig. 1: Example of a simple shape grammar

Figure 1 depicts two simple shape grammar rules. The first rule splits the given area into two equal subareas. The second rule places a grey square at the centre of the given area. Applying both rules results in the placement of a grey square into the centre of each subarea.

In general, the use of shape grammars allows for the compact specification of complex geometrical designs by means of a set of rules. As shape grammars provide a very general paradigm, their use in the field of architectural design has been at different levels. Their main application in architecture was related to the generation of floor plans, as this was the case with Palladio's work (Hersey & Freedman, 1992; Sass, 2007; Stiny, 1975; Stiny & Mitchell, 1978) or with the work of Frank Lloyd Wright (Koning & Eizenberg, 1981).

Some efforts have been made to generate facades using shape grammars such as (Calogero & Arnold, 2011). Also ornament design was a subject of design with grammar rules, for example the Islamic ornamental patterns as described in (Cromwell, 2008; Lu & Steinhardt, 2007). Examples of design grammars for structural composition and traditional building techniques can be studied in detail in (Li, 2001).

As the work on shape grammars advanced, parametric shape grammars have been introduced. In this case rules can have parameters as means to take into account some context of their application. In figure 2 the rule SPLIT(y, 50%, 50%) would be a parametric expansion of the simple graphical split rule □→⊟ from figure 1. The parameters in parentheses (y, 50%, 50%) indicate that the split will happen along the local y-axis into two parts, each of which will occupy 50% of the area. Similarly for the rule PLACE, by adding parameters like a position and a shape, with this single rule one can not only place a grey square at the centre of the area, but any shape at any position related to that area.

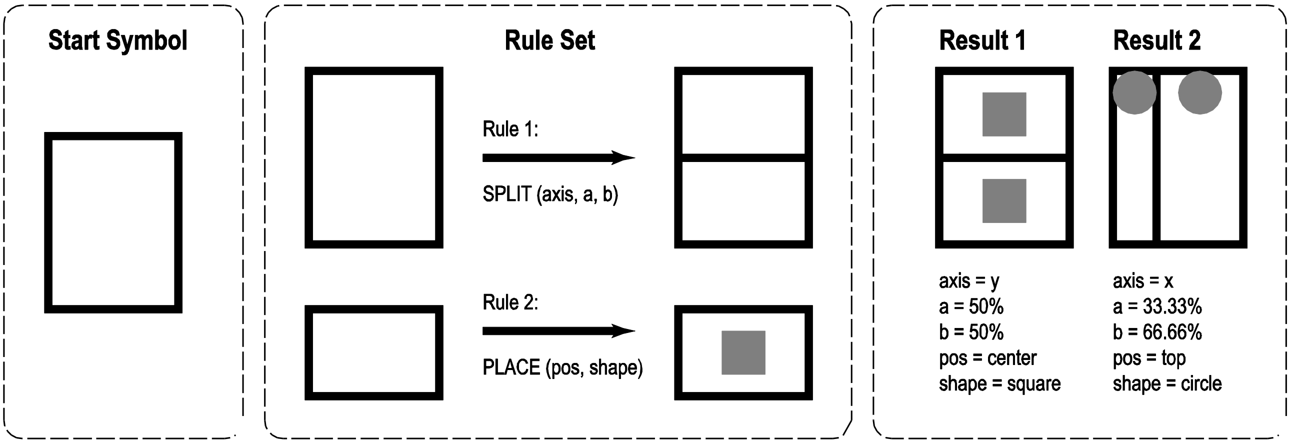

Fig. 2: Simple parametric shape grammar

FLEXIBILITY LEVELS IN DIGITAL DESIGN

The current popularity of this approach might be due to two aspects: affordable computational power and the computational awareness in architectural design. According to (Kotnik, 2006) the use of the computer for architectural design can be viewed at three successive levels other than representation:

Operative level: The available computational power opened possibilities in modelling by means of the implemented geometric operations in modelling software.

Parametric level: This level became popular with NURBS-geometry, and brought a more mathematically based view on architectural design. A shift could be noticed from stable to variable, from single to multiple. Also, the use of time as a parameter like in morphing, key-frame animation, particle systems, etc. was an essential aspect.

Algorithmic level: Taking parametric design a level further resulted in algorithmic descriptions of the design by using a suitable software tool to implement the description and generate the according 3D models. This includes procedural modelling, and implemented shape grammars.

Contemporary shape grammars are an example of the algorithmic level which combines the shape grammars' original algorithmic strength with the computational power of today. This makes shape grammars interesting again for architecture, and especially for architectural heritage. With practical shape grammar implementations available, they can readily be made visible as 3D models, and thus as virtual architecture out of a formal description, capturing the essence of a cultural style or époque.

This exactly represents one of the advantages of shape grammars over general programming languages: the formal description as rules can be viewed as an illustration of building principles and the construction process, which might not be explicitly visible in the generated 3D models. So with shape grammars, one not only aims for an appropriate reconstruction, but also for a formalisation of the underlying principles or style. So the rule sets serve as a means to preserve tradition. Furthermore, the rules can be used for educational purposes.

Influences onto procedural modelling

The basic idea behind procedural modelling is to generate 3D models not entirely by hand but rather with the aid of parameters, shape grammars, scripts or even programming. In this respect it can be viewed as an extension of parametric design. In architectural contexts, procedural modelling can be applied to every scale, ranging from entire settlements to the creation of certain building typologies, and even to specific architectural details.

Influences onto procedural modelling among others can be located in L-systems (Prusinkiewicz & Hanan, 1989; Prusinkiewicz & Lindenmayer, 1990), fractals (Barnsley, 1988), CSG (Requicha & Voelcker, 1983), and parametric surfaces (Piegl, 1991) as well as in shape grammars. Current implementations of shape grammars appear under the term of procedural modelling and incorporate the above mentioned influences to a varying extent.

IMPLEMENTATIONS AND TOOLS

"Shape grammars naturally lend themselves to computer implementation" (Tapia, 1999) as "the specifications introduced are algorithmic and made in terms of recursive schemata" (Stiny & Gips, 1972). Nevertheless, widely useful implementations are scarce. (Chau, Chen, & McKay, 2004) gave an extensive overview of shape grammar implementations. For our purpose of architectural heritage 3D reconstruction, the software tool "CityEngine"[1] seemed most appropriate. It has been successfully employed for similar reconstructions as demonstrated in (Dylla, Frischer, Mueller, Ulmer, & Haegler, 2009; Müller, Vereenooghe, Wonka, Paap, & Gool, 2006).

The software tool CityEngine

In the CityEngine, a design grammar called CGA is employed to generate extensive 3D environments. It "is an enhancement of the set and shape grammar syntax developed in the last decades and is optimized for architectural content. It makes it possible to control or vary volumes, architectural assets, proportions, rhythms, and materials." (Müller, Haegler, Ulmer, & Van Gol, 2006)

Tools like the CityEngine allow for an efficient generation of architectural models and entire urban structures of a specific contemporary or historical style. The final rule set contains a whole range of attributes which can be adjusted to appropriately set the appearance of the generated models. This "allows for the testing of several hypotheses by adjusting some of the parameters. This results in a powerful platform for archaeological discussion and exploration." (Müller et al. 2006)

A GRAMMAR FOR BALINESE TRADITIONAL ARCHITECTURE

Traditional Balinese architecture is known for its extensive rules at both, the microscopic and the macroscopic level, ranging from the design of architectural elements to entire villages. It is based on ancient Bali-Hindu philosophy which can be observed in traditional man built environments in Bali (Bidja, 2000; Budihardjo, 1995; Davison, 2003; Gelebet, Meganada, Negara, Suwirya, & Surata, 1981). In our approach we set out to formalize these rules with a shape grammar.

Typically, composition rules are derived by analysing the appearance of architectural representations, thus leading to formalistic design patterns. Our approach focuses on the underlying philosophy of Balinese architecture, too. It so takes into account appearance as well as ancient building principles. As these principles are adaptable to location as well as the owner, a parametric, rule-based digital model seems well suited to aid this complex design process. For a practical evaluation we implemented the grammar in the CityEngine as it allows for parameters and design variations.

A hierarchical rule set

For the generation of entire traditional Balinese settlements, the rule set has been divided into separate sections. These are devoted to different spatial levels ranging from the layout of a village, to the arrangement of pavilions inside a house compound, to constructional aspects of building parts forming a single pavilion.

We chose a top down approach that takes the underlying Hindu-Balinese philosophy into account. According to that, a settlement has to be orientated along the mountain-sea axis. Along this axis the three village temples are placed. The central area consists of several public buildings, whereas the housing areas are surrounding the village centre, see left part of figure 3. These constraints are grouped into rules for a general settlement layout. The result of these rules are shown in the right part of figure where purple patches indicate the lots for the three temples, the yellow patch is for the palace, the blue patches are lots for public buildings (such as the market, the assembly hall and the bell tower), and the orange patches are lots for houses.

[1] http://www.esri.com/software/cityengine/index.html

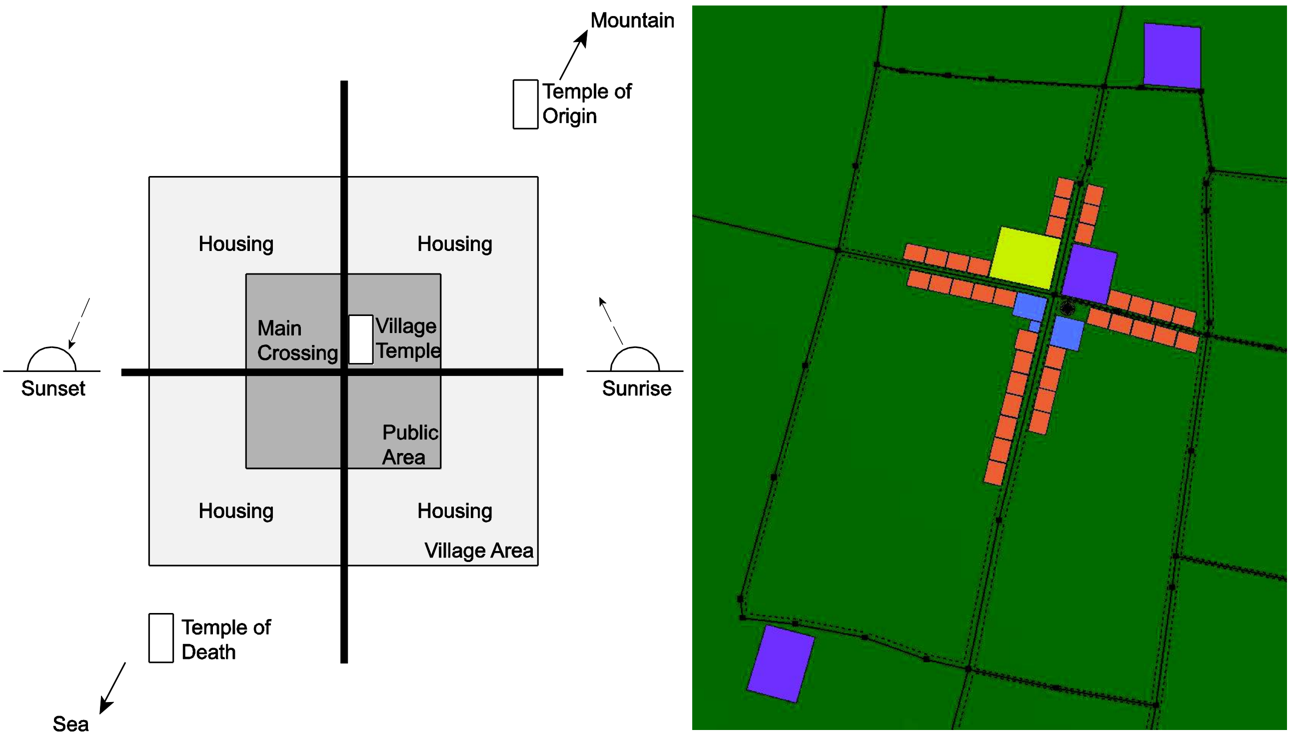

Fig. 3: Traditional Balinese settlement layout. Left: schematic, Right: screenshot from CityEngine

As a next step, the individual buildings within the settlement are generated. This process starts with the creation of appropriate floor plans for the diverse types of buildings. As an example the layout of a typical house compound is shown in figure 4. Hereby the pavilions of a traditional house are arranged according to the hierarchy of space and the orientational mandala, see (Bidja, 2000; Budihardjo, 1995).

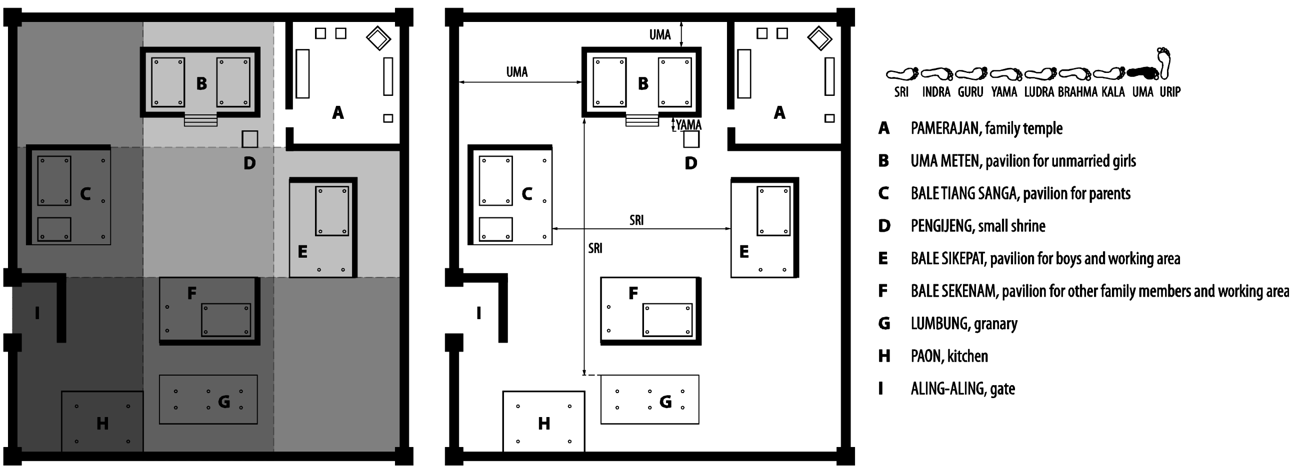

Fig. 4: Layout of a typical house compound. Left: shading according to the orienting axes mountain - sea and sunrise – sunset
Right: Distances related to Hindu deities

The distances between the pavilions are in correspondence to certain numbers – associated to Hindu deities – multiplied by the foot length of the household owner. Additionally, the width of the same foot is added to "give life to the building", for further details see (Dwijendra, 2010). After the layout of the house compound is created each pavilion is generated at the appropriate area.

Traditional Balinese architecture is based upon a very general and adaptable construction, the pavilion. As can be seen in the layout of the typical house compound, several different pavilions are placed at well defined locations within the compound, each serving a specific purpose. So we exemplify the more detailed generation of traditional Balinese architecture through erecting pavilions.

The construction of a typical pavilion is demonstrated in figure 5 as CGA shape grammar rules in graphical form. According to the underlying philosophy and building principles (Bidja, 2000; Gelebet et al., 1981), a pavilion basically consists of a base, columns and a roof. The graph of rules in figure 5 reflects this aspect as well as it reflects the entire construction of a pavilion.

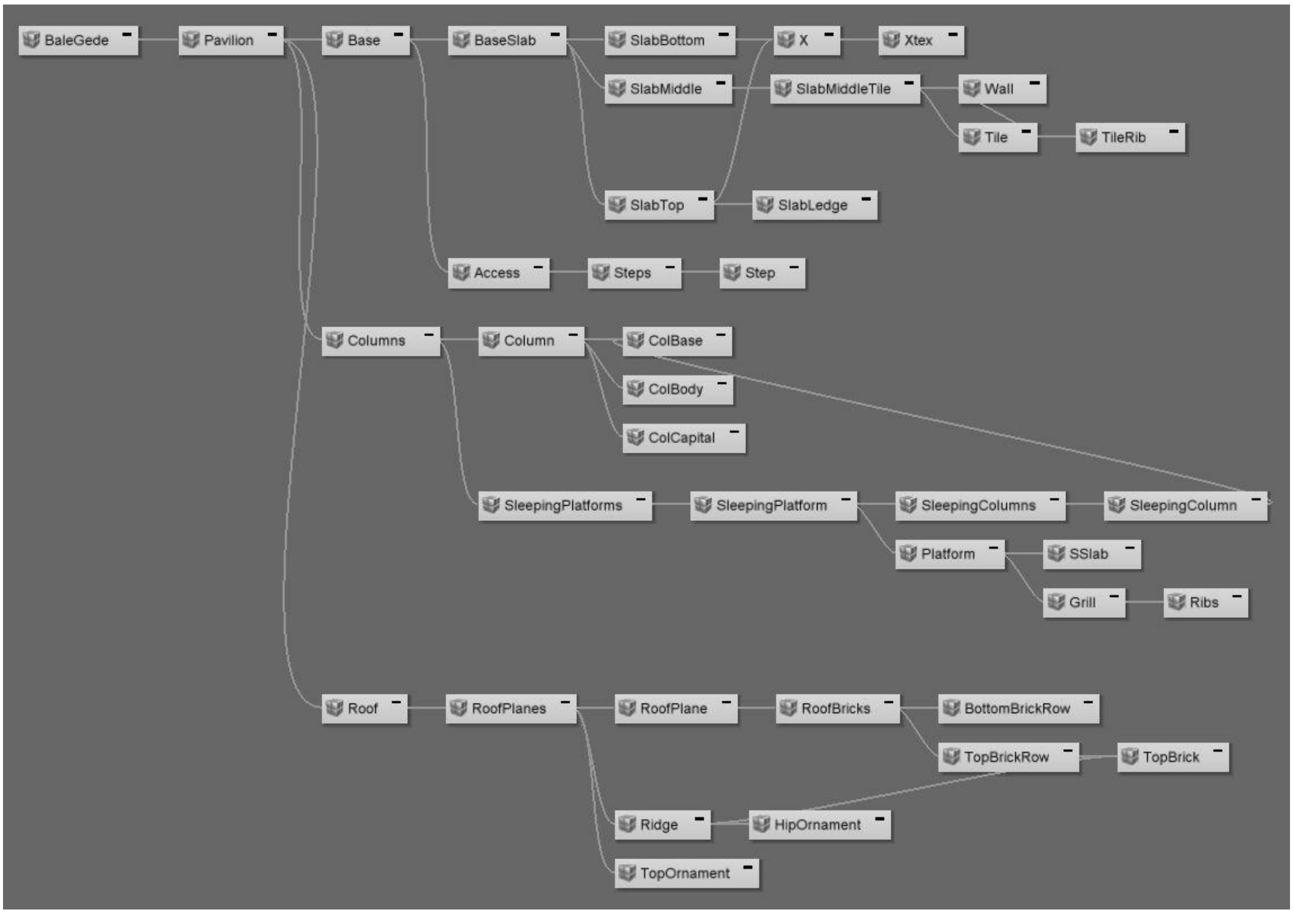

Fig. 5: Rules for a typical pavilion

As an example, the construction of a single column is depicted in textual form below from the CityEngine rule editor. According to the underlying philosophy and building principles, also columns basically consist of three parts: a base, a shaft, and a capital. The respective rules define these parts. The rule in the highlighted line contains the split into these three parts.

```
Column-->
        s(col_width, '1, col_width) centre (xz)
        split(y)(col_base_height : ColBase | ~1 : ColBody | col_sulur_height : ColCapital)
```

In the above example the split rule for columns also demonstrates the usage of parameters in a shape grammar. “split (y)” indicates a split along the y-axis. The following part in parentheses {} defines the exact parameters for the split, in this case a proportion of base : shaft : capital, as depicted in figure 6.

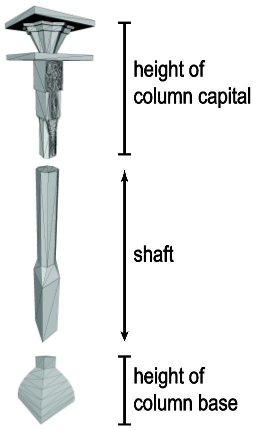

Fig. 6: Column proportions

The height of the base and capital depend on the model used. The shaft length is indicated by ~1 in the rule, meaning that it is calculated so that the overall column height is in proportion with the rest of the pavilion (which is set in a different rule). This is actually a complex calculation which can elegantly be described in conceptual terms within the parametric grammar.

Vocabulary elements

Rule sets need to have terminal symbols, so that at some stage the generation process can terminate with a collection of these terminal symbols put together in the desired way. In the case of our shape grammars these terminal symbols are 3D shapes and textures, as depicted in figure 7. In addition to our own models we used the built-in primitives of the CityEngine (such as a cube) and colouring.

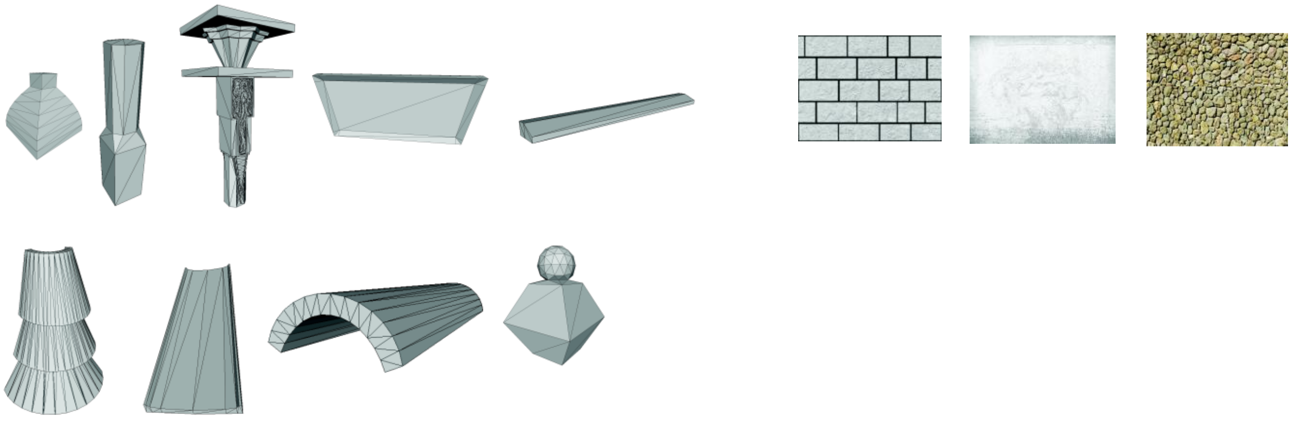

Fig. 7: Terminal symbols for a pavilion, models and textures

Generation process

With the rule set completed the generation can start. To demonstrate this process, the erection of a pavilion is shown in four basic steps in figure 8. This also reflects the actual traditional construction process.

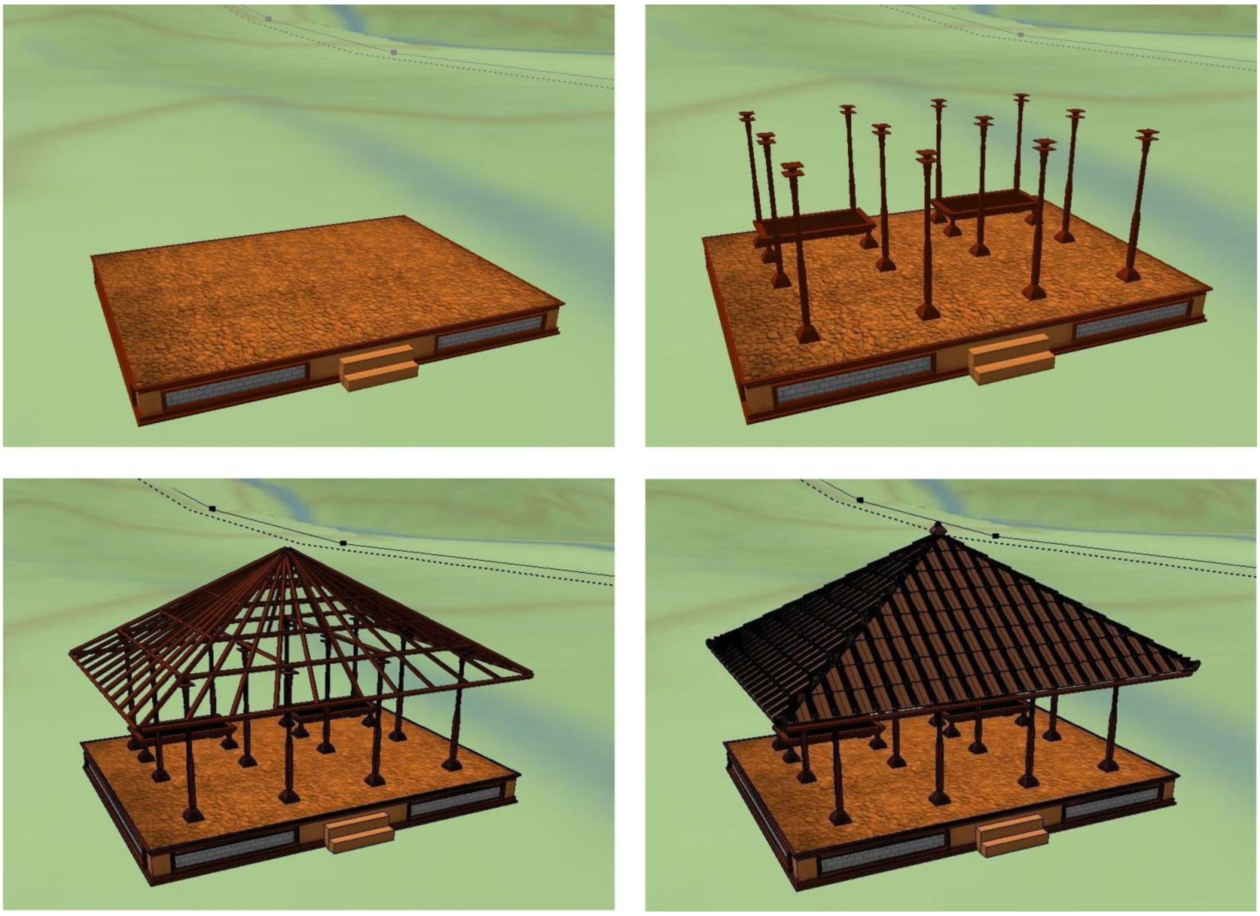

Fig. 8: Construction sequence of a pavilion

Each of these steps is divided into further sub steps (not shown). This is done recursively in the grammar until terminal symbols are reached. As with traditional building they represent elements that are delivered to the building site, such as wooden beams, stones, column bases, roof elements etc.

The parametric Balinese pavilion

As the pavilion is one of the most fundamental buildings in traditional Balinese architecture, we created flexible, parametric rules for this building type. In order to do this, we derived floor plan descriptions with typical dimensions of the buildings after analysing the available literature.

We exemplify parametric pavilions in figure 9. The presented variations are contained in the rules and range from adapting a pavilion to different base sizes, or to different functions and different materials. These variations depend on diverse parameters.

Fig. 9: (top row): Automatic placement of columns according to basement size and type of pavilion
(middle row): Variants of pavilions (open, half open or closed)
(bottom row): Variation of roof construction (natural grass and brick tiles)

As can be seen in the top row of figure 9, with the size of the base also the number of columns changes, and vice versa. The appropriate number of columns and its placement onto the platform is described in the rules and is set automatically in accordance with the building principles. As pavilions are a general structure, their appearance is adapted to their function. This includes the number of walls, as is depicted in the middle row of figure 9. Another possible variation is demonstrated with respect to the roof construction and material used for covering it. The bottom row of figure 9 shows a traditional roof using natural grass as a thatch, and another variant using brick tiles.

A typical traditional Balinese settlement

To construct an entire village, rules for each type of building have been developed. Putting all these rules together and applying them in the CityEngine results in the construction of the models for the village as shown in figure 10. It provides a view at the village centre with the village temple behind the banyan tree, the palace at the upper left, the assembly hall left in front of it, the bell tower next to the banyan tree, the open ground for the market and the cockfighting hall behind it. In front there are some house compounds.

Fig. 10: Automatically generated entire traditional Balinese settlement, view to the main square

DISCUSSION

As a result of our approach to formalise traditional Balinese architecture we can conclude with the following observations:

Using shape grammars not only enables 3D heritage reconstruction but also facilitates a formalisation of the traditional construction principles. Furthermore, it allows to formalise style, thus capturing the “typical”.

Parametric shape grammars are a very compact and powerful way to represent a certain architectural style. In order to define a shape grammar for a certain building type, a building style or entire settlements one has to find an abstraction or a generalisation of an architectural principle and its corresponding parameters.

If the rules are defined hierarchically concerning the spatial structure, entire settlements as well as buildings and architectural detail can be formalised in the same rule set.

Aside from reconstructing a single building exactly, one of the great advantages of procedural modelling lies in the ease of generating a vast number of similar buildings of the same style, thereby producing “hypothetical” settlements in the same historical style or according to the same documented building principles.

As there exist various approaches to architecture (e.g. aesthetical composition principle, construction technique, cultural style, functional aspect) we could demonstrate that they can be incorporated into a common rule set. In our example of Bali we demonstrated functional aspects as well as construction technique.

If some architectural principles are defined as a set of rules, large structures like entire urban environments can be generated automatically, where an adaptation of these structures is possible with respect to topography, existing street networks or other constraints that might be defined by integrating a GIS-system.

Variations of design or reconstructions could be generated as well, if the rules are defined with parameters that allow the exploration of various alternatives.

A drawback of the use of shape grammars is the required knowledge and skills to generate a parametric set of rules, although once this is acquired, the invested time pays off by the flexibility, variability and speed of generating buildings.

Future work will be addressed to an extensive comparison of design variations with actually built examples of traditional Balinese settlements that goes beyond our single field trip, to extend the rule set with additional parameters and further detail.

The presented shape grammar can be used for educational purposes in order to demonstrate traditional Balinese architecture both, theoretically and via the exploratory 3D reconstructions.

Finally, it might also be of interest to adapt the traditional set of rules to modern Balinese architecture in order to meet the contemporary needs of living.

ACKNOWLEDGEMENTS

We like to thank: the staff at the Gedong Kirtya Lontar Museum in Singaraja North Bali for their kind support, the conference organizers Erich Lehner and Ulrike Herbig for helpful hints, our driver on Bali I Made Sukerta for showing us around, Marcus Bleckert and Barbara Di Angelo for some of the illustrations, and the students Bertomeu Genis Jose Francisco, Brauner Friedrich, Erdag Melike, Ertürk Nilgün, Grankov Damjan, Haji Mirarab Mahan, Jevtic Aleksandar, Jusufovic Zinaida, Kolar Birgit, Lachberger Christoph, Malic Jelena, Miskovic Nenad, Soleimani Babakamali Ronak, Strassl Benjamin, Uhde Gulliver, Veres Orsolya, and Wieser Daniel for the 3D models.

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