AN APPROACH TO FORMALISING TRADITIONAL BALINESE ARCHITECTURE WITH DESIGN GRAMMARS

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Introduction

Our intention was to create an interactive digital 3D reconstruction of traditional Balinese architecture, not only at the level of single buildings, but in a generalized way. The aim was to conserve and exemplify the underlying building principles which – by being strict and extensive – lend themselves perfectly to a formalization and implementation in software. Formalization of design has been employed before in architectural theory, design computing, and computer graphics.

In architectural theory and design computing, design grammars have already been introduced and used in several examples (cf. section "Design grammars"). However, they were mainly conceptual tools. Computer implementations of design grammars are not widespread. Computer graphics, on the other hand, has a long history of procedural modelling. Only procedural urban modelling appeared more recently. Recent software tools have expanded the idea of design grammars and allow for rapid generation of architectural models and entire urban structures of a specific contemporary or historical style.

Of these, the most widely-used and elaborate software tool is the CityEngine [@CE] which provides a "unique conceptual design and modeling solution for the efficient creation of 3D cities and buildings". This software tool seemed well suited for implementing and visualizing our formalization of traditional Balinese architecture and was therefore used for the proof of concepts.

In this article, we first present the principles of traditional Balinese architecture on which our approach is based. Then we summarize the use of design grammars in architecture and their application to procedural modelling. Finally, we apply the traditional Balinese building principles to the development of a design grammar and implement it in CityEngine. Results are presented as a visualisation of our approach. The final section contains a discussion of the summary of the results.

Principles of traditional architecture

Traditional Balinese architecture is based on ancient principles which „create balance, harmony and propriety between building, microcosmos and macrocosmos, man and his God" (Budihardjo 1995). This Bali-Hindu philosophy can be observed in traditional built environments in Bali.

Conservation of ancient knowledge

Ancient Balinese knowledge has been conserved in palm leaf manuscripts, called *lontars*. The society's knowledge and traditions were engraved on specially prepared leaves of the *Borassus fabellifer* palm. *Fig. 1* shows a typical *lontar* next to its engraving tool and the paste which makes the engravings more visible.

Lontar subjects cover not only architecture, but rather span a huge variety of aspects of human life including religion, healing, the arts, history, etc. The *lontars* are quite durable and several hundred years old. They were engraved in the ancient Balinese *Carakan* alphabet which is still used today, although mainly for religious purposes.

There have been efforts to translate the contents relating to architecture into Tulisan Bali (modern-day Balinese) and Indonesian (Bidja 2000; Dwijendra 2010). Some of the basic principles of traditional Balinese Architecture can also be found in English publications (Budihardjo 1995; Eiseman 1996).

Fig. 1: Typical *lontar* (palm leaf manuscript) with engraving tool and „ink".

The *lontars* themselves are kept in the Gedung Kirtya Lontar Library Annex Museum in Singaraja, a town in Northern Bali. *Fig. 2* depicts the shelves where the *lontars* are kept in wooden boxes.

Fig. 2: Lontar museum in Singaraja

Building principles

The underlying philosophy of Balinese architecture is reflected in seven building principles (Budihardjo 1995): hierarchy of space, cosmological orientation, balanced cosmology, human scale and proportion, open air "court" concept, clarity of structure, and truth of materials.

1. Hierarchy of space – Tri Angga / Tri Loka

Tri Angga means "three parts". *Tri Loka* means "three places". Both reflect the tripartite nature of the universe in Bali-Hindu philosophy. It ranges from the philosophical threefold quality of "god – man – demon", "pure – neutral – impure", "heaven – world – hell" to the location-based quality of "up – middle – down" and the time-based quality of "future – present – past". These qualities can also be observed in nature e.g. in the quality of "sunrise – noon – sunset" as well as in the landscape quality of "mountain – land – sea" or the human body quality of "head – body – legs". In Balinese these qualities are called *utama*, *madya* and *nista (Fig. 3)*.

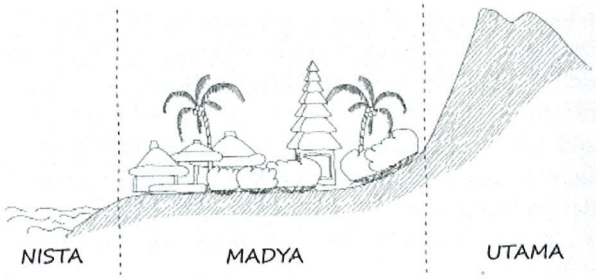

Fig. 3: *Tri Angga / Tri Loka*

2. Cosmological Orientation – Nawa Sanga mandala

The *Nawa Sanga* mandala is an orienting framework based on Bali-Hindu philosophy. Each of the eight cardinal directions plus the centre are associated with certain colours and deities. These directions are then combined with the mountain-sea axis, and the sunrise-sunset axis. The "holy" (*utama*) orientation on Bali is towards Mt. Agung, part of the mountain range northeast of Denpasar. If another mountain is clearly visible in a certain location, it will assume the orienting function of Mt. Agung for that specific location.

The application of this principle to architecture is reflected in the orientating of both the house compound and the entire village. Based on the applied orientation scheme, the building is divided into nine areas according to the hierarchy of space (see *Fig. 4*), thus attributing a specific quality to each area.

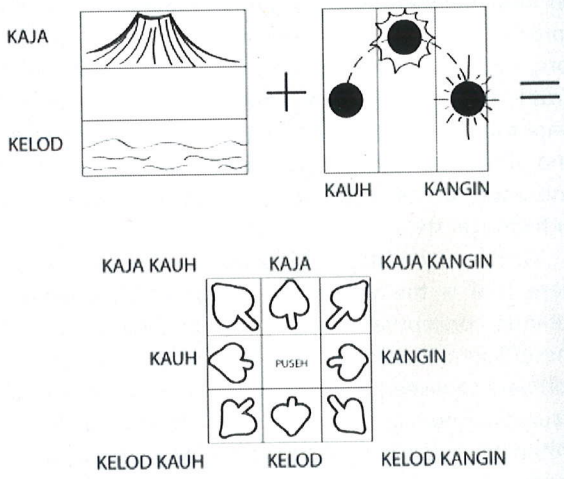

Fig. 4: *Nawa Sanga* mandala

3. Balanced cosmology – Manik Ring Cucupu

In Bali-Hindu philosophy, one always has to try to balance the threefold quality that is inherent in everything. This also means that man, nature and architecture are closely linked. In this respect we can see "architecture as the son of nature" (Budihardjo 1995).

4. Human scale and proportion

In order to create balance, measurements are based on the body parts of the person responsible for the building, as shown in *Fig. 6*. The foot length (*tampak*) is a very common measurement unit. To add life to a building, a specific "little bit" (*urip*) is added, such as, for example, the foot width (*tampak ngangdang*).

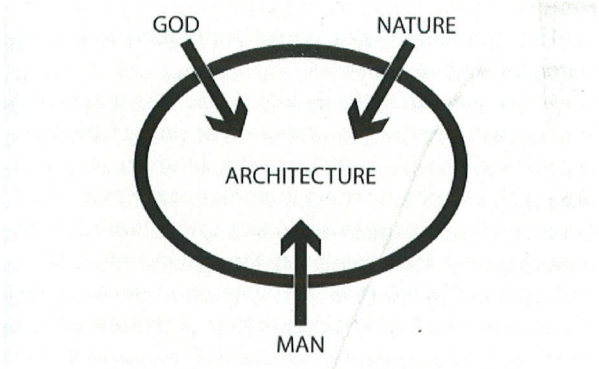

Fig. 5: Balanced cosmology

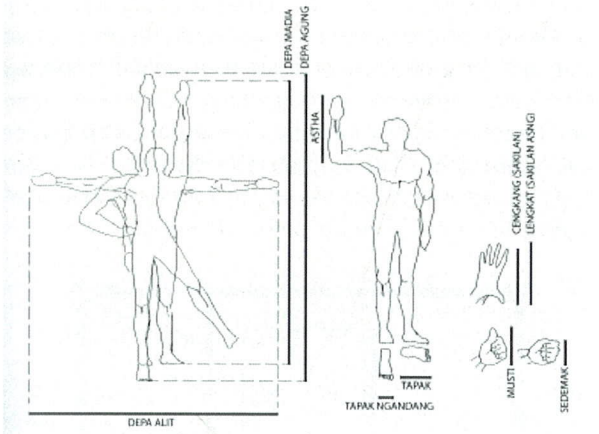

Fig. 6: Body measurements as proportion system, based on Gelebet et al. 1981

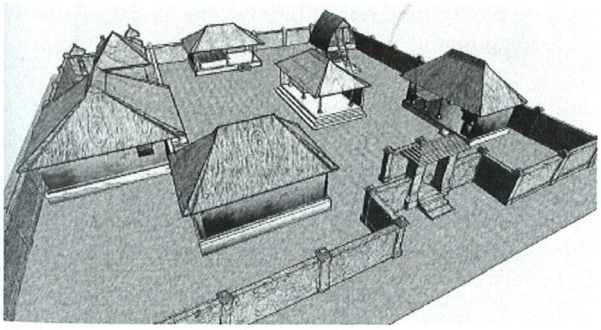

Fig. 7: Open air house compound

5. Open air "court" concept

On Bali, buildings are open structures and often partitioned into separate units with special qualities.

So, a building such as a house typically consists of several free-standing pavilions, each of which serves a distinct function. The pavilions are enclosed by a surrounding wall with a street-side entrance gate. *Fig. 7* depicts a schematic drawing of the open court concept of a typical traditional house compound. In a traditional Balinese house, the pavilions (*bale*) are arranged around a central court. Often these pavilions are designed as partly open spaces themselves, oriented to the central courtyard.

Fig. 8: Clearly visible structure

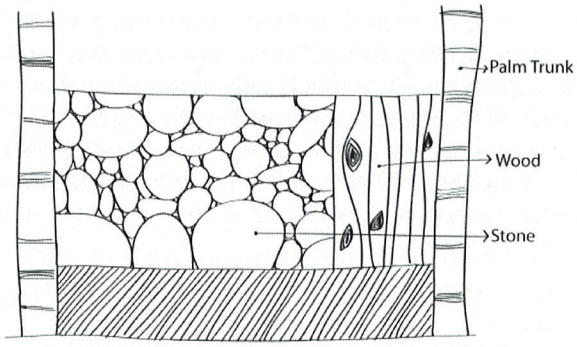

Fig. 9: Truth of materials, based on Budihardjo 1995

6. Clarity of structure

The structure of a building is always clearly visible, as can be seen in *Fig. 8*: the stone foundation of the pavilion, the supporting wooden columns including their stone bases, the screening walls as well as the wooden roof construction. The clear structure is neatly accompanied by the principle of "truth of materials".

7. Truth of materials

Materials are explicitly exposed (as can be seen in *Fig. 8*) so that their essence is revealed. On Bali, natural beauty is appreciated. With this truth of materials (see *Fig. 9*), harmony between nature and buildings is enhanced.

Application of principles to built structures

Village layout

Application of the building principles results in a typical village layout, which is depicted in *Fig. 10*. There are three main temples in a village, positioned according to the mountain-sea axis. The temple of origin (*pura puseh*) is positioned uphill, in the part of the village that is closest to the predominant mountain in the area. In absence of any clearly visible mountain, this temple points towards Mt. Agung. The village temple (*pura desa*) is positioned in the village centre, again pointing in the direction of the orienting mountain. The temple of the dead (*pura dalem*) is positioned in the downhill part of the village pointing towards the sea.

The village centre is situated at the intersection of two main roads, usually marked by a tall banyan tree. In addition to being the site of the village temple, it provides space for other public buildings as well, such as the palace (if there is one), the market, the bell tower, and the assembly hall. Before gambling on cockfights was outlawed, the cockfighting hall was also in the village centre. Houses are positioned in the remaining areas along the roads.

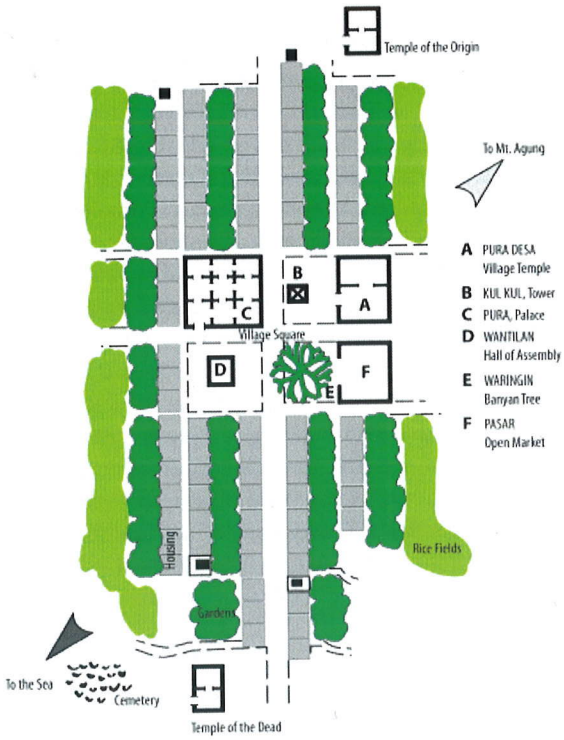

Fig. 10: Typical village layout, based on Budihardjo 1995

House compound

The orientation of a house compound is also towards Mt. Agung.

This means that the family temple (structure A in *Fig. 11*) will occupy the *utama*-most part of the compound and will be built first. The other pavilions are placed at distances that are multiples of the main measuring unit (usually the owner's foot length (*tampak*)). The multiples bear the qualities of the associated deities as indicated in *Fig. 11* under the symbolized feet. So, *uma* distance means 8 *tampak* (or multiples thereof) plus an additional distance called *urip* (as defined earlier).

Design grammars in architecture

Design grammars in architectural theory existed long before their implementation in digital machines. March 2011 provides a good overview of the use of design grammars in architecture. An excellent introduction into shape grammars in general, with particular focus on their use in architecture, can be found in Özkar et al. (2009).

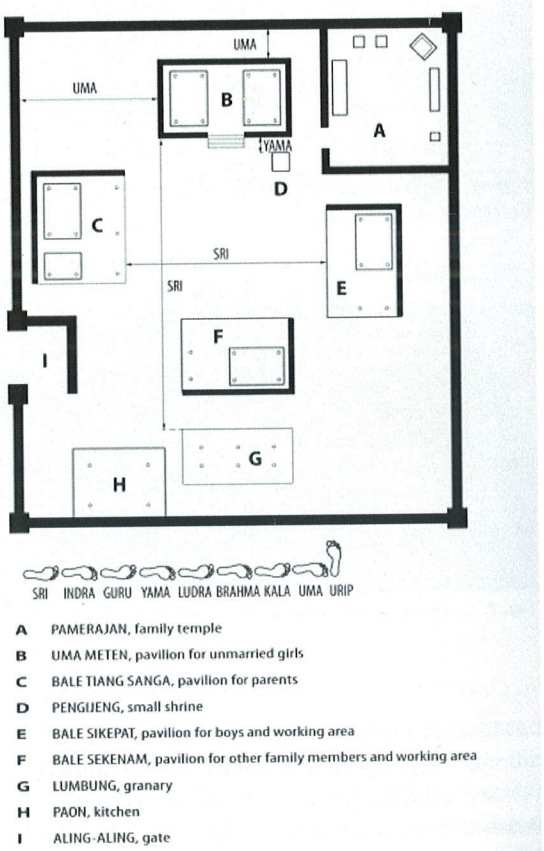

Fig. 11: Typical house compound with distance qualities, based on Dwijendra 2010

Figure 12 shows two simple shape grammar rules. The first rule uses a proportional split of an area into two subareas. The second rule places a pre-defined object (grey square) at the centre point of an area. Applying both rules results in the placement of grey squares into the centre of each subarea. In general, the use of design rules with shape grammars allows the compact specification of complex geometrical designs with only a small set of rules. As shape grammars provide a very general programming paradigm, they have been used at different levels in the field of architectural design.

Their main application in architecture was related to the generation of floor plans, as was the case with Palladio's work (Stiny 1975; Stiny et al. 1978; Hersey et al. 1992; Sass 2007) or with the work of Frank Lloyd Wright (Koning et al. 1981). Some efforts have been made to generate facades using shape grammars, cf. Calogero et al. 2011. Also Ornament Design was subject of design with grammar rules, for example the Islamic ornamental patterns as described in Lu et al. 2007; Cromwell 2008. Examples of design grammars for structural composition and traditional building techniques can be seen in Li 2001.

Design grammars with CityEngine

The "CityEngine" software tool is based on procedural modelling (Parish et al. 2001), where geometry is not all created by hand, but largely through a set of rules. In CityEngine, a design grammar called CGA is used 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" [@CE].

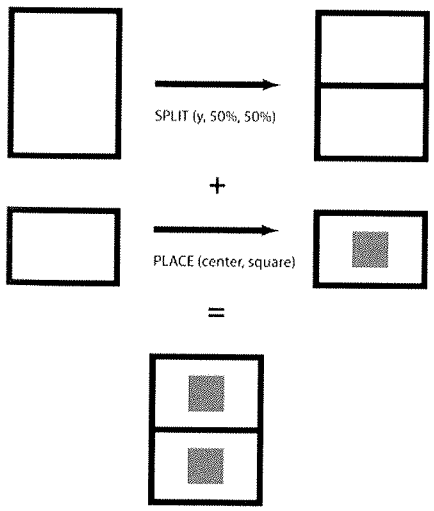

Fig. 12: Example of a simple shape grammar

Tools such as CityEngine allow for an efficient generation of architectural models and entire urban structures of a specific contemporary or historical style. Typically, composition rules are derived by analysing the appearance of architectural representations from plans, drawings and photographs, which lead to formalistic design patterns. 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).

Some examples of CityEngine applications can be found in Watson et al. 2008; Haegler et al. 2009 for the reconstruction of ancient Rome (Dylla et al. 2009), for the procedural modelling of Mayan architecture (Müller et al. 2006). For variations of the Louvre with the use of CityEngine see Calogero et al. 2011.

Constructing a traditional Balinese village with a design grammar

In order to appropriately formalise traditional Balinese architecture, it is necessary to take into account appearance as well as ancient building principles. As these principles are adaptable to location as well as the owner (cf. section "principles of traditional architecture"), a parametric, rule-based digital model seemed well-suited to assist in this complex design process. We therefore used the parametric rule-based modelling technique supported by CityEngine to demonstrate and visualize our approach of formalising traditional Balinese building principles. The creation of a typical traditional village served as a test case for this purpose.

Village layout

A street network from a Balinese village was exported from Open Street Maps [@OSM] and used as a basis for creating a traditional Balinese village with a design grammar in CityEngine. To this street network was added the typical layout of a Balinese village with coloured areas for each building type. The result of this process is shown in *Fig. 13*.

The three temples are represented by purple patches, with the house compound areas in orange. The public buildings are shown in yellow for the palace, light

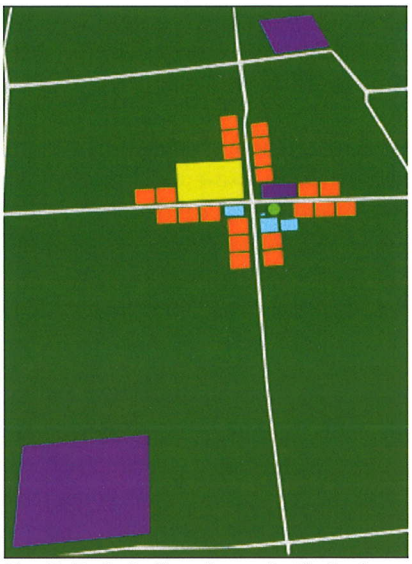

Fig. 13: Typical village layout in CityEngine

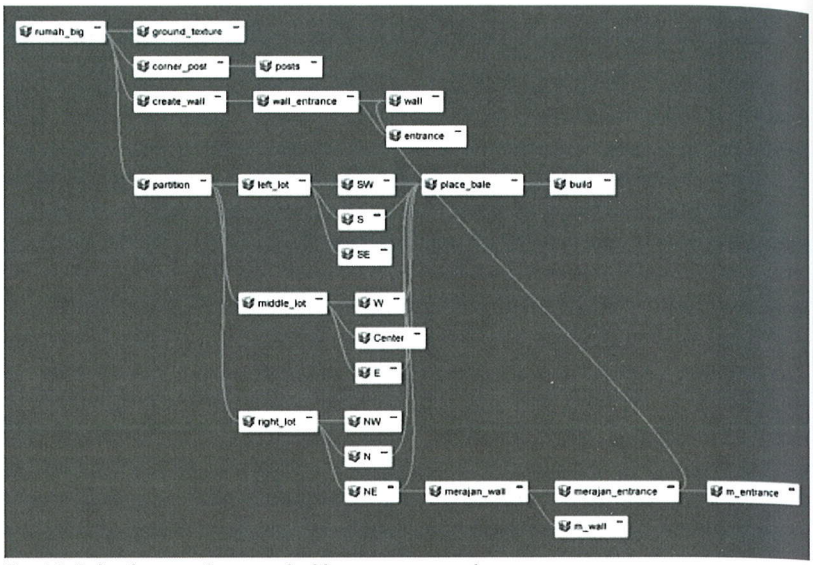

Fig. 14: Rules for creating a typical house compound

green for the banyan tree, and light blue for the assembly hall, the market, the cockfighting hall and the bell tower.

These diverse building areas serve as a starting rule for the design grammar that was implemented. The design grammar to construct a typical village consists of a range of rules: several rules for building elements and one for each building type. To exemplify those rules, the construction of a house compound is demonstrated in detail.

House compound

The rule for a house compound (*rumah*) is shown in *Fig. 14*. It starts with creating a basic layout with corner posts, the surrounding wall, placing the ground, and splitting the area into nine parts according to the building principles of (1) hierarchy of space and (2) cosmological orientation. Then a suitable pavilion is positioned in each part of the compound and the entrance is positioned street-side in the *nista*-most part of the wall. The house temple is positioned in the *utama*-most area of the compound and is surrounded by its own wall with a temple entrance inside the compound. The creation of the respective pavilions is accomplished with a separate rule set (cf. Section Pavilions).

Applying these rules in CityEngine to create a 3D model results in a house compound as shown in *Fig. 15*.

Pavilions (bale)

Pavilions are the main generalized form of structure within traditional Balinese architecture as most buildings consist of a collection of different types of pavilions.

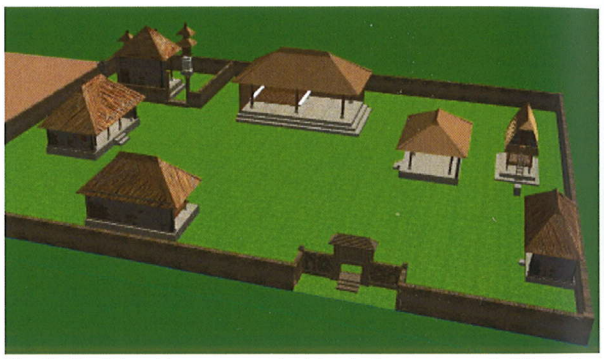

Fig. 15: Traditional house created with a design grammar in CityEngine

To demonstrate the power of rule-based model creation, different types of pavilions were created with one single rule set. *Fig. 16* shows some parts of the respective rules in textual form. In the first section, the variations for the construction of the pavilions are set to be randomly chosen at a certain percentage, e.g. the two available types of foundations ("*bale_base*") are randomly chosen at 50% each, while the wooden platform ("*platform*") will appear in 80% of the generated models.

The central rule ("*bale*") will construct the single pavilions and thereby split the structure into "Base", "Column" and "Roof". Further on, the excerpt only shows the complex construction of the columns. Rules for the foundation and the roof are not shown.

Application of these rules in CityEngine results in the pavilions which are shown in *Fig. 17* where the variation can clearly be seen: the two bases in front are different from those at the back; the number of side walls varies

```
// random choices
attr bale_base =      50%: "models/base1.dae"
                      else: "models/base2.dae"
attr column_base =    50%: "models/columnbase.dae"
                      else: "models/columnbase2.dae"
attr column_shaft =   50%: "models/shaft1.dae"
                      else: "models/shaft2.dae"

attr platform = 80%: true   // wooden platform
                else: false
attr walls =  80%: 2        // number of walls (0,1,2)
              10%: 1
              else:0


//start rule for bale
bale-->
       s(6,0,5)
       center(xz)
       extrude (bale_height)
       split(y) {~base_proportion: Base |
              ~column_proportion: Columns |
              ~roof_proportion: Roof }

Columns-->
       offset(-roof_over-column_in,inside)
       PlaceColumns
       PlacePlatform
       PlaceWalls

PlaceColumns-->
       case column_number == 2: CornerColumns
       case column_number == 3: CornerColumns comp(f)
              {bottom: split(x) {~1: comp(e) {1:
              MiddleColumns | 4: MiddleColumns} | ~1:
              NIL}}
       case column_number == 4: CornerColumns comp(f)
              {bottom: split(x) {~1: comp(e) {1:
              MiddleColumns | 4: MiddleColumns} |~1:
              comp(e) {1: MiddleColumns | 4:
              MiddleColumns} | ~1: NIL}}
       else: NIL

CornerColumns-->
       comp(f){bottom: comp(e) {all: Column("corner")}}

MiddleColumns-->
       Column("middle")

Column(type)-->
       r(-90,0,0)
       s(0,column_height,0)
       set(scope.sy, scope.sy/8*1) ColumnBase
       set(pivot.py,pivot.py+scope.sy)
       set(scope.sy, scope.sy/1*7) ColumnShaft(type)
```

Fig. 16: Rules for pavilions

between 0 and 2; some pavilions have a platform; two different column bases are used.

Fig. 18 shows a graphical overview of the rule set for the pavilion variation. The parts which are shown in textual form in *Fig. 16* are indicated in red.

Village

To construct an entire village, rules for each type of building have to be developed. Putting all these rules together and applying them in CityEngine results in the construction of the models for the village as shown in *Fig. 19*. It provides a view of the village centre with the village temple on the upper right, the palace on the upper left, the assembly hall in front of it, opposite the banyan tree next to the bell tower, and the open ground for the market and the cockfighting hall behind it. In front there are a number of house compounds.

Fig. 17: Different types of pavilions created with a parametric rule

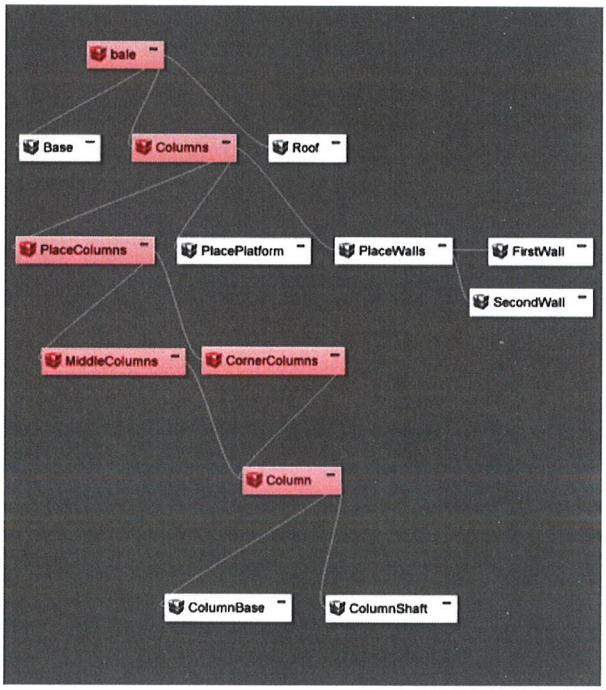

Fig. 18: Rule for pavilions

Fig. 19: Entire village with all rules combined

Discussion

Since the principles of traditional Balinese architecture are kept as written instructions on ancient palm tree leaves (*lontars*), this rule-based design is very well suited to implementation as a set of shape grammar rules as was done with the aid of CityEngine. Shape grammars can be defined for each structure of typical Balinese settlements (entire villages, different building types and even diverse building elements). Parametrisation of the rules also allows for the integration of human proportions (in the form of actual dimensions of the body parts of the head of a building).

Therefore, the exemplified translation of the ancient *lontar* scripts into digital shape grammar rules might be of great value in the preservation of Balinese architectural heritage. The main drawback to this approach is the intensive initial training required to learn rule based modelling.

Future work will focus on additional and more detailed translations of the ancient *lontar* scripts, with particular emphasis on providing a better explanation of the complex distance rules as applied in the layout of a house compound.

Additionally, a more extensive parametrisation of building rules should be formalized and implemented to account for the great variety in building styles. In addition to the detailed implementation of housing structures, a similar approach should be taken to temples and other public buildings

The demonstrated formalization and implementation of ancient Balinese building rules thus far is only a first step. Additional studies of original literature as well as on-site in Bali itself are required to achieve a deeper understanding of this topic and to better preserve these valuable rules in the age of digital information technology.

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

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