

Parametric Balinese Rumah

Procedural Modeling of Traditional Balinese Architecture

Peter Ferschin, Monika Di Angelo, Galina Paskaleva

Faculties of Architecture and Planning & Informatics

Vienna University of Technology

Vienna, Austria

ferschin@iemar.tuwien.ac.at

Abstract—Traditional Balinese architecture is based on ancient Bali-Hindu philosophy which can be observed in traditional built environments on Bali. The underlying architectural principles are very complex containing intrinsic “parametric rules” based on both a philosophical and a building tradition. The parameters are in relation to the religious belief system as well as being derived from the bodily dimensions of the “head” of a building. We aim at determining in which way these underlying building principles can be preserved by contemporary digital means. As a hypothesis we test a parametric formalization as CGA shape grammar made operative using the CityEngine. In order to formalize these building principles the following methods were devised: identification and collection of appropriate literature in English and Indonesian, partial translation of available material to English, field trips for contextual information and additional knowledge, and transformation of all sources of information into a shape grammar. An interactive visualization of ancient Balinese building principles is exemplified through the traditional house compound, the “rumah”, demonstrating the strength of a parametric approach. Moreover, it includes both, tangible and intangible heritage aspects by analyzing the appearance of (tangible) built heritage, as well as the (intangible) underlying philosophy and traditional knowledge. Our contribution aims at supporting the understanding and preservation of the architectural heritage of Balinese building principles.

Keywords—Procedural modeling; traditional Balinese architecture; shape grammar; intangible heritage; parametric modeling.

I. INTRODUCTION

Ancient Balinese knowledge and traditions have been conserved in palm leaf manuscripts, so-called *lontar*. Contents on the *lontar* do not solely cover architecture, but a huge variety of aspects of human life including religion, healing, arts, history, and so on. The parts covering building principles are referred to as *Asta Kosala-Kosali* [1]. Traditional Balinese architecture is known for its extensive rules ranging from the design of architectural elements to the layout of entire villages. It is based on ancient Bali-Hindu philosophy which can be observed in traditional built environments on Bali [1-4].

In order to make the *lontar* available to the international community they have been scanned and digitally archived at the Lontar Digital Library which is hosted by [5]. Some of

them were translated into Indonesian and English. Preservation of architectural traditional knowledge by contemporary means could go beyond mere digitization and be made more useful by applying a formalized approach. Ideally, this formalization should incorporate the design intent as well, which represents the intangible aspect of a building tradition. Current formalization of architectural heritage as in [6], [7] put their main focus on capturing the appearance rather than the underlying philosophy and design principles.

We aim at determining in which way these underlying building principles can be preserved by contemporary digital means and simultaneously be made operative.

This could be useful for architects who are interested in extending traditional building principles towards contemporary use and people in history of architecture, building archaeology, and restoration. On the one hand, it would aid the adaptation of building traditions for contemporary needs (e.g. tourism). On the other hand it could facilitate a wider comprehension and appreciation within the research community as well as the parties involved.

We set out to formalize the contents of the *Asta Kosala-Kosali* and provide a visualization of these Bali-Hindu design principles. Our approach aims at conserving and exemplifying the underlying building principles which – by being regulated, detailed and extensive – perfectly lend themselves to a formalization and implementation in software. As these principles are adaptable to the location as well as the owner, a parametric, rule-based digital model seems well suited. As a hypothesis we test a parametric formalization as CGA shape grammar made operative by means of the CityEngine.

Formalization of design already has been employed in several fields, such as architectural theory, design computing, and computer graphics. In architectural theory and design computing, design grammars have been introduced and used in several examples, e.g. [8-17]. Computer graphics, on the other hand, has a long history in procedural modeling. 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. The most prominent and elaborate software tool among these is the CityEngine which provides a “unique conceptual design and modeling solution for the efficient creation of 3D cities and buildings” [18]. This software tool seemed well suited for



Fig. 1. Photographs of a traditional Balinese house compound (*rumah*) in Batuan, consisting of several pavilions in an open court.

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 building principles for a traditional house compound (*rumah*) on Bali. This includes the principles of traditional Balinese architecture which our approach is based upon. Then we formalize these traditional building principles by means of a shape grammar for Balinese vernacular buildings, and present our implementation of a virtual parametric Balinese house compound in the CityEngine. For the formalization of the traditional building principles the following methods were devised: identification and collection of appropriate literature in English and Indonesian, partial translation of available material to English, field trips for context information and additional knowledge (e.g. *lontar* museum in Singaraja, traditional housing in Batuan village), and transformation of all sources of information into a shape grammar. In this paper we discuss the application of the distance rules to generate an appropriate floor plan for a house compound to exemplify the complexity of the traditional building principles. Additionally, the construction of the diverse pavilions within a house compound serves as a demonstration of the strength of a parametric approach. A discussion of the results concludes this formalization of traditional Balinese architecture.

II. THE TRADITIONAL HOUSE COMPOUND (RUMAH)

On Bali, buildings are open structures and often partitioned into separate units with special qualities. So, a building like a house typically consists of several disconnected pavilions which serve a distinct function each. They are enclosed with a surrounding wall and a street-side entrance gate. Fig. 1 depicts the open court concept of a typical traditional house compound (*rumah*) where the pavilions (*bale*) are arranged around a central court. Often these pavilions are designed as partly open spaces themselves, orientated to the central courtyard.

The underlying philosophy of Balinese architecture is reflected in seven building principles [2]: hierarchy of space, cosmological orientation, balanced cosmology, human scale and proportion, open air “court” concept, clarity of structure, and truth of materials. For the formalization, three of those concepts are essential and therefore explained in more detail.

Hierarchy of space reflects the tri-partite 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 –

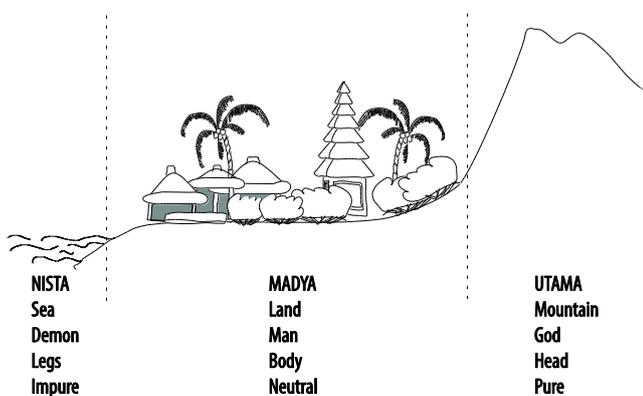


Fig. 2. Hierarchy of space

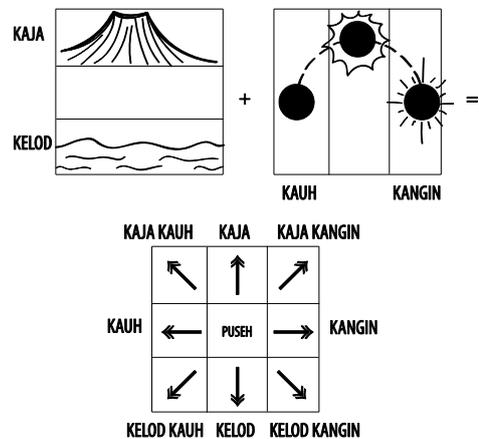


Fig. 3. Cosmological orientation - Nawa Sanga Mandala

TABLE I. BALI-HINDU DEITIES

Deity	Number	Balinese direction	Compass
Sri	1	kaja-kangin	NE
Indra	2	kangin	E
Guru	3	kelod-kangin	SE
Yama	4	kelod	S
Ludra	5	kelod-kauh	SW
Brahma	6	kauh	W
Kala	7	kaja-kauh	NW
Uma	8	kaja	N

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 – nista*. A graphical representation can be seen in fig. 2.

For the cosmological orientation, the *Nawa Sanga Mandala* (as depicted in fig. 3) is an orienting framework based on Bali-Hindu philosophy. The eight cardinal directions plus the center are each associated with colors and deities. These directions are combined with the mountain-sea axis, and the sunrise-sunset axis. The “holy” (*utama*) orientation on Bali is towards Mt. Agung which is situated in the mountain range North-East of Denpasar. If another mountain is clearly visible in some place, this mountain will take the orienting part of Mt. Agung for this specific location. According to the principles hierarchy of space and cosmological orientation a building is divided into 9 areas, thus attributing a specific quality to each area.

The principle of human scale and proportion is incorporated in order to create balance. Therefore measurements are based on the body parts of the person responsible for the building, as depicted in fig. 4. These body parts are used to parameterize buildings.

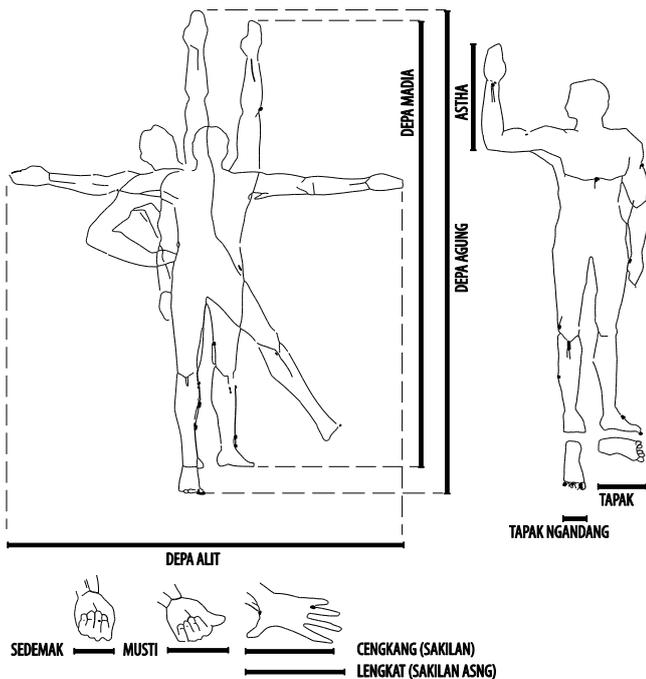


Fig. 4. Body measurements as proportion system, based on [3]

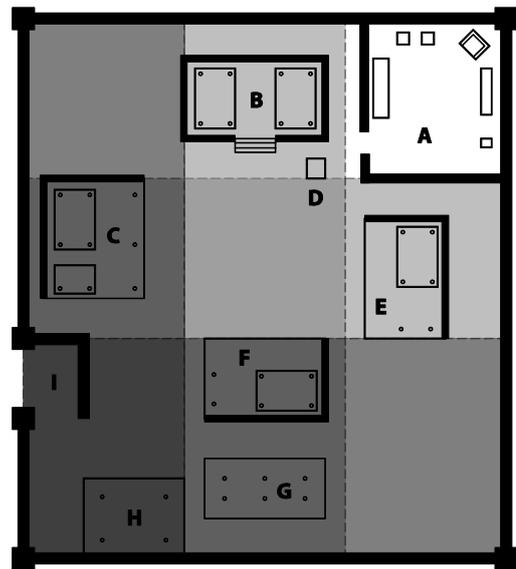


Fig. 5. Layout of a typical house compound (*rumah*) according to the hierarchy of space and the orienting mandala, indicated by the different shades of grey.

A ... family temple; B,C, E, F ... pavilions; D ... shrine; I ... entrance
G ... granary; H ... kitchen

The layout of a typical house compound is shown in fig. 5, where the pavilions are arranged according to the hierarchy of space and the orientating mandala, see [1], [3]. For example, the family temple is always situated in the *utama*-most area of the house compound, usually closest to Mt. Agung or a clearly visible other mountain. The other pavilions within the *rumah* have to be placed in an area with the appropriate quality aspect according to their respective function.

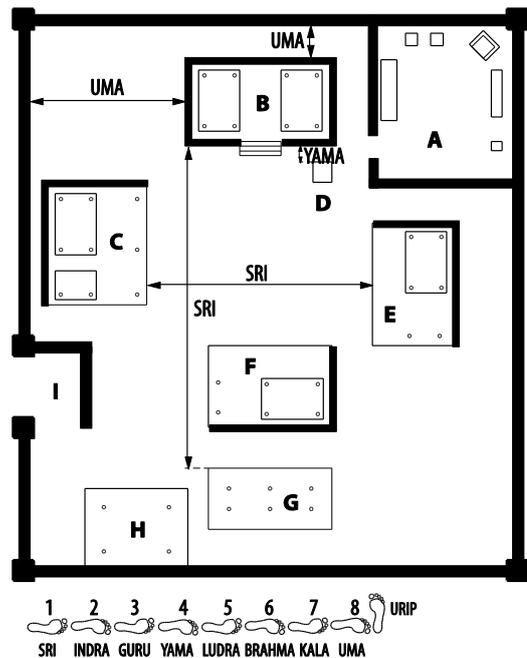


Fig. 6. Distance measurements within a house compound

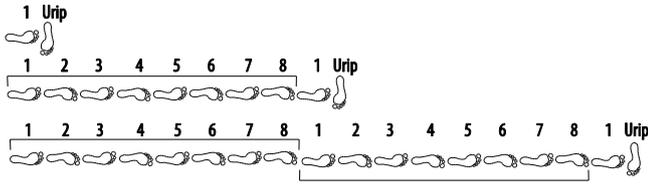


Fig. 7. Example of possible distances for a rice barn

III. MEASUREMENTS OF A RUMAH

After the area for a pavilion has been determined (fig. 5) its exact distances have to be calculated (fig. 6). For the distance rules which are applied in a Balinese *rumah*, the following principles [4] are considered: There are eight deities who play a major role in a distance calculation. Each deity is associated with certain attributes which are, among others, name, number, cardinal direction, and sphere of life. The associated number is used for distance calculations (Table I).

Besides the deities, the body parts of the owner are of additional importance for the calculation of measurements. In case of distances between pavilions within a house compound the dimensions of the owner's foot are used. The main parameters for a distance calculation are called *tampak*, the length of the owner's foot, and *tampak ngandang*, the owner's foot width.

In order to "add life" to a building, a "little something" called *urip* is added to all measurements. In case of distance measurements, *tampak ngandang*, the owner's foot width, is used as *urip*. Within a house compound two measurement systems [16] are used: the *sikut natar* (7-step) for distances between general pavilions, the *sikut wawangunan* (8-step) for distances to specialized buildings (granary, shrines, kitchen, etc.) So, for a distance within a house compound, the general formula would be either

$$\text{distance}_7 = (\text{deity} + 7 * n) * \text{tampak} + \text{urip} \quad (1)$$

$$\text{or} \quad \text{distance}_8 = (\text{deity} + 8 * n) * \text{tampak} + \text{urip} \quad (2)$$

where n is a natural number including 0. This yields a minimal distance of 1 foot length + 1 foot width. Notably, distances are based on multiples of 7 or 8, whereby the deity determines the "quality" of the distance. In some sense, the deity corresponds to the residue class modulo 7 or 8 of the distance (minus the *urip*). Of course, a "mathematical" deity with value 0 is rather represented with the deity associated with the number 8 (or 7) for semantic and practical reasons.

For example, the rice barn inside the house compound is calculated according to the *sikut wawangunan* system and associated with Sri, the goddess for rice and fertility. This determines the possible distances (cf. fig. 7) for placing a rice

3. Dapur, dari bale gede sejauh 6 tampak + 1 tampak ngandang ke barat didirikan dapur.
4. Lumbung, jarak 17 tampak + 1 tampak ngandang ke utara/timur dari dapur.

Fig. 8. *Lontar* excerpt (Indonesian) - distance measurements, from [1]

```
KITCHEN, RICE BARN
kitchen, from bale gede as far as 6 tampak + 1
tampak ngandang westwards
distance_gede_dapur = 0*8 + brahma + urip

barn, distance 17 tampak + 1 tampak ngandang to
north / east from kitchen
distance_dapur_lumbung = 2*8 + sri + urip
```

Fig. 9. Defining basic measurements in the CityEngine, partial excerpt

barn in relation to the pavilion *uma meten*. More details regarding the distance rules used in this work can be found in [4], [19].

IV. FORMALIZATION

In order to devise an appropriate shape grammar of Balinese vernacular buildings (and to be able to implement it) it is necessary to formalize the knowledge inscribed in the *lontar*. This requires a translation of the relevant contents into Indonesian and/or English, and a subsequent transformation into grammar rules.

For the housing compound, the creation of an appropriate floor plan is essential. It requires the application of the distance rules, as laid out in section 2, and a formalization thereof. The pavilion types *dapur* and *lumbung* serve as examples of the formalization. Fig. 8 shows an excerpt of the *Asta Kosala-Kosali* [1], where distance specifications for a house compound are given (in Indonesian). Before transforming the distance specifications into rules, the Indonesian texts were translated into English. Fig. 9 shows a partial listing (from the implementation in the CityEngine), where a literal translation from Indonesian into English can be seen.

After the distances for the individual pavilions have been determined, they need to be constructed. Fig. 10 depicts the

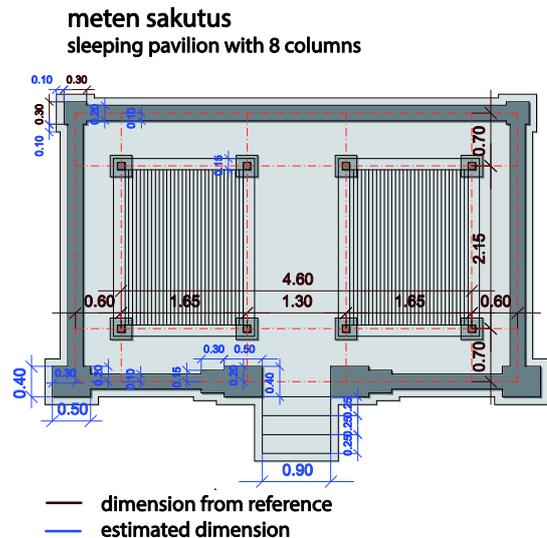


Fig. 10. Detailed floor plan for sleeping pavilion *saktus*. Red lines indicate distances that are documented in the available literature [3], while blue lines indicate distance that have been either derived from secondary information, or estimated.

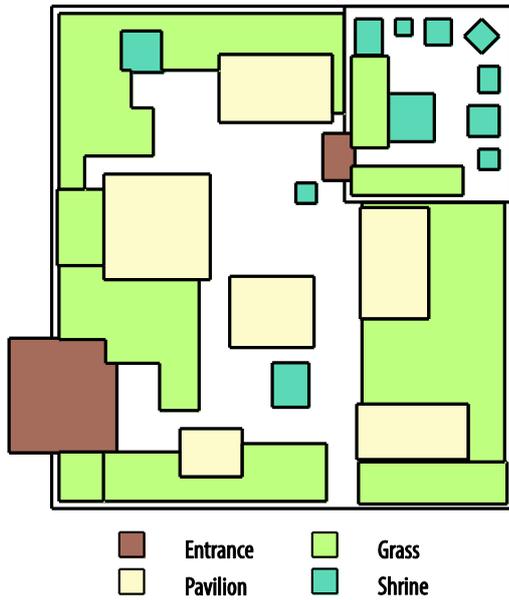


Fig. 11. Floor plan of a house compound in the CityEngine

floor plan of a pavilion of type *uma meten/meten sakutus*, where red lines indicate dimension from reference [3] and blue lines indicate estimates. This information is also transformed into shape grammar rules, along with the specification of the other types of pavilions of a house compound.

V. SHAPE GRAMMAR IMPLEMENTATION

Shape grammars in architectural theory have existed a while before their implementation on computers. Their main application in architecture was related to the generation of floor plans, as this was the case with Palladio's work [17], [20], [21] or with the work of Frank Lloyd Wright [22]. Some efforts have been made to generate facades using shape grammars such as [23], [24]. Also ornament design was a subject of design with grammar rules, for example the Islamic ornamental patterns as described in [25], [26]. Examples of design grammars for structural composition and traditional building

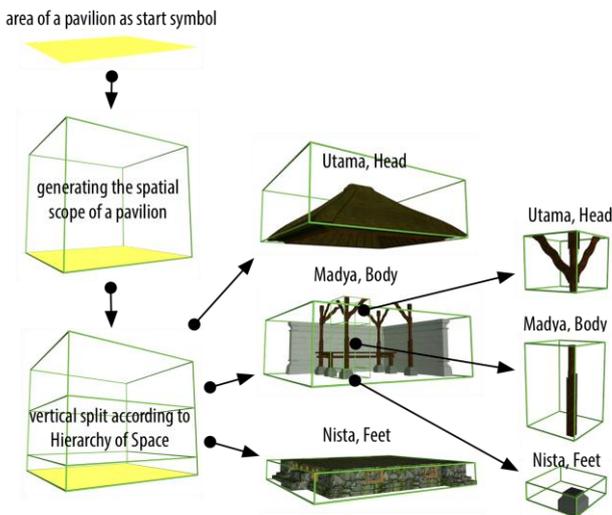


Fig. 12. Spatial scope and vertical splitting rules

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

Fig. 13. Grammar rule for column (CityEngine)

techniques can be studied in detail in [27]. In [28] a good overview of the use of shape grammars in architecture is provided.

Shape grammars are a production system that generates 2D or 3D shapes out of an initial shape (start symbol), and consists of rules and a generation process. A rule defines how an existing shape (or part thereof) is transformed into another. The generation process is responsible for activating the proper rules that eventually produce the desired shape(s). In general, the use of shape grammars allows for the compact specification of complex geometrical designs by means of a set of rules. An excellent introduction into shape grammars in general with a particular focus on their use in architecture can be found in [29].

The CityEngine [18], [30] provides a state-of-the-art implementation of procedural modeling, using a shape grammar called CGA. 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." [16]. With the aid of tools like the CityEngine urban structures of a specific contemporary or historical style can be defined and generated very efficiently. In [6], [7] its use for historical reconstructions is demonstrated. The parametric rule set "allows for the testing of several hypotheses by adjusting some of the parameters. This results in a powerful platform for archaeological discussion and exploration." [16]

In this paper we take a closer look at a single housing compound, a *rumah*, and the grammar rule set for constructing a typical *rumah*. The generation of a house compound takes the associated lot as a start symbol for the respective rule set. It starts with the creation of a suitable floor plan according to the orientation scheme (cf. fig. 3 and 5) and the distance rules (cf. fig. 6 to 9). With this, the traditional building principles in general, and the requirements for a house compound in particular (as laid out in section 2) are incorporated. The respective rules determine a floor plan which is shown in fig. 11. The colored areas are used as start symbols for the rule sets in the CityEngine that generate the appropriate pavilions (yellow), shrines (blue), entrances (brown), types of ground (green, white) and walls.

The rule set for erecting a pavilion takes the determined area as a start shape (e.g. yellow rectangle, as shown in fig. 11). As a next step in the shape grammar, this rectangle is extruded by the final height of the pavilion, thereby defining the spatial scope of the building. Fig. 12 depicts this scope as an orientated bounding box, which will be vertically split by subsequent rules according to the concept of hierarchy of space.

In order to increase the power of shape grammars, parameters have been introduced for the rules as means to take into account some context of their application. As an example for the use of parameters in our shape grammar, the

construction of a single column is demonstrated. The corresponding grammar rule is depicted in textual form in fig. 13 (excerpt from the CityEngine).



BrickROOF	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
HighLOD	<input type="checkbox"/>	true (AttributeSetup)	Off	<input type="checkbox"/>	On
attr_axis_depth	<input type="checkbox"/>	2.15 (Rule)	<input type="range" value="2.15"/>		
attr_axis_width	<input type="checkbox"/>	1.65 (Rule)	<input type="range" value="1.65"/>		
col_nrDepth	<input type="checkbox"/>	2 (AttributeSetup 1)	<input type="range" value="2"/>		
col_nrWidth	<input type="checkbox"/>	2 (AttributeSetup 1)	<input type="range" value="2"/>		
highStylobate	<input type="checkbox"/>	true (Rule)	Off	<input type="checkbox"/>	On
narrowStylobate	<input type="checkbox"/>	false (Rule)	Off	<input type="checkbox"/>	On
scaleFact	<input type="checkbox"/>	1 (Rule)	<input type="range" value="1"/>		
sl_platf_1	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
sl_platf_1_half	<input type="checkbox"/>	true (Rule)	Off	<input type="checkbox"/>	On
sl_platf_2	<input type="checkbox"/>	true (AttributeSetup)	Off	<input type="checkbox"/>	On
wall_back	<input type="checkbox"/>	true (AttributeSetup)	Off	<input type="checkbox"/>	On
wall_front	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On
withStylobate	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On

Fig. 14a. closed pavilion with thatched roof (left) and corresponding parameter settings (right)



→ BrickROOF	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On
HighLOD	<input type="checkbox"/>	true (AttributeSetup)	Off	<input type="checkbox"/>	On
attr_axis_depth	<input type="checkbox"/>	2.15 (Rule)	<input type="range" value="2.15"/>		
attr_axis_width	<input type="checkbox"/>	1.65 (Rule)	<input type="range" value="1.65"/>		
col_nrDepth	<input type="checkbox"/>	2	<input type="range" value="2"/>		
col_nrWidth	<input type="checkbox"/>	2	<input type="range" value="2"/>		
→ highStylobate	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ narrowStylobate	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On
scaleFact	<input type="checkbox"/>	1 (Rule)	<input type="range" value="1"/>		
→ sl_platf_1	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On
→ sl_platf_1_half	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ sl_platf_2	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ wall_back	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ wall_front	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
withStylobate	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On

Fig. 14b. open pavilion with tiled roof and platform (left) and corresponding parameter settings (right). Red arrows indicate changes in parameters as compared to fig. 14a.



→ BrickROOF	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On
HighLOD	<input type="checkbox"/>	true (AttributeSetup)	Off	<input type="checkbox"/>	On
attr_axis_depth	<input type="checkbox"/>	2.15 (Rule)	<input type="range" value="2.15"/>		
attr_axis_width	<input type="checkbox"/>	1.65 (Rule)	<input type="range" value="1.65"/>		
col_nrDepth	<input type="checkbox"/>	2	<input type="range" value="2"/>		
→ col_nrWidth	<input type="checkbox"/>	4	<input type="range" value="4"/>		
highStylobate	<input type="checkbox"/>	true (Rule)	Off	<input type="checkbox"/>	On
narrowStylobate	<input type="checkbox"/>	false (Rule)	Off	<input type="checkbox"/>	On
scaleFact	<input type="checkbox"/>	1 (Rule)	<input type="range" value="1"/>		
sl_platf_1	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ sl_platf_1_half	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ sl_platf_2	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ wall_back	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
→ wall_front	<input type="checkbox"/>	false	Off	<input type="checkbox"/>	On
withStylobate	<input type="checkbox"/>	true	Off	<input type="checkbox"/>	On

Fig. 14c. open pavilion with tiled roof and 8 columns (left) and corresponding parameter settings (right). Red arrows indicate changes in parameters as compared to fig. 14a.

According to the underlying philosophy and building principles, also columns basically consist of three parts: a base, a shaft, and a capital. The respective rule `split(y){...}` splits a column into these three parts.

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 vertical axis (y). The following part in parentheses `{...}` defines the exact parameters for the split, in this case a proportion of base : shaft : capital. The height of the base and capital depend on their generated 3D models. 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. These rules are hierarchical, and use further rules to eventually build the respective parts. Rules are terminated by 3D shapes that are inserted into the appropriate scope (fig. 12).

VI. RESULTS AND DISCUSSION

To exemplify this variability of parametric shape grammars some variation of possible pavilions together with the parameter settings are depicted in fig. 14a-c. As a final result, the whole house compound (*rumah*) is assembled in the virtual environment which is shown in fig. 15. The strength of this approach lies in its parameterization of possible *rumah* according to the traditional Balinese building principles.

Aside from reconstructing a single building exactly, one of the great advantages of procedural modeling lies in the ease of

generating a vast number of similar buildings, thereby producing “hypothetical” *rumah* in the same historical tradition according to their building principles.

Using shape grammars in architectural heritage not only enables 3D heritage reconstruction, but also facilitates a formalization of traditional construction principles. Although shape grammars are context-free, an expansion with parameters provides means to take contextual information into account. The main disadvantage of shape grammars is the necessary effort to acquire knowledge and skills to generate a parametric set of rules. The invested time pays off by the flexibility, variability and speed of generating buildings. In the current implementation the defined CGA grammar is difficult to communicate to non-experts in shape grammars. So it might be necessary to create visualizations for intermediate steps in the shape grammar sequence beyond the usual graph representation. The visualization should rather focus on the construction domain. Concerning the parameterization it would be helpful to visualize the relationship between the building parts and the human body as well as the Hindu deities.

Our approach is not intended for a complete automation of design generation. It rather provides a flexible frame work supporting design decisions. Human feedback and interaction as part of the design process are incorporated, but should be extended.

As our knowledge of the building traditions is not sufficiently complete, some dimensions have been estimated without using a parameterized formula. Therefore a flexible environment is necessary that supports exploration and testing of hypotheses and useful estimates as well as a feasible



Fig. 15. Typical house compound, generated with the CityEngine

adaptation of rules in a rapid prototyping manner. For our first approach the CityEngine fulfilled these requirements. However, it might be advisable to test other tools as well.

A new aspect of our approach within procedural modeling lies in preserving the design intention as well as the appearance, thus including both, tangible and intangible aspects of architectural heritage. Balinese traditional architecture has a rich base of intangible aspects. These are reflected in the orientation and dimensioning of buildings, for example.

Future work will be addressed to extend the rule set with additional parameters and further detail based on an extensive comparison of design variations with additional examples of traditional Balinese settlements that go beyond our single field trip. This includes the consultation of an *undagi* (traditional architect/builder/priest) to verify our approach against contemporary traditional building practices. Further translations of the *lontar* containing architectural knowledge into Indonesian and English are desirable. It would also be of interest to adapt the grammar to incorporate the traditional building process (sequence of construction). Furthermore, the scalability should be tested with respect to different building types (e.g. temples, public buildings). Many buildings contain a huge variety of ornamental detail and art work which could be 3D scanned to extend the terminal vocabulary of the shape grammar.

The presented shape grammar can also be used for educational purposes in order to demonstrate traditional Balinese architecture both, theoretically and via the exploratory 3D reconstructions. A useful area of application of this approach would be in the adaptation of building traditions for contemporary needs (e.g. tourism). Furthermore, it could facilitate a wider comprehension and appreciation within the research community as well as the parties involved.

ACKNOWLEDGMENT

We like to thank: the staff at the Gedong Kirtya Lontar Museum in Singaraja, North Bali for their kind support, and our driver on Bali, I Made Sukerta, for showing us around.

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