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DESIGNING WITH DISCRETE GEOMETRY

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Abstract. There has been a shift in aesthetics from the modern orthogonal building envelope to more elaborate curved and folded forms. Non-orthogonal forms are often associated with complete freedom of geometry, entrusting the advancement in custom manufacturing and robotic fabrication of one-off building parts to realise the design. This paper presents a methodology that allows non-orthogonal surfaces to be designed using a constrained library of discrete, tessellating parts. The method enables the designer both to produce 'approximations' of freeform designs in a top-down manner or to generate 'candidate' designs in a bottom-up process. It addresses the challenge in the field of design engineering to generate architectural surfaces which are complex, yet simple and economical to construct. The system relates to the notion that complexity derives from simple parts and simple rules of interaction. Here complexity relates to the holistic understanding of a structure as an interaction between its local parts, global form and visual, as well as functional performance.

Keywords. Geometry system; form generation; form growth; discrete growth model; design tool; complex geometry.

1. Introduction

Non-orthogonal architectural forms not only extend the catalogue of visual variety; they also have the potential to integrate performance qualities such as structural behaviour or environmental (e.g. heat, ventilation and sound) performance, which are inevitably linked to the geometry of a structure.

The current paradigm in the design-making of non-orthogonal form is such that an overall geometric form is conceived first and it is then broken down into buildable local parts (façade cladding, or structural elements) in retrospect. Subsequently, there is a division between the creation of the design and then the reverse engineering of it. Sophisticated procedures are in place and continue to be developed to tackle this deductive task. The need for intelligent use of technology has led to a new type of service in the building industry, which concentrates on the computational detailing of non-orthogonal building hulls such as Designtoproduction (2013), Evolute (2013) Rechenraum (2013) and Imagine Computation (2013). The effort usually requires, not just the breaking up of structure into smaller parts, but also that aspects of fabrication and construction be considered to reduce cost. Even though these tools are being rapidly adopted there is still a substantial amount of time, and subsequently cost, being spent on reverse engineering designs. The two main cost factors in elaborate building design remain long design cycles and the manufacture of custom one-off building parts.

This paper presents an alternative approach, whereby non-orthogonal surfaces are designed using a system that employs a constrained library of discrete, tessellating parts. The building parts are chosen first and the global structure derive from them. The discrete geometry description allows for fast and thereby cost efficient design development cycles (design, analysis, detailing), superseding the post-processing of designs. It allows for the control of repetition of building parts used to create the designs.

This paper is organised into five parts. First the two different approaches in the design-making of non-orthogonal form are briefly reviewed. In the second part one example is given where designs have been created using a discrete geometry set and then goes on to the third part in which the objectives that guided the development of the here presented geometry system are listed. In the fourth part the computational design method is presented. Finally, conclusions are drawn and aspects highlighted aiming at encouraging the discussion on the potential use of discrete geometry to design non-orthogonal surfaces.

2. Reverse-engineering versus generation of form

In the engineering of non-orthogonal form, a distinction is made between post-rationalisation and pre-rationalisation. (Hudson 2010) describes the two different approaches to rationalisation in the following way: “Post-rationalisation is a top down-approach where the final geometry is defined and the parametric design task is to find rational geometry that gives a very close match. Pre-rationalisation is a bottom-up or generative method where the parts are defined and building geometry is a result of combining these”. Reverse-engineering architectural surfaces in a post-rationalised manner is one way to make use of computational resources. This is a centralised approach, where the design is understood to be finalised when the global form is described. Smart processes have been developed, and continue to be, to tackle the challenge of discretising elaborate form in retrospect (Shepherd; Richens 2012). Perhaps it is thanks to the designs which were conceived without considering how they would be realised, that the vast progress in such smart technological methods and manufacturing techniques was made.

However, this approach splits the process of design into two separate tasks, the conception of form and the engineering of form, which should be brought closer together rather than pushed further apart.

The work presented here points towards an opportunity for an alternative way to make use of computational resources and to thereby overcome recurring problems in reverse engineering. This is by setting up and deploying decentralised design processes with a discrete element growth model. Such processes allow for the integration of explicit considerations regarding design realisation during the conception. A generative system that employs clearly described geometry enables the controlled exploration of the catalogue that is possible within its geometric framework.

3. Designing with constrained geometry sets

A classic example for the use of discrete and constrained geometry sets is Eladio Dieste, an Uruguayan engineer and architect (1917–2000). He gained recognition for his elegant masonry shells, which he built from locally manufactured brick, using only a small number of different brick shapes (Figure 1). The forms of the global shells, mostly Gaussian vaults, are what resist structural forces. Dieste created a technique to pre-stress masonry, which allowed him to construct shells with a single layer of bricks. He also invented a particular movable formwork to support the construction (Pedreschi 2000). Limiting his work to a single material product with a small number of local shape variables, Dieste established extensive knowledge of the handling of the material and explored the catalogue of possible structures, which derived from the association between the local component and the performance-driven global geometries. He established an associative material system consisting of the local bricks, their material and shape, and the assembly of these to form larger structural shells, which allowed him to create a large catalogue of integrated designs.

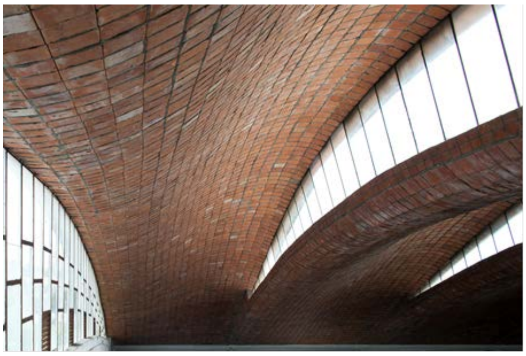

Figure 1. Citrícola Salteña, Salto, Uruguay. Pre-stressed brick shell by Eladio Dieste. Photograph © Nathan Willock.

4. Objectives for the development of a geometry system

Once the potential of generative design processes that use discrete geometry sets has been recognised, the question remains of how to actually create them. In particular the definition of a novel growth model calls for some kind of innovation, which in turn would explain why there are few existing examples. The term ‘growth model’ refers to the digital representation of components and rules for how these components can connect to each other. The growth model is part of a generative process to create and assemble local geometries to form larger structures.

The objectives for the project presented here were as follows:

- The growth model should allow the creation of articulated global surface geometries, meaning that they could be doubly curved and folded.
- The elements of the growth model should represent buildable components. The considerations were the fabrication of the parts, the

necessary material offset and the connections, i.e. the angle to neighbouring components.

- The number of differently shaped elements and connections should be controllable (parametric), so that the number of components could be adjusted, depending on the economic constraints and the design preferences.
- The same set of element shapes should create a wide range of different global configurations. The elements did not have to be planar.

5. The computational method

The growth model is integrated into a wider design methodology, which is implemented as computational tool. The user of the tool can approximate given surfaces or generate new surfaces with a constrained number of tessellating parts. With the same kit of parts, different global geometries can be defined (Figure 2).

The tool can be used to design or to rationalise surface structures, i.e. envelopes, roofs, facades and partitions, or to create the substructures for any of these types of surfaces. The system considers two representations, surfaces and frames, which could represent cladding panels or their supporting structure respectively. The number of surface elements and the number of node types are displayed to the user whilst the system is running.

The method relates to the notion that complexity derives from simple parts and simple rules of interaction. Here complexity relates to the holistic understanding of a structure as an interaction between its local parts, global form and visual as well as functional performance.

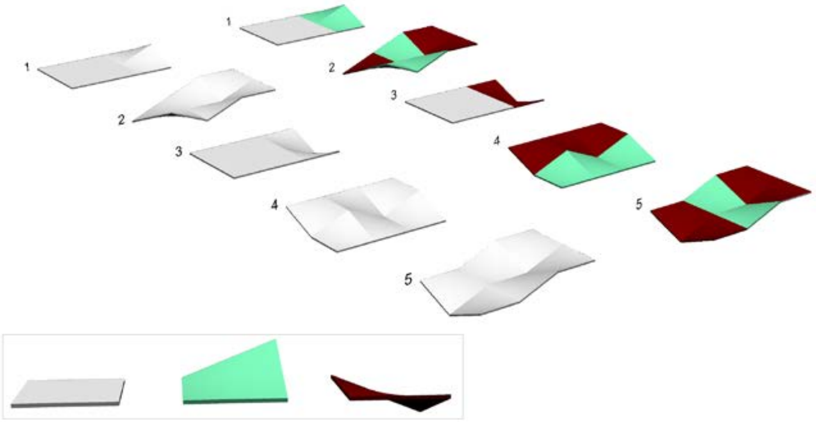

Figure 2. Five surface assemblies (above) using the same set of three element types (below).

5.1. SYSTEM STRUCTURE

The computational method is structured into three parts. The first part is the so called element factory. It is a process that generates kits of elements under user specified parameters. The second and the third parts are the two different modes of applying the specified kits of parts; either to approximate given surfaces or to generate new ones (Figure 3).

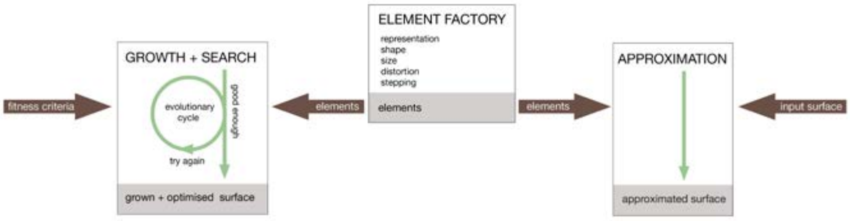

Figure 3. Structure of the computational method.

5.2. APPROXIMATION AND GROWTH

The first approach is a top-down method which approximates a given surface. The user inputs a surface and selects a tessellation type that specifies a tiling pattern, size and ‘distortion’ measure that determines the degree of curvature in the individual element. Figure 4 shows an approximation of the original model of the British museum roof (Williams 2001) (left), replacing the diagrid with a regular triangulation (middle and right). The model in the centre is a coarser approximation than the one displayed on the right. The colour coding indicates element of a similar shape, i.e. the closer the match to the input surface has to be the greater the number of element types needed to describe the geometry.

The second approach is a bottom-up process where surfaces are ‘grown’ using user-specified parameters and fitness criteria. At the beginning of the process a custom kit of parts is generated, which is then employed to create global surfaces that adapt to fitness criteria by using an evolutionary optimisation mechanism, thereby improving the outcome over the course of generations (Figure 5).

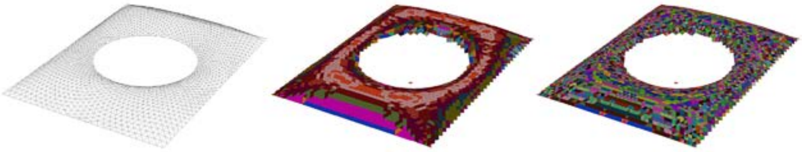

Figure 4. Two approximations (middle and right) of the Great Court Roof model (left).

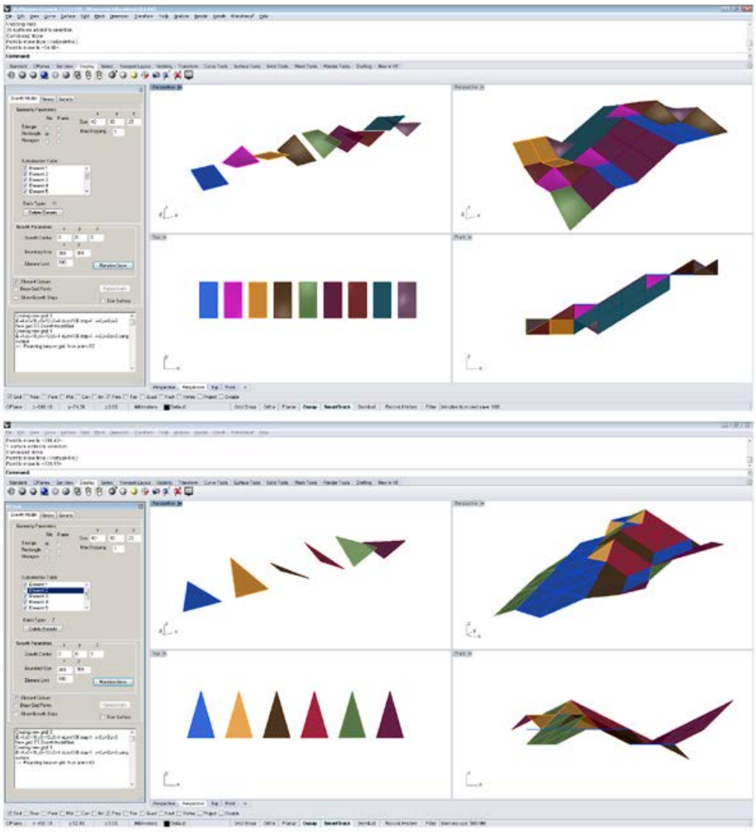

Figure 5. Two screen shots showing the growth process running. In the left column two different families of parts are displayed, one kit of rectangular parts (top-left) and one kit of triangular parts (bottom-left) In the right column examples of corresponding surface configurations are shown.

2.1. THE PLACEHOLDER PRINCIPLE

The elements signify either literal building components or placeholders for them. Specific features have to be maintained while others are free to become the subject of design exploration.

The digital elements can act as placeholders for more elaborate description of the basic geometry types. These elements can be simple or complex, as long as their repetition can be controlled.

During a design workshop at the University Iberoamericana (IBERO) in Mexico City organised by Pablo Kobayashi and the lead author (Codigoabierto, 2012), an investigation was carried out as to whether diversity was possible despite the constraint of the geometry system, or whether the outcome would become locked-in to a particular 'look'. The design studies, which were developed during the course, proved that the control did not limit the diversity (Figure 6). There is extensive scope for design exploration within the constraints of the geometric framework of the growth model.

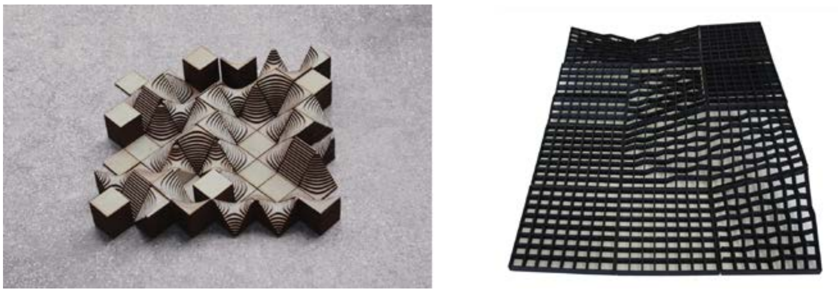

Figure 6. Two example outcomes from the workshop showing the diversity that can be achieved with the geometry system. The model on the left by Teddy Nanes uses six element types. The model on the right by Fancisco Villalon uses four different element types. Both models can be rearranged to form different configurations.

6. Conclusions

The dominant realm in industry is still that computational capability is mainly used to break geometry down into building parts retrospectively.

In this paper it is demonstrated that new technology can be utilised to design with discrete geometry sets, which are embedded in a generative process. The challenge is the need for both a mechanism for simulating combinatory assembly and a means for selection.

It remains to be seen how inductive design processes using discrete geometry will be adopted in practice. There has been a revival of modular designs, and projects such as the Queen Alia airport in Amman by Foster + Partners (Whitehead 2013), have been positively received. Popular existing analogue design systems, such as Eladio Dieste’s reinforced brickwork system (constrained product) or Antonio Gaudi’s constrained geometry (constrained modelling), form a good basis for the study and development of computational processes with a discrete representation of geometry. What these examples have in common is a wide catalogue of possible solutions. However, an underlying fear might still be that designs could be too easily recognised as outcomes from a particular tool. It requires courage to recognise that the desired visual complexity does not need, and possibly does not derive from, complicated models. It is also evident that present modular designs are often reconfigurations of the same parts and do not make use of the potential that computational geometry systems could offer.

The system presented here overcomes the challenge of producing predefined discrete parts with explicit connection and joint conditions that can tessellate in three dimensions. It addresses the two main cost factors in the engineering of non-orthogonal designs; namely long design cycles and the manufacture of custom building parts. The discrete geometry description allows for fast and thereby cost efficient design development cycles (design, analysis, detailing), superseding the post-processing of designs. The control of building element types is particularly interesting for materials where prefabrication, formwork and construction sequencing play an important role. Through the reuse of formwork, sustainable and inexpensive designs can be attained. The system allows for the customisation of designs, while maintaining the benefits of a regular prefabrication product, so that their cost and performance can be improved over time.

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