From generic to specific; prototyping a computational growth model

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INTRODUCTION

KIEPU is a design methodology that allows complex doubly-curved surfaces to be designed using a constrained library of buildable, tessellating parts. It enables the designer both to produce ‘approximations’ of freeform designs in a top-down manner or to generate ‘candidate’ designs from libraries of buildable parts in a bottom-up process.
The method addresses the challenge in the field of design engineering to generate architectural surfaces which are complex and aesthetically pleasing, yet simple and economical to construct.
The main focus of the system is the control of the number of different element types and their discrete yet generic representation. Surfaces and curves signify placeholders for physical building components and the use of discrete geometry promotes fast design iterations and simple detailing.
The authors are applying the system to a specific material product through a case study, a large scale concrete roof in the hillside on the outskirts of Mexico City. The material to be employed is a variation of regular BubbleDeck (Harding 2004, pp.15-16), concrete with predefined spherical voids, a system with high load-bearing capabilities which is commonly used for flat slab structures. The two considerations for this project are to apply the generic representation to the material, concrete, and the manufacturer’s scheme of prefabrication.
The process aims to demonstrate a construction system that is extendable and applicable to a wide range of projects, by applying a complex computational system to the real world.
This paper presents the computational method and documents the first steps in which a conceptual idea is verified through real world prototyping.

The development of the design process was motivated by the idea that complexity can derive from simple parts and simple rules of how these parts interact. The underlying concepts are emergence (DeLanda 2011, p.3) and artificial evolution applied to design (Steadman 2008, p. 172).
The discrete geometry description allows for fast design development cycles (design, analysis, detailing) superseding post-processing of designs. The control of building element types is particularly interesting for materials where prefabrication, formwork and construction sequencing plays an important role. Through reuse of formwork, sustainable designs can be attained. The system allows the customisation of designs while maintaining the benefits of a regular prefabrication product.
The method offers an alternative approach to ‘planarization’ or ‘same-length members’ in the post rationalisation of complex designs through repetition; allowing for a control of number of element types (surfaces, connections, nodes).

This paper is organised into four parts. Firstly the digital method is explained, its functionalities and potential application areas. In the second part a workshop is described which served as proof of concept for the method. In the third part, the case study, the prospective roof structure is described, and then goes on to discuss the integration of the digital method with the specifics of the material, its manufacture and construction in reference to the design brief. Finally, conclusions are drawn on the experiences made and an outline is given on the direction of future work.

THE COMPUTATIONAL METHOD

The underlying principle of the computational method is a parametric kit of parts, a growth model, from which architectural surfaces can be generated. The term ‘growth model’ refers to the digital generative process of creating and assembling local geometries to form larger structures. Important for constructional efficiency is the control of the number of element types and repetition in componential surface designs. Many units drawn from the same small set of element types can form very different global surface geometries akin to the principle of LEGO (Kristiansen 1999). There are two approaches to using the principle, each currently implemented as a separate plug-in.

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 which determines the degree of curvature in the individual element. 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 units is generated, which is then employed to create global surfaces that adapt to fitness criteria applying an evolutionary optimisation mechanism; improving the outcome over the course of generations.

Approximation

The first approach is a top-down approach implemented as a C# Grasshopper component for Rhino. The left column in Figure 1 shows the same freeform input surface as the right column. The difference between both examples is that the surface on the left side is approximated with a smaller 'distortion' value and bigger hexagonal elements than the one on the right. The colours within each figure indicate which elements are the same. A closer fit to the reference surface results in more element types needed to describe the surface while a description with less element types produces a more abstract interpretation of the input geometry. Figure 2 shows a familiar dome shape as an input surface, which is approximated using the same hexagonal pattern as the examples in Figure 1 and two different 'distortion' value settings. Figure 3 displays the Great Court Roof of the British Museum in London (left), which was designed by Foster + Partners and engineered by Buro Happold. In the middle and right, two approximations of this model are displayed using the methods outlined in this paper. Both have the same triangular pattern, but different distortion values and thereby different numbers of triangle types. The example shown in the middle of uses 31 element types to describe the reference surface and the example on the right uses 222 different types but gives a closer approximation to the reference surface.

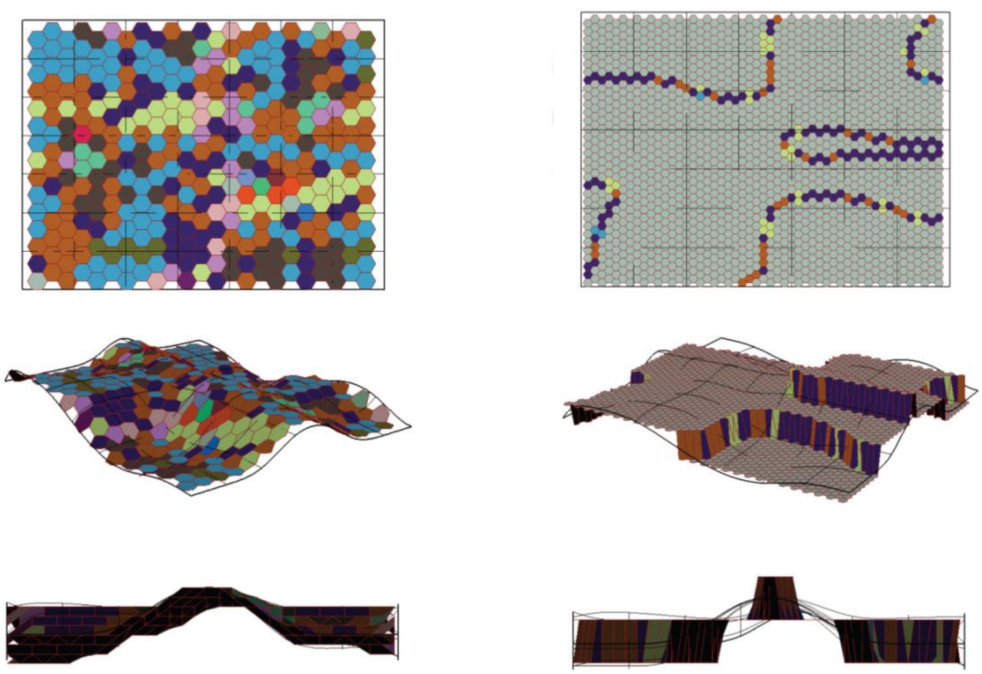

Figure 1: Two approximations of the same freeform surface.

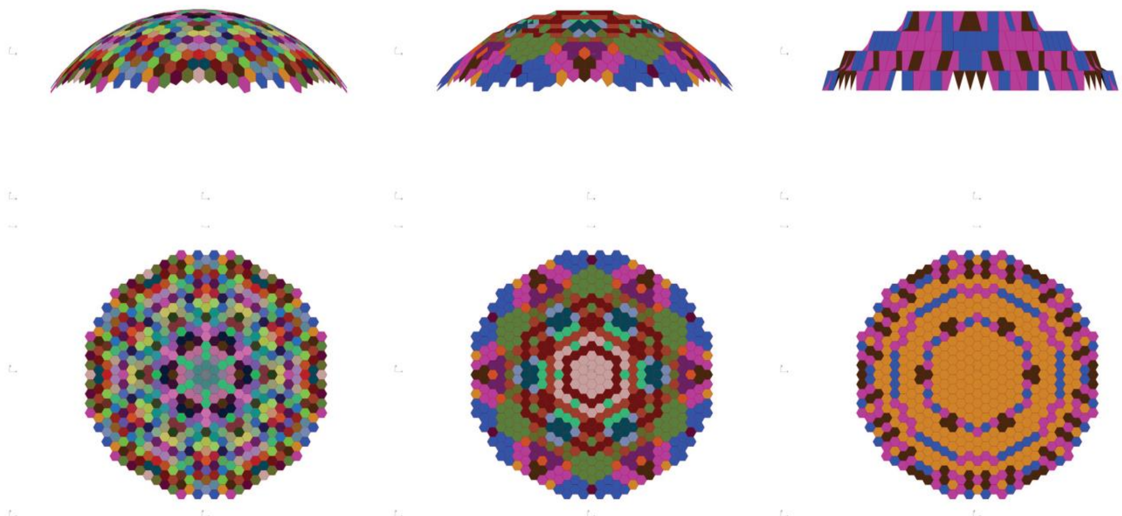

Figure 2: Three approximations of the same dome shape.

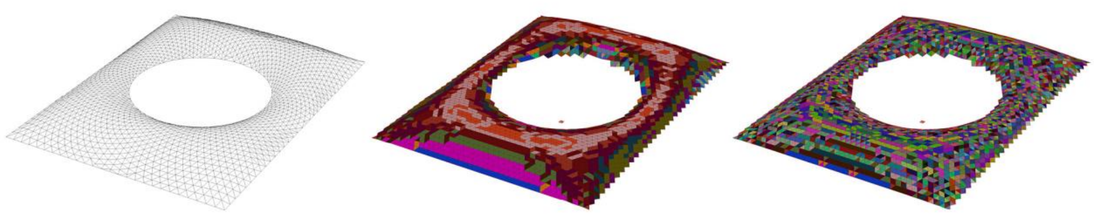

Figure 3: Two approximations (middle and right) of the Great Court Roof model (left).

Surface Growth

The second approach is implemented as a C# plug-in to Rhino. It combines a generative geometry system with a genetic algorithm. The user specifies growth parameters and fitness criteria and surfaces evolve under these settings. Figure 4 and Figure 5 show two example scenarios. On the left side in both figures the family of parts is displayed which are used to generate the example surface shown on the right side.

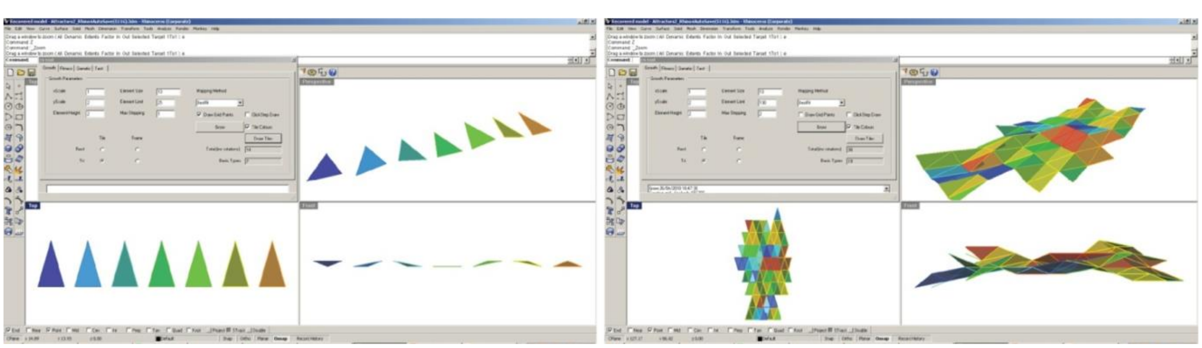

Figure 4: Screen shot of the Surface Growth plug-in showing a family of triangular parts (left) and an example surface (right).

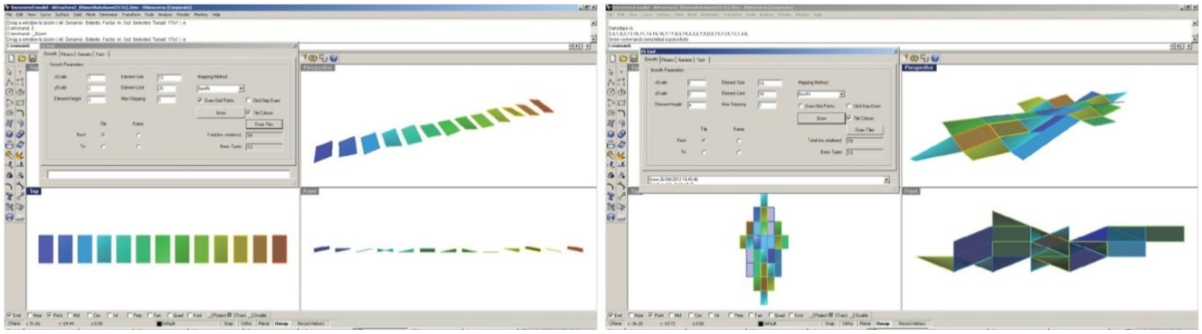

Figure 5: Screen shot of the Surface Growth plug-in showing a family of rectangular parts (left) and an example surface (right).

PROOF OF CONCEPT

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 while the system is running. The surfaces and curves signify either literal building components or placeholders for those. Specific features have to be maintained while others are free to become the subject of design exploration.
There were two important questions in relation to using the KIEPU methodology in design practice. The first question was whether a variety of designs could be created using this method or whether the geometry system, which forms the basis for both tools, was too constrained and the outcome thereby locked into a particular 'look'. The second question was on the level of the two clearly distinct approaches to using this geometrical principle; the surface growth and the approximation. The question was whether one approach was more suitable to design than the other.

Workshop

A workshop was held at the University Iberoamericana (IBERO) in Mexico City for Proof of Concept of KIEPU. It provided first hand user feedback; on the user friendliness of the software tools i.e. the interface and provision of input and output parameters and most importantly, the course delivered valuable clues to the usability of the technology in design practice. Participants were introduced to the use of computational design tools, both conceptually and practically by using KIEPU to develop detailed design systems.
The workshop was open to students of architecture at IBERO and external applicants from both education and practice. Eleven participants took part in the workshop, ranging from second year undergraduates studies to the final year of Diploma school and practitioners. They were supervised by four tutors (Figure 6). The workshop was structured into two modules. The first module covered the introduction to the design processes and the development of a design using the presented methods. The second module concentrated on the extrapolation of the design into a material system.
The first module, which this paper focuses on, was divided into two phases. In the first phase (first week) both tools and the underlying concepts where introduced and the participants had a couple of days in turn to experiment with each tool. In the second phase (second week) participants decided to use one or both tools to develop a detailed design system that considered the idea of modularity vital to both methods. During the second module participants were asked to advance their design by planning and prototyping a real scale system.

Figure 6: Workshop participant using the system.

Participants were encouraged to challenge the constraints of the growth model. While at the beginning mixed and more elaborate tessellation patterns were used, in the on-going of the workshop the tendency moved towards using simple shapes such as squares and triangles with the aim to reducing the number of types. Participants used the two representations, surface and frame, in equal shares to create their designs. Figure 7 shows four models produced during workshop. Each example can be reconfigured to create a different configuration using the same components. Each design displays an individual system. The top row in Figure 7 shows designs using surface elements while the two examples in the bottom row are built from frame elements. Teddy Nanes' model (Figure 7, top, left) consists of five different element types. Their base shape is the square. The digital elements were placeholders for more elaborate description of the five local geometry types. Francisco Javier Regalado Abascal designed a family of four different triangular shapes which he literally translated from the digital into the physical model (Figure 7 top, right). Working with frames Paulo Lemus focused on the construct of the nodes, subdividing each node into two rib sections sliding together to form a node. He also worked on the design of the connection between node elements along their rods (Figure 7 bottom, left). Elias Kalach Hanano worked with a hexagonal pattern and a high 'distortion' value to derive his system. He produced four types of frames elements with which he assembled the presented example configuration (Figure 7 bottom, right).

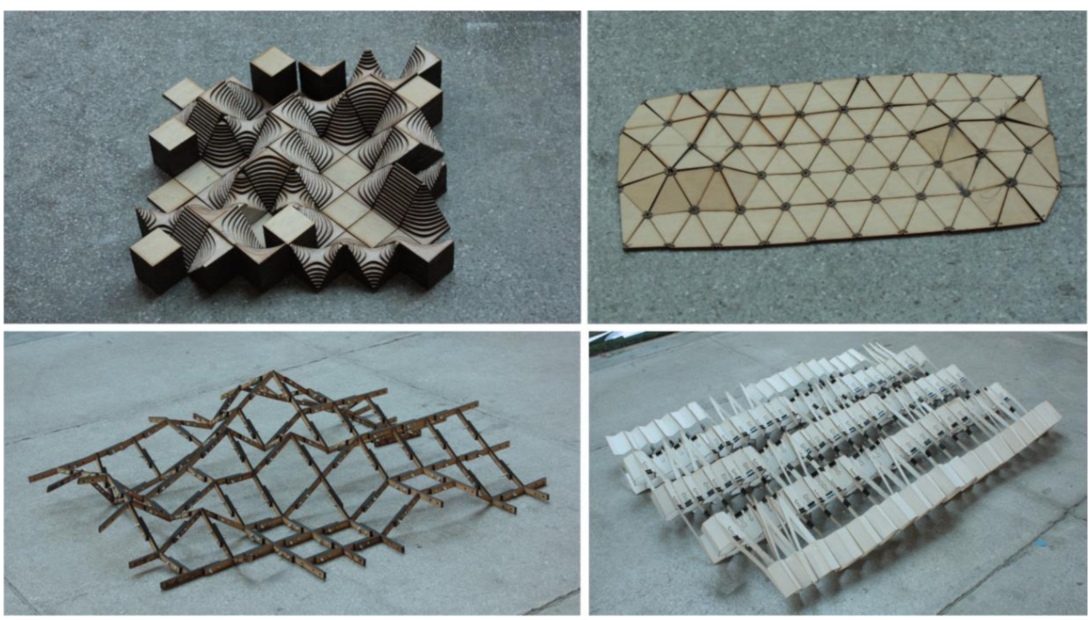

Figure 7: Models by participant from the workshop. The top row shows two designs using surfaces by Teddy Nanes (left) and Francisco Javier Regalado Abascal (right). The bottom row shows two different models using frame elements by Paulo Lemus (left) and Elias Kalach Hanono (right).

Workshop results

The assumption prior to the workshop was that the fast, responsive top-down approach to approximating an input geometry would gain greater popularity than the conceptually far more complex bottom-up process of growth. In the latter the geometry is truly ‘generated’ which means that the user has to set up the whole framework to create a model, defining parameters for the local geometries and generating the kit of part and spatial control points to guide the articulation of the surfaces to be grown, as well as driving the evolutionary operators. The number of interrelated parameters is large and therefore the feedback and control slower; not so much in computational time, but in the sense of design output.
It therefore came as a surprise that both approaches were used equally and that in the final feedback from participants the majority enjoyed generating a kit of parts and initiating their design exploration with this constrained set of building elements. They also liked the ability of viewing the development of surfaces over the course of generation and receiving alternative surface solutions to the same framework set up; both features of the surface growth’s evolutionary technique. Participants said that at first they preferred the easy use of the approximation and the flexibility through the Grasshopper environment but once they understood the different levels of control in the growth method they appreciated that it initiates a different, a decentralised, strategic way of thinking.

One observation was that the approximation technique, which was conceived as an optimization, since it is the reverse-engineering of an input geometry, turned out to be suitable for intuitive experimentation. This is due to the fact that the geometry logic is plugged onto any given input geometry. Hybrids are created as the logic of the geometry system is forced onto the independent geometry logic of the input surface.
On the other hand the less deterministic growth process which was conceived as a conceptually driven design approach, turned out to provide greater control and therefore a more strategic design development.

The results of the workshop in form of design models confirmed that there is extensive design scope despite or possibly because of the constraints the method dictates. Each result is an independent design system.
There is scope for investigating what the implementations are and which parameter bears greater scope for varying the resulting design, the pattern of the tessellation of the componential surface or the complexity of the individual local geometry. The fewer the number of parts involved in the generation process the more recognisable the system-nature of the method becomes.

CASE STUDY AND MATERIAL APPLICATION

Prefabrication industry has been working for more than fifty years under the paradigms of mass-production: repetition of parts and processes towards the reduction of costs. One of the consequences of this principle has been the constant effort to reduce the number of moulds; the more often a mould is used to fabricate the same piece, the more cost-efficient the production of a structure becomes.

Applying the KIEPU methodology to precast concrete was driven by two promising hypotheses: Firstly that an initial family of parts can be used to create different global surface articulations; allowing for repetition over a large number of projects. As the number of moulds can be controlled, the individual element of such a kit of parts can be complex without compromising the overall cost even for a single project application as each element type is repeatedly used to create this one articulation. Secondly the discrete description of the local elements facilitates the manufacture and construction of the pieces.

Roof design

The case study is a large scale roof canopy covering a production line of a precast concrete factory in the hillside on the outskirts of Mexico City. The design brief for the roof is informed by both technical constraints as well as a set of social-community integrating purposes that the roof top surface will serve. A covered area of 8000m² has to be provided, with a maximum span distance of 25m. The covered space will be used for a production line where high-load cranes move precast concrete modules of considerable weight. The top of the roof will be dedicated to a mixture of uses that range from a football field to a display area for mock-ups. The roof surface should be conceived as an artificial topography that at the same time extends and contrasts the surrounding undulating landscape.

The first attempt to design the roof was to analogously model a freeform surface that considered the programmatic requirements and visual intends. The resulting surface served as reference surface to which the approximation approach was applied.
In a second iteration the reference surface derived from a relaxation process, where only a number of support points were defined on a planar mesh that was then relaxed to obtain a minimal surface. This second surface was used to test variations in grid pattern, element size and 'distortion' factor. Figure 8 shows two examples with a different homogenous tessellation pattern.

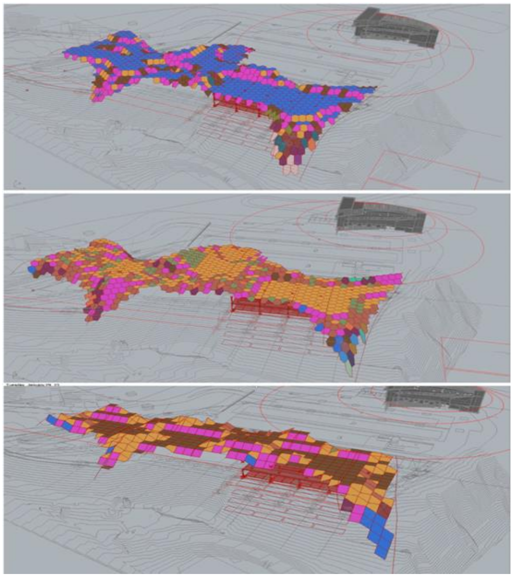

Figure 8: Initial roof studies.

Material specifics

The roof will be built from BubbleDeck. This product combines concrete with predefined spherical voids, to produce lightweight high load-bearing prefabricated elements. BubbleDeck is commonly used for large span flat slab structures. It is usually constructed as set of precast modules where the reinforcement holds a series of spheres to a thin base layer of concrete. These modules are placed on scaffolding structures next to each other. Concrete is then poured onto the pieces to form the closing top layer, creating a monolithic lightweight slab.

The challenge is the adaptation of this material system to produce prefabricated doubly curved elements which transfer axial as well as bending moments and provide improved punch-shear resistance in comparison to regular doubly curved concrete elements.
The characteristics of this material system, in respect to using the KIEPU methodology to design the roof, led to a series of questions regarding the settings of the growth model parameters for designing the tool. Considering the specific programmatic and site constraints as well as the characteristics of the material system one of the question was whether the digital geometries would be translated literally or if they indicated placeholders. Another question was, whether a mix of shapes or a homogenous pattern would be used. These questions formed the basis for both the digital exploration and the first prototypes.

Prototyping

The square shape was taken forward simply as through its symmetry and number of vertices it provided a small family of parts which can yet describe a wide range of global surface articulations. It was decided to focus the production tests to one of the hypar surfaces, choosing an element that kept three neighbouring corners in plane while one corner is raised, and lowered by 2/3 of the side length respectively. This module was chosen because of its complexity; testing whether or not the sandwich construct of the BubbleDeck could be used to produce this hyperbolic paraboloid (hypar) shape.

BubbleDeck system slab modules are commonly precast on flat, high-polished steel tables to ensure a smooth surface finish of the base layer of concrete. To produce doubly curved elements using the BubbleDeck build-up brings the mould production to the centre of attention. The mould for the first prototype of the hypar surface was made from wood boards. A series of vertical slabs formed the ruled profiles of the surface geometry, defining its curvature. The gaps between the slabs were filled with polystyrene foam which was then sanded until a smooth surface finish was obtained. It was coated with a thick layer of epoxy resin that was further sanded and polished until the desired smoothness was achieved (Figure 9). This technique was adapted from previous experience with ruled surfaces that formed 12m high by 7cm thick concrete helixes.

Figure 9: Mould making.

The elements that derive from the KIEPU method do not have a common offset that is normal to the surface geometry but an orthogonal offset. This produces elements with a constant width along each edge but a varying thickness in the surfaces themselves. This characteristic affects the geometry of the reinforcement grid, as well as the size and placement of the spheres (Figure 10). Ruled surfaces allow the reinforcement bars to be straight, defining the bi-layered grid that holds the spherical voids in place. Contrary to the direction of the extrusion of the surface, the position of these spheres and the reinforcement grid is defined by the intersection between the grid vertices and vectors from this intersection with a direction normal to the surface. Because of the curvature of the element the concrete mixture has a tendency to slide towards the lower corners of the module, creating greater thickness in this area. The alloy of the concrete mixture had to be designed to prevent the sliding. It had to remain liquid for long enough to be able to place the rebar grid without pushing it outwards. This proved difficult because of the negative push that the spheres inflicted on the grid. At the same time the mixture had to be thick enough to stay in place. Fibre glass reinforcement was used to avoid cracking and give the 2.5cm surface more resistance for handling.

Figure 10: Making of the BubbleDeck element.

Joints

The joint between the prefabricated elements is currently envisaged as a constant seam. The main function of this seam would be to create continuity of the tension grid through reinforcement bars; creating a monolithic, continuous surface. The number and position of these rebar sections is determined by the angle between the surfaces, the distance to the crossing of two seams (where four module corners touch each other) and the position of the seam relative to its neighbours. This seam would fade once the upper layer of concrete is poured, remaining visible only on the lower face of the surface, where the separation between pieces is still evident. This is an important design consideration, since it creates different results between the top and the bottom face of the surface. Should the sharp, geometrised surface be desired on the top face, then a cap mould would have to be used to control both the top and the bottom edge of each element. This would also allow controlling the flow of the concrete mixture better.

Manoeuvres and logistics

Aside from the cost for the moulds, another important cost factor in precast structures is the logistics and installation manoeuvres. Any rotation of a piece weighing more than one ton represents an increase in risk and machinery use. Therefore the crane accessories need to be well designed. Using the KIEPU method offers the advantage that each generated surface maintains a two dimensional grid in projection independent from the articulation of the overall structure. This means that the elements could be lifted orthogonally into position without any tilting, rotational or lateral movement. The crane accessory would consist of a single square frame with adjustable lifting lines, which hold the element in the correct angle close to its four corners while it is lowered into place.

CONCLUSIONS

Using the KIEPU growth model to design a precast concrete structure offers the construction advantage that each generated surface maintains a two dimensional grid in projection independent from the articulation of the overall structure. This means that the elements could be placed orthogonally into position without any tilting, rotational or lateral movement.

The fact that the computation method promotes repetition is a significant cost advantage when considered for prefabricated concrete material as moulds are reused. The design system allows for the generation of kits of parts which tessellate in three dimensional space; the same kit of parts can form different global configurations.

Focusing on the single form for the prototyping already proved that the construct of precast BubbleDeck can be adapted to produce doubly curved elements and thereby to the growth model of the KIEPU method.
The prototyping of the hypar element described in this paper was closer to a crafting process than an industrial standardised manufacturing procedure. Some steps in the process, like the laying out of the reinforcement grid, can be optimised. However, positioning of the spherical voids for example remains a manual, labour intensive task.
The control of the alloy of the concrete mixture is important unless moulds consisting of two parts will be considered. This would then also allow controlling both the internal and external surface finish and the edges of the elements. The tessellation pattern could then be visible from the outside as well. This however would result in a different construction and joining technique than common for BubbleDeck.
For a serial production the mould would be made from concrete which allows for more complex articulations and surface finishes of the elements.

The workshop proved that a wide range of designs can be created using the computational method described in this paper. The growth model which is at the heart of the method is not so much an optimisation means but a design approach.

Next steps include further design studies both on the global spatial articulation of the roof as well as on the family of local parts from which this global roof will be generate. A number of technical questions such as the mould production, the making of the individual composite elements, the construction of the precast modules and the joining mechanism will run in parallel to the development of the analysis routines to both optimise the structural performance of the individual component locally as well as monitoring the behaviour of the global roof structure.

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