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Constructive design of double curved shells for 3D concrete printing

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Abstract
If we look at the cost intensity of buildings (Lee et al., [2]) and the current demographic and economic developments, the demands for cheap, fast, location-independent, and flexibly adaptable residential and industrial buildings are becoming increasingly clear (Welpe & Grundke, [8]). That brings up the need for some kind of automation, as well as, effective usage of the most popular building material, concrete. The answer can be in prefabrication and optimization. With the development of the technology of concrete 3D printing, the authors' team project aims to explore the design and production of individual segments (modules), followed by the assembly of the entire shell structure without using formwork. This paper deals with the particular problems of development and segmentation of these designs for satisfying the scalability and adaptability as well as other production conditions. The optimization of material usage lays in constructing/ designing the shapes where the principal force directions are distributed in the direction of shell segmentation. The idea of this research is a constructive design of double curved shell structures for modular 3D concrete printing. The parametrization of construction arcs and algorithm of PQ circular mesh generation (Tellier & Baverel, [7]) that connects them, are defining the modular segments, which are analyzed for calculation. Using methods based on the descriptive differential geometry, for generating meshed shells, this research shows how contemporary architectural designs can be integrated into the demands of 3D concrete production.

Keywords: conceptual design, constructive design, computational design, optimization, concrete shells, circular mesh systems.

1. Introduction
The buildings and construction sector are accounted for 39% of energy and process-related carbon dioxide (CO2) emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement and glass. Increases were driven by strong floor area and population expansions. In addition, on site extensive construction works create constant traffic jams, progressing bad impact on the environment. While efficiency improvements continued to be made, they were not adequate to outpace demand growth (Global Alliance for Buildings and Construction, [1]). Global Roadmap recommendations among all include: recycling construction materials, innovative and improved building materials and spreading awareness of the problem in the industry. Parallel to the material improvements it should be possible to build faster, with little waste (mostly provoked by

extensive formwork with concrete building), with more control over the process and more precision. With available technology for production and material improvements, it is possible to think about serial, adaptive, modular, little waste prefabrication of the concrete elements. This process enables more control and networking on the line design – digital model – prefabrication – control as well as shortened work on site with only assembly of the construction. The first step in that process is surely prefabricated oriented design, definition of modules, chosen production technology and material depending on the construction topology. Free form concrete shell structures are one of the most ambitious when it comes to shape, modularization and structural optimization given the freedom of design. Recently conducted researches on the topic are using special flexible formwork for module production (Schipper, et al., [6]) or in the work of Lim et al. [3] where the formwork is not used as the very precise printing process defines double curved modules of the shell structure. Although very advanced, the processes still are not feasible for mass production, as well as the key parts such as storage and transport due to, in the first case, the complexity of the creation of this formwork type, in the second case, the longevity of the printing time and lack of reinforcement. In this paper, authors choose 3D printing technology and robotic textile mesh production without formwork that as a result has assemblable modular free form shell construction. The process consists out of an overview of the technology limitations, demands and conditions in order to design, segment and optimize this type of structure. The goal is to optimize the material usage with structural optimization, design keep the designed shape and establish printable modules, that can be incorporated into flowable mass production without major changes in the process.

2. Production technology and conditions

In this research, the modules should be 3D printed without using formwork and then assembled on site into entire shell construction. There are two types of materials used, depending on the position in the module. The edge part of the module is 3D printed with printable strain-hardening cement-based composite (PSHCC), and the infill part is made of self-compacting concrete (SCC) reinforced with textile mesh. As a stiffer material, PSHCC is extruded from the nozzle, and SCC is poured in a thin layer in the middle (Figure 1).

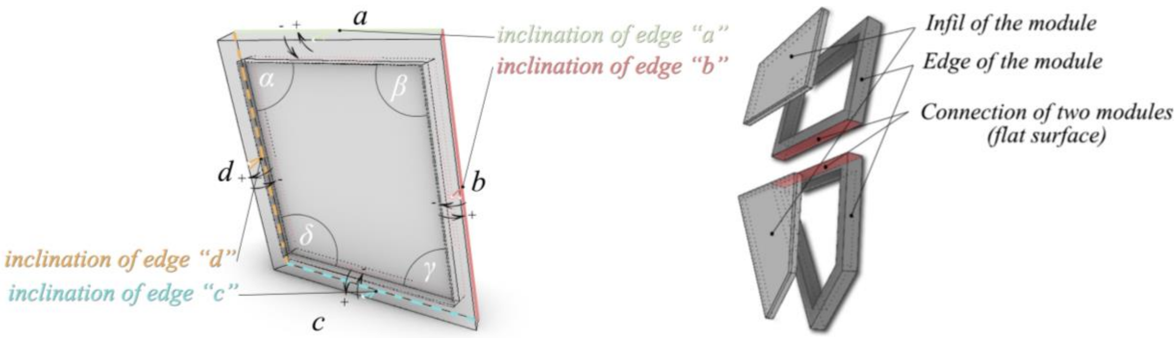

Figure 1: Representation of the module as a unit for 3D concrete printing in free-form shell construction with its distinguished parts

The width of the rectangular nozzle of the 3D printer will determine the cross section of the module edge part and should be coordinated with the chosen scale of the construction and elements. That is why one of the goals for the subdivision is to use the maximum of the edge cross sections, while the thinner (inner) part serves more for the spatial stability and shear force transmission. Based on this, the authors have to design construction that will enable segmentation in the principal stress directions and at the same time fulfil the geometric demands of production. In order to ensure the possibility for flow mass production of the existing technology, without any crucial changes in the technology, the modules have to be adaptable and scalable. Overlooking the edge size, the size scale of the modules, as well as the shape, edge dimensions and angles between them are limited with the printing platform of 1.4 m x 1 m x 1.2 m. One of the most problematic geometrical conditions for the free form shapes when it comes to shells and subdivision is zero geometry torsion (Pottmann H., [4]). These conditions derive from the module-to-module connection, where modules can be printed only with a flat edge side due to the designed trowels on the side of the nozzle (Figure 2). The authors use the methods from discrete descriptive geometry to overcome these challenges described in the next section.

Figure 2: Picture of the nozzle and a printed module (left); Detailed picture of the nozzle with side and back trowels

3. Design and methods

In order to fulfil the geometrical and structural conditions stated in the previous section, a prefabricated-oriented design is necessary to implement in this case. The actual exterior form is based on a design idea in which shells with three openings are combined to form a functional ensemble (Figure 3.). The proportions of the areas were developed on a ground plan. The ground plan of the shells is based exactly on these specifications. The openings lie in one plane and are oriented vertically. The arches correspond to a hanging line where the height of the opening's underlays the design. The contact points with the floor are laying on a circle. The shapes now result from the fact that a minimum surface or soap skin is drawn over the edge curves. For further studies, we choose the smallest shell which corresponds to the one on the right side in the front of Figure 3.

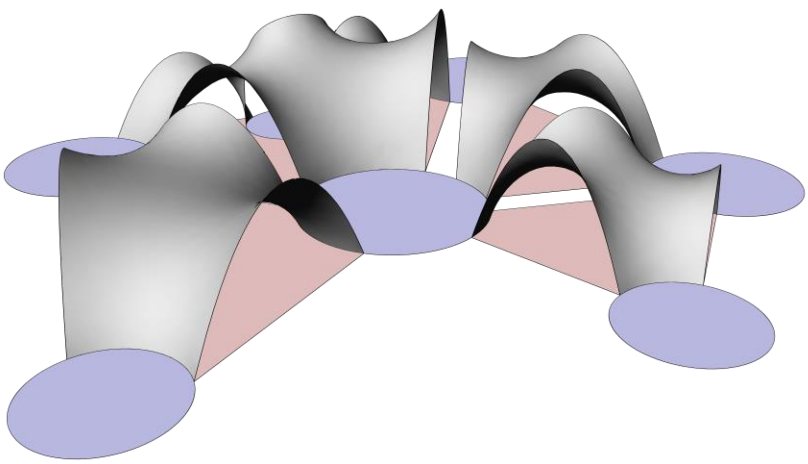

Figure 3: Starting Design Idea

The method that authors take is top-down/ global approach of free form shell design, which starts from the arc basis design with erected arcs to meshed minimal surface computed with Kangaroo, Grasshopper plugin (Figure 4). After that, the principal stress and principal curvature directions are compared. The goal of this method is evaluation of the starting design, since it is known that minimal surfaces represent very good membrane structures (without shear forces), which is crucial for optimized shell structure. As the shell should be subdivided into planar modules, a good starting reference when it comes to free form surfaces is discretized version of principal curvature directions (Pottmann H., [4]). The design evaluation measurement can then be overlapping of principal curvature and stresses directions and since there are two directions intersecting in every surface point, discretized PQ (planar quad) mesh system is an obvious solution. The other reasons for this choice, as opposed to trivial triangular solutions, are production-driven; Less complicated connections in between modules in the edges and nodes (a smaller number of edges per node), sharp module angles and smaller elements. Since there will be two different materials, it is also important to optimize the usage of the extruded concrete where it is not needed.

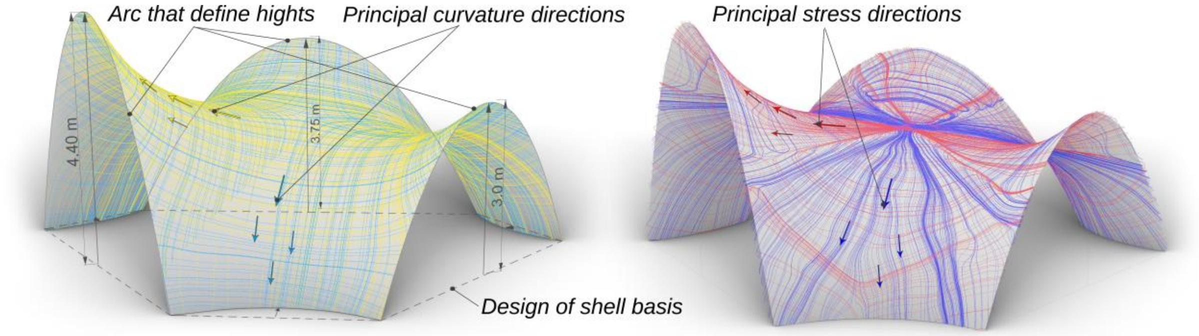

Figure 4: Starting free form shell design with analyzed principal curvature and stress directions

Although the authors use represented minimal surface as an inspiration, for the design, the specific method of computational designed algorithm based on the geometrical methods from discrete differential geometry is used for creating/ building up the PQ mesh system of the surface. The algorithm is developed in C# for Grasshopper (Rhino plugin) which uses two curves as an input, based on the chosen number of elements it generates a planar circular quad (circumscribed circle per quad) using orthogonality driven quad-by-quad system. This means that, starting from the point of intersection between input curves, the algorithm draws quads one by one, trying to make orthogonal quad edges, fixing vertices on the matching circle and driven to create zero geometry torsion per node. Circular meshes and orthogonality in between the edges, as an implemented method, come from the discrete differential geometry (Pottmann H., [4]), which states that two orthogonal systems of principal curvature lines of free form surfaces, represent optimal nodal discretization and circular quad definition of these shell designs (figure 5). The first two are quite straightforward, while zero geometry torsion means that intersection of the all four outer edge planes (edge sides) per node has to be in one line (figure 6). This ensures that the printing nozzle can be used with the outside trowel as showed in Figure 2. Otherwise, the side edges will have to be printed as a ruled *(twisted)* surface, which is not possible for now with this production technology without formwork and module-to-module connection.

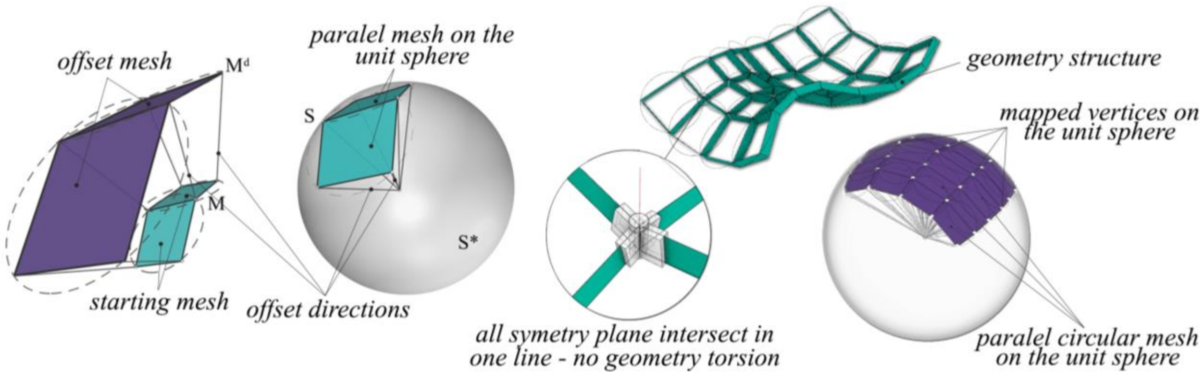

Figure 5: Mesh offset properties of the circular mesh system within the unit sphere (left) and computed for the entire structure (right)

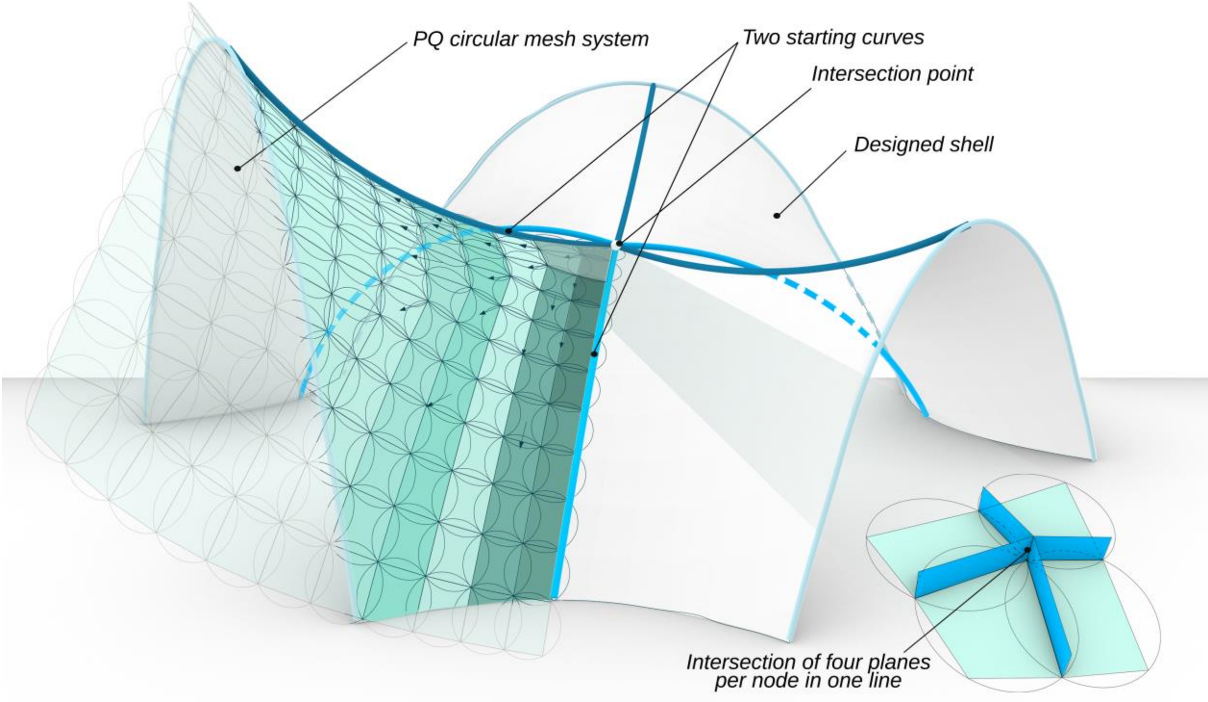

Figure 6: PQ circular mesh generation from two curves on one part of the free form shell design with detail explaining no geometry torsion solution for prefabrication

4. Geometrical and structural optimization

When compared with Figure 3, it is clear that principal curvature lines of the designed surface were used as a starting point for the input curves integration. The algorithm was tested on spatial curves, in plane curves of third order and arc - curve parametrization, where geometrical and structural PQ meshed shell properties were compared. Both showed that the best starting curves parametrization were arcs. This definition was implemented to find the best PQ circular mesh system for geometrical production demands with optimal structural properties. Parameters that were used for the optimization were: *height of the arcs (varying 1 m), the position of the intersection point for input arcs and normal in that point that defines arcs curvature* (Figure 6). As the PQ circular mesh system goes beyond the surface edges, they were cut for the final shell calculation.

The shapes cannot be mapped exactly by the described discretization. So, the first thing we do is to optimize the PQ meshes with respect to the maximum deviation from the design. In the previous chapter, it was already described that the meshes are uniquely defined by six arcs. These arcs result from seven points. Three on the arcs and three on the curves, which at the same time form the supports. The intersection or centre point is additionally located on a plane to which the start vectors of the arcs are oriented parallel. For geometric optimization, 7x3 free parameters result through the points and two additional parameters for the orientation of the plane. 23 parameters are a lot of free variables for optimization algorithms. We use the add-on Galapagos for Grasshopper3D. This is a generic solver where a landscape spanned by the parameters is randomly populated with values to find a maximum or minimum. More detailed principles can be found in (Rutten, [5]). Especially with many parameters, the algorithm tends to find local maxima. To mitigate this effect, the parameters are set manually at the start, so that an approximation is already guaranteed. This is integrated as the start population. Additionally, only results where the geometric torsion tends to zero are considered as output. In the end, two variants were selected from several local maxima (Table 1), which satisfy both geometric and mechanical requirements.

The main results of the calculation are the maximum utilization and the maximum displacement. For faster processing, this calculation step does not distinguish between edge zones and infill. Assumed loads are wind with 0.8 kN/m², snow with 0.85 kN/m² and the weight of the structure. All panels are assumed with a thickness of 10 cm and with the properties of conventional concrete C20/25. In addition, a safety factor of five is included, which allows to cover any load cases from the erection phase. The support points are secured against displacement but not against torsion. The results can be found in Table 1.

When it comes to construction properties *deformation, utilization and mass* are meant to be minimized as well as geometrical such as *geometry torsion, distance from initial design,* then *orthogonality between edges* and *size of modules*, that will fit the printer platform. After few simulations, two results of PQ meshed shells are presented in Figure 7 with characteristic geometrical and static properties.

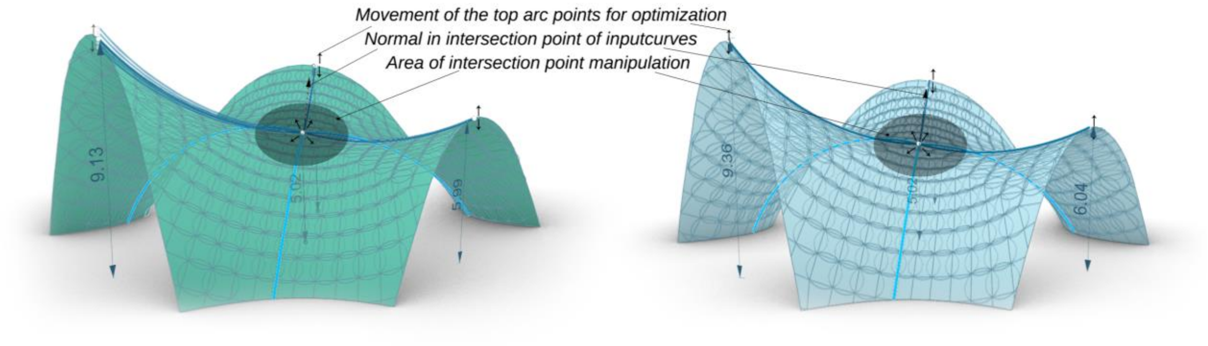

Figure 7: Display of the two solutions from the Galapagos optimization process with input parameters

Table 1: Geometrical and construction properties of the first two solutions

	Geometrical properties					***Construction properties***	
Solution	Number of quads	Angles between quad edges	Length of quads edges [m]	Number of triangles	Average distance to initial surface	Max. deformation	Max. utilization
Shell 1	437	54° - 125°	0.47-1.28	342	79.87 cm	0.56 cm	2.16
Shell 2	429	55°- 125°	0.48-1.23	342	88.52 cm	1.04 cm	1.20

Looking at Table 1 it can be seen that geometrical results are pretty similar and without geometry torsion, which was one of the critical features of free form shell segmentation. That is why the authors decide for the second solution based on the construction properties, valuing more impact of the utilization in the shell structure then deformation, as later, and final, better potential for cross section optimization is crucial for the optimal solution.

5. Final modularization and material optimization with results

For the final definition of the modules, certain modifications in modularization needed to be made when it comes to boundary triangle faces on shell edges. They needed to be transformed, so that it would be possible to produce them with the described procedure. The authors choose to extend the modules on the edges and tried to keep as many quad modules as it is possible in order to avoid sharp angles and small triangulated edges for production. The scale of the edge length, the number of triangles and angle edges should be balanced for the flow production process. Some of the smaller triangles had to be kept as well in order to preserve no geometry torsion regulation. From the comparison of tables 1 and 2, it can be seen that the number of modules is lowered as well as triangles. There is still 3% of angles between edges that are less than 60°, which can make a problem during 3D printing. This limit has to be tested, since it depends on the ratio between edges length, thickness and angle. Although the mentioned platform for printing is for now limited to 1.40 m, the authors consider these lengths of edges (Table 2) realistic, due to other future technology possibilities, such as a robotic arm with the maximum radius of 2.7 m. When it comes to connections, a module-to-module concrete connection is under development, which is possible due to the flat side edges i.e., zero geometry torsion. That has to be taken into consideration during shell calculation and the final definition of edge thickness.

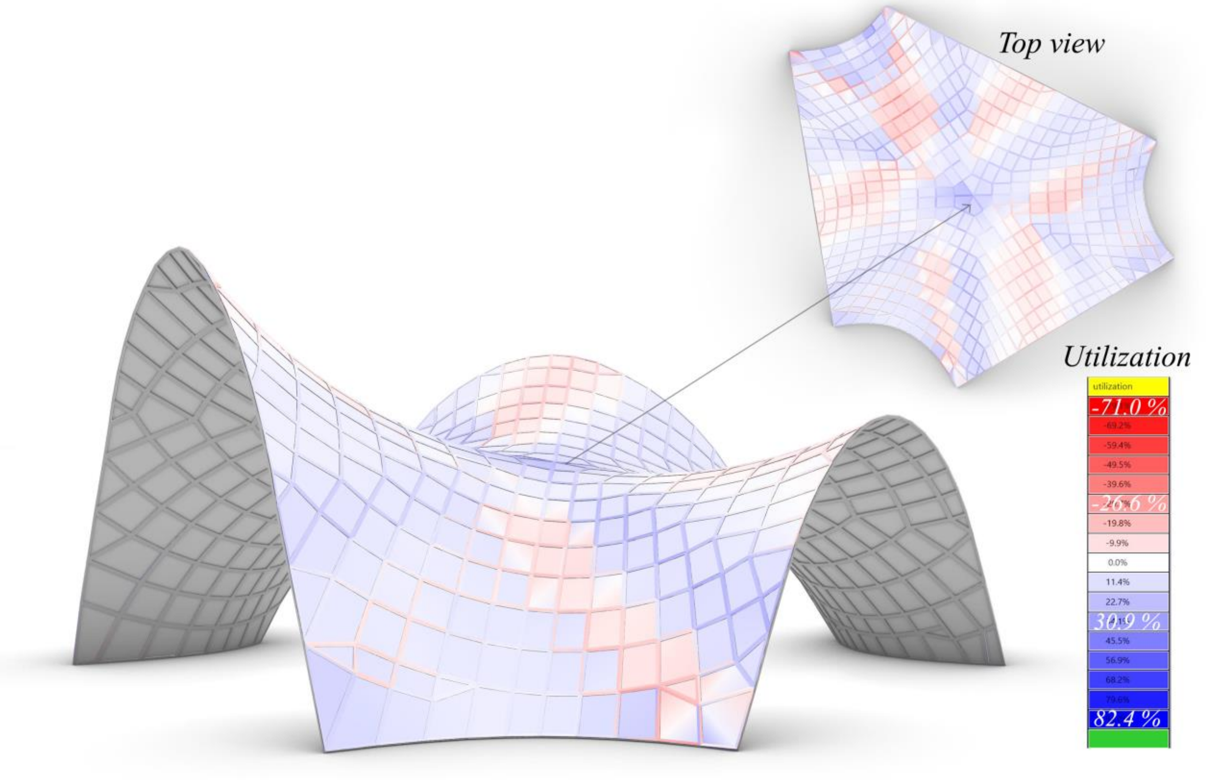

Figure 8: Display of the shells calculated utilization in perspective and top view with critical numbers in the scale

When this procedure is done, the final calculation can be processed with cross section optimization, as now construction is calculated as a combination of concrete grid shell system of thicker module edges and continuous thinner shell design, that represents modules infill. External and internal elements are modeled as shells that are rigidly connected to each other. The boundary conditions correspond to the previous calculation. The cross-section of edges is determined before optimization based on the current size of the printing nozzle and minimum thickness for establishing module-to-module connections. Thus, only the amount of infill is optimized. Here, we refer to the current state of the art. The 3D printer is set to a width of filament where only the slope of the outer sides can be varied in real time. The optimization is now a loop that is terminated when a defined threshold value is undershot. In our case a deformation of 1 cm at maximum utilization of 100%. As start values a cross section of 5x5 cm and a height of the infill of 1.5 cm were defined. In the loop, there are two parameters that can be set. The factor by which the material thickness is increased F and a value by which the utilization of a single panel is increased as a reference R. As an example, we choose a panel with a utilization of 80% (Figure 8). We have now set the algorithm in such a way that a value of $R = 80$ is always added for a factor $F = 0.2$ The factor of raising for each panel is therefore calculated as follows:

$$\frac{\left((U_n + R) - 100\right) \cdot F + 100}{100} = f_n; U_n = Utilization\ of\ panel\ n$$

For this example, a factor of $f = 1.12$ is obtained which is then multiplied to the infill thickness. The value R was introduced so that optimization is not too local and also takes adjacent panels into account. For the shell shown in Figure 8, the limit value was undercut after 4 iterations. The parts with the highest utilization are located at the ends of the opening arcs.

Table 2: Geometrical and construction properties of the final solution

	Geometrical properties				***Construction properties***			
	Number of quads	Angles between edges	Length of edges [m]	Number of triangles	Max. deform.	Max. utilization (infill)	Max. utilization (edge)	Mass [kg]
Shell	494	30° - 135°	0.39-1.98	29	0.96 cm	0.70	0.82	21411

After material and statical optimization, the final modularized shell is presented in Figure 9. Triangle elements are highlighted and they are located at the shell edges, as they are the result of final shell shaping. Edge's thickness differentiates from infills on the inner side of shell structure, which defines the printing side of modules. Important to note is that the focus and criteria of modularization with prefabricated elements didn't disrupt the starting aesthetic approach of smooth concrete shell on the top.

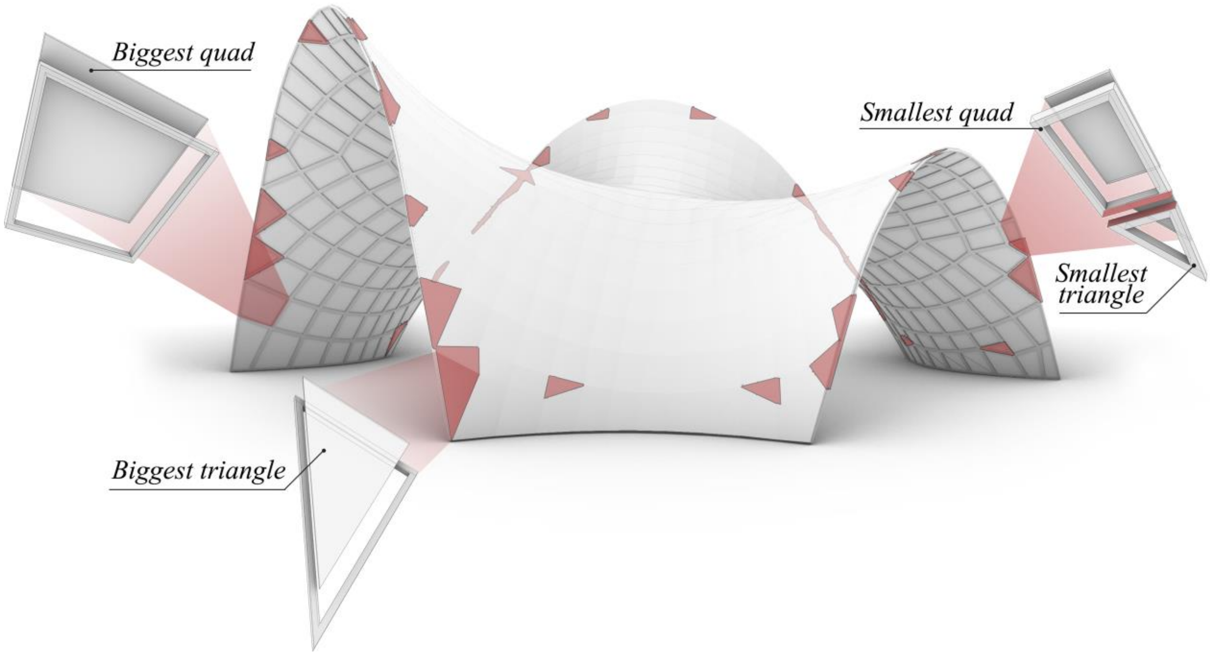

Figure 9: The final shell presented with four characteristic and highlighted triangle modules

6. Conclusion and final remarks

There is a lot of influence of building industry on the environment not commented in public or even between engineers. That is why our job is to spread awareness and discover innovative solutions for contemporary problems using available resources such as digitalization, contemporary means of prefabrication and already existing design and optimization methods. Prefabrication is the word mostly associated with blocks, same modules and repetition. That is why the authors challenge to design, optimize and subdivide free form concrete shell for 3D concrete printing without formwork can sound ambitious. Nowadays, modules can be considered as unique produced parts that represent one puzzle of the entire system and designed in such a way that they fit into the entire flexible production process. The goal is achieved with scalability and adaptability of the modules that, for some values, have to be tested, but shouldn't disturb the main production processes. However, better controlled mechanism has to be found that fits the outer shell design and at the same time optimizes the geometry of cut modules. Still, with computational design and discrete differential geometry, authors used a pre-rationalized starting design of minimal surfaces, which shows very good results with circular mesh generating algorithm. They define good starting parameters so that specific inputs *(usually geometrical)* can be precisely fitted for the optimal solution with multiple output parameters. Even now precisely defined, future research will show more results on the production area, dealing with limitations, tolerances and connections, which should be implemented into the design process. Moreover, digitalization methods should enable more control in modules geometry, but at the same time spread the field of free form shell designs.

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