Design Rationalization of Irregular Cellular Structures

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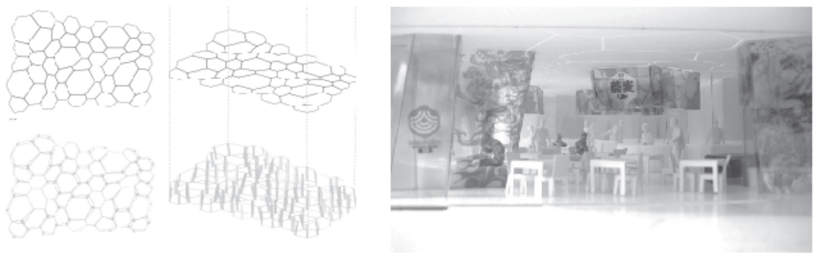
Complex geometries found in nature are increasingly used as images and analogies for the creation of form and space in architectural design. To be able to construct the resulting complex building forms, strategies to handle the resulting production requirements are necessary. In the example of a design project for a Japanese noodle bar, a strategy for the realization of an irregular cellular spatial structure is presented. In order to represent its complex geometry, building principles relating to foam are applied to transform and optimize the design, which is based on hexagonal, cellular compartments defining the different interior spaces. The principles are converted into software code and implemented into a digital design toolbox to be used within a 3D-modelling environment. Utilizing the tools within the redesign process made a rationalization of the cellular structures possible without sacrificing the desired visual irregularity. The toolbox also enables the extraction of the cell geometry to support the generation of production documents. The result is the dramatic reduction of production effort to realize the complex cellular structures by keeping a maximum of design flexibility and desired visual appearance.

1. INTRODUCTION

As current building forms tend toward increasing complexity, nature frequently serves as an inspiration in the form-finding process, either as an image, and analogy but also increasingly as the generative system [1]. Natural structures and forms can be of intriguing visual and spatial quality, their building principles and characteristics such as the efficient use of material (minimal surfaces) or ideal flow of forces often closely relate to architectural design tasks. The employment of biological analogies has been the subject of substantial research in the past. Following intensive experimentation with physical models, Frei Otto for example, was able to derive structural rules that could be translated into architecture [2]. Some of the natural phenomena Otto analysed were the properties and principles of dry and liquid foam, which can be found as the guiding design principle in several examples of current architecture. Several projects from small to large scale use analogies related to either form or the generative principles of foams, such as the M.ANY project [3] or the new Beijing National Swimming Centre [4]. Due to the inherit complexity of the underlying geometry, powerful modelling software is used for its generation. The realization, however, poses new challenges for designers and engineers. The requirements for the precise geometric description of the different parts and components are high. Complex geometries therefore often result in large numbers of different parts to be assembled as described in Fischer [5], requiring substantial engineering efforts and causing significant production costs. Rationalisation strategies and methods are necessary to face these challenges and thus to be able to transfer complex forms from the virtual space into physical reality. Different strategies to achieve this transfer have been subject to research and realization of small to large-scale buildings. The range thus spans from strategies such as the seamless use of digital data throughout the entire architectural design process to the geometric approximation of the intended form. In this work methods and tools for the design rationalisation of an irregular spatial structure for an interior design are presented. The work was part of the design project "ANAN", a Japanese noodle bar, designed by Hosoya Schaefer Architects [6] as part of the Volkswagen "Autostadt" [7] in Wolfsburg, Germany, which was constructed in 2007. A set of geometric principles was developed to transform and optimize the existing cellular design. These principles were implemented into a digital design toolbox in order to facilitate the rationalisation and production of the elements. The resulting tools apply these transformations in a post-rationalization process, effectively reducing the production efforts by keeping the desired design intent of high visual irregularity.

1.1. The ANAN project

As the driving conceptual element of the design, a distribution of hexagonal cells covers the restaurant space. A typology of different cell types was created to define compartments, spaces for sitting and eating, wardrobe and menu display. In the original design sketch, two different two-dimensional cell lattices at the floor and at the ceiling define the compartment volumes. The connection of a cell of the ceiling lattice to its counterpart on the bottom lattice extrudes the cellular compartment. Shifting the edges of either of the cells leads to an inclination of the referring compartment surface. This shift has to stay parallel; otherwise the resulting surface would be double curved. Combining the six surfaces between the ceiling and floor cell results in an irregular, three-dimensional, hexagonal compartment (Figure 1). Visually, the resulting structure mimics idealized, simplified foam. For the definition of the different spatial compartments, nine cells in the lattices were selected. The complete lattices remain as cell patterns on the floor and on the ceiling. This leads to highly irregular interior spaces bounded by the room-high compartments, each one different in position, size and inclination (Figure 1).

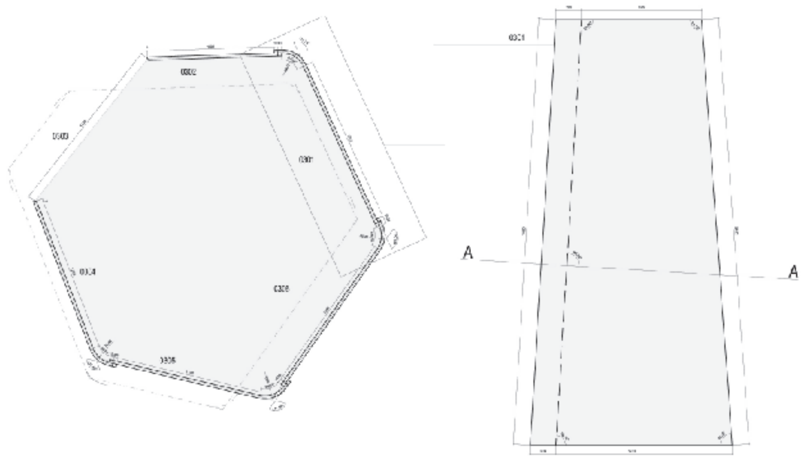


◀ Figure 1: Cell lattices (left) and working model of the original design (right) [6]

For the construction of the compartments, acrylic glass panels of 30 mm strength were chosen. The detailing of these glass panels proved to be difficult as the cells edges were to appear as "smooth" as possible. Due to the approximated maximum size of a cell element about 3.50m x 1.5m, each compartment had to be assembled out of six separate acrylic glass panels. The challenge was to devise a corner detail which enabled a strong connection between the compartment surfaces, and which would still be highly visually appealing. After evaluating a range of detailing alternatives, the chosen design involved the bending of one end of each acrylic panel as the panels were supposed to overlap at the corners to appear as smooth as possible (Figure 2). Acrylic glass can be bent into shape by using compression moulding [8]. At a temperature of 180-250°C it is deformed thermoplastically. The panel is bent into shape by the surrounding compression mould. The chosen detailing of the original design made 54 different moulds necessary as each corner between two compartment surfaces had a different angle and thus had to be bent individually. The resulting production costs for the 54 moulds proved to be very high, endangering the realization of the concept.

Therefore it was necessary to reduce production costs. In addition to this economic constraint to minimize the total number of moulds, the most important design constraint was to keep the desired visual appearance of the cellular compartments. The total number of individual cells and their positions had also to remain the same as other collaborators such as the kitchen planners were already involved and supplied with the design sketch. The challenge therefore was to minimize the number of moulds necessary whilst keeping maximum visual irregularity of the existing design.

► Figure 2: Original design detail of a cell structure, horizontal and vertical section [6].



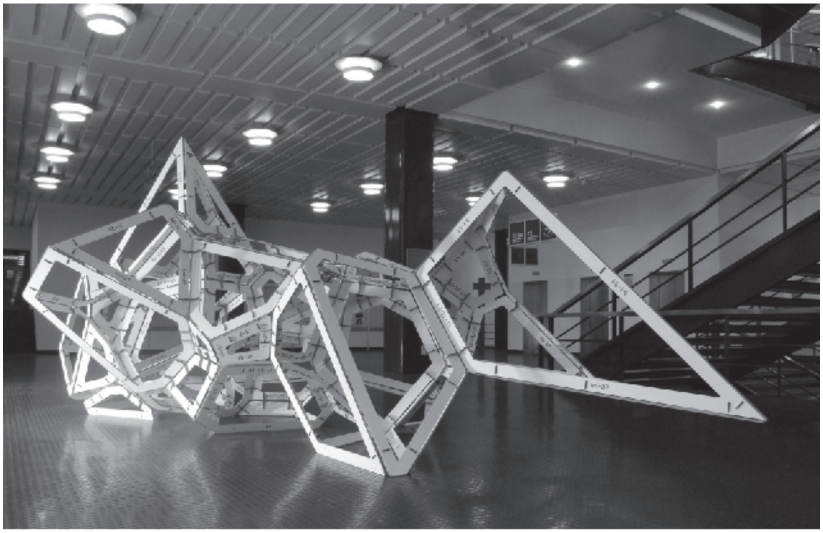
2. REALIZATION OF COMPLEX FORMS

As complex forms are relatively easy to create in modelling software, the requirements on the geometry behind are challenging when it comes to realizing its elements. Complex forms often generate large numbers of different parts and components, especially if the achievement of visual irregularity is the key task. As shown on the ANAN project, this leads to high design, engineering and manufacturing costs, often endangering the whole design concept.

Two general strategies to reduce production costs can be identified: the concept of the "digital chain" and the idea of "design rationalisation".

2.1. The "Digital Chain"

The concept of the "digital chain" utilizes digital data from initial design stage to the production of building components on computer numerically controlled (CNC) machinery. The seamless passing on of digital design data makes the production of thousands of different parts at reasonable production costs possible. The digital design data derived from the geometric model can be directly processed on CNC-machinery, resulting in a high level of automation and thus a significant reduction of necessary manual labour. Due to the high level of automation, production costs can



◀ Figure 3: The realized structure of the M.ANY project [3].

even be lower than standard geometries realized with traditional production methods [9]. This concept is taken further in the "digital matrix" where even the manual form finding is replaced by form generation principles following design rules, as described in Schlueter [3]. Here, an ideal model of three-dimensional dry foam serves as the generative principle for architectural form. As an analogy to foam occurring in nature, the generation of the architectural object is influenced by contextual parameters of the surrounding space, internal rules of construction and production parameters. Voronoi diagrams are used for the description of the model geometry, generating completely irregular three-dimensional cell structures. The final form is achieved by iterative design loops, considering parameters of all stages of the generative design process. All geometry and the necessary data for the production of the several hundred individual components is automatically created and passed on to production machinery. However, this strategy can only be applied if a fully digital architectural process is possible, narrowing down the choices of appropriate production means, materials and machinery.

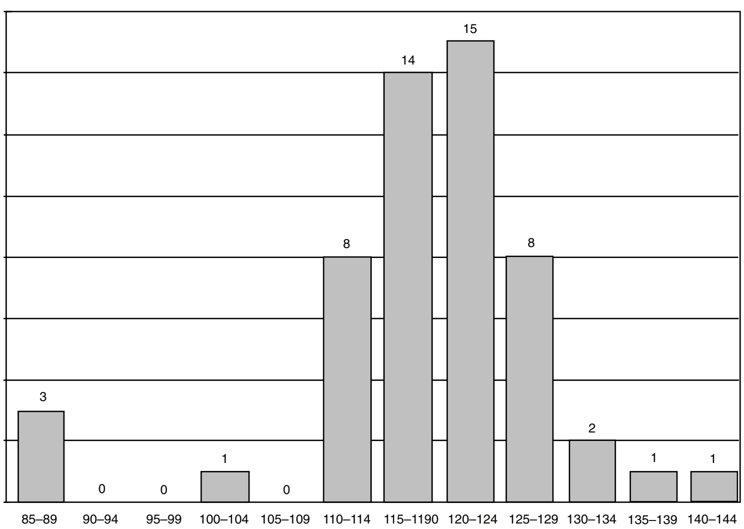
2.2. Design Rationalisation

Second, the concept of "design rationalisation" [5] aims at limiting the production costs of complex forms by utilizing geometric principles to reduce the necessary number of different elements to be assembled. In general, design rationalisation can yield at a variety of tasks such as fulfilling constraints of the production process or machinery, meeting structural performance criteria or efficient use of material. In order to realize complex building forms, the focus is on optimizing the construction systems. Different strategies of design rationalisation for construction purposes can be identified, depending on the stage of the design process the rationalization is applied [5]. Pre-rationalisation involves considering the constructive system already before the actual design process whereas co-rationalisation applies the optimization alongside of the design progression. Post-rationalization is the retroactive fitting of a construction system onto an existing design. For rationalisation purposes, geometric principles can be utilized to achieve visual irregularity by using only a small number of parts. For three-dimensional assemblies, packing principles of polyhedrons, for example, allow visual irregularity by using only few individual parts. The packing principle discovered by Weiare and Phelan [10] uses two different types of polyhedrons, one of which is not fully symmetrical. It is repeated and rotated throughout the structure. The highly efficient packing principle is derived from Kelvin's packing of truncated octahedral polyhedrons. An evolution of this packing was applied to rationalise the façade geometry of the already mentioned Beijing National Swimming Centre [5]. For the ANAN project, only post-rationalisation was possible due to the developed detailing and the cell topologies already being communicated to the customer and other collaborators. As the moulding and bending of the acrylic glass plates was expected to be done manually and thus resulting in a high effort for each individual mould, the focus had to be on rationalising the design of the nine cellular compartments by optimizing their geometry. This way, the desired corner detailing of the edges between the compartment surfaces could be kept.

3. METHODS

Starting point of the rationalisation approach was the analysis of the existing, manually designed cellular lattices. So far, the initial design had only been executed in 2D as drawings of floor and ceiling lattices. A manual connection of bottom and top lattice lead to an initial design of the three-dimensional

► Figure 4: Distribution of internal cell angles



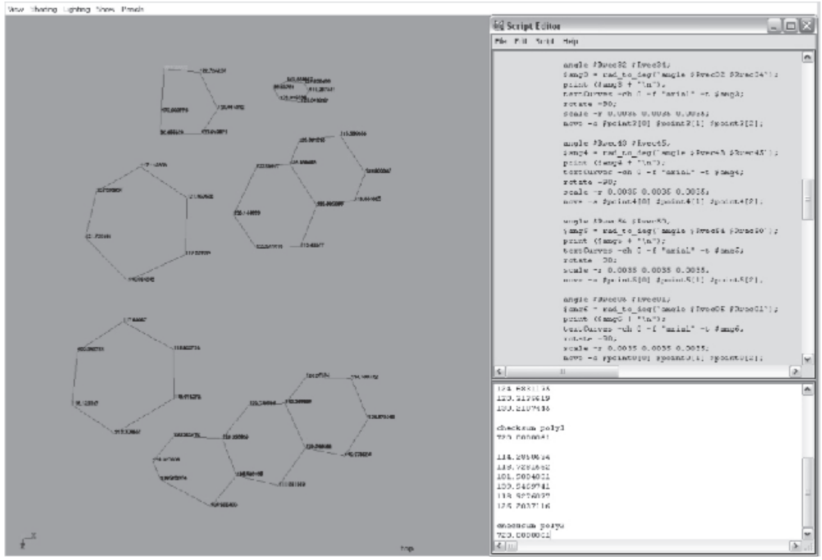
cellular compartments. In terms of its visual appearance, this design sketch served as the example that the redesign would be compared with.

3.1. Geometric background: foam

For the rationalisation approach, the principles of the generation of foam were researched. Foams can be described as a two-phase system in which gas cells are enclosed by liquid. As solid cellular structures are often solidified liquid foams, many of the generative principles of foams can be applied to cellular structures in general. In nature, foams are mostly disordered and show a variety of cell sizes depending on the individual cell pressure and its surface tension [11]. Within a foam structure local equilibrium rules determine the geometry of the cell network. Most of the times these rules relate to foams in the dry limit where the very thin films between neighbouring cells can be idealised as single surfaces. Each cell must conform to the law of Young-Laplace, relating pressure difference to mean curvature of the cell surface in equilibrium [12]. In addition, the equilibrium laws of Plateau have to apply. The most important law states that dry foam films can only intersect three at a time at an angle of exactly 120° [13]. Considering the original design intent and specifications, it is reasonable to choose the building principles of two-dimensional foam for the rationalisation approach. The original design can be viewed as a section through a foam sandwich where the average cell diameter is much greater than the sandwich height. Furthermore, as the cell surfaces were to be constructed as planar acrylic plates, the cell boundaries could be approximated as straight lines. This constitutes an enormous simplification. In this case, according to the law of Plateau, a relaxed cell can be geometrically described as a regular hexagon with an internal angle of 120° between all edges. The distortion between the floor and ceiling lattices of the design can be regarded as a difference in the individual cell pressure. An important geometric constraint is the equal number of cells in top and bottom lattice. Special constraints apply for the cell edges. In order to obtain planar surfaces when connecting top and bottom cell, both cell shapes must be topologically identical, their number of shape edges must be the same and all corresponding edges parallel.

3.2. Design analysis

The first step to identify the parameters responsible for the visual irregularity was to analyse the 2D geometry of the existing lattices. The lattice drawings were transferred into 3D-modelling software and an analysis tool was applied. The tool automatically analyses the cell geometry by parsing and listing all internal angles of the cells shapes (Figure 5). The goal was to identify the scattering of the internal cell angles in order to find approaches to simplify. The analysis showed what was already suspected: Nearly all internal angles of the manually designed cells showed only slight variations of



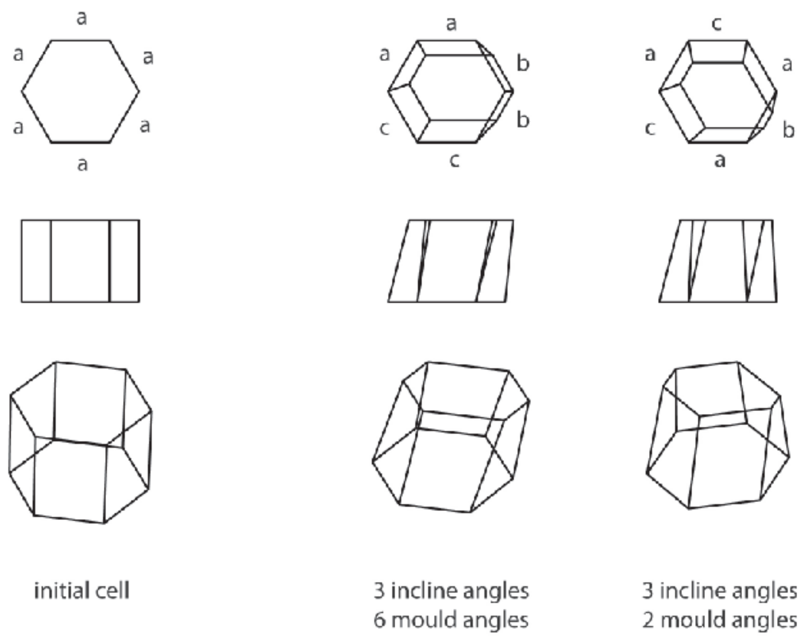
► Figure 5: Geometry analysis tool

the ideal angle of 120°. 90% of the angles are within +/- 10° form the ideal angles, more than 50% even within +/- 5° (Figure 4). Visual irregularity was obviously achieved by only minor changes of internal cell angles.

The mere analysis of the 2D cell shapes, however, does not automatically allow drawing the conclusion for the angles existing in the three-dimensional cellular compartment and thus the number of necessary moulds. As described, the floor and ceiling lattice can be viewed as sections through the compartments at a certain levels, resulting in characteristic cell shapes at every chosen level. If the bottom and top cell shapes are not identical, the surfaces in between the shape edges incline. The different inclinations of the surfaces and their sequence within the hexagonal compartment result in individual angles between the neighbouring compartment surfaces. These angles are referred to as the mould-angles. Therefore, to define the angle necessary for the production of the moulds, the angle between the two compartment surfaces at a section perpendicular to their shared edge has to be considered.

3.3. Geometric transformations

Following the building rules of an ideal foam, the design process of a rationalised cellular compartment starts out with a relaxed cell, a regular hexagon. For the optimization of the design, three transformation principles are defined. They can be performed any number of times and in any sequence. The first principle enables a translation of the compartment surfaces. The translation process changes shape, size and volume of the cellular compartment and still maintains the mould-angle between the neighbouring surfaces. As a second principle, each compartment surface can be inclined in a specific angle (Figure 6). An increase in the total number of



◀ Figure 6: Second principle: Inclination of compartment surfaces

different angles of inclination naturally implies an increase in different mould-angles. The number of *n* different angles of inclination results in a maximum of permutations of

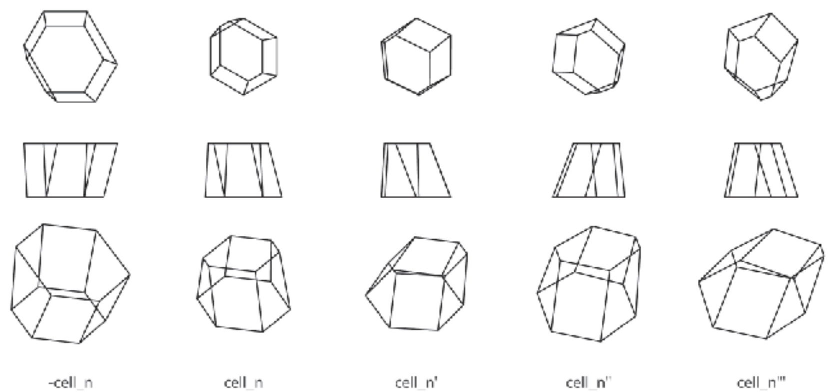
$$\frac{n*(n-1)}{2}+n \qquad (1)$$

Therefore, depending on the sequence of the incline angles, the number of total mould-angles can be decreased down to *n* - 1 for *n* > 1. Applying three overall angles of inclination thus results in six different mould-angles. However, if they are applied in the right sequence, three angles of inclination result in only two mould-angles. Additionally, a mirroring of the angles of inclination can be performed. Switching all angles of inclination from a positive angle to its negative equivalent also doesn't affect the total number of incline angles.

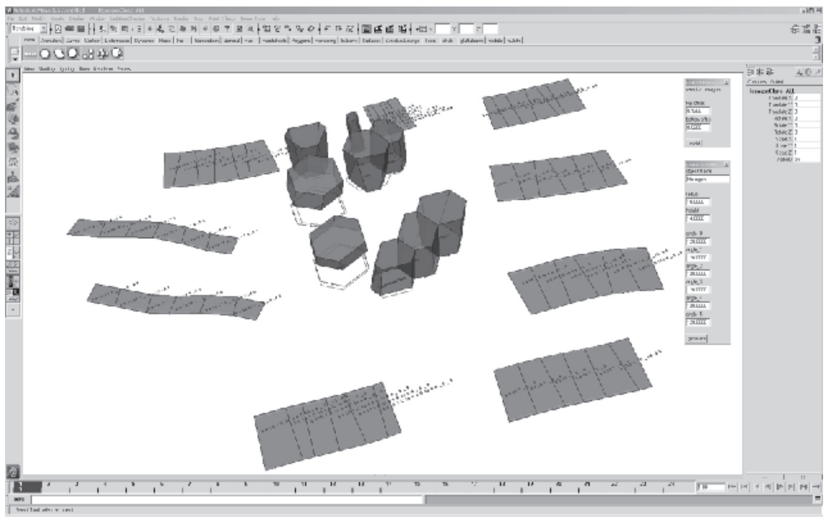
As a third principle, the whole cellular compartment can be rotated in relation to its cutting plane. As this transformation step is applied to all compartment surfaces, the individual angles of inclination towards the ground plane change but the mould-angles between the surfaces are maintained. All transformation principles applied in an arbitrary sequence increase the visual irregularity of the initial regular hexagon. Limiting the number of different angles of inclination and deciding on the sequence in which they are ordered within the hexagon can precisely control the number of different mould-angles.

Therefore, a single configuration of mould-angles between the compartment surfaces can be transformed into infinite variants, achieving very different visual appearances (Figure 7).

► Figure 7: Third principle: Rotation of the cellular compartment in relation to the cutting plane



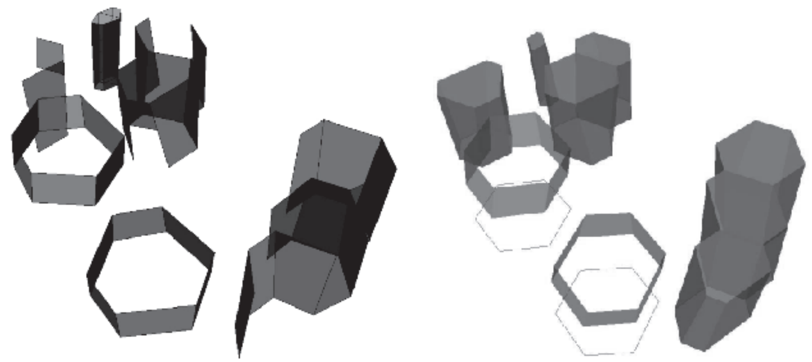
► Figure 8: Modelling software with design toolbox (icons upper left corner) and final design



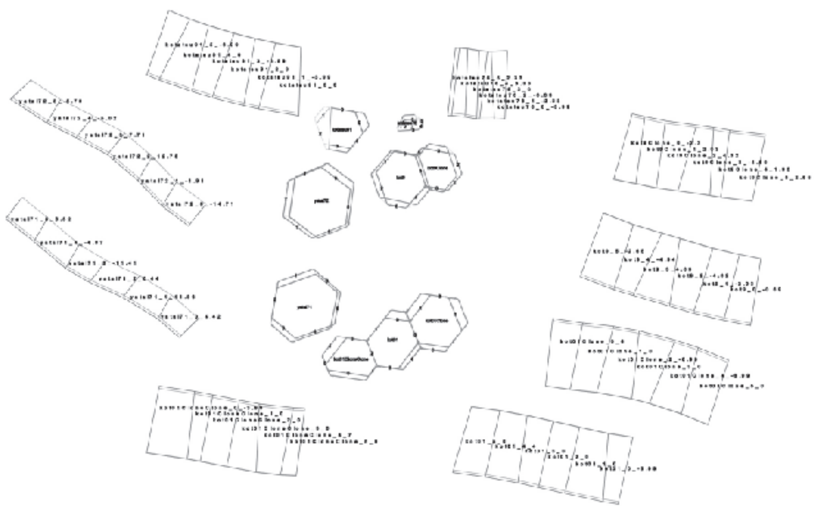
The described principles were converted into software code and implemented in three-dimensional modelling software as a digital design toolbox. The toolbox provides the tools for each transformation step to be applied within the design process. The aim was not to initially generate an optimised design but to supply intuitive design tools that can keep a maximum degree of flexibility in design while staying within the given constraints. As the 3D-model adapts to every transformation, direct visual feedback is given. Each individual design step can be undone at anytime. In addition, a tool was added to support the facilitation of the necessary shop drawings. By unfolding all cellular compartments, creating all surfaces to be cut and adding all necessary design offsets for the production, the tool greatly simplifies the otherwise tedious, manual drawing of the shop drawings.

4. RESULTS

Within a joint workshop together with the design team, the form and spatial configuration of each individual cellular compartment was



◀ Figure 9: Original design using 54 different angles (left), final redesign using 3 different angles (right)



◀ Figure 10: Generated production drawings of the final design.

redesigned. Experiments with different numbers of inside angles were executed to evaluate how many (or better, how few) angles are necessary to achieve the desired visual appearance. As the compartment surface inclination in relation to the horizontal cutting planes (floor and ceiling) greatly impacts the visual perception of the compartments, the rotation of the whole cellular compartment proved to be most effective. All cells were rebuilt for final form finding. The final result uses only three different angles of inclination for all cellular compartments to achieve the identical visual irregularity than the original design using 54 angles of inclination (Figure 9). This reduces the number of necessary moulds likewise from 54 moulds down to three. Even an extreme solution using only one incline angle delivers a highly irregular visual structure. However, three angles were used to be able to react to different cell topologies such as a very small and high cell and to the grouping of multiple cell elements. The developed principles of design rationalisation therefore lead to a significant reduction of necessary moulds for the bending of the acrylic glass plates, resulting in dramatically reduced production costs.

► Figure 11: ANAN – the realized project [6, Image by Udo Meinel]

For the production of the shop drawings, the unfold tool provides the two-dimensional cutting patterns to be imported into a CAD software. Each surface is automatically labelled with name and related mould-angle. Two additional section planes at the bottom and top are generated to define the cutouts for the suspended ceiling as well as the floor construction (Figure 10). Concluding, the digital toolbox makes the digital creation and intuitive rationalization of the cellular structures as a part of the design process possible. Alternatives can easily be created and evaluated. The automated generation of all compartment surfaces also supports the building of a physical scale model. The generated cutting patterns can simply be printed on a CNC-laser cutter.

5. CONCLUSION

The methods described and implemented show that in this case, three-dimensional cellular structures can be rationalised with a set of easy but effective geometrical transformations in order to facilitate their realization. By utilizing geometric building principles of a simplified foam model, the foam analogy can not only be used as visual and conceptual metaphors but also as a key to the optimization and rationalization strategy. During the progression of the redesign, the intended post-rationalisation converted into co-rationalisation within the given constraints. By supplying a digital design toolbox, rationalisation principles were able to be included as an important part of the design decisions and were not simply delegated to an engineering team. Even more effective, however, would have been the pre-rationalisation. The application of geometric building principles to "grow" the foam from the beginning of the design on would have offered more flexibility and would also have supported the conceptual and spatial elaboration of multidimensional foams. Additional constraints such as the fitting of the lighting inside of the ceiling cell grid could have been considered. However, due to the collaborator involved with the production of the acrylic elements, the final production method for the compartments surfaces was changed from bending the acrylic plates by using moulds to milling the rounded cell corners out of a solid block.

In 2008, the ANAN project was awarded with the "Contractworld Award 2008" for the "successful realization of the restaurant concept in the interior design of the space" [14].

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