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Surface Structures and Robot Milling

The Impact of Curvilinear Structured Architectural Scale Models on Architectural Design and Production

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Abstract
In the last decade Computer-Numerically-Controlled (CNC)-milling technologies enabled new possibilities in constructing complex digitally-generated architectural shapes. International projects (like Neuer Zollhof Düsseldorf, Frank O. Gehry; EPFL Learning Center Lausanne, SANAA - Sejima & Nishizawa; Kunsthaus Graz, Peter Cook & Colin Fournier) show different applications of milling technologies in the production of architecture at the end of the architectural process. We focus on an application of milling technologies at an earlier stage, namely in the architectural design process, where architectural scale models are commonly used (as a tool for design-development). In this paper we discuss an innovative application of CNC-milling technology for the generation of architectural models. We show how curvilinear structures may be milled into physical volume models. With curvilinear-engraved scale models of complex shapes, one of the biggest problems with realizing digital-generated designs is affected: the structuring and segmentation of double-curved (and thus non-developable) surfaces.
Currently, the translation of a large complex surface geometry into a buildable structure comes along with diverse difficulties and often results in clumsy and aesthetically unsatisfying solutions. We argue that the use of “structure-models” (i.e., scale models representing buildable, technically feasible structures) could help to build freeform surfaces in a more satisfying way. Such structure-models are a useful communication tool for architects and construction engineers. By generating these models, architects will be encouraged to include surface-segmentation and CNC fabrication technology already in an early stage of the design process. Furthermore and above all: physical pre-studies showing different variants of macro-surface-structure are a suitable basis for aesthetical evaluation and decision-making.

Keywords: architectural model making, digital model making, CNC-milling technology, computer aided manufacturing (CAM), robot milling, structure, surface design, freeform architecture

1. Introduction: Problems in Realizing Freeform-Architecture

Today, the linkage of digital design and modern production methods creates so far undreamt possibilities in architecture. But the construction of digitally generated complex forms also often meets a variety of difficulties. Architects mostly are overstrained with the requirements coming along with the production of complex shapes. For the purpose of presentation they start with renderings ("pictures") showing the visible hull and not the structure of an architectural object. These digital 3-D models, created to convince clients and constructors, tend to neglect manufacturing structures and feasibility. The engineers and consultants, faced with these ambiguous pictorial representations, have to convert the data (from implicit to parametric representation) and have to specify and substantiate the construction design following the laws of statics, the constraints of costs and manufacturing. But the results are not seldomly opposing the aesthetical vision of the architect.

Due to the fact that architecture can not be built in one piece and requires the prefabrication of surface-units, the question of structuring and segmentation is crucial. Computer-aided Design (CAD)-tools do not automatically solve this problem. On the contrary and as already noticed by other authors the CAD-based generation of complex shapes in most cases leads to arbitrary graphic structures that are usually not buildable, technically feasible structures. Regarding the commonly used 3-D geometry representations in CAD systems, we have on the one hand *polygon meshes* usually consisting of triangles, quadrilaterals and other polygons (often visualized showing the mesh *edges*), and on the other hand non-uniform rational B-splines (NURBS)-*surfaces* (often visualized using their *iso-parameter value curves*). For a concise description of different types of 3-D geometry representations we refer to L. Kobbelt (2003) and H. Pottmann et al. (2004). For both, meshes and NURBS-surfaces, their standard representation in CAD-systems follows the logic of the particular 3-D modeling tool and not the logic of building.

Because architects usually do not have access to differential geometry, mathematicians are getting more and more involved in the solution of the posed problems. One of the goals of industrial geometry is to solve approximation problems aimed to the representation of 3-D-data of different sources from and in different media (Pottmann et al. 2004). One approach in architectural geometry is to take manufacturing constraints into account. As pointed out in Pottmann H. et al. (2007a), geometric knowledge of e.g. PQ (Planar Quadrilateral) meshes could foster the feasibility and manufacturing of freeform surfaces. Due to the limited capabilities of CAD tools, additional programming and parametric modelling approaches are needed to meet manufacturing and structuring constraints.

Although the achievements of CAD and computer graphics lead to impressive visualisations, the communication between different disciplines seems to be exceedingly difficult. The communication (among other things) is complicated due to the fact that architects, engineers and manufacturers work with different tools and types of 3-D geometry representation. We assume that conventional graphic and pictorial representations (plans, renderings) are insufficient means of communication and have to be complemented with physical 3-D-models, which are a direct physical output of digital 3-D-models. The implementation of digital production techniques or, to be more precise, the use of *digitally manufactured structure-models* in the early phase of the design process would have a positive impact on the process of architectural design and production. With such models representing feasible structures, architects not only have at hand an informative tool for communication, but also a new working aid to develop structures of large complex surfaces - which is both an artistic and technical task. Furthermore, architects will be encouraged to consider digital production methods and production constraints from the beginning.

2. Digital Production and Architectural Models

Architectural models are (like sketches, plans, or renderings) a common means of architectural representation. Considering the recent achievements of computer-aided design (breathtaking visualizations, renderings, digital 3-D-models) the production of physical models seems to be superfluous. However, in architecture digital 3-D-models have not replaced physical models. Architects could not get on without final representation models in competitions and design presentations, furthermore they still appreciate the model as a correctional, experimental, comparative and visual means during the design process. But true is also, that digital design-strategies have complicated and pushed back for a while the production of models, because complex, digitally-generated shapes are very difficult to produce with conventional analogue techniques. It was only within the last few years that *rapid prototyping* resp. *rapid manufacturing* techniques (for an overview on this subject see Gebhardt 2007) have allowed the translation of digital 3-D-models into physical models. Therefore, it is no longer necessary to translate digital three-dimensional objects into plan drawings on paper. The manufacturing of solid objects can be purely based on digital 3-D data (the so-called CAD-CAM process). From a historical viewpoint, the application of digital manufacturing techniques in architectural model making is only at the very beginning. But it is foreseeable that these new production methods will revolutionize and transform the hitherto handcraft dominated occupation of model-makers in the near future; they will also have an impact on the architectural design process - insofar that these new techniques will not only be confined to the production of final presentation models, but also will foster the production of models which are used in subsequent stages of the design process for comparisons and variations.

Models as a working aid in architectural design

Common and generally well-known are architectural models made from designs which are already completed. These are final models, mostly produced to overcome usual communication barriers between planners and clients, future inhabitants etc. (first of all laymen) or to convince a competition-jury. Beyond this type of model, which ideally is a small-scale representation of the future structure, models are important for architects as tools for design-development. For an architect "the significance of a model lies not only in enabling him to depict in plastic terms the end-product of his deliberations, but in giving him the means - during the design process - of actually seeing and therefore controlling spatial problems. For him the model, like the pencil [and the CAD-tool] is a tool for achieving architectural form." (Janke 1978: 18) In the theory of architectural model making not only different model types (town-planning models, building models, construction models, detail models, interior models, special models for static tests, acoustic investigations etc.) are distinguished. According to the point of production (during the process of design) also a distinction is made between *preliminary*, *experimental* and *final* models. Whereas the preliminary model is more or less "the spontaneous product of the designer's first ideas, a sketch-like improvisation, seldom made to a definite scale" (Janke 1978: 18), hand-crafted with basic available materials, mostly by the designer himself, the experimental scale model is a three-dimensional representation of an already sketched, preliminary draft, most times produced by co-workers in the office or workshop. Models which are used in subsequent stages of the design process normally fulfill the function to check and evaluate the three-dimensional shaping of a building. Furthermore the valuation of structural aspects could play a role.

When we henceforth are talking about architectural models, we mean experimental models and approach digitally manufactured architectural models as a *working aid* in the design process. It is especially this category of architectural models, where the application of digital manufacturing techniques seems to be promising for the future. We will later on argue why and how an early application of digital production methods could improve the process of digital design and construction. For the moment we want to reason out why the preoccupation with structure in experimental models is useful and especially why CNC-milling technology is an appropriate means to produce structured scale models.

Representation of structure by digital manufactured models

As carried out in the beginning, the logic of digital pictorial presentation tends to cloud aspects of manufacturing structures and feasibility. Furthermore, the struggles with different types of geometry representation within computer-aided design cause a delayed (and often delegated) occupation with the questions of construction and segmentation of large complex shaped surfaces. Using preliminary and experimental models based on analogue handcraft techniques in general is a good thing and could complement studies of digital 3-D-models concentrating on buildable structure. But studies based on analogue techniques are in a certain sense formative (meaning that physical qualities of the used materials play a crucial role in the representation of digitally generated complex shapes) and at least could only offer approximations. In contrast, digitally manufactured models, which could be seen as a direct physical output of a digital 3-D-model, represent the geometry exactly and true-to-scale. Nevertheless, up to now digital manufacturing in architectural model making is limited to the production of solid objects representing the shape of the building but nothing else. In our experimental research we attempted to cope with this shortcoming. Our aim was to visualize structures on digitally manufactured freeform-shaped models.

To avoid misunderstandings - if we are talking about "structure", we do not think about surface effects arising from using digital fabrication technologies, especially decorative effects of (milled or cut) tooling path patterns. Our idea was to engrave curvilinear structures into a complex solid shape to represent not only the physiognomy of a freeform-shaped building, but also its segmentation into buildable parts. For this purpose we made use of CNC milling technology.

3. Application of CNC milling Technology in architectural model making

Why milling technology?

As could be observed on examples of final models for competitions *additive* (e.g. selective laser sintering (SLS); stereolithography (SLA); 3D-printing) or *subtractive* (CNC-milling; laser-cutting) fabrication techniques are used for manufacturing solid objects. Whereas most additive fabrication techniques make visible the layers of application and come along with an irregular, uneven and sometimes disturbingly rough texture, with subtractive methods a comparatively smooth surface could be reached - which is a precondition for a following treatment of a solid-model. Besides the expense factor (additive techniques are incomparably costly) there is another decisive factor for the use of subtractive fabrication techniques: to have visible linear structures or segmentations on a solid model means that the structure previously has to be defined in the CAD-model. Therefore additive methods require the definition of threedimensional information (the applied or deepened solid structural lines), whereas subtractive production gets along with the definition of curves (B-splines). Because the generation of NC data helps breaking down complex geometry into producible units, the milling of single paths is comparable easy.

In general, both subtractive and additive fabrication methods do not follow the logic of "real" digital production in 1:1 scale. Scale models are produced in one piece whereas buildings (architectural prototypes) are joined together and made of a plenty of (individual or similar) pieces. Nevertheless, some applications of subtractive manufacturing techniques come quite close to the methods of 1:1 production. In comparison to digital additive techniques, which are (with few exceptions, for example the additive fabrication of non-standard brick walls with a robot, cf. Bonwetsch et.al.) intransferable to building scale, subtractive techniques could be applied in scale models and protoypes resp. building components (we recall the examples at the beginning). In any case, the use of digital manufactured models will encourage architects to think about the application of digital manufacturing methods for construction earlier. Especially the production of structure-models would force them to deal with buildable structures and façade segmentation in an early stage of the design process.

Why working with a robot?

Milling with a *robot* is an unusual thing. Robots are largely used in the automotive industry, where they usually do a single routine, a so-called *job*. Each robot executes a single *job* geometrically following a set of 3d-Curves (circular or linear interpolations or PTP (Point to Point) movements), programmed once to do the same operation for the whole lifecycle. Milling with a robot means to program prototypical tasks for different *jobs* and therefore is a fairly new application for robots and not widely used. Programming the robot's kinematics is still a big challenge because the robot's programming software does not support automatical programming of multiple tasks and spline-geometry. Software using direct CAD data to NC-files for a robot is so far commercially not available. First efforts of spline interpolations for robots by T. Horsch and B. Jüttler lead to hope, that CAD methods can be used as an interactive design tool for CAD design and the Robot´s *teach–in* programming. To solve the Robot´s kinematics, we generally use 5-axis milling software. A postprocessor interprets the G-Codes of the milling software to the Robot's kinematics. With using CAM software we have the advantage that we can use the CAM-strategy of *contour milling*, the end mill can follow the splines according to the surface normals.

Compared to portal milling machines, milling with a robot is *advantageous* in several aspects:

● Through the flexibility in workspace the robot supports *undercuts* and can work from all directions. Positioning the stockmodel with respect to the robot is important; one can use a tilting table or, when working with a 7th axis, a rotational table. This is a major advantage for structure milling, where the TCP (ToolCenterPoint) has to follow the structure lines e.g. according to the surface normal.

● A further advantage is the (non-cubic) *workspace*. In contrary to portal milling machines, a robot does not operate within a fixed frame. Flexibility in workspace is increased according to object dimensions. The additional tilting table and rotational axis (7th axis) help the robot in its ability to reach all requested areas and results in increased productivity.

● A further advantage is *calibration* and *self-reference* of the robot: the robot can reference its own position to the model. The process of rough/ fine cut followed by structure milling does not necessarily have to follow on top of each other. With the TCP one can calibrate and reference any stock model and pre-milled model to its digital data, the structure lines can be *milled* or *pencil drafted*.

● Generally should be noted, that an industrial robot as a numerically controlled (CNC) machine allows various applications. In the field of architecture, an industrial robot could be applied to additive fabrication/3-D-printing (such as the prototypes of informed walls, originated at ETH Zurich, Bonwetsch et al. 2006) as well as for milling or drafting. So its *flexibility* enables us to experiment with different tools to visualise curvilinear structures on solid objects.

Definition and milling of surface structures

In this report we present the first results developed with students of architecture, carried out at Vienna University of Technology in 2008. The aim was to further develop designs (elaborated in other courses by the students or, exceptionally, already built by architects), by refining curvilinear surface structures (referring to a buildable surface in large scale). After developing several variants, some solutions had to be manufactured with the aid of CNC milling technology. The situation was conceived as test set-up for simulating the situation of an architect starting to consider the feasibility of his/her just digitally generated shape.

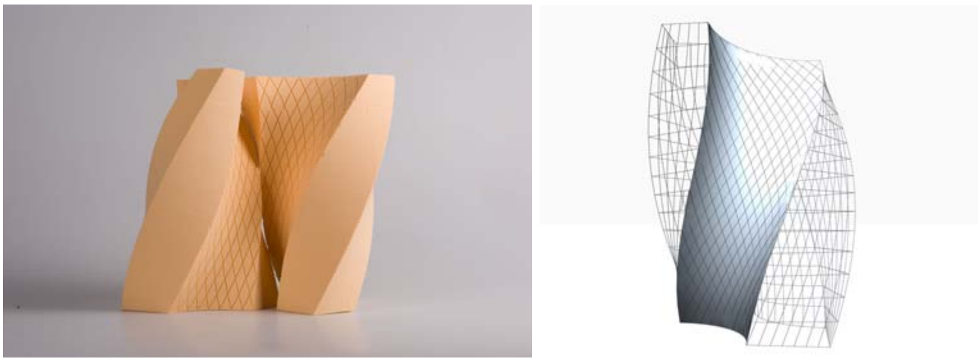

Fig.1: milled structured scale model (left), digital structured CAD model (right), study 1, Daniel Galonja (2008)

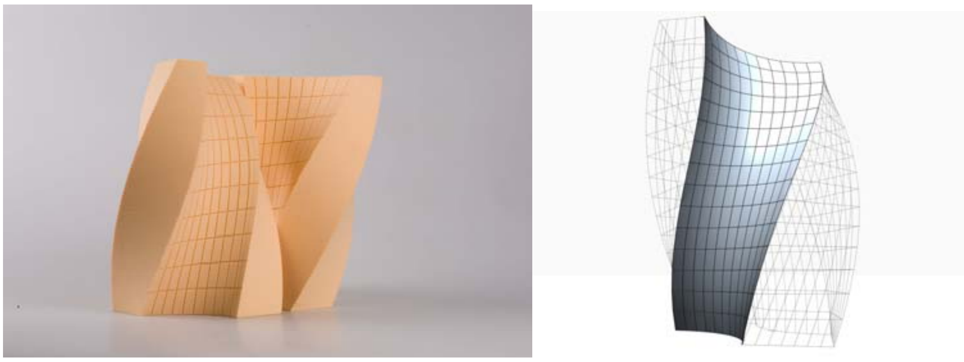

Fig.2: milled structured scale model (left), digital structured CAD model (right), study 2, Daniel Galonja (2008)

As a first step the students had to reflect, revise and refine the more or less implicit structures of their digitally generated designs, in such a way that the arbitrary linear structures became consciously considered structures (representing the segmentation of a façade). The shapes and curvilinear structures have been generated with a variety of CAD tools (the students used different software-packages such as Cinema 4D, Rhino or 3d-Max). To receive appropriate structures for milling - the CAM-strategy of *contour milling* in the available robot-milling software (Hypermill) has to support the geometric curves used - the students pursued different strategies. The following CAD-driven procedures could be distinguished:

● The easiest CAD-approach is to choose the "source" curves of the surface wireframe - as could be seen at realized projects (such as the BMW-Wave from Bernhard Franken), where the iso-parameter-lines are identical with the structure-lines of the bearing structure. This approach very often has been the starting point for the students. As an axample we show a structure-study (Fig x. galonja left), where the source curves for the NURBS-generation have been used as structure curves.

● This first strategy can be developed further by additional geometric transformations. Seen for example at the "double-cone" of the BMW-World by Coop Himmelblau in Munich, where the isoparametric curves of the double-cone additionally have been rotated. But as practice in architecture shows, in most cases source curves cannot be used. Therefore, the design of additional curvilinear structures is necessary. To achieve a variety of aesthetically satisfying structural solutions we asked the students to continue their initial designs of "just digitally" pre-determined surfaces. The project shown in figure 1 and 2 was followed up with a diamond structure - drawing on the surface while diagonally connecting the intersections of the initial source curves with the result that the same surface is motivated in a different way. Another example is a project (Fig.3), where a student generated the surface of his pavilion design with a triple transformation of a 3d-Spline (copy, scale and rotate) in Cinema 4D. In this case the curvilinear structure of the surface-result was not "dynamic" enough, therefore he defined additional *Akima* curves with an angled deviation on the surface geometry.

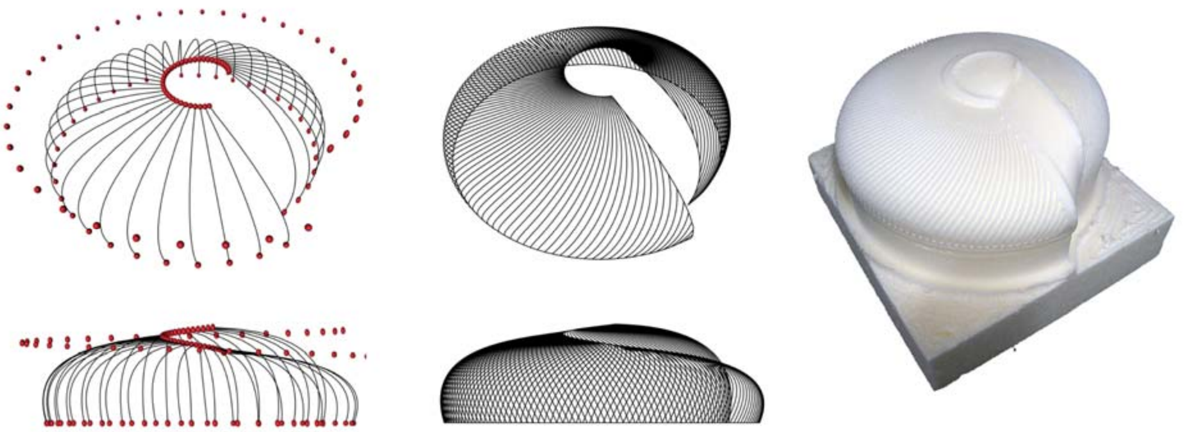

Fig.3: milled structured scale model (right), digital structured CAD model (left), Philipp Latzer

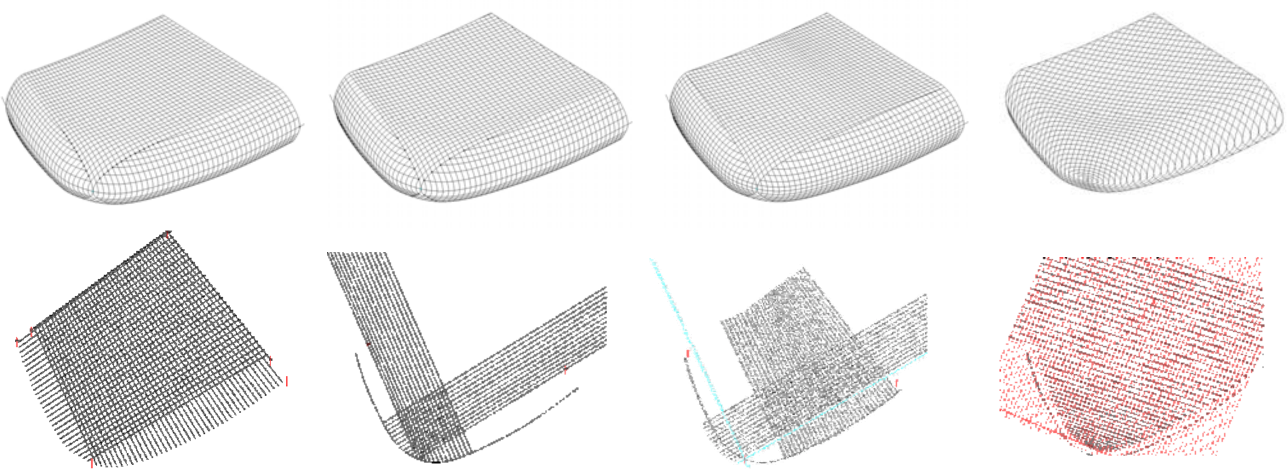

Fig.4: diverse structure-studies, digital CAD model, Ching-Hua Chen, Benjamin Stangl (2008)

● Another CAD-approach works via *projecting* spatial curves onto surfaces at hand (the Kunsthaus Graz is such an example). This strategy was chosen by students who decided to work with an already built shape (Bercy 2 Shopping Center near Paris, Renzo Piano; fig. 4, 5). The challenge to define a segmentation, where (horizontal and vertical) structures drifting apart come together, was solved by modifying the strategy of "projection". The students forced the curvelinear structure manually, such that lines meet in intersecting points.

Approaches apart from a CAD-modeling technique are parametric modeling, where for example source input curves can vary according to different surface conditions such as curvature deviations. A sophisticated approach is of course to account manufacturing constraints in the component layout for the surface generation. We are still in the test phase and hope to elaborate further results in the ongoing courses.

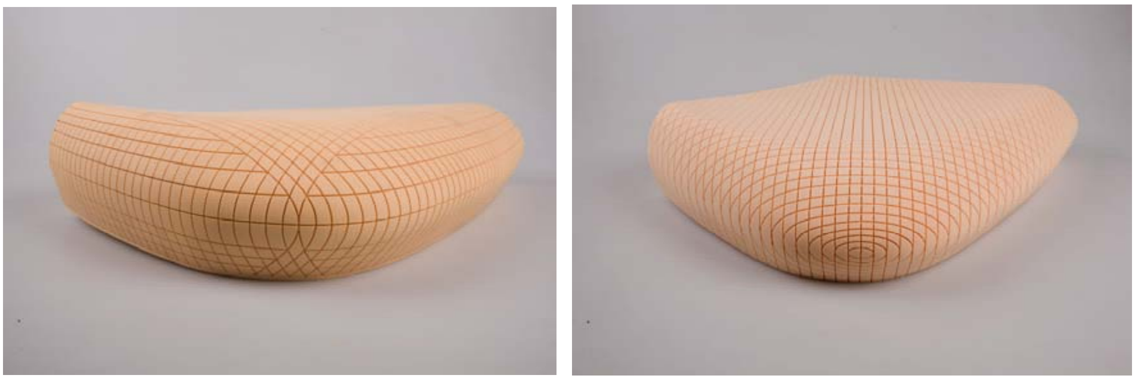

Fig. 5: milled structured scale models, study 1 + 2, Ching-Hua Chen, Benjamin Stangl (2008)

Fig. 6: analogue developed and manufactured design; cupboard; Martin Kappelmüller

Positively could be noted that the students have been sensitized for the constraints of 3-D geometry representation in CAD systems as well for the aesthetic dimension of façade-segmentation. Critically has to be said that the practice-detached academic sphere of teaching implicates not only "acting as if", but also the separation of working steps. The limitation on solid objects and segmentation of surfaces involves the risk that structuring takes on a life of its own and a posssible load-bearing structure is not considered accordingly. Furthermore it has to be mentioned that with milling curvilinear structures the feasibility of double-curved surface is not solved, if flat building material should be used. In that case the particular double-curved fields have to be triangulated and require an appropriate physical 3D representation(Fig. 6).

Conclusion and future research

Reflecting the first student results one could notice that the application of milling technology in the field of architectural model making is a practicable and promising thing. Due to the advantages and limitations of milling technique the application of milling technology is especially suitable for solid freeform shapes. The visualization of structures on milled solid objects has been reached with a subsequent milling step, but application of laser technology or drafting is possible as well.

The implementation of *structure-milled models* as a working aid in the architectural design process is recommended for a variety of reasons: Architects might be stimulated to develop parallel digital freeform surfaces and feasible surface structures and will consider manufacturing constraints previously. Possible variations could continuously and (relatively) easily be produced and refined. This would lead to less arbitrary 3-D- forms and structures. Certainly, *structural models* are no panacea, but they could serve as an effective and appropriate means for architects to value and verify artistic decisions. They are an ideal means for communication and should accompany the architectural design process in addition to other established and proven digital and analogue working aids.

In the light of our experiences manufacturing of more than two or three solids - in order to visualize different segmentation variations of one object - is elaborating, time-consuming and costly. Therefore we advocate a more sustainable method with less material waste: The experimental approach we call *3-D structure drafting* is based on a combination of milling technique and deep-drawing. A milled stockmodel is used to deep-draw any number of polystyrene sheets on which curvilinear structures could be drafted. We already carried out first tests with 3-D structure drafting and hope to bring good results soon. Beyond the undertaking to furnish the robot with a laser application, programming the robot's kinematics is also a big challenge and thus a topic of future research.

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