Journal for Geometry and Graphics
Volume 12 (2008), No. 2, 205–214.

Geometric aspects in Producing Non-Standard Architecture with Standard Tools

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Abstract. This paper presents geometrical approaches, considerations and computations of a concept how to produce non-standard architecture, namely façade design consisting of intelligent ornaments. The façades are assembled with polygonal parts derived from flat ornaments cut out of panels of a certain size. The panels are machined by a CNC milling cutter and afterwards they are glued together on their perfectly mitered sides. As a starting point for the construction we use a parametric driven CAD-package where an irregular space grid consisting of variable data points is generated. The space points can be placed and moved interactively by mouse dragging in the virtual space almost independently. For reasons of interest and challenge quadrangular polygons are used. Hence dependencies arise and some of the grid points can only be moved in a restricted way. Especially this way of working interactively on a design object supports the creativity of a modern architect in an appropriate way in order to create Non-Standard Architecture.

Key Words: parametric design, Cad-Cam, offsets, ornaments

MSC 2000: 51M20, 52C15, 68U05

1. Introduction

The development of new media and digital technologies in the last 15 years has enabled not only to generate and visualize complex geometries in architecture but also to transform it into buildable objects. This led to a new form of architecture, an architecture which can now fulfill much more design ideas and individual desire [4]. We try to explore ornamental patterns which can be used to enhance materials characteristics. We use standard building materials and develop a parametric design framework for the assembly [9]. Existing rules of ornamental geometry are applied to a parametric controlled structural model so as to endow

ISSN 1433-8157/$ 2.50

the building parts both with stability and aesthetics. The architectural background of this concept can be found in [8]. In this work the geometrical aspects are discussed. We will start our discussion with ornamentation (Section 2) and the generation of spatial structures. Section 3 deals with rules and constraints which are necessary to form our models. In Section 4 the intelligent ornament is described. Finally Section 5 shows the production line and how we implemented the concept.

2. Ornamentation

One important initial point of our approach is ornamentation. Through the whole history ornamentation played more or less an important role in architecture depending on fashion and technical developments. The continued use and development of ornaments indicates that there is a special human interest in "translating" these special geometric forms into buildable objects. Various approaches to the complexity of the subject matter of ornamentation can be found in [2], [5], [7], [11], and [12]. In the majority of cases ornaments are used in 2D form and in symmetrical appearance (Fig. 1).

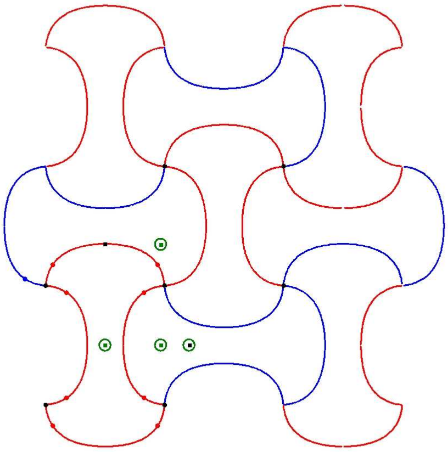

Figure 1: Flat ornament

We abandon this beaten path and convert the flat forms into spatial shapes. But we do not extrude the 2D ornaments into 3D-space like CAD-packages do (simply by extrusion) but rather give the third dimension an additional meaning.

Fig. 2 (left) shows a spatial model of the flat ornament of Fig. 1. Each prototype pattern got a curved and spatial form by using a Bézier surface (Fig. 2, right). The control points are positioned in a special way so that the adjacent parts join C^2-continously (see for instance [1], [6]). Moreover each prototype is congruent and offers still two symmetries.

If we go one step further we can abandon this "rigorous" geometric form and generate an "open" kind of symmetry and regularity. In our sense this means that we develop a shape which offers no geometrical symmetry or regularity but is developed from such a form. Figure 3 shows an example of such a procedure starting with a square grid, developing a quadrangular tessellation and ending with an arbitrary quadrangular grid (in the plane). The mutation of the objects in this example is not the direct use of geometric transformations but more an interactive one (by moving the grid points).

In this example the common structure consists of quadrangular regularity — in each vertex four quadrangles are joining. Then we pick up the grid points and drag them out of the plane

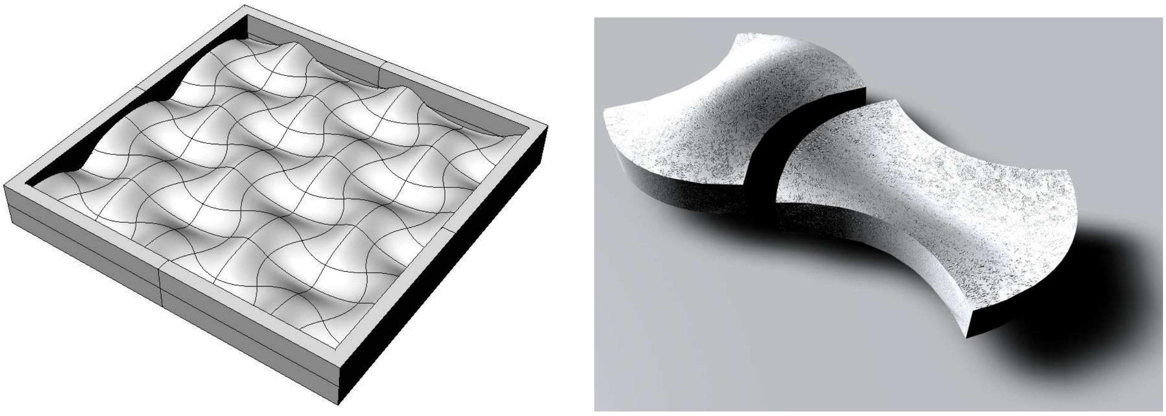

Figure 2: Left: Spatial form of the flat ornament shown in Fig. 1,
Right: C^2-continuous prototypes with thickness

to form a spatial grid whereas four neighboring points which formed a flat quadrangle before now build a spatial quadrangle. One possible way to fill such a quadrangle with a surface is to use a hyperbolic paraboloid (HP), as shown in Fig. 4.

However our intention is to use standard building material with flat faces like timber to produce our forms. HP shapes are not adequate for our project and so we try to flatten our spatial quadrangles. Hence, several geometric rules and restrictions have to be applied to generate the spatial ornaments, since the grid points are no longer free to move in space.

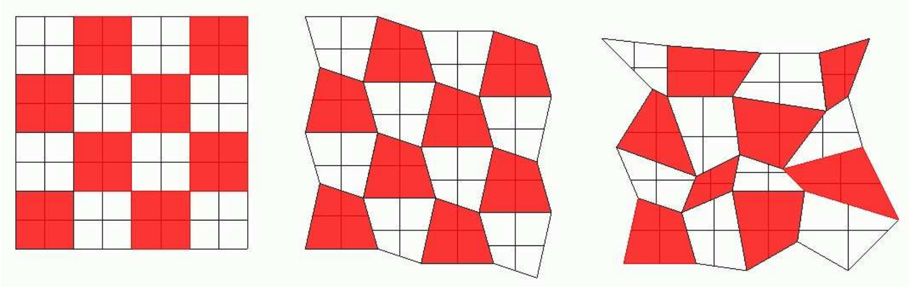

Figure 3: From the regular symmetric to the regular non-symmetric form

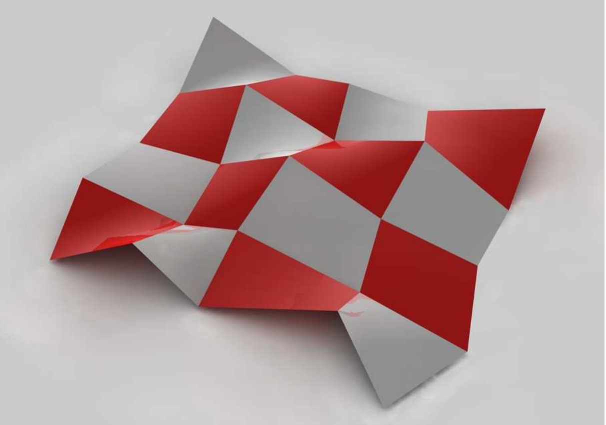

Figure 4: From the flat form into space

3. Rules and constraints

By means of a parametric driven CAD package we can "translate" the rules and constraints into parameters and generate a virtual model. Now changing the design by moving one grid point of the ornament the construction is automatically adapted by the used software.

3.1. Planarity

The best way to avoid problems when creating spatial structures with planar faces is to use triangulation. But the outcome is often neither aesthetically satisfying nor interesting but rather boring [3]. So we use flat quadrangles which automatically lead into problems. The grid points and the quadrangles are no longer free to move. Some of the points can only be moved in predefined planes and the quadrangles are mutually dependent with different degrees of freedom. Although in principle all parts are equal there exists a certain hierarchy depending on the instancing which is shown in Fig. 5 as an example. The starting panel A is free to move. The adjacent panels B are dependent on A, and the Cs are dependent on the Bs and A. This is just one possible approach of configuring this structure but there exist many more. In this essay this issue will not be discussed any further.

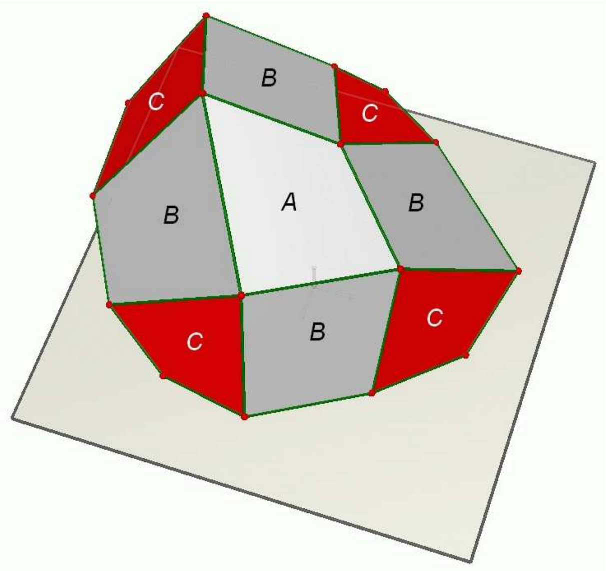

Figure 5: Planarity and hierarchic dependencies. The panels C are dependent on the Bs and the Bs are dependent on A

3.2. Material thickness

Material thickness induces an additional restriction to the geometric design. If we put panels of a certain thickness together we have to miter the parts along each side part. The obvious way doing it is to use the appropriate symmetric plane between joining grid faces which carry the panels (Figs. 6 and 7 left). Geometrically spoken we have to generate and to intersect offsets of our grid structure. Three panels can join arbitrarily in one vertex because the three associated miter planes meet always in one intersection line L. Moreover they are always tangent to common spheres with midpoints on L. Since this fact in general is not true for four parts we have to ensure that they are also tangent to a common sphere. This is due to the fact that all four associated symmetric planes have to meet in the intersection line L (see Fig. 7). All points on L have the same distance to the grid and the offset faces and so they can be used as midpoints for tangent spheres.

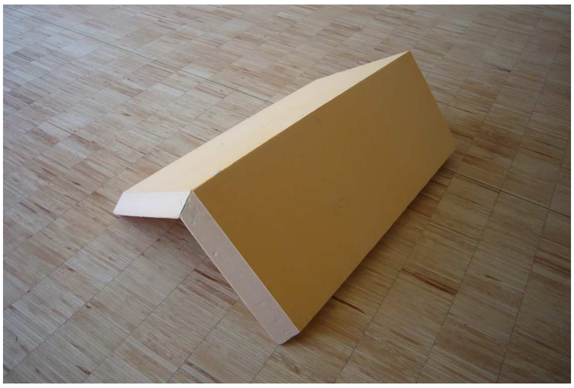

Figure 6: Material thickness induces miters in order to put panels together appropriately

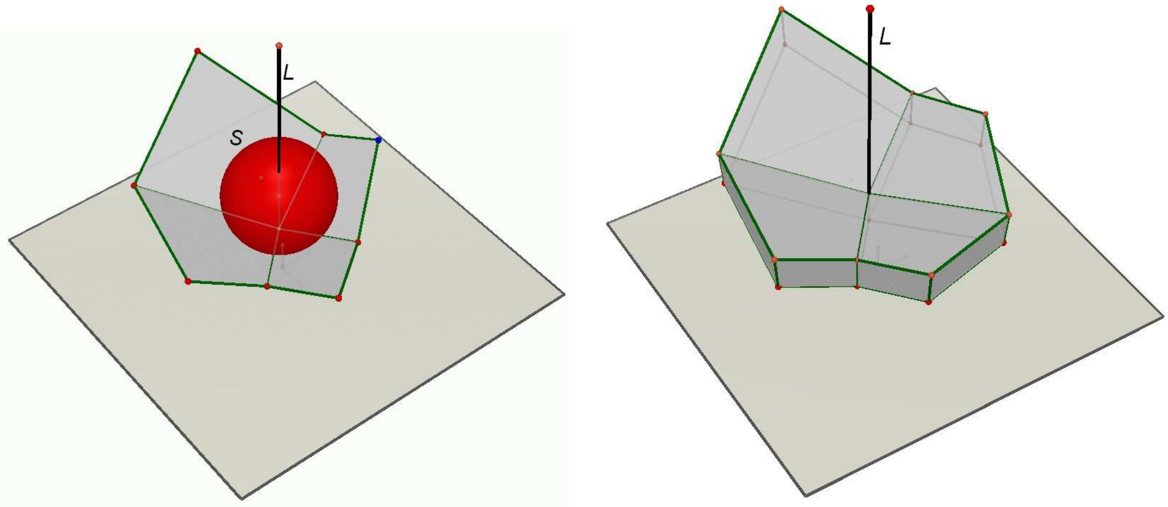

Figure 7: In order to put four panels of a certain thickness together they must be tangent to a common sphere S (left). The four symmetric (miter) planes meet in one intersection line L (right)

3.3. Size and angle restriction

One problem which is easier to handle is caused by the panel size which must not exceed a maximum width and length. This can be achieved be limiting the border lines and diagonals to the given size depending on the industrial produced building material. For the milling operation we use a special disc tool with limited workspace. Following this limitation we must restrict the angles between two adjacent panels because of the radius of the disc (see Section 5).

4. The intelligent ornament

Since we use a structure which can be compared with a matrix configuration the involved panels can be stored in the same scheme. Thereby each part knows its location in the scheme and so the neighbors, the angles between the faces, the thickness and also the milling paths for manufacturing can be stored (Fig. 8). When we use object oriented programming with class structures, objects, methods, attributes etc. each part (= instance) can immediately calculate its size, milling path length, milling time, etc.

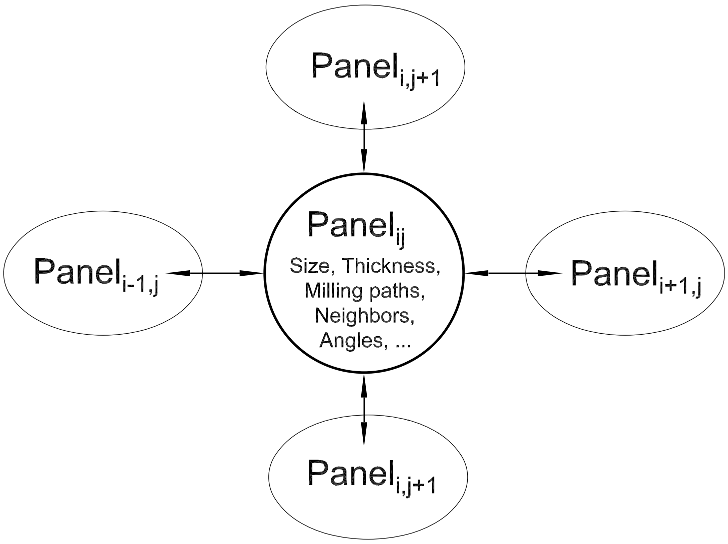

Figure 8: Matrix scheme of the panel configuration

Object oriented programming offers an ideal structured tool for working with parametric controlled ornaments. For that reason we speak about intelligent ornaments [8].

5. Production line

5.1. Design

The design and configuration of our spatial ornament can be performed with a parametric and feature based CAD package. The ornament grid configuration is generated in a 3D sketch in the assembly mode with all the rules, constraints and configurations. Each panel (including thickness) is an instance of a prototype part and is inserted in the assembly mode based on the 3D sketch (Fig. 9).

In this operation mode one can easily change the design — in this case moving the vertex points in space — certainly depending on the constraints causing the whole virtual model to adapt. For this step we used the CAD package SolidWorks. Since it was impossible to incorporate all our demands we had to adapt some steps in order to use the program's features. For the rules and constraints we used the integrated Visual Basic tool but without performing the object orientated approach.

5.2. Tooling

Professional CAD packages include plug-ins for generating data to operate milling machines. In order to manufacture our panels in one production step we had needed a 4 or a 5-axis

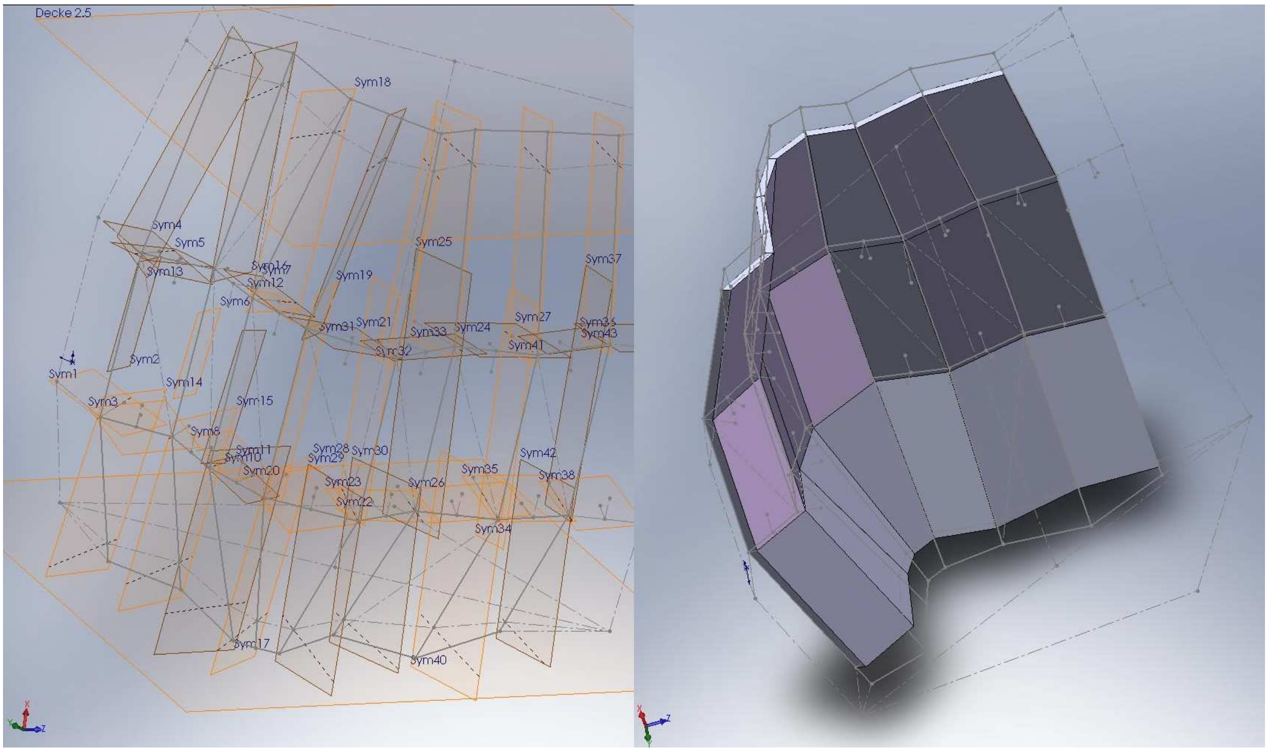

Figure 9: 3D sketch (left) and the assembled panel parts (right)

Figure 10: A manufactured panel with an undercut shape

machine because our ornament model produces panels with undercuts (Fig. 10).

Since we had only a 3-axis machine available we transformed this machine by using a special milling tool, namely a disked shaped saw blade with twelve teeth which we fixed horizontally with vertical axis (Fig. 11).

Therewith we were able to mill all four miters in one operation step after performing a roughing job with a standard tool to millcut the contour of the panel. As no software could produce milling data for such a configuration we had to program our own G-Code to feed the milling machine [10]. We did this with C++ and created a small software tool to translate the three dimensional panel data into machine ready milling paths (see Fig. 12 left).

Horizontal (waterline) milling was operated in constant z-levels. The circle curved teeth

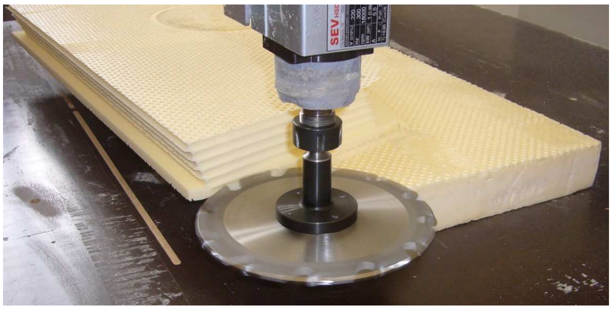

Figure 11: A disk shaped tool made of a regular saw blade

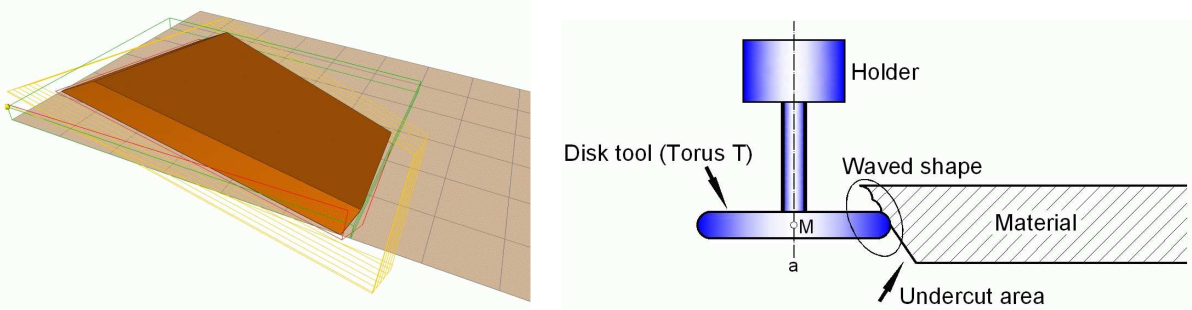

Figure 12: A panel and its milling paths (left). A disk tool can mill an undercut (right)

of our rotating disk tool generate a torus T with vertical axis (Fig. 12 right).

When the midpoint M of T is moved on a horizontal line the torus T envelopes a cylinder (Figs. 11 and 12 right). So when you move M in a plane following horizontal lines with infinitesimal distance T envelopes a plane as well. As it is impossible to mill in infinitesimal steps a discrete amount of z-levels are necessary. This produces a drawback namely a waved shape of the milled faces (Figs. 11 and 12 right). But as the panels join right there no visual damage occurs (Fig. 13). This leads to the calculation of milling paths which lie in appropriate offset planes of the miters. They depend on the disk tool radius and the disk teeth radius.

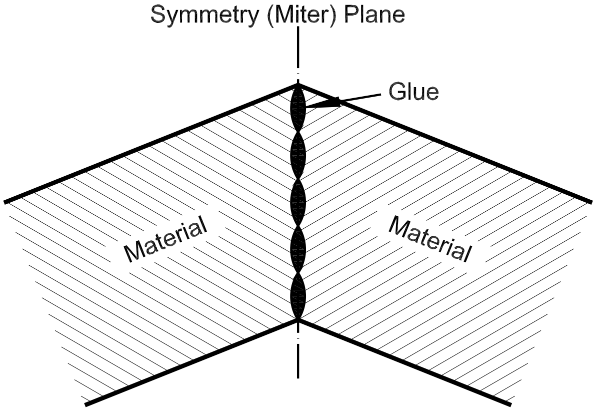

Figure 13: Two adjacent panels are glued together

5.3. Outcome

Figure 14 shows one outcome consisting of 21 parts joined together. It was designed and produced by a group of students in a special workshop by using glued extruded polystyrol foam panels.

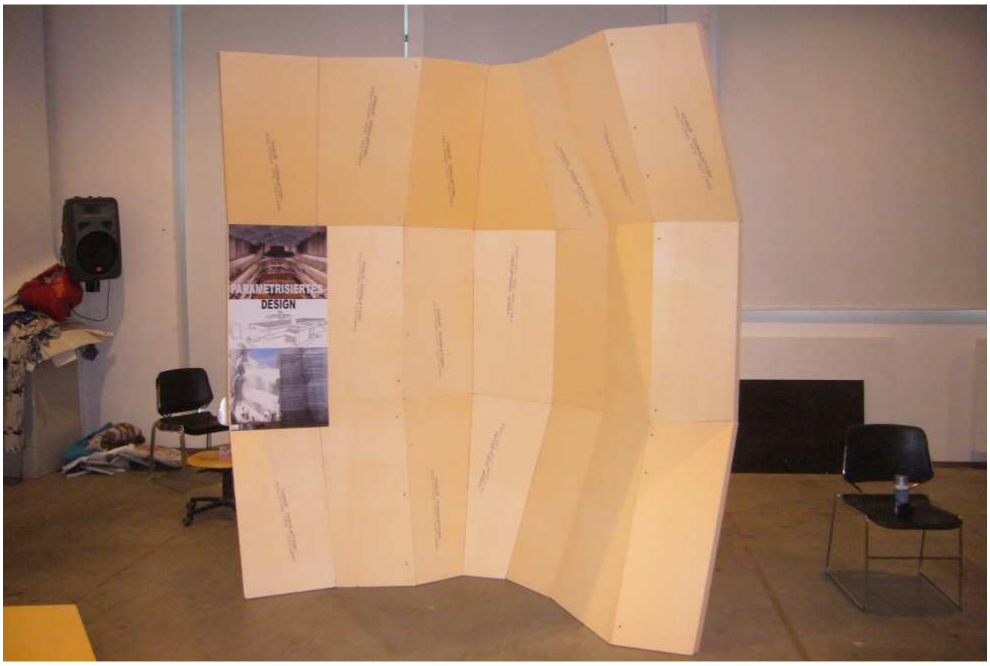

Figure 14: Non-standard form

6. Conclusion

Summing up it may be said that the shown CAD-CAM workflow from the virtual design of façade elements to the real production with a CNC machine is constantly accompanied by geometric considerations and influences. Although the geometric parts of the task seem trivial, in detail they are very complex and deserve a funded geometric knowledge. Especially when you leave traditional paths and use new possibilities and technologies to develop mass customized design products as shown above geometric perception and visualization can tremendously support the spatial relation through the entire workflow.

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Received August 4, 2008; final form December 3, 2008