"Inventioneering Architecture" – building a doubly curved section through Switzerland

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Abstract

This paper describes the automated detailing and fabrication of a complex doubly curved exhibition platform (designed by Instant Architects) accomplished with a continuous digital process chain. The project analysis points out a shift in value creation from material processing to information processing.

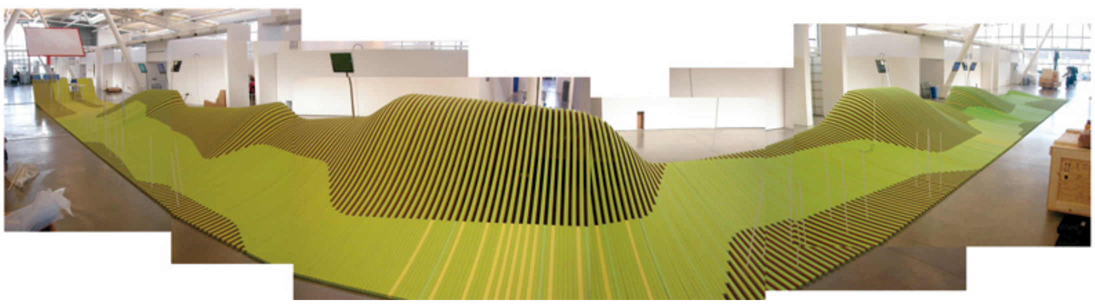


Figure 1: The 1100 rafters of "Inventioneering Architecture" at the CCA San Francisco (Image: Instant Architects)

1. Introduction

Building doubly curved surface is an old architects' challenge. Before free form could be described in CAD-systems, definition and construction of complex shape was a result of physical form-finding techniques:

In the early 20th century, Antoni Gaudí pioneered them as a design tool in three dimensions using hanging chain models (KILIAN 2004).

Heinz Isler, Swiss pioneer in building thin concrete shells, discovered his optimization method in 1955 by watching a freezing jute cloth on an core grid (RAMM 2002).

Frei Otto developed since 1964 at the Institute for Lightweight Structures at the University of Stuttgart his complex lightweight tensile and membrane structures from experiments with nets, stockings and soap-bubbles and scaled the results. (NERDINGER 2005).

The possibilites to realize a doubly curved surface are nowadays greater than ever. The designers on one side are supported by powerful 3D CAD-modellers that help with form finding and are eager to use this potential. Descriptions like NURBS[1] made it easy to define freeform surface. On the other side computerized (CNC) fabrication technologies enable the creation of individually parameterized parts for almost the cost of a standardized mass product. But in between those two sides often insurmountable challenges arise when it comes to detailing: Since free forms in architecture consist of a large number of individual components the planning effort scales with the number of parts, often not even linearly. The amount of border conditions to fulfil and plans to draw is in many cases out of the ordinary planning process.

Although there is a wide range of current architectural projects experimenting with doubly curved surfaces, we know little where planners managed to connect directly their planning tools with the fabrication. By introducing continuous and uninterrupted digital chains from form finding to fabrication, the Chair for Computer Aided Architectural Design (CAAD) at the ETH Zurich seeks to rationalise the materialisation process of complex design. With applicable projects we want to test the possibilities of establishing "digital process chains" in building practise. As "Inventioneering Architecture" our most public and applicable work, we want to demonstrate and analyse our working process with this example.

2. Inventioneering Architecture

“Inventioneering Architecture” is a traveling exhibition about the education at the four Swiss architecture schools (ETH Zurich, EPF Lausanne, University of Geneva and USI Mendrisio). Gerhard Schmitt, Vice President ETH Zurich, describes the exhibition's intention and content: *Providing a contemporary survey of the Swiss educational landscape, the work spans the interrelated domains of teaching and research. Not purely a collection of artefacts, the probes shown are are expressions of diverse points of view, positions held by established professionals such as among others Jacques Herzog, Pierre de Meuron, Peter Zumthor, Roger Diener, and Marcel Meili as well as a younger generation including Marc Angélil, Andrea Deplazes, Valerio Olgiati, and Christian Kerez.* (SCHMITT 2005).

"Inventioneering Architecture" is a statement of Swiss Architectural Education. It was first shown at the California College for Arts and Crafts (CCA) in San Francisco in October 2005 and is now touring the world[2].

2.1. The project: from a crosscut section through Swiss topography to an exhibiton platform

For this project the young Zurich office Instant Architects[3] designed a stage that was inspired by a section through Swiss topography along the line connecting the four cities of Mendrisio, Zurich, Lausanne, and Geneva. The doubly curved platform measures 40 by 3 meters with varying heights up to 1.5 meters. A footpath meanders along the surface, passing the exhibits.

Usually, doubly curved surfaces are accomplished either by approximating the continuously curved surface with a polygonal structure (e.g. the roof structure for the Milan Fair by Fuksas (SANCHEZ-ALVAREZ 2005) or by assembling deformed sheet material on a supporting structure (e.g. the BMW Pavilion by Bernhard Franken (CACHOLA SCHMAL 2004)). When Instant Architects started developing the shape for “Inventioneering Architecture”, they first thought of a third principle: milling the doubly curved terrain of the 120 square metre platform out of foam material and coating it with plastic. It turned out that production costs would be well over the top of the available budget.

2.2. The method : a digital process chain from design to production

Since the appointment of Ludger Hovestadt in 2000[4] the development of digital production chains in the field of architecture is a main focus at the Chair of CAAD at the ETH Zurich. By a "digital process chain" we understand an uninterrupted digital process from design (determination of shape and structure) to construction (detailing) and production (CNC-manufacturing). The single steps are scripted units interconnected by defined interfaces. The computer is not used as a passive digital drawing board but as a tool which actively influences and optimizes the design. The role of the architect shifts from form designer to process designer. Since 2001 numerous experiments with digital fabrication in 1:1 scale were accomplished at the Chair of CAAD by diploma students, postgraduates and researchers – but always in an academic context, not commissioned by an external client. With this project, we were seeking to test our knowledge in a professional environment.

When Instant Architects asked us for advice how to realize their idea, it was a great opportunity to verify the experiments' results in a demanding project and in cooperation with external partners. From mere theory, economic reflections became the key factor of our work. The aim was to implement a “digital process chain” that contains all necessary information in one parameterized digital model and allows for CNC manufacturing of many individual parts without having to manually design every variant.

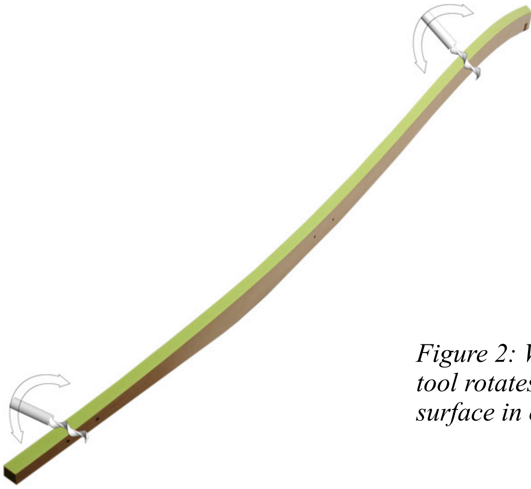


Figure 2: While cutting the upper surface of the rafter, the milling tool rotates around the milling path, thus creating a doubly-curved surface in one go.

2.2.1. Step 1: Design requirements

For the Inventioneering Architecture platform the overall geometry was predefined by the architects in the CAD software Maya. Functional requirements were given by the footpath across the structure and the need for easy assembly and shipping in a standard overseas container but there were no prerequisites for the construction method.

2.2.2. Step 2: Respecting machine and material capabilities

As we had just a few weeks before finished a pavilion for the Swiss building fair SWISSBAU 05 (SCHEURER 2005), we were familiar with the capabilities of the five-axis router of our external partner Bach Heiden AG. We proposed to build the hilly platform from 1000 individually curved rafters, milled on the five-axis machine out of medium density fiberboard (MDF). They are assembled in comb-shape, so that their overlapping sections form the closed surface of the path while the exhibition area is marked by gaps. The whole detailing was derived from the specific movements of the CNC-router. The 40m long platform is divided into 40 millimeter wide sections, each describing the upper surface of one rafter. The milling tool follows the center path of the section and rotates around it at the same time, cutting out a so called "ruled surface" that follows the topography of the platform both along and across the section. Thus it is possible to manufacture a three-dimensional, doubly curved surface from two-dimensional sheet material at very low cost. The rafters are connected by dowels and supported by perpendicular boards.

2.2.3. Step 3: Design automation

The form of the stage was designed by the architects by creating a NURBS-surface with the modelling software Maya. The built result was required to match this geometry exactly, so the coordinates and curvatured were to be read directly from the

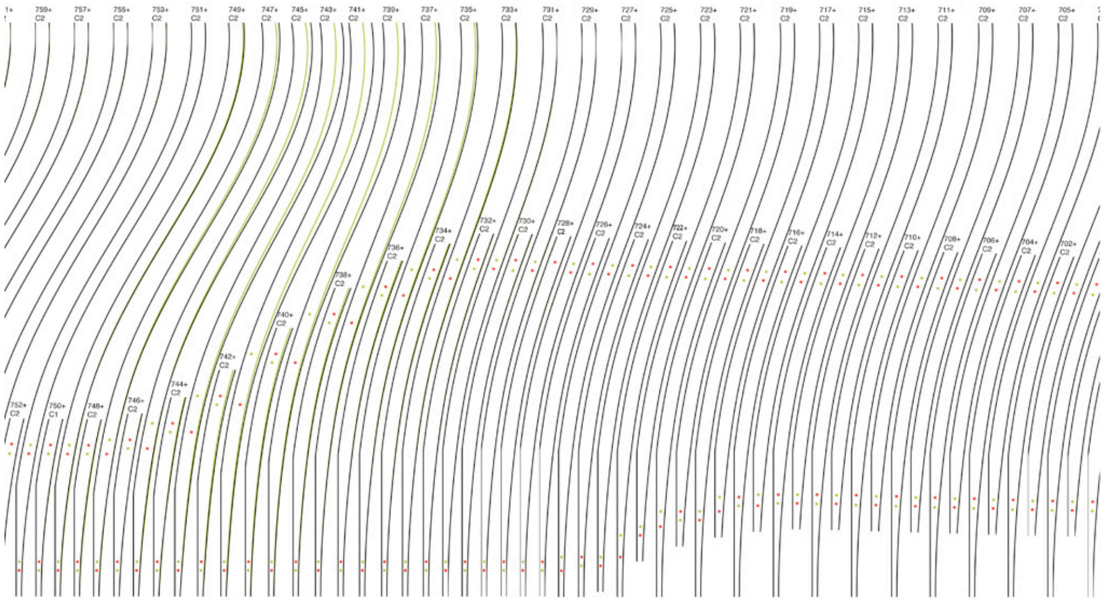


Figure 3: A selection of the platform's milling paths, as generated by VectorScript. The rafters are defined by Spline-curves, but since the CNC-router only uses straight lines and radii, the curvature had to be approximated by polygons with a point distance of 9.0 mm.

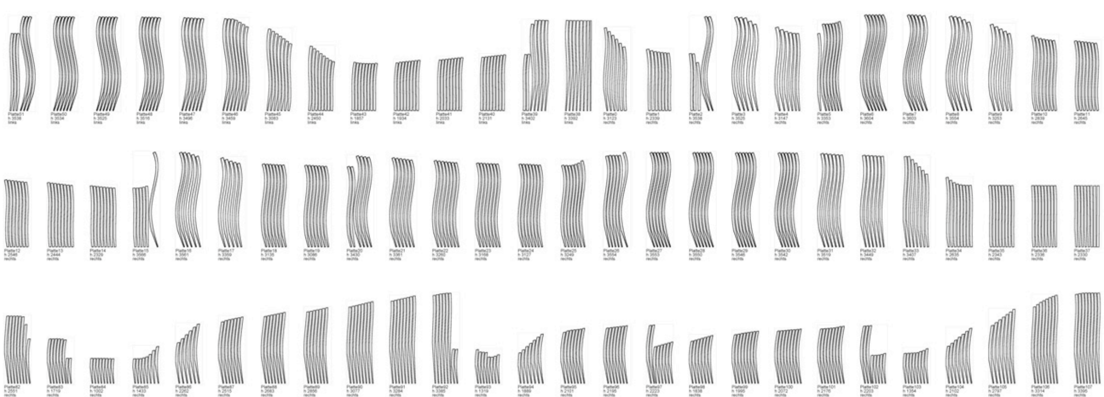


Figure 4: The platform's 1100 rafters are automatically nested and optimized on 152 MDF-boards. One G-Code per board is generated for the 5-axis router.

NURBS surface.

2.2.3.1. Defining the geometry

The landscape was explicitly shaped until it fit the requirements of the designer and then cut into sections as proposed in Step 2 (Chapter 2.2.2). Since the cut structure consists of roughly 1000 individually shaped parts, the crucial point was to automate the translation of the platform geometry into the geometry of the single parts and finally into the code controlling the CNC mill. This was accomplished by a set of scripts in the CAD-package Vectorworks. The first script imports the original design defined as a NURBS-surface from the modeling software Maya, reads the coordinates of the platform's cross-sections for every rafter and determines the angles of bank.

Automated detailing

Reading the coordinates of the surface only returned the geometry of the upper surface of every rafter. After defining the exact geometry of the structure, this "abstract" description has to be translated into detailed geometries for the single parts. A second script adds to the surface geometry the complete geometry for all 1000 rafters, including all drillings for the connecting wood dowels.

Automated nesting

A third script arranges the rafters on the MDF-boards to minimize waste and optimize cost. On the manufacturing side, the material can now be prepared by cutting up the raw boards into appropriate chunks. Also arrangements for numbering the single parts – in our case by sticky notes – took place at this stage. 120 MDF-boards sized 1.0 by 4.2 meters were used to position all rafters.

Generating NC-Code

The production code (NC-code or G-code[5]) for the CNC-machine is the final result of the digital production chain. G-code is basically telling the machine which tool to choose and where to move it. Usually, this is programmed by the manufacturer on the basis of detailed construction drawings. For the automated generation of the G-code in our digital process chain, a single exemplary rafter of the structure is processed "manually" and the resulting code is used as a prototype for the other parts. A final script is created which generates the appropriate code for all MDF-boards from the CAD-model of the nested rafters. Those codes are then handed back to the manufacturer and fed directly into the five-axis-router to start roughly 50 milling hours of production.

3. Analysis

In the analysis of the project we focussed on two aspects as mentioned in the introduction: first, a classification of the chosen path to construct the doubly curved surface, and second, an examination of the manufacturing process from an economic point of view.

3.1. Constructive

The construction and detailing is reflecting the application of a digital process chain:

3.1.1. The adaptive system

For "Inventioneering Architecture" an adaptive building system was developed: A sequence of 1000 rafters, each of them individual. Although we may speak of a "system" as all its elements are part of the same order, it is highly individual on two scales: First, the system was developed specifically for this design. While in the 1960ies architects sought for general solutions to fit all kind of building problems[6], this is an individual solution that does not claim to be assignable to other designs and it will probably not fit with many. It is an individually tailored system for a specific design. Second, the system consists of 1000 unique pieces, which are all variants of the same element and differ only in a few parameters, namely the control points of the surface. They are parametric: serialized, but individual. The topography of the platform could be very different (within the borders of the router's table dimensions, defining the maximum size of a rafter), and still the elements would belong to same family. To distinguish between the *general system* approach of the industrial age and the individual system in the information age, we want to introduce for our construction the term *adaptive system*.

3.1.2. The integral process thinking

The constructive solution that was developed for "Inventioneering Architecture" is a "building system" in the sense Helmut Spieker describes the term: *Basic characteristic of the system principle is that it demands in much stronger way an integral, systematic view on planning and building, i.e. the linkage of planning, submission, production, assembly, use and disassembly, during which the methodolody of joining is of central significance.* (SPIEKER 1989). What Spieker refers to is a general system

Figure 5: The generated code for the 5-axis router is directly fed into the machine without manual revision.
The three CNC-fabrication steps are:
Drilling: crating dowel holes for the connections
Roughing: pre-cutting the form of the rafters
Finishing: smoothing the surfaces

from the industrial age as decribed in chapter 3.1.1. – but the definition as well covers our process for the adaptive system from chapter 2.2. What makes the difference, is the substance of the process: Our digital chain is not about material processing, but about information processing. While the information is translated into the script and program languages of the different applications until it is transformed into the NC-code, it still contains the data of the surface definition in the very beginning. Interesting seems to us the idea that even the CNC-router at the end of the chain is not processing material but is processing information into material.

3.1.3. Refinement through CNC-production

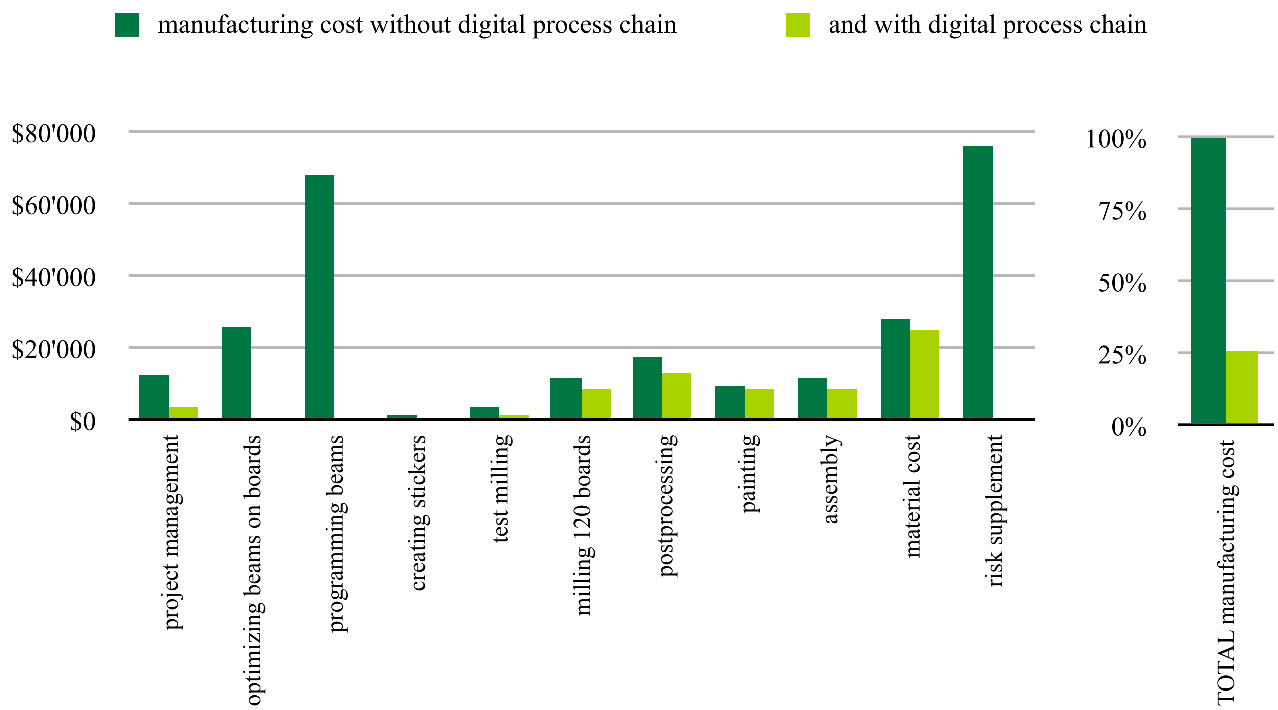
The interaction of design and production is set up as a digital process chain in both directions: from design to production and from production to design. Taking the capabilies of the chosen CNC-machine into account turns around the usual design process: the machine features define the detailing. First, this is necessary to identify at an early stage points in the production chain, where material and machine properties can be exploited and at the same time cost intensive manual labour can be avoided. Second, respecting machine and tool charecteristics opens possibilties to develop a construction that goes beyond manual labor in tolerance and speed. The detailing and the ruled surface as decribed in Chapter 2.2.2 could definitely not have been crafted manually in this precision. It is a construction that reflects a new *refinement*, potentiated by the adequate use of CNC-machines.

3.2. Economical: Complexity becomes feasable

In the economical analysis after this project three results became very clear. Quality, flexibility and efficiency were the main issues in the project. The potential of the presented process to resolve those issues actually made it possible to realize the project, which would have been too complex and cost intensive otherwise.

3.2.1. Quality

With CNC manufacturing it is possible to achieve a level of exactitude that is not within reach of manual work at this project scale. By implementing a digital chain this quality can be maintained throughout the whole process, which essentially makes it possible to create structures from a few thousand individually shaped parts which fit to the tenth of a millimetre at every contact point. Usually the tolerances of the CNC machines are very reliable and the material tolerances (especially when working with wood) are much more challenging. At the same time the digital process requires an algorithmic approach to quality management with more bug-fixing in software development than measuring of fabrication tolerances. The generation of geometries and fabrication codes by software mostly leads to either entirely correct or entirely flawed results but the flaws are sometimes difficult to detect due to the complexity of the



structure. Plausibility checks have to be carefully designed and performed after every step of the process.

3.2.2. Flexibility

Since the whole process relies on a parametric digital model, it responds very well to changes. Late design alterations as well as other changes are no problem as long as they lie within the boundaries of the model. The details for the connections of all 1000 parts for example were changed by the architects several times few days before the production was to start. The new G-Codes for the CNC-router could be generated practically over night, so the production schedule was not influenced.

3.2.3. Economic efficiency

Detailed calculations provided by the manufacturer[7] showed how much it would have cost to fabricate the project on the same CNC-machine but without a digital chain delivering the machine-ready data. The figures are impressive: the reduction of manufacturing cost reaches 74 percent. Primary cost factor in the “conventional” CNC-process is the programming of the NC-Code and the optimization for production, which was completely taken off the manufacturer’s shoulders and done much more efficiently by the use of parameterized CAD-models. A second decisive cost factor is the so-called risk supplement: A percentage the entrepreneur adds to the total to estimate unexpected risks such as manual flaws, repetition of elements etc. In the case of "Inventioneering Architecture" the carpentry shop would have calculated a risk supplement of 40 percent of the total. Because of the high safety the digital process could guarantee our external partner did not add any. While the latter "risk supplement" is a soft subjective factor estimated by the company (and can only be reviewed by sub-

Figure 7: Inauguration of the exhibition (Images: Instant Architects)

Figure 8: Every rafter has a different profile.

mission), the automated NC-code programming of the single beams is a hard objective factor calculated in hours (based on the carpentry's long experience with CNC-production).

As our participation was a university research, we did not count our hours. If we had considered our work as a commercial consulting and had taken into account our time for developing and programming, the saving potential were still around considerable 25 to 50 percent of the total budget.

4. Conclusion: A new building economy – Added value through information processing

The economic context was crucial for our participation in the project. Without the digital process chain the project could not have been realized within the budget and time constraints. We have realized that we can influence the total building cost significantly by the way we handle information about the building elements. The decisive factor was not the automatization of the production, but the automatization of the information processing. Assuming that material cost is the key factor of the agrarian age (craft) and the machine time key factor of the industrial age under tayloristic imprint, information processing is the key factor of the information age. There is a shift of added value from material processing to information processing.

The processes in the information age do not replace the processes of the industrial age, but supplement them: The machines and processing tecniques have largely remained the same. Architecture today is still constructed from concrete, steel, wood, plastics, and glass. Decisive is the substance of the process. Key and focus of today's process thinking and value creation is the information processing which controls the industral material processing.

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in collaboration with Instant Architects, Zurich, www.instant-arch.net

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6. Notes

[1] NURBS, short for non-uniform, rational B-spline, is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. Development of NURBS (actually the Bézier curve) began in the 1950s by engineers who were in need of a mathematically exact representation of freeform surfaces like those used for car bodies and ship hulls, which could be exactly reproduced whenever technically needed. Prior representations of this kind of surfaces only existed as a single physical model created by the designer.

[2] Inventioneering Architecture Exhibition: San Franscisco, California College of the Arts CCA, 10-03 through 10-27-2006; Boston, Boston Logan Airport 01-20 through 03-31-2006; Berlin, Kulturforum Potsdamer Platz 05-11 through 06-30-2006, see the project website www.inventioneering-architecture.ch

[3] Instant Architects Zurich/Berlin (Hebel, Dirk / Stollmann, Jörg), www.instant-arch.net

[4] The Chair of CAAD at ETH Zurich was established in 1988 by Gerhard Schmitt and directed by him until he became Vice President of the ETH in 1998. From 1998 to 2000 Maia Engeli held an interim position. In 2000 Ludger Hovestadt was appointed Professor of CAAD.

[5] G-code is a common name for the programming language drive NC and CNC machine tools. G-code is also the name of any word in a CNC program that begins with the letter G, and generally is a code telling the machine tool what type of action to perform.

[6] An example for a building system is the "General Panel System", developed by Walter Gropius and Konrad Wachsmann between 1941 and 1947 and described in WACHSMANN 1959

[7] provided by the carpentry Bach Heiden AG, CH 9410 Heiden. Prices are Swiss Building Standard and reviewed through submission.