The M.ANY Project - Exploring a Matrix Model for a Fully Digital Workflow in Architectural Design

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Current information technologies facilitate the design of highly customized architectures using complex geometries. In order to be able to realize such architectures a generative design approach including the seamless use of digital design data is essential. The m.any project displays a fully digital workflow from parametric design to production on CNC-machines. An irregular spatial structure generated by algorithms is controlled and manipulated through an especially developed software. In addition to the calculation of the complex geometry, the software also generates necessary construction elements for the realization. These elements are processed on computer controlled fabrication facilities. Based on the m.any project we illustrate how the common workflow in architectural design changes when fully incorporating digital tools. Instead of a linear sequence of design decisions we introduce the concept of a process matrix which meets the multiple dependencies of a digital workflow. The realization of a physical prototype is presented as the result of the implementation of the matrix concept on an architectural design task.

Keywords: Generative design; digital chain; digital fabrication; voronoi algorithms; programming.

Introduction

The m.any project was set up as a case study aiming for a fully integrated digital workflow from conceptual design to production rather than for a defined design output. The initial decision to create a spatial structure only obtainable by using dynamic processes made the seamless use of digital design information mandatory. Due to the targeted generation process the resulting structures were expected to be complex, and therefore only processable using digital design data. Using a parametric digital model as a “workbench” throughout all work phases, the data was finally used to directly output the physical elements of the structure on CNC-machinery.

Instead of working in a linear sequence of design decisions, the working process had to be set up like a matrix in order to capture the evolving parametric dependencies throughout the phases. Each working section had to claim their dependencies on the
overall design, collectively and constantly shaping the final result. These dependencies had to be integrated through parameters within the generating software.

Horizontally, this matrix consisted of four working sections: conditions, programming, construction and production. Vertically, the working sections evolved throughout four consecutive phases: concept, feasibility, development and production.

The final prototype was thus not defined by a specific design output but evolved by process decisions within the digital workflow. These decisions were integrated into the programmed model by parameters, controlling the dynamic creation of the structure. In a group of seven postgraduate students, the project was developed from concept to production within three months.

**Conditions**
Starting point was the definition of the desired spatial topology. For the case study, a three-dimensional spatial structure as found in natural cellular and crystalline structures was chosen because of several reasons: Conceptually, these structures impose a new understanding of space: The generated space is not defined by fixed boundaries (wall, floor, ceiling) but by its dynamic relation to neighbouring “sites”, which allow a different three-dimensional disposition of space. These sites are created by growth process, which are influenced by inner and outer parameters such as physical forces (inner parameter) or the situational context of the proposed building site of the structure (outer parameter). The manifestation of space is therefore process-driven rather than design based. These structures defined by numerous dependencies can only be evolved in a dynamical system. In order to design and realize such a system a digital workflow from design to production is necessary. The structure, its elements and their dependencies are to complex to be shaped, drawn or manufactured by hand.

**Programming**
Inspired by analogies to nature the generative process is based on a dynamical system, mimicking the natural abilities of e.g. foams to find stable approximations of global states based on local acting rules. Based on the concept of cellular automata (Wuensche, Lesser, 1992) the generative system is composed out of single cells, with each cell having an identical set of simple rules and its development depending on its neighbouring relations. Spheres represent the cells which are the individual void spaces of the design. A three-dimensional Voronoi diagram of the spheres center points in space defines the structural grid. A Voronoi diagram is a spatial description of a set of points, where the area circumscribing each point is maximised, which results in multi-faceted polygonal compounds. As a general characteristic the nodes in Voronoi diagrams in three-dimensional space are always connected.
to exactly four neighbouring nodes and each edge is associated to three polygonal faces which are always planar. These characteristics were an important precondition for the development of a construction system. The generation of the Voronoi diagram was implemented using a modification of the “DeWall” algorithm (Cigoni, Montani, Scopigno, 1998).

The software simulates a growth process of the structure. In analogy to the chosen natural examples, inner and outer parameters were defined within the software. They allowed a certain extent of control over the growth process. The software lets designer determine the maximum volume of the construction as well as the number of cells and defines a particular value for the minimal and maximal length of the structure. With the help of force vectors and cutting planes, it is additionally possible to control the distribution of density within the whole structure and apply external influences. The program allows the organization of the cells according to the predefined parameters. If, for example, the maximum length of the edge is exceeded, the affected cell will divide and build an additional sphere. This process will continue until the system stabilizes. The designer is able to constantly vary the input and thus create a multitude of possible variants. Nodes in three-dimensional space accurately define the programmed model. This data can be saved in an XML file (Extensible Mark-up Language) and passed on to other programs. The program is written in JAVA and uses the JAVA 3D API for real-time visualisation (http://www.java.com/). The designer can control the form-finding process directly by changing and adjusting parameters.

In a second step the stored geometry is imported into a commercial CAD-Software (Rhinoceros, http://www.rhino3d.com/). An especially programmed parser interprets the data of the model related to a set of construction parameters and creates the physical elements to be produced: After a rebuilt of the imported geometry data, the construction data is calculated and visualized according to construction
and material parameters, such as inner and outer radii of the construction elements. These parameters can be customized in real time during the processing of the data.

Finally, the programmed script automatically creates and arranges the necessary cutting plans for the CNC-machines. Each polygonal element, a so-called “frame”, is rotated into an even plane, and the necessary milling offsets for the machine paths are automatically calculated. A second procedure builds up the geometry for the frame connectors, as well as the cutting plans needed for fabrication. Of the several hundred individual frame connectors, each one shaped in an individual angle derived by the geometry of the overall structure.

**Construction**

The constructional challenge of the many project was to realize a construction of complete irregularity. It was necessary to develop a spatial system able to cope with entirely different cellular elements that connect to form a stable structure. This led to the proposition of four conditions that had to be met:

- **Flexibility**: As given by the geometric model, the constructive system had to cope with connecting elements in any angle possible in order to achieve a completely irregular structure. All nodes as well as all elements were expected to be entirely different.

- **Stability**: Due to the irregularity as well as the not yet foreseeable arrangement of cells, varying loads depending on the position of the cell within the structure as well as the size of the cell itself were expected.

- **Material**: Materials capable to be manufactured on CNC-machinery were researched, covering a range from inflatable textiles over chemical foams to lasercutted steel plates.

- **Assembly**: The prototype had to be assembled without machinery or tools by a couple of people by hand in a short amount of time. This implied a setup system for several people to work on the structure at the same time as well as a connection system that was stable enough but still could be assembled by hand.

Material research and the concluding analysis showed that the most suitable material for the realization of many on the CNC-machines available was coated MDF (medium dense wood fiber) plate material. Further development of the programmed geometrical model showed that there would only be two types of nodes within the structural system: One node type connecting four cell surface elements on the inside and another connecting three cell surface elements on the outer boundary of the structure. The surface elements had to be connected on the conjoint edges. The shape of each surface element is parametrically defined by the edge length and the corner radius of the outside and inside edges. By changing the radii, the shape and therefore the visual appearance can change from being very polygonal using only small corner radii to appearing very organic by using large corner radii. The parameter of the inside edge offset influences the stiffness of the single element edge as well as the overall structure. Furthermore, this offset parameter controls the opening ratio of the surface and therefore

![Construction prototyping and mockups, final prototype](Figure 4)
the specific and overall density of the structure. This results in very different visual appearances of the structure, changing from very lightweight to completely closed surfaces. The opening ratio influences the overall weight as well as the resulting loads on the connections. Experimenting with these parameters makes it possible to balance between self-weight, stability and visual appearance. For the final construction, these frame elements were linked by “connectors” - elements either connecting two or three “frame” elements.

Production
The prototype was to be produced entirely on CNC (computer numerically controlled)- machinery. Therefore the geometry had to be exactly defined within the model, incorporating production constraints such as milling radii or lasercutting precision and possible cutting depths. The used CNC-mill employs an imprecision of 0.5 mm to 1.5 mm, the CNC laser cutter only around 0.2 mm. For the production of the connecting pieces an extremely precise result was needed in order to be able to assemble the structure manually and still achieve enough stability. The lasercutter was used to cut, or better, to burn away the MDF material achieving an additional induration of the component edges. Another example of a parametrical constraint is the maximum production size. In this case, no element was allowed to be larger than the size of the available milling table. This had direct consequences on the construction as larger frame elements had to be divided into two as well as on the geometric model – no edge was allowed to exceed this size. These production and assembly parameters had also to be integrated into the programmed model in order to deliver correct production data.

Results
The experimental prototype - m.any - is a structure alterable in form, dimension and density. It can be created at any place in as many variations as necessary. The developing principles are always the same, but changing values of the broad set of individual parameters affect its generation and therefore its appearance. Rather than a determined design the m.any project offers a framework in which a design can evolve.

For the physical prototype of m.any the parameters effecting the generation of the design were set according to the actual space where the structure was to be displayed (i.e. the overall volume of the structure, boundary conditions etc.) The prototype structure fits into a bounding box of roughly three by three by eight meters and consists out of over 2000 unique parts. Still, the overall time from the start of the generation process of the final prototype up to the finished production of all physical elements was only eleven hours. In contrast, it took four persons the same amount of time to assemble the prototype. This final working section, the assembly, was underestimated in the process, especially the consideration of the large amount of individual parts to be assembled in the exact order. The discrepancy in time and effort revealed that a holistic approach towards digital developed architecture cannot end with the manufacturing process, but must also consider the
final assembly, especially when transferring this task to a realistic building site.

Discussion

The physical output of the m.any prototype exemplarily displays a complete digital workflow within the scope of architectural design. The project revealed that in using solely digital tools one has to refrain from common architectural design practice, which more or less consists of a linear workflow with clearly defined work packages. Instead of passing on a finalized version from one assignment to the next all process steps from the architectural design up to construction and assembly have to be considered in parallel. The process steps constantly influence one another. As a result there is no clearly defined image of the construction output or even the architectural design until the entire process is finalized. In contrast to a “linear chain” we introduce a “process matrix” as a process model which considers the interdependency of all working sections and is able to capture the full potential of an integrated digital workflow. Working with this matrix has to be realized with an evolving parametrical design model that can be developed from abstract to specific, looping in design iterations.

Using the “process matrix” implies a strong conceptual approach towards an architectural problem: In order to incorporate upcoming dependencies from each work section, the design has to stay very abstract and volatile until the very end when the physical elements are produced. Insights gained in one section can fertilize the developments in the other sections. This leads to a constant readjustment of the process steps.

The m.any project exemplarily highlights that unlike a traditional approach towards architecture of constantly refining a determined design, the “process matrix” offers a framework in which a design can evolve. This implicates that up to the very end of the working process many design elements remain ambiguous. In contrast, once the “process matrix” is finalised, a multitude of design variants can be produced in a minimum of time.

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