PROJECT WAVE 0.18

Intelligent joining systems for freeform panel-based structures with particular focus on production and assembly.

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Abstract. Currently, many parametric designs focus primarily on the geometric or formal expression. Typically this leads to very complex and formally elaborate but difficult to realise approaches. As part of the research and teaching project the aim was to develop new joining and construction systems with a view to optimising both the prefabrication of building elements as well as the entire production process right through to disassembly and test it in a 1:1 prototype.

1. Background

In 1959, Konrad Wachsmann described the onset of prefabricated building construction methods as a “The Turning Point of Building” in his seminal publication “Wendepunkt im Bauen” and with it identified what was to become a central preoccupation for many generations of architects to come. To celebrate the 50th anniversary of its publishing, the Pinakothek der Moderne in Munich hosted an exhibition “Wendepunkte im Bauen” from March to June 2010 (Nerdinger, 2010).

The exhibition provides an overview of the topic of industrial prefabrication in construction, for experts and laypeople alike, illustrated with numerous models and animations from over the years.
In addition to the chronological presentation of construction systems from the last 150 years, the exhibition also points to a second turning point in building: the paradigm shift from serial production to individualised mass production made possible by computer-based design and fabrication methods.

As part of this topic, a joint teaching and research project was undertaken at the Chair for Architectural Informatics. The initial impetus for the project was the increasing number of projects over the last few years that make use of the new possibilities of computers as a design tool. The computer facilitates a digital chain from initial planning through to the final production of building elements that is more efficient and makes it possible to realise more architecturally complex structures. In most cases, however, the efficiency achieved through highly automated processes employing computer-controlled machines usually ends with the production of a building element. Many of the new approaches are therefore in effect merely a form of digital morphogenesis. The use of digital production machinery and their consequences for detailing and practical application are, however, often neglected. While it is possible to produce thousands of different items at the touch of a button, their assembly and joining often turns out to be both time consuming and cost intensive.

An example is the Watercube Building in Beijing which required hundreds of welders to assemble the computer-optimised structural frame over a period of many months. Here, the labour-intensive on-site assembly contradicts the aims of industrial production, namely to alleviate the need for strenuous manual labour.

As part of the research and teaching project at the Chair for Architectural Informatics at the Faculty of Architecture of the TU Munich, 15 students analysed aspects of automation and developed new solutions on a 1:1 scale prototype.

2. Aims

Currently, many parametric designs focus primarily on the geometric or formal expression. The possibilities – as well as the limitations – of individual digital production methods and the resulting consequences for the parametric model, construction, material and manufacture are, however, rarely given the same degree of attention. Typically this leads to very complex and formally elaborate but difficult to realise approaches.

The aim of the project was to develop new joining and construction systems with a view to optimising both the prefabrication of building elements as well as the entire production process right through to
disassembly. The goal was to overcome the current discrepancy between efficient, digital production and manual fabrication and assembly.

This was achieved by undertaking a detailed and exacting analysis of existing production and manufacturing processes coupled with an extensive background knowledge of materials and the means of their connection. Only by taking a broader, more forward-looking approach it is possible to pursue a different path to the burgeoning number of purely geometric approaches, structures and surfaces.

![Figure 1. Ascendancies](image)

As a consequence, the following requirements for a construction were formulated:

- Production using simple-to-operate 2½ axis or 3 axis milling machines.
- The use of weatherproof and low-cost panel materials.
- Integral detailing to facilitate easy assembly without screws, nails or other external connecting pieces.
- Special attention should be given to the connecting element – the realised prototype is intended only as an example.
- Simple transport, assembly and disassembly by a small team of workers.

3. Boundary conditions

If computer models are to become built architecture, it is equally important that alongside architectural and structural aspects, the resources need to be planned in detail, just as with a conventional design project. To ensure a
high degree of automation, one needs to take into account not only the costs but also the machinability of the material, the machining technology and above all the available human resources. As with other industrial production methods, this requires the close collaboration of many different competencies. Specialists in geometry work alongside programmers and craftsmen in a team. Through this teamwork approach, the specialists undertake what is more usually the realm of the architect: the development of the geometry of a construction and how it effects and creates space (Kockelkorn, 2008). This highly integrative workflow makes it necessary to carefully consider the entire manufacturing process in detail and in advance.

To be able to optimise the degree of automation, all of the boundary conditions for the entire project need to be examined in greater detail than usual to inform the programming process right down to the detailed solution.

3.1. MATERIAL

Wood is in many respects well-suited for mechanical production methods. It is easily machined using CNC machines and, in addition to different kinds of wood, a wide range of wood-based composite materials are also available. To overcome the anisotropy of wood (a product of the irregular material properties of the organic material) and therefore to achieve predictable material properties, composite wood materials are typically sawn and rejoined. This results in panel materials with different kinds of properties which are known under collective terms (see Wagenführ, 2008) such as “laminated wood materials” (for example veneer laminate), “wood-particle materials” (such as OSB, Oriented Strand Board) and “wood-fibre materials” (for example, MDF, medium-density fibre board). Coniferous woods are especially suited for use outdoors without the need for additional waterproofing. In addition to the kind of wood, the manufacturing process, e.g. the bonding technique used, needs to be taken into account.

After due consideration, we elected to use pine plywood.

3.2. MACHINE TOOLS

The choice of manufacturing machinery is of central importance. The kinematics and the tool used can have implications for the possible geometry of the building element and inform optimisation parameters for the tool’s economic application.

CNC machine tools can vary significantly in terms of their mechanical mechanism and possibilities they offer. The following criteria are of particular importance:
- Number of axes and their arrangement.
- Type of axial movement: one differentiates between rotation and translation.
- The shape and size of the working envelope: the above criteria in combination with the distance between the axes or their respective travel distances determine the kinematic working envelope.

Further important parameters in the choice of appropriate machinery include the speed, production tolerances, maximum element size and weight, the tension of the building elements and not least the machine’s feed mechanism.

Because the programming of mechanical systems with more than 4 axes is complex, time- and cost-intensive, we elected to use a Hundegger SPM2, a 3-axis panel processing machine. A key factor for this choice was its fully automated feed mechanism and material loading and the high operating speed and good accuracy of the machine.

3.3. CAM

In the case of 2½ axis processing, the complexity of the building element is achieved through a build-up of layers. In such cases, the CNC milling machine need only be supplied with 2D vector data, obviating the need for the time-consuming use of other CAM programs. As, at present, there is no commercially-available CAD software for converting 3D data automatically into .bvx format (Hundegger’s proprietary format for describing building materials and their manufacture), the transfer of data from a CAD program (Rhino 3D) to the CNC machine using CAM software would either entail considerable manual work (with a concomitant higher risk of error) or a significant programming task under tight time constraints. 2D vector data can, however, be passed directly to the manufacturing software in DXF interchange format. The software automatically recognises circles as drill holes and polylines as internal and external contours. The software’s nesting function is particularly useful as it allows hundreds of building elements to be optimally arranged within the dimensions of the panel, maintaining the correct grain orientation of the wood and minimising material offcut.

3.4. TRANSPORTATION / ASSEMBLY / DISASSEMBLY

Further boundary conditions include easy transportation and simple and fast assembly and disassembly by a small number of unskilled workers.

All of the individual elements should weigh less than the maximum lifting weight stipulated in industrial safety regulations (<30 kg for a male labourer undertaking regular lifting work). The low weight of the individual
elements is a product of the material (39 mm pine plywood). In addition the construction elements were structurally optimised as hollow structural members (see Figure 7). This obviates the need for special lifting gear during assembly.

The individual elements should be stackable in a compact form and prior to assembly not exceed external pack dimensions of 6.0 m × 2.5 m.

The structure consists of the additive assembly of individual elements, the detailing of which makes it possible to assemble them manually. The ribs have an intelligent connecting joint that is developed out of the structure of the building element.

The construction is designed in such a way that it can be assembled quickly and easily using hand tools alone. Once the elements have been assembled, they are pressed together with a tensioning band. A hand-held tensioning tool tightens and then welds the PET strapping band (polyethylene terephthalate band similar to that commonly used for packaging), pre-stressing the elements at their junction with a force of 4000 N and eliminating all seam joins. The breaking loads of the individual nodes is 20,000 N (Figure 2).

Cantilevered elements are held in place with a second band to prevent an element from detaching should a band fail. There is therefore a redundant connection between each element at each joint. The entire assembly is non-destructive and can be re-assembled as often as desired.

Disassembly should be just as easy and quick to undertake using hand tools. To disassemble the construction, the bands are severed with a pair of pliers. The notched joins are machined so exactly that friction stops them from being simply pulled apart. The detailing of the joint therefore includes additional notches at the top and bottom into which a lever can be inserted to prise the building elements apart without damaging the facing surfaces.
4. Programming

With regard to the later production, assembly and the limited time span available – just eight weeks from the first sketch to the exhibition – the decision was made early on to undertake the entire planning and detailing using a continuous parametric model. This was the only way to control the complex relationships within the structure and remain able to react flexibly to changes arising from the design process.

Taking into account the predetermined boundary conditions as well as additional design factors, it was therefore possible to realise the conceptual idea in digital form. Of particular relevance in this respect is a differentiation between two different categories of parameters: parameters that are determined manually by the designer and parameters that are determined and optimised automatically. The former include:

- Length and width,
- Grid dimension / structural module,
- Column position,
- Material,
- Oscillation amplitude,
- …

In addition to these so-called soft factors, a number of automated optimisation parameters are controlled automatically using digital algorithms. In particular, these include dependencies resulting from the boundary conditions, such as:

- Structural depth,
- Dynamic cantilevering – according to distribution of forces,
- Detail articulation,
- Tenon placement,
- Arrangement of the element layers,
- Channel for tensioning band,
- Weight optimisation,
- Position of fixing dowels,
- Element numbering.

The digital design was undertaken using Grasshopper 3D. This software provides an ideal basis for the development of own parametric structures and can in addition be extended with additional functions using own components programmed in VB or C#.

This combination makes it possible on the one hand to undertake the formal design of the exhibition object, and on the other to adapt the
individual nodal points to the different requirements that arise within the system using one all-encompassing model.

Through the predefined boundary conditions, the programming could be directly tailored to the specific requirements. For example, because the elements are to be produced using a 3-axis CNC machine, the model is conceived especially for the creation of 2D production files. Based on a three-dimensional point grid, the final cutting lines can be output to the CAM interface as pure 2D splines. This obviates the need to construct three-dimensional volumetric bodies resulting in much improved performance and making it possible to simply and directly manipulate the final form via individual polygon nodes. The ability to manipulate the splines directly is also used to develop the details obviating the need to use any basic solids or boolean operations. This makes it possible to create a non-resource-intensive, universal basis for all kinds of connections.

4.1. INTEGRAL INTELLIGENT JOINING DETAIL (IIF)

Through the use of computer-controlled manufacturing equipment, the detailing of the connecting points of the structure can be developed out of the specific construction of the building element itself. This obviates the need for additional connecting pieces and the building element and its connection can be fabricated in one step. Early examples of integral joining details can be found in historic roof truss constructions and Japanese timber construction.

To keep production simple and straightforward, the decision was made not to use complex and difficult-to-program five or six axis milling machines. All the elements are designed so that they can be fabricated using simpler 2½ or 3 axis milling machines out of large-format panel materials.
4.2 TWISTING FORCES

Taking their cue from Konrad Wachsmann’s General Panel Node, the individual ribs of the WAVE 0.18 prototype each consist of three layers that meet at the nodal points, interlocking slightly in a windmill-like fashion. The fully parameterised adaptation of the outer layers to the material thickness and its position in space makes it possible to take up specific stresses and distribute them separately. Compression forces are, therefore, taken up by the outer facing layers while the central layer absorbs tension and bending forces.

4.3 SELF-ORIENTATING

At each of the nodal points, four individual polygonal-shaped ribs meet and slot into one another in the respective axes with an overlap of 8 cm using a pair of mortise and tenon joints. The logarithmic rising arc of the columns means that individual soffit inclines of more than 45° with respect to the horizontal are possible. The “intelligent” placement of the tenons in each element ensures that they do not project through the edge of the element.

Because the individual ribs communicate with one another, the tenon direction is determined individually for each junction. This makes it possible, despite the steeply rising or falling soffit, to interconnect the individual ribs over an area of 10 cm to ensure the horizontal stiffening of the grid in both directions.
4.4 SELF-ADJUSTING

Because the connections are developed directly out of the supporting structure, the joint detail abuts the element’s end cross-section directly, ensuring the best possible transfer of loads. In high-load sections – for example the columns – the intersecting surfaces, and therefore the horizontally stiffening sections, automatically adapt to the additional load. In these sections, the vertical overlap can be as much as five times higher than areas of the structure that are subject to lower loads.

4.5 WEIGHT-OPTIMISATION

To reduce weight, the detail programming creates cavities at those points where the material is subject to the least structural load, namely in the horizontal and vertical centre of the element. The form of the hollow sections responds to the form of the respective construction element.
4.6 BAND

The tensioning band used to join together the individual elements should provide the strongest structural connection at the upper and lower edges of the elements. The channel in which the band lies also needs to be curved to distribute the tension effectively and to avoid damaging the band as it is under tension. The curved form for this channel was derived using an algorithm and is adapted dynamically to fit the specific geometric conditions of each individual nodal point.

5. WAVE 0.18 | The experiment

In March 2010 we had the opportunity to build a prototype for the Pinakothek der Moderne in Munich, one of the most important museums of art in Germany.

A structure was requested that could serve as a representative exhibition object that would appeal both to the general public and to expert visitors alike and illustrates the topic of digital formal expression and production.

Out of the almost endless possible forms, a baldachin-like roof construction was chosen for the exhibition object with a grid arrangement that reflects that of the overhead indirect lighting. The 13.5m × 4.5m × 4m large “WAVE 0.18” serves both as an artistic and thematic expression of the digital ‘turning point’. The following facts underline the efficiency of the optimised production and assembly system:

- Human resources: 5 people
- Manufacture: 5 days
- Erection: 1 day
- Structure: 192 ribs made of 1100 individual parts

The result is a high-precision and stable structure (figure 9).

With regard to the goal of the research project to develop an optimised construction detail solution for production and assembly, a fully parameterised timber construction was developed and tested in practice.
Taking into account as many boundary conditions as possible in the manufacturing process, it demonstrates that a system can be developed that optimises both the planning as well the production process and facilitates prefabricated construction right the way through to disassembly.

Figure 9 WAVE 0.18
6. Future Research

In future research projects we plan to deepen the knowledge we have gained so far and to extend our investigations into the topic of integrated assembly methods using further prototypes. Further research projects are also planned for the field of CAD-CAM control systems in particular, as well as the prefabrication of individual rib elements. These include:

- Improving the degree of automation in manufacturing,
- Dissolution of the orthogonal grid,
- Roofing as a rain shield.

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