Tree-Structure Canopy: A Case Study in Design and Fabrication of Complex Steel Structures using Digital Tools

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This paper describes and reflects on the design and manufacturing process of the Tree-Structure canopy for the WestendGate Tower in Frankfurt upon Main, completed early 2011. The project investigated fabrication and assembly principles of complex steel structures as well as the integration of contemporary computational design, engineering, optimization and simulation techniques in a collaborative design approach. This paper focuses on the notion of modular standardization as opposed to non standard customized components. It also engages with issues relating to digital production tools and their impact on construction cost, material performance and tolerances. In addition it examines the reconfiguration of liability during a planning and construction process, an aspect which can be strongly determined by fabrication companies rather than the architect or designer. This paper is written as a reflection on the complete building process when contemporary digital tools are used from design through to fabrication. It studies both the generation of the steel structure as well the ETFE cushion skin. It reports on a collaborative project, where the main author was responsible for the canopies design, parameterization, digitalization and fabrication, as well as for the dissemination of the outcomes and findings during the design and realization process. As such it represents an example of research through design in a contemporary and evolving field. The canopy received a design award by the Hellenic Architecture Association.

1. INTRODUCTION

1.1. Project description

WestendGate, also known as the Marriott Hotel, is one of the most iconic towers in Frankfurt. At a height of 159 meters and 47 storeys, the original structure ranked as the highest tower Germany during the 70s and early 80s. Built in 1976 by the architects Siegfried Hoyer and Richard Heil in the Westend of Frankfurt am Main, the building became the trend setter and exemplar for high-rise construction in both this district and the broader city of Frankfurt. The Marriott Hotel Group moved there in 1989, and the building remains the highest hotel in Europe. The Hotel occupies the top 18 of the 46 storeys of the building; a three winged structure in plan. It has its own lobby on the ground floor and uses the second floor as a ball room. All the remaining levels, which are accessible via a second lobby, are occupied as office space and building services.

The project described in this paper is a canopy, referred to generally in this paper as the 'Tree-Structure'. This Tree-Structure canopy was designed in order to protect the newly designed outdoor entrance and departure area. Besides providing performance needs such as weather protection the brief for the canopy included the key criterion to generate a prestigious new entrée to the hotel experience. A requirement was that the new addition should contribute significantly to the building's visual impact at the human scale: it already had significant impact at the urban scale. It was also to provide visual signals to reinforce primary pedestrian movement flows. The Tree-Structure covers an area of 1200 m^2 with its height varying between 8 and 14 meters. The defining perimeter is between 85 and 14 meters in length depending on section location. The lead author worked with Just/Burgeff Architekten in collaboration with structural engineer Viktor Wilhelm.

1.2. Definition of design parameters

The entire design approach for the canopy was based on a set of parameters, determined by a given range of conditions, such as structural layout of the underground parking, local building code restrictions, construction cost as well as programmatic and circulation requirements. Some of these conditions applied during the construction phase not all were end state conditions. In particular:

- the Tree-Structure columns positions had to match with the existing column grid of the Underground parking. Any other position could not be accommodated structurally.
- Hotel and office facilities in the tower had to continue operating during the entire construction phase.
- Construction cost and council regulations were given and could not be violated.

◀ Figure 1. Aerial photograph of the Tree-Structure Canopy in Frankfurt. (Photography by Eibe Sönnecken.).

Consideration of these parameters led to the design decision to adopt a prefabricated structure; one which would allow fast and welding-free assembly on site.

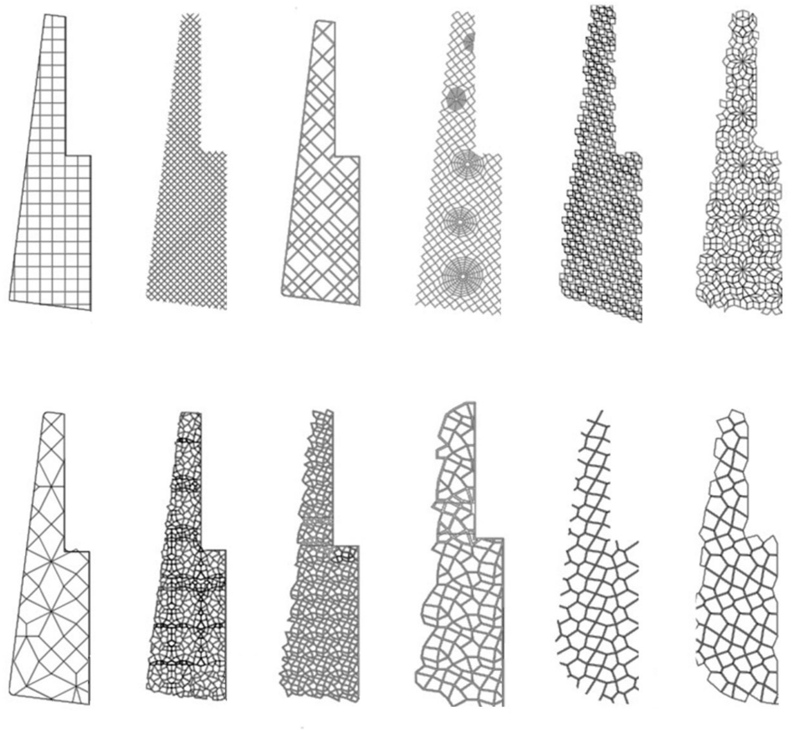
2. DESIGN PROCESS

2.1. Definition of Structure

The Westendgate proposed canopy was not designed in a conventional top-down design process, where the architect determines design and passes it on to engineers and fabricators for further processing. It was developed in a bottom up iterative and interactive process as described by Kloft [1], where all different team members agreed on a negotiated co-decision process through which they could enrich the procedure with their expertise. Several sets of different, planar mesh structures and structural principles were examined in relation to their performance, construction cost and design quality (see Figure 2) for the team to consider and evaluate as a team. In contrast to the Ornamental Discretisation of Free-form Surfaces approach described Manhal et.al. [2], where an algorithmic tool has been developed in order to tessellate double curved surfaces, the design team questioned and thus avoided the necessity of such complexity as part of their approach.

The dimensions of the different planar meshes were determined in relation to the practical constraints imposed by the possible roof cladding materials; glass, ETFE foil and polycarbonate panels. Through evaluation of the merits and demerits of each case, the team decided to continue with a semi-regular voronoi mesh, including eight different standardized polygonal

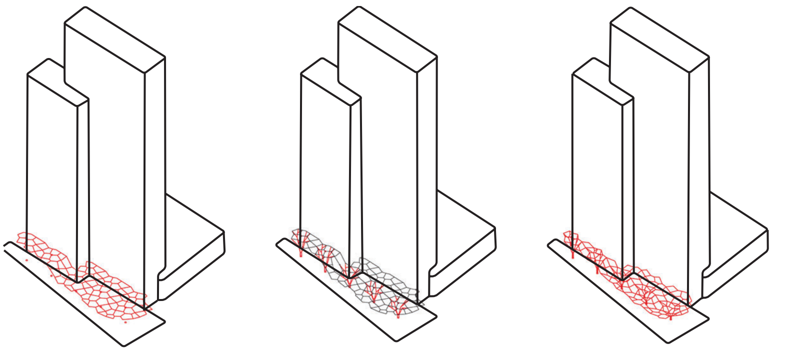
► Figure 2. Iterations of mesh structures.



frame units, which would repeat themselves through the entire structure. The solution bears interesting comparison to the one adopted for the Campus Restaurant and Event Space Roof in Ditzingen, Stuttgart, by Barkow & Leibinger architects [3].

Finally, branched columns were generated from selected voronoi intersection points. The location of the trunk of the tree that the branches would spring from was determined by where they would meet with the position of the existing underground column grid at the ground slab level (Figure 3). The schematic structure was subsequently digitized in a bottom-up and interactive 3-D model. This model would allow the team to optimize and update the canopy's geometry through the entire design process.

► Figure 3. Design process: Generation of columns from voronoi grid.



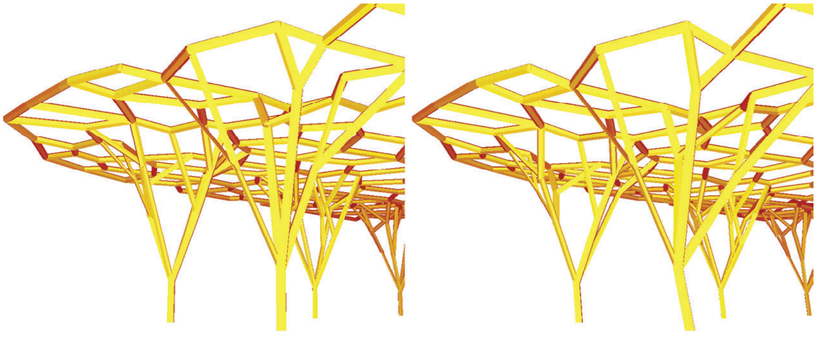
2.2. Structural Simulation: an Instrument for Form Definition

Finite element analysis techniques were applied to the mesh which was represented as an axial 3D model, in which each element of the mesh was defined as a bar element. Defining the mesh this way made it possible to optimize both load transmission and drainage behavior of the canopy mesh and branched columns, with the targets for optimization being defined as minimization of steel weight, and parallel reduction of construction cost. In this respect the technique follows a process similar to that described in the "*it's small world*" exhibition stand [4]. However in the case described here, although the process was comparable, the optimization process was based on different parameters, different material and the final structure was, consequently, significantly different.

The performance simulation analysis was repeated in a series of iterations, to reach an optimum position in terms of geometry, load transmission and steel weight (see Figure 4). As a result, the mesh structure was transformed, overall, into a doubly curved surface (Figure 5), the elements of which were composed of unique, non standard polygonal mesh components. The geometry of these mesh elements was defined by the responsive reconfiguring of their joint conditions and angles to meet a combination of constraints and optimization criteria.

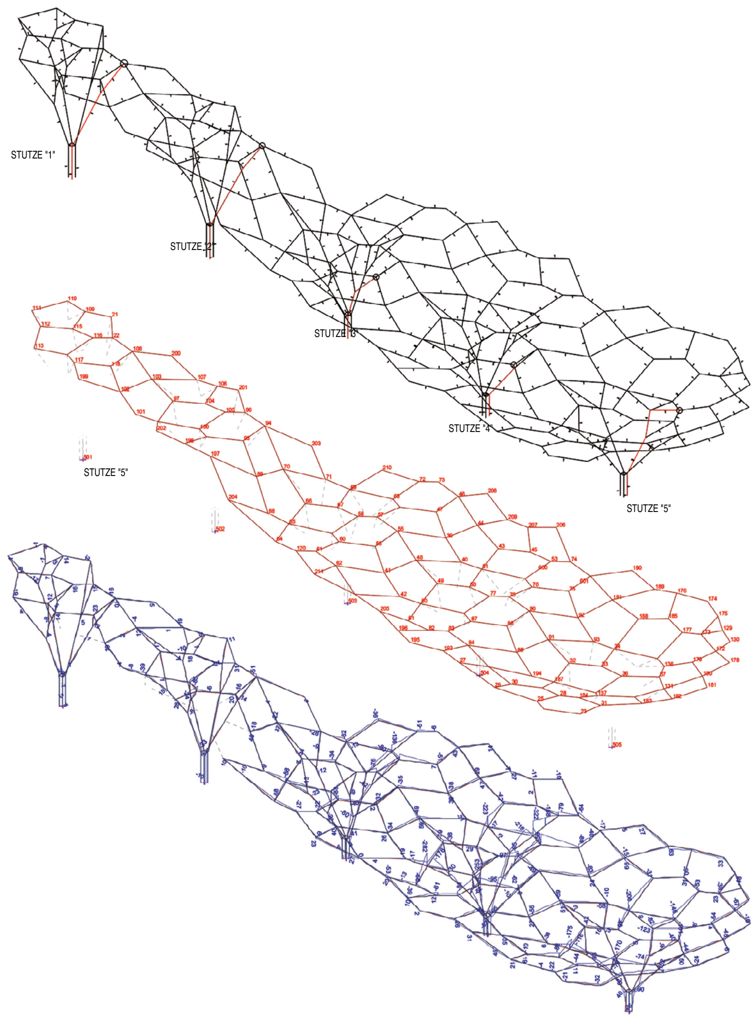
The mesh outer edges were lifted upwards, while the inner areas were pushed downwards in the digital representation, allowing optimum drainage and improved load flow from the mesh surface to the branched columns. However, this outcome went against the team's initial assumptions, which included the premise that the outcome would be several standardized frame units defining the mesh structure. We found that a double curved geometry would result in a significantly lighter steel construction in comparison to the standardized solution.

As a consequence of the geometry now being adopted, the canopy's physical appearance changed significantly. Its form and structural behavior would resemble forms and load transmission processes akin to those in nature and similar to those described by Otto and Rasch [6], who promoted the approach of starting with natural forms and then refining



◀ Figure 4. Optimization process, Finite Element Analysis.

► Figure 5. Optimization result: double curved surface, composed of unique, non standard polygonal frames.



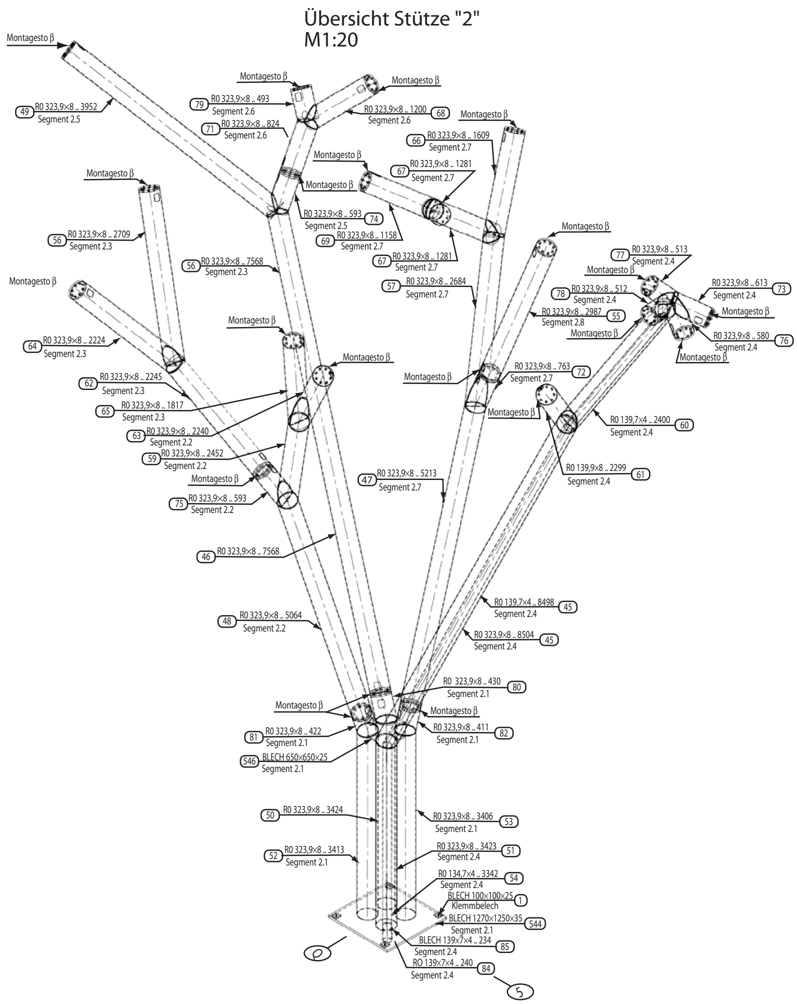
based on constraints and optimization. The introduction of the double curved mesh roof, contributed to the choice of ETFE foil cushions as roofing material. ETFE foil is lighter than most comparable roofing materials and had a particular advantage that the cushions can be mounted on non planar, doubly curved frames.

3. FABRICATION PROCESS

3.1. Definition of Joints and Units

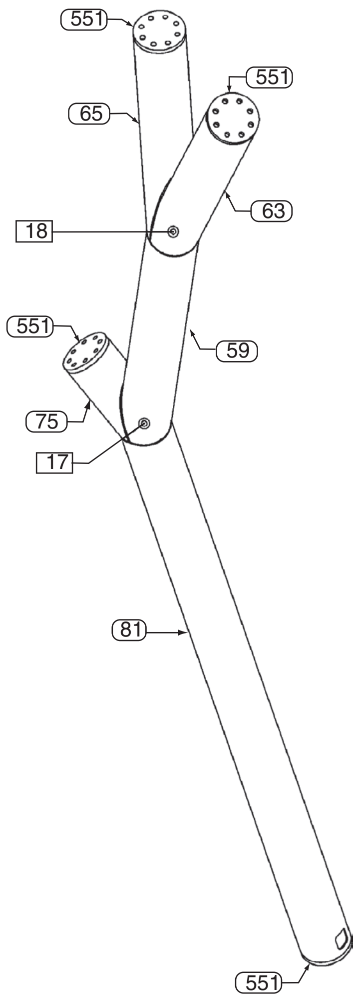
Determination of assembly joints and frame units was a key issue in order to resolve the construction details and manufacturing method of the Tree-Structure canopy. Due to the complexity of the joints, where each one becomes a crossing point for up to five different axes, the only geometrically feasible steel section profile proved to be the tube (or CHS, circular hollow section). Rectangular or T-shape profiles could not intersect in a geometrically calculable joint. The flat plate steel profiles as used in the TetraScript pavilion [6], could have worked geometrically. However this would have had two important design implications. First the FEM structural analysis was based on axial elements and the flat plate cross section is significantly less efficient as a compressive axial element than a tube (CHS) section. Secondly it would have had a very significant and undesirable effect on the visual appearance of the canopy.

In addition, the project team decided to avoid a Mero knot based solution system, which has been used in comparable junction details in structures such as the Eden Project by Nicholas Grimshaw [7], due to its impact on the design outcome and additional difficulties in drainage and roof cladding details. Considerations of the parameters prescribed earlier led to the introduction of a standardized 'screw-knot', that gave a prefabricated unit as shown in Figures 6 and 7. As a result, the roof mesh



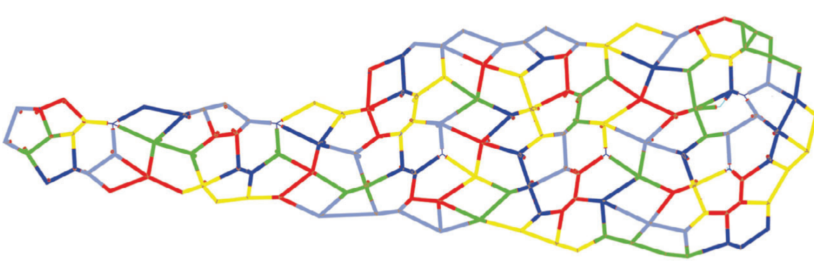
◀ Figure 6 (left). tree column construction drawing.

► Figure 7 (right). Standardized assembly screw-knot.



was divided into 72 non standard steel branch units (Figure 8). The dimensioning of these branches was defined by the size of galvanizing pools in which they were to be coated, and transportation requirements. A similar technique was applied to the canopy's columns each of which were divided into four individual units.

► Figure 8. Construction units, Divisions of different Branches.

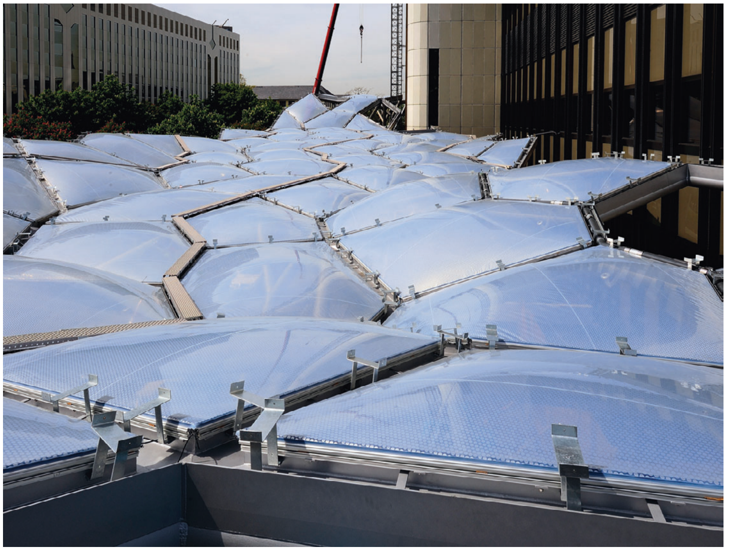


3.2. Drainage and Roofing System

The drainage and ETFE-cushions cladding systems are strongly linked, since they are both attached to each other and have to be assembled as a pair on the canopy's tubular roof mesh. The drainage-cushion assembly detail is an evolved version of the detail principle used in Herzog and De Meuron's Allianz Arena in Munich [8]. This system had to be modified in order to adapt to the irregular geometry of the Tree-Structure canopy. It consists of flat laths, welded onto the pipes, covered by a grating, in order to protect the drainage from collection of debris.

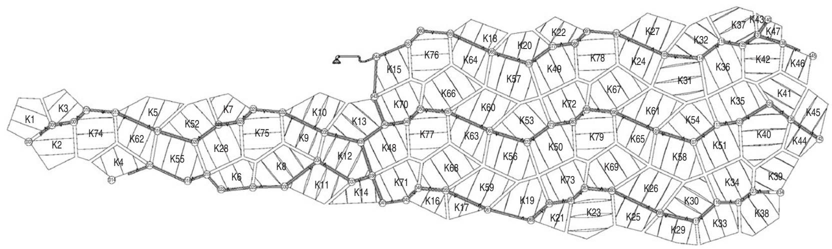
In addition, all of the ETFE cushions could be conveniently fixed to the drainage laths (Figure 9). Each cushion is made of several ETFE strips, aligned parallel to each other (Figure 10). This determines the cushion's maximum

◀ Figure 9 (left). Drainage system (Photography by Eibe Sönnecken).



◀ Figure 10. ETFE cushion fabrication drawing.

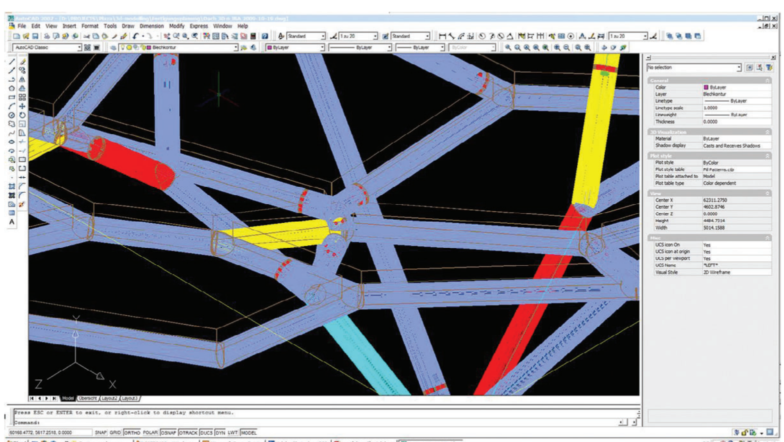
footprint, in combination with its structural performance. To maintain the cushions under constant air pressure, they had to be connected to an air pump. The pipes used for air supply are positioned in the drainage gutter under the grating (Figure 11).



► Figure 11 (right). Drainage gutter and grating.

3.3. Fabrication Drawings and Principle Details

All principal details and fabrication details had to be designed in a 3D environment. Due to the canopy's complex geometry, they could not be efficiently described in a 2D representation system. As the same 3D model would be used for all design and fabrication faces (Figure 12), the 3D representation became the main medium of information exchange between architect, engineer and the steel fabrication company. The main exchange file format between different software platforms such as Rhinoceros, Autocad, FreeFem++ became DWG. This choice was primarily defined by the CNC plasma cutter hardware database, used by the steel manufacturer to fabricate the steel tree/knot components. Each tube's assembly profile was calculated, numbered and used as fabrication data (Figure 13). As soon as the plasma cutting process had been completed, all different branch units were welded together (Figure 14) and then assembled into the roof mesh in an upside down position (Figure 15), in order to avoid mismatching joints. In addition, the welded branches were galvanized and spray painted (Figure 16) before they were transported to the construction site.



► Figure 12. Collaborative 3D Model used for the canopy's construction.

◀ Figure 13 (left). CNC plasma cutting of steel pipes.

◀ Figure 14 (right). Welding of plasma-cut pipes.

◀ Figure 15. Test assembly of tree structure mesh.

► Figure 16. Spray painting the branch.

4. CONSTRUCTION AND ASSEMBLY

4.1. Assembling the Structure

Assembling the 1200 m^2 structure on a site, which has to service hotel guests 24 hours a day, 7 days a week, proved to be a challenging task. Construction started from north to south, since it had to be synchronized with the hotel events operating schedule. The canopy's branches were assembled from column to mesh, growing in linear progression like a giant puzzle (Figure 17). Each branch was placed to its

► Figure 17. Assembly process.

◀ Figure 18. Assembly process, tightening the joints. Photography by Eibe Sönnecken.

exact position by crane and then bolted to its neighbors by hydraulic screwdrivers. The workers were able to reach the joints by the side assembly holes, which were integrated close to every branch unit (figure 18). After the whole structure was completed, each bolted joint was tighten again, thus the tolerances could be minimized. Finally all assembly holes were sealed.

4.2. Assembling the Cushions

Soon after the structure was completed, assembly of the cushions started in a similar manner. Assembly was made easier, quicker and less expensive due to the fact that workers were able to walk on the structure. Enabling this feature was a parameter defined in the design process, and this affected the choice of steel tube diameter. Adopting this defining parameter for minimum tube dimension would prove to significantly simplify assembly and maintenance processes. Each cushion had to located in the correct position, be unrolled and fixed to the steel framework. Rubber gaskets between cushion and frame ensured a seal. Finally all cushions were connected to the pumped air supply system.

5. DISCUSSION

5.1 A century of Standardized Constructions

"Each time the architectural production technology changes, then architecture changes as well" argued Conrad Wachsmann in the late 50's [9]. And it is indeed true, that significant technological developments have always had an impact in architectural design and production.

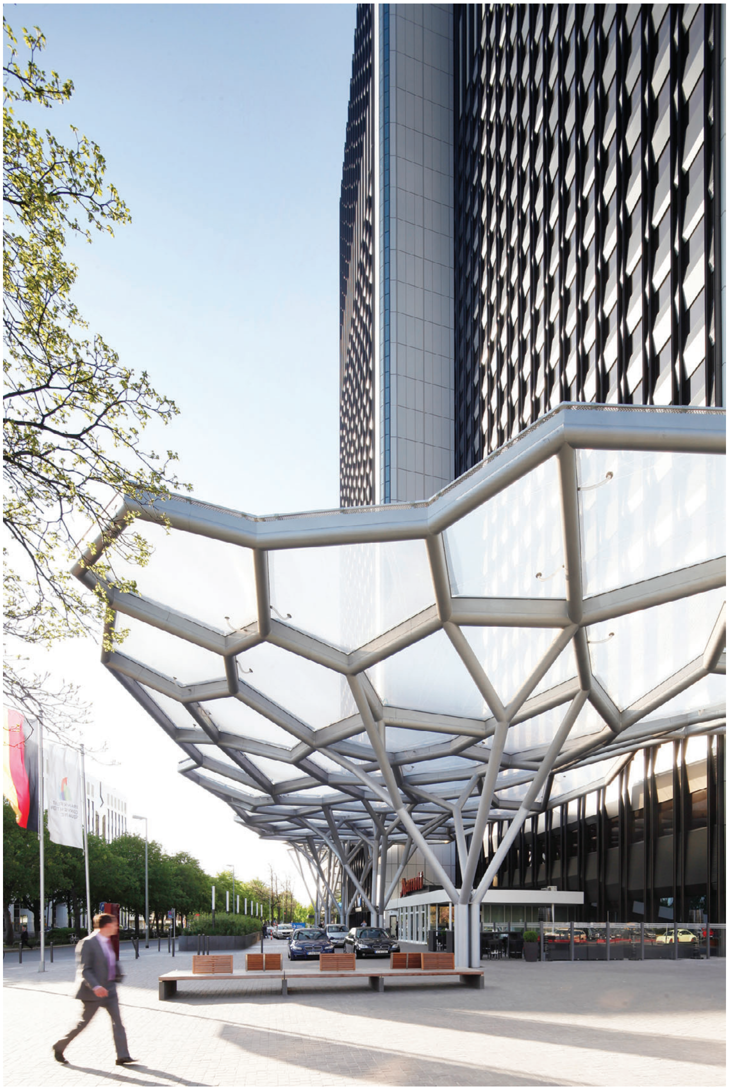
Paxton's Crystal Palace, built in the late 19th century, played a key role in inaugurating a new era, when the development of techniques to produce innovative iron and glass components began to revolutionize the construction, structure, and consequently, design of buildings. It heralded the dawn of a new architectural aesthetic. Following the introduction of the recently invented assembly line [9], industrial production set of on a new march towards faster construction time, at low cost and greater efficiency.

The urge to fulfill those three requirements motivated the Russian engineer Vladimir Grigorjewitsch Suchov to develop his hyper-parabolic mesh structures [11] in the same century. They consisted of mass produced iron 'sticks', welded together in a minimal structure which combines fast construction requirements with an optimally efficient geometry. Like Otto [5] he had the goal of achieving essential coherence between form, structure and production process. His intelligent structural system was used for the construction of at least 200 telecommunication towers throughout the Soviet Union. The use of the industrial manufacturing processes of his time played a fundamental role in conceiving and delivery of the hyperbolic towers.

With further industrialization of architectural technology taking place in the beginning of the 20th century, serial mass production became more refined. The notion of industrialization became a synonym for the notion of mass production. The fully automatized factory could only operate efficiently if it could produce huge numbers of self-similar copies. The initial form-giving tool is the major new component in such a process, thus also, indirectly the final product. Wachsmann's "modular coordination" [9] describes an order, based on a system, in which all components have a clearly defined relation to each other. It tries to define one universal unit categorized by geometries, tolerances, valuation and construction. This order is, for him, the only way to guarantee reliable construction quality. It also dictates a new relation between design and structure: he argued that "Industrial production cannot be abused as an excuse for realizing freely designed conceptions. It can only be used as a direct cause for the development provision of a product, which in a combination with the rest provides the finalized form".

5.2 CAD/CAM: Techniques for Non Standard Constructions

Today, emerging CAD/CAM design and manufacturing technologies allow a differentiated view of the assertions made above. The use of the computer in the contemporary design process now appears to be merging design and production into a shared environment that we might call firmware. Mass fabrication and custom made production are unifying and becoming mass customization. The use of structural simulation techniques and algorithmic tools in an architectural process are decoupling the former limiting relation of costs - quality - efficiency and the associated repetitive production processes



◀ Figure 19. Tree-Structure Canopy (Photography by Eibe Sönnecken).

this led to. Furthermore, novel digital manufacturing techniques allow designers and architects to extend former boundaries of geometry and form.

Wachsmanns "modular coordination" is being replaced by the notion of performance [12], which includes coordination of more than one parameter, into a more complex balanced equilibrium system that is facilitated by the new computational tools. The pre-digitized production criteria now appear to many to be outdated and limiting. In their place, individualized structures, as found in nature, are proving to achieve a greater degree of efficiency. With the further spread of CAM technologies and rising cost of resources, criticisms traditionally leveled at such structures, such as high production cost and outlay, are fading away and wider adoption is becoming more accepted as a norm.

7. CONCLUSIONS

Looking back in the overall design and realization process of the Tree-Structure canopy, it is apparent that the conventional design procedure became naturally transformed into a collaborative virtual system, where architects, engineers and manufacturers were linked together in a constantly updated common flow of information. Typical architectural drawings, such as sections, elevations and floor plans are losing their importance, because they are unable to entirely describe complex geometrical structures. Meanwhile, the role of interactive digital models is gaining in importance. Various CAD file types and application formats such as DWG, IGES or STL are becoming the common data currencies, that both define the building, and carry the responsibility for efficient transmission of design information between the actors. Thus, our understanding of advanced design, precision and structural tolerance is being transformed. We can relate ideas and decisions directly to the relevant requirements of each manufacturing machine.

These changes have a strong impact on a contemporary design and construction process. For instance, because of the fabricator's expertise in determining planning and production tolerances, that fabricator gains more responsibility for implementation planning and finalized product. However, the question of the legal responsibility of the architect can become more complex in such cases: can an architectural practice be legally responsible for production drawings, which are increasingly dependent upon advice and intervention from external agents?

On a technical level related to the Tree-Structure project described here, the introduction of the screw-joint, used for assembling the different branch unit, proved to be an efficient innovation, which could be used for a wider spectrum of contemporary projects. It is a construction solution, which, unlike the Mero knot separates the geometrical knot junction from the actual assembly junction, allowing a flexible subdivision of units. Other parameters such us the unit's weight or the size of the galvanization pools could thus be made more optimal.

It is also essential to mention that the implementation of finite element analysis simulation played a key role in the switch from a partly standardized to a non standard structural system and geometry. The initial assumption, that by reducing the number of individual frame and cushion units would reduce the cost of construction proved to be irrelevant. On the contrary, the structurally optimized, non-standard frames proved to be lighter, and less expensive. The increased complexity related to the frame's manufacturing process was counteracted through the integrated, interactive, parametric design environment linked to finite element analysis and computer aided manufacture (CAM) systems.

It is becoming clear that Conrad Wachsmanns theses about the relation of technology and architecture are more relevant than ever. We live in a time when digital manufacturing technologies are revolutionizing the architectural practice and construction procedures. The transformation emerging goes beyond morphological characteristics. It has an impact on the essential procedures, on which architectural production had become based for decades.

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