

JUST IN TIME DESIGN

Developing parametric design tools for architectural design

SIGRID BRELL-COKCAN, JOHANNES BRAUMANN,
BARIS COKCAN AND MARTIN KLEINDIENST

IIArchitects-Int, Istanbul, Turkey

office@2architects-int.net

Abstract. In this paper we will present custom design and parametric programming strategies for the design of complex spatial structures based on our applied research for a 10.000 m² freeform technology centre in Düzce, Turkey. The goal is to develop intuitive, easy-to-use parametric design components for layout, analysis, optimisation and aesthetic architectural free form design.

Keywords. Parametric design; freeform architecture; quadrilateral meshes; software development; fabrication.

1. Introduction

The ease of freeform modelling in CAAD (Computer Aided Architectural Design) software tools has introduced a wide variety of new forms into architectural design. Even though freeform designs can be perfectly represented in the virtual space, common CAAD tools are not optimised for the actual realisation and fabrication of large scale freeform architecture. Taking on these issues as a business opportunity, specialised geometry and computer science consultants such as designtoproduction or Evolute support architectural offices in optimising initial designs for fabrication. Even before this new trend, building contractors had developed their own “in house” software tools to solve geometry and fabrication related problems and to break down geometry into machine code, production drawings and mounting plans. However, consulting services and their software tools are exclusive to a number of well-known architects, but not affordable for small scale architectural offices.

In this paper we will briefly discuss the major developments and trends in the last decade and present a first new approach of customised design and

programming strategies for a wide range of architects, based on our applied research for a 10.000 m² freeform design, the Düzce Teknopark, a technology centre for Düzce University in Turkey (Figure 1). The goal of our research and practice is to implement intuitive, easy-to-use digital design tools for layout, analysis, and aesthetic design strategies for architectural freeform structures. We will further discuss how to break down freeform building envelopes into manageable program modules for sharing data with consultants such as structural engineers and building physicists and how to streamline the workflow without having to rely on existing BIM software (Building Information Modelling) such as Digital Project.

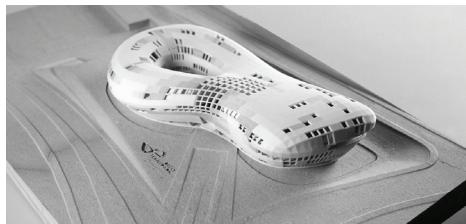


Figure 1. Scale model of Düzce Teknopark (3D-print on CNC-milled site model).

2. Düzce Teknopark

On November 12, 1999, the city of Düzce was shook by the 7.2 magnitude Düzce Earthquake. The remaining architecture is a wild mixture of quick reconstructions following the disaster. In 2002, the University of Düzce was founded to attract young people and has since become one of the main driving forces for future developments in Düzce.

The new building of Düzce Teknopark is situated on a geographic saddle, at the same time overviewed by Düzce University's rector's building while having a wide downhill view of the whole Düzce University campus. The fact that the building can be seen from a bird's eye's view represents a unique situation which requires the "fifth" façade – the roof – to integrate seamlessly in the overall design.

Infinity of science and the convergence of industrial and academic research were the inspiration to develop a multifunctional twisting, three-dimensional loop emerging from a toroidal primitive. The environmentally self-sufficient and self-supporting building envelope will house office spaces and research labs for industry and university spin-offs. Incubating these new technologies and innovations requires highest security standards where each floor has to be encapsulated. In the foyer, the double façade twists like a conch shell into an

overwhelming entrance space, creating a pocket within the double-façade. As an analogy for the fertilisation process, the penetration of the building with researchers, clients, and visitors is articulated in the atmospheric climax of the entrance hall as a meeting area “In-Between” (Figure 2).



Figure 2. Interior view of the entrance hall in between the outer and inner skin.

3. Deep structure – necessity and simplification

The technological challenge of freeform architecture is not just a question of segmenting NURBS or subdivision surface to producible units, but to consider the complete spatial structure of the building, which links the interior to the exterior and vice versa, where data is fed in either from the interior, e.g. according to structural requirements, or from the exterior, e.g. due to material changes of the cladding elements or building physics. However, most current research aims to resolve just the freeform skin to meet structural and production constraints. This results very often in a posteriori solutions where the spatial structure of the inner and outer space alike is already given. (Pottmann et al. 2006, Eigensatz et al. 2010). Other research deals mostly with surface structures and ornaments (Dimcic and Knippers 2011).

In our applied research for Düzce Teknopark we aim to optimise the building not according to a *layered* system e.g. refitting the mesh to floor planes only (Figure 3) - but rather as a parametric, interdependent *3d space structure* considering *micro* (e.g. joint conditions), *macro* (material conditions) and *spatial structures* bounded by 3-dimensional *space edges*. The representation is simplified to points, curves or surfaces to which we consider a *deep structure*. The term deep structure is originally a linguistic expression and refers to a technical construct that seeks to unify several related structures. (Chomsky 1965) *Deep structure* best explains the requirements for a parametric design tool and the necessity of creating predefined *relations* of inner and outer spatial systems which are not an inherent subdivision of space.

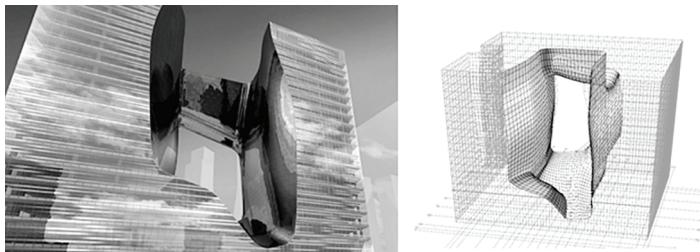


Figure 3. The Opus (image courtesy of Zaha Hadid & Associates) (left), planar quadrilateral mesh refitted to floor slabs (right).

The major constraints of the parametric model are determined by the relation of e.g. environment, structural behaviour, building physics, material and production requirements. Parametric design ensures that flexibility is guaranteed throughout all construction phases, so that unforeseen events can be accommodated. As an example of the importance of flexibility, the 3D data model of the outer skin of Kunsthaus Graz (Cook and Fournier 2003) differed from the realised acrylic glass surface up to 30 cm and had to be manually refitted onsite (Figure 4) compared to a bride who has to be squeezed into her wedding dress before the ceremony due to weight gain. However, when material does not allow such flexibility as acrylic glass, this refitting process has to be performed on the 3D data. *Refitting* is therefore an important constraint that is omnipresent from design to fabrication and needs a lot of attention, analysis and a flexible parametric strategy.



Figure 4. Onsite refitting of acrylic glass panels of Kunsthaus Graz (left), digital NURBS surface (right).

Our research on parametric deep structures and fabrication strategies is a direct result of such onsite experiences. In the following chapters we will explain our strategies for the development of a parametric design tool, that allows architects to increase and decrease information by simply plugging and unplugging separate components for design and tools for analysis.

4. Teknopark parametrics

Subdivision modelling allows the rapid generation of freeform shapes, which can be adaptively subdivided and easily modified even after they've been created, while keeping the continuity of the surface. An alternative modelling concept is NURBS (non-uniform, rational, B-spline) modelling, which mathematically describes iso-parameter value curves or surfaces and therefore offers total accuracy (e.g. for fabrication), while the accuracy of subdivision surfaces depends on the degree of subdivision. By translating the subdivision surface into a NURBS surface for further editing in the CAD software Rhinoceros, we are combining both techniques for Düzce Teknopark and gain the ease of freeform-modelling from subdivision surfaces and the accuracy of NURBS (Figure 5).

Built on top of Rhinoceros is the parametric design plugin Grasshopper which can reference all geometry inside the CAD program and include it in its parametric model. The advantage of Grasshopper compared to scripting, is that changes propagate immediately through its parametric graph and cause the visual preview to refresh, allowing a near-realtime environment where the designer can immediately see the effects of his actions.

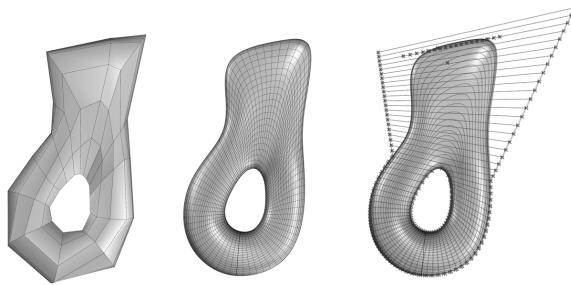


Figure 5. Coarse mesh for subdivision (left), NURBS surface (middle), parametric panelisation in GH (right).

4.1. INTERIOR AND EXTERIOR

As we consider the whole deep-structure of the building, various parameters have to be considered, dynamically changing the thickness of the outer skin, as required by material properties or building physics (Figure 6).

This value has a direct impact onto the available office space, but also on the interior structure. The general typology of the interior support structure was a collaborative effort with the structural engineer, defining simple, struc-

tural rules such as “one concrete column every n meters” with “a maximum angle in x degree according to the tilt of the outer skin”. By parametrising the shape of the support structure as well as its spacing and orientation, we are able to implement a good representation of the final structural members inside, while still allowing rapid changes due to e.g. increased external loads, material changes, or building physics.

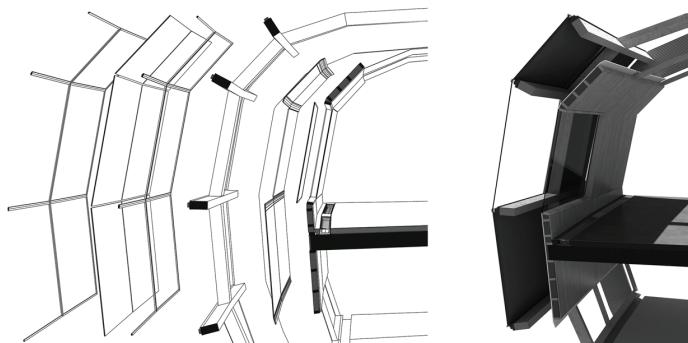


Figure 6. Dynamic depth of the façade structure (left), 3D-section (right).

4.2. REDUCING AND ADDING INFORMATION

Keeping the 3D model in Grasshopper as abstract as possible with a minimum amount of geometry represented by points or curves - unlike the solid representation seen in the 3D-section (Figure 6) - is crucial for the near real-time 3D data processing. Another relevant factor, which we have experienced in our practice are the different tolerances of programmes resulting in a problematic data exchange between different software tools. Most structural engineering software e.g. for finite element analysis needs point accuracy of 0, while many CAD programmes have rather high tolerances, such as Autocad’s default setting of 24 digits or Rhinoceros’ with only 3 digits. A similar problem can be experienced with CNC machines. Exchanging surfaces or solids within different software environments can cause edge discontinuities and unforeseen differences in surface parameterisation or mesh representation. A reduced 3D model concept only representing deep space edges and points is therefore a promising approach. Adding more information to the 3D model can also be automated see Figure 7. Our tools will allow flexible “dress codes” according to various occasions such as structural behaviour, building physics, mechanical engineering etc. incorporating dynamic changes and mitigating “weight loss/weight gain” problems.

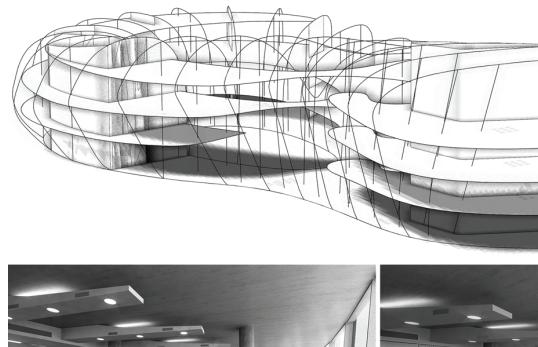


Figure 7. Simplified deep structure of interior space (top), example for results of inner spaces with different amount of information (bottom).

By parametrising the interior of the Teknopark, we receive a maximum of freedom of design when dealing with the outer skin, which has to be considered the cost-driver of the project and the building part with the most financial headroom for optimisation. Therefore, the parametrically gained freedom of design can be translated into tangible optimisations and reductions of costs. Going back to the example of the Opus by Zaha Hadid, the parameterisation and planarisation of the freeform surface enabled a cost saving of 25%, as estimated by the contractor.

4.2. QUADRILATERAL MESHES

In order to create a strategy for quadrilateral meshing of the Duezce Teknopark, it is important to carefully analyse the NURBS surface and its isocurves. We can formulate the initial requirements for a quadrilateral mesh as the following: The primary support structure *must not twist geometrically in space*, it should *be distributed evenly along the building*, leading to *elements of similar size*, and it has to be *aesthetically pleasing*.

In contrast, the secondary structure can follow the isocurves of the toroidal area to profit from the inherent planar segmentation of the geometric primitive. To be able to distribute the quad panels more evenly, the parametric system allows us to dynamically move away from the isocurves in the non-toroidal areas of the loop (Figure 8, left and middle).

4.3. ANALYSIS

Due to the fact that the outer skin is the biggest cost driver of the project, and that small changes to the geometry can have a drastic impact not only

on finances, but also on building physics, structural integrity, and fabrication, various analysis tools are implemented in the parametric definition. The analysis tool with the biggest impact on cost is the planarity visualisation. In the discourse of planarity in architecture, it is important to consider that mathematically absolute planarity with zero tolerance does not exist. All construction elements depending on the material used have certain tolerances, as well as not being mathematically planar in the first place. While allowing the general optimisation of the planarity value, this analysis function also allows us to assign quads to so-called “planarity-groups”, which all have a common amount of planarity tolerances. We can therefore aim to e.g. place glass only on panels with a unplanarity of less than 6 mm for glass panes $>1.5 \times 1.5$ m, while areas with higher unplanarity can be assigned with more flexible materials (Figure 8, right).

Further analysis functions measure the uniformity of all panels and output the result as a graph or calculate the angle between the panels’ normal vectors and the vectors of sunlight, allowing an approximate estimation of the solar gain on each panel. All these analysis functions can of course be superimposed, so that e.g. only the solar gain of panels with high planarity is evaluated.

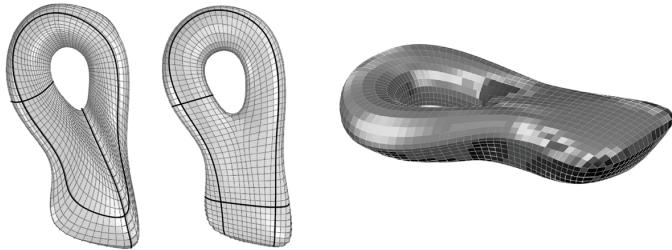


Figure 8. Optimisation and Analysis: Top view before (left) and after (middle) mesh optimisation, planarity analysis (right): blue is within required glass planarity tolerances.

4.4. MODULARITY, ADAPTABILITY AND OPTIMISATION

It is important to consider that the origin of the parametric definition is the initial driving surface, as it was imported from the subdivision modeller. Therefore, whenever the initial surface or design values are altered the definition stays valid as long as the general surface topology stays the same. This allows a new freedom for designers, where all parts can be changed at any time instead of having to lock important input geometries at a certain stage, which can cause problems peaking in the onsite manual refitting of the outer skin layer, seen in projects such as Kunsthaus Graz.

Another relevant aspect is performance and modularity: Grasshopper itself consists of components containing specified functions which are laid out as an acyclic graph. Changes to that graph propagate upwards, meaning that only components where the input data is modified get refreshed. If e.g. changes are performed to the planarity analysis, the other analysis functions do not refresh. In reverse, if the user adjusts the quadrilateral mesh, all analysis functions, the interior, and the support structure have to be recalculated and updated. As this process can take a few seconds, the immediate feedback is no longer given and working with the definition becomes slow and cumbersome. However, due to the modular nature of Grasshopper, it is possible to quickly disconnect ranges of components from the graph, so that only the currently relevant components are calculated (Figure 9). As all relationships between the components are clearly displayed by Grasshopper's graph, the user can quickly judge if disabling a group of components will affect a relevant function. Compared to traditional scripting, Grasshopper's modularity allows a much bigger flexibility and more effective optimisation when working with large parametric setups (Davis et al. 2011).

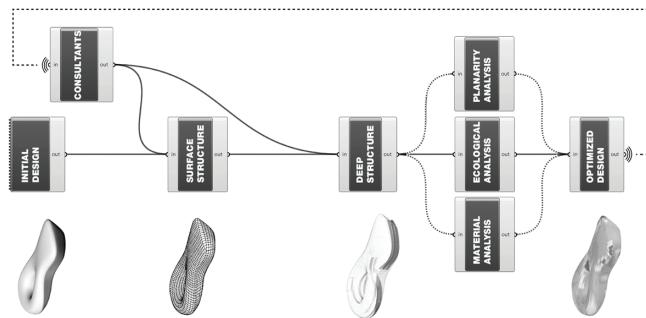


Figure 9. Modular Grasshopper workflow: Plug and unplug components for customised feedback and performance optimisation.

4.5. OUTPUT

This elaborate parametric model not only allows a fluent interaction with the building, but also the automated extraction of e.g. panels and structural members into individual files, and the generation of basic floor plans that clearly show all structural elements and the space edges of the deep structure of the building. Keeping the 3D-model as “slim” as possible is one of the major challenges in a project of such a scale as Düzce Teknopark. Our various “intuitive” design approaches have shown that a slim parametric model

reduces the risk of losing track of information and facilitates reusing existing groups of components.

5. Conclusion and outlook

The flexibility of the digital tools presented in this paper is expected to enable us to quickly implement constraints that we do not know at this stage of design, e.g. the *human scale* onsite, where CAD illiterate workers have to process complex data for mounting and assembling. From our experiences at projects such as Kunsthaus Graz, BMW Munich or Martha Herford and our own projects executed in non EU countries, overloaded construction plans are obstructive onsite.

Our tool will follow the question of how to filter the architect's desire to control all 3D data of all parties simultaneously on the one hand and how to easily break down 3D data according to the needs of all involved parties and the building site on the other hand. We refer to this software development strategy as *Just in Time Design*, where parametric schemata are developed in small portions "on the fly" and expanded, adapted, plugged and unplugged for the following design phases.

Inhouse customised tools allow small architecture firms to convince clients of their technological capabilities: Freeform architecture therefore does not have to be the sole property of the big players anymore.

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