Form, Force, Performance

Multi-Parametric Structural Design

In the 20th century, the classification of structures according to defined building typologies was central to engineering design. Here **Professor Klaus Bollinger**, **Professor Manfred Grohmann** and **Oliver Tessmann** of design engineers Bollinger + Grohmann challenge this preconception. By considering each structure as an individual case in point with inherently complex behaviour, they move away from the notion of a building being a variant of an established type. They further discuss this mode of working, in relation to their own recent projects, in terms of relevant methods and generative techniques, as well as the respective consequences that it has had on the relationship between force, form and structural performance.

Bollinger + Grohmann conceive of structure as an integral part of architecture. The overall performance of an architectural project results from negotiating and balancing a complex network of multifaceted, interrelated requirements. As the design of structure is just one aspect within such a network of manifold relations, the appropriate structural systems cannot be found through single-parameter optimisation. The specific forms derived through such a multi-parametric design process need to be analysed in order to identify zones of favourable structural performance. The related structures adapt their load-bearing capacities to the form and its particular local forces. Thus the resultant structures are highly specific, differentiated systems rather than variations of a defined typology.

The distribution of forces within a massive beam is hidden from the observer's eye as the mass-active system does not indicate its specific load transfer. However, if one visualises the isostatic force trajectories, a number of system-inherent structural types can be recognised; for example arch, truss, lenticular girder and suspension system. The predominance of such vector-active lattice systems can be traced back to a technical innovation in 1866 when Karl Culmann, a professor of engineering science at the Eidgenössischen Polytechnikum in Zurich, published his *Graphic Statics*, including his development of the most important graphic methods for calculating structural behaviour.

Based on Jean Victor Poncelet's scientific work on projective geometry, these versatile graphic methods were also a response to the increasing use of cast-iron structures in the field of construction. With these novel methods being particularly suited for the calculation of lattice girders, no other structural typology signifies better the succinct impact of new calculation methods on the changing understanding and employment of structures.[1]

In the following years, scientific calculation methods and theories gained increasing importance with the simultaneous decline of traditional approaches founded on experience and observation of built examples. In the 1920s the teaching of structures was no longer based on precedent buildings and examples, but general theories and analytical methods.[2] Only in the second half of the 20th century were Culmann's methods of graphic statics superseded by computer numeric procedures. However, the preconceived generic structural typologies defined in the early 20th century and the related scientific methods that prioritise partial analyses and understanding over increasing integration continue to predominate in structural design.

> *Science works always to achieve general theories that unify knowledge. Every specific natural event, to be scientifically satisfying, must ultimately be related to a general formulation. Engineering, in contrast, works always to create specific objects within a category of type. Each design, to be technologically satisfying, must be unique and relate only to the special theory appropriate to its category.*
>
> David P Billington, *The Tower and the Bridge: The New Art of Structural Engineering*, 1985[3]

Bollinger + Grohmann agree with Billington's understanding that structural design provides a unique response to the specific requirements and situation of each project. Moreover, we do not think that structures need to be conceptualised through predefined typologies or conceived of as variations of a particular type.

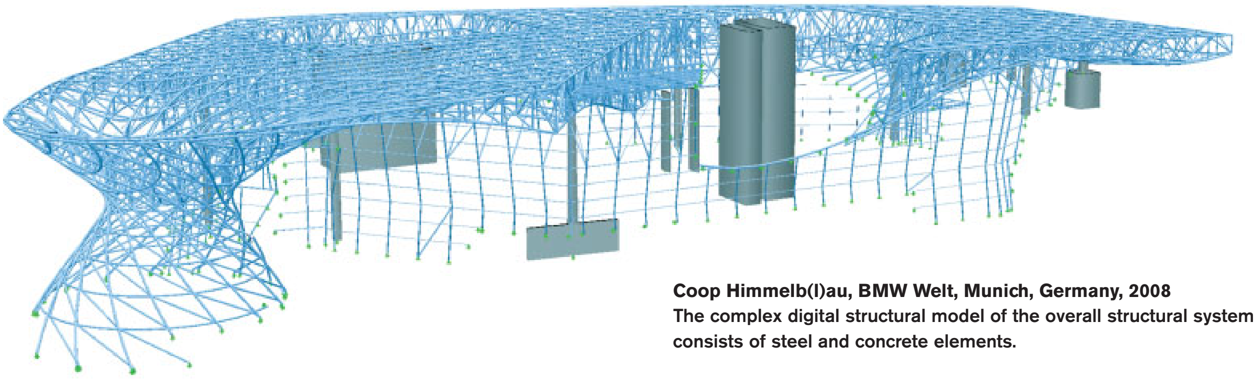
In our collaborations with architects, form never constitutes the optimum shape derived through a form-finding process driven only by structural optimisation, but rather embodies and integrates a multitude of parameters. Within an overall system we analyse regions with structural capacity and identify morphological zones that can be altered without affecting the architect's spatial and programmatic concept. The structure then unfolds from these regions and adapts its capacity to local requirements. This opportunistic approach erodes predefined typologies in favour of emergent hybrid systems, such as flat space trusses showing shell behaviour or concrete shells turning into landscape.

In this process, external force is just one design aspect among many and thus not the only shape-defining parameter.

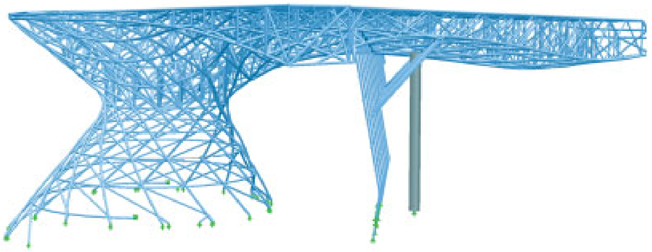
Architectural design needs to incorporate complex organisational and functional requirements, and therefore constitutes a recurrent negotiation of analysing existing and requisite conditions as well as generating and evaluating possible responses. Additional knowledge gained through such iterative processes may require further analysis of the specific context or even the adjustment of previously defined design objectives.[4] A project's diverse design criteria can be understood as a network of interdependent nodes. Once this network settles into a state of equilibrium of various influences a high level of integral performance of the building and its structure has been attained. This capacity cannot be achieved through single-parameter optimisation of the overall system, as the linearity of such processes cannot account for the complexity of architectural projects. Thus one of the key aspects of our practice and research work at Bollinger + Grohmann is the integration of optimisation strategies within the complex network of design criteria.

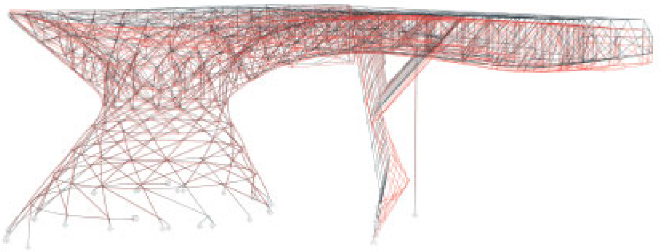
In the following paragraphs we will present strategies for the generation and integration of structure in a number of our recent projects.

Coop Himmelb(l)au, BMW Welt, Munich, Germany, 2008
The shell-like behaviour of the double-cone steel structure gradually transforms into the roof with bending behaviour.



Coop Himmelb(l)au, BMW Welt, Munich, Germany, 2008
The complex digital structural model of the overall structural system which consists of steel and concrete elements.





Digital model of the double cone and folded facade (above) indicating the behaviour of the structure under the influence of force (right).

BMW Welt, Munich

The structures we develop do not need to adhere to idealised typologies, which are usually in conflict with the architect's concepts anyway. Rather they result from a multiparty design process. In the BMW Welt project by Coop Himmelb(l)au, which is located right next to the Olympic quarter and adjacent to the BMW head office and plants in Munich, the complex roof structure was designed in a collaborative process.

During the competition we developed a double-layered girder grid which demarcates the upper and lower boundaries of the roof-space phase in alignment with the architectural concept of a floating cloud. Driven by the simulation of anticipated loading scenarios, the initially planar girder grid was deformed so that the upper layer assumed a cushion-like bulge. The lower layer also reacts to a number of spatial and structural criteria; for example, the roof integrates the customer lounge, a large incision that opens the views towards the famous BMW headquarters tower and channels the forces to the defined bearing points. The combined capacity of both girder grid layers to act as one spatial structure with locally differentiated behaviour is achieved through the insertion of diagonal struts within the interstitial space. In response to local stress concentrations, the structural depth of the system varies between a maximum of 12 metres (39.4 feet) and just 2 metres (6.6 feet) in areas of less force. In the northern part of the building the roof merges with a double cone, typical of Coop Himmelb(l)au's work, to form a hybrid shape. Similarly, the related bending behaviour of the roof structure gradually transforms into the shell-like behaviour of the double cone.[5]

From a structural engineering perspective one particular challenge proved to be the geometric complexity of building elements and their interaction, as each local change had consequences on the global scale of the system. This high level of interdependency needed to be integrated in the analytical models of the structure, which required, for example, the set up of an extensive model of the complete roof structure including all load-bearing elements. Any significant change to the stiffness of one of the cores, for instance, had considerable repercussions for the overall behaviour of the structure necessitating the re-evaluation and recalculation of the overall system. Consequently, this elaborate, iterative design process depended entirely on intense collaboration with the architects and related, clearly defined protocols of data exchange.

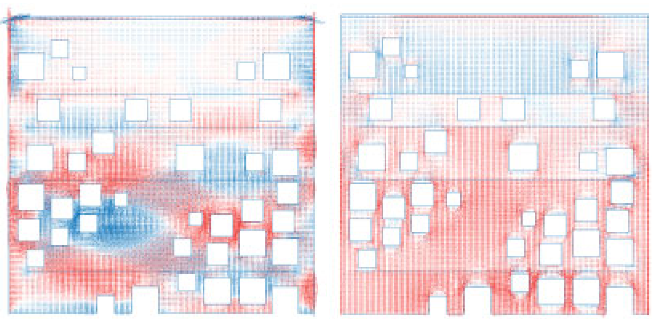
School of Management and Design, Essen

In 2006, the School of Management and Design was completed in the former coal-mining area of Zeche Zollverein in Essen, which has been a World Heritage Site since 2001. In response to the industrial scale of the surroundings, Japanese architects Kazuyo Sejima and Ryue Nishizawa (SANAA) proposed a cubic building. The monolithic character of the concrete block is perforated by a large number of rectangular openings.

The structure consists of flat slabs supported by two steel composite columns, three cores and the external walls. With clear spans of up to 16 metres (52.5 feet), the weight of the 50-centimetre (19.7-inch) thick flat slabs needed to be reduced through void formers. The distribution of these hollow plastic spheres needed to be negotiated with the placement of the reinforcement, the thermal activation pipework and the lighting inserts. This required close collaboration between the HVAC and light and structural designers in order to find specific local solutions for each sublocation within the overall structure. For instance, the high degree of reinforcement required by crack limitation in the lower layer of the ceilings and necessitated by substantial shear load concentration close to cores and columns needed to be coordinated with the placement of void formers and the installation of thermal activation systems.

To reduce wall thickness to conform with the architectural concept, the structural external walls are at the same time an active thermal insulation integrating hot-water pipes cast into the concrete and fed by the 30°C (86°F) waste water of the former coal mine, which used to be channelled straight into the river Emscher. This formerly untapped resource of energy now warms up the external walls, constituting not a heating system, but rather an integral active insulation in place of common passive thermal insulation packages.

SANAA, School of Management and Design, Essen, Germany, 2006
The void formers and thermal activation pipework in the concrete slabs, as well as the active thermal insulation of hot-water pipes cast into the concrete of the external walls, are still visible during the construction process.



Digital structural analysis showing the main moments (left) and membrane forces (right) within one of the external walls perforated by a large number of rectangular openings.

This integration of insulation, structure, cladding and drainage in one element allowed for a considerable reduction of wall thickness.

Such compactness cannot be conceived of as a reduction of each single element as, for example, the dimensions of the reinforcement in this case rather increase and the insulation pipework's diameters are predefined. Thus all necessary elements and related functions need to be integral systems within the walls' highly confined internal space, which contrasts with their archaic external simplicity. In order to achieve such high-level integration, the design process recurrently negotiated the positioning of openings, the layout of active insulation and drainage pipework, the distribution of reinforcement and the anticipated formwork. This entailed intense collaboration with all the engineers and construction companies developing the specific systems and construction sequences, which were tested on a full-scale prototype on site.

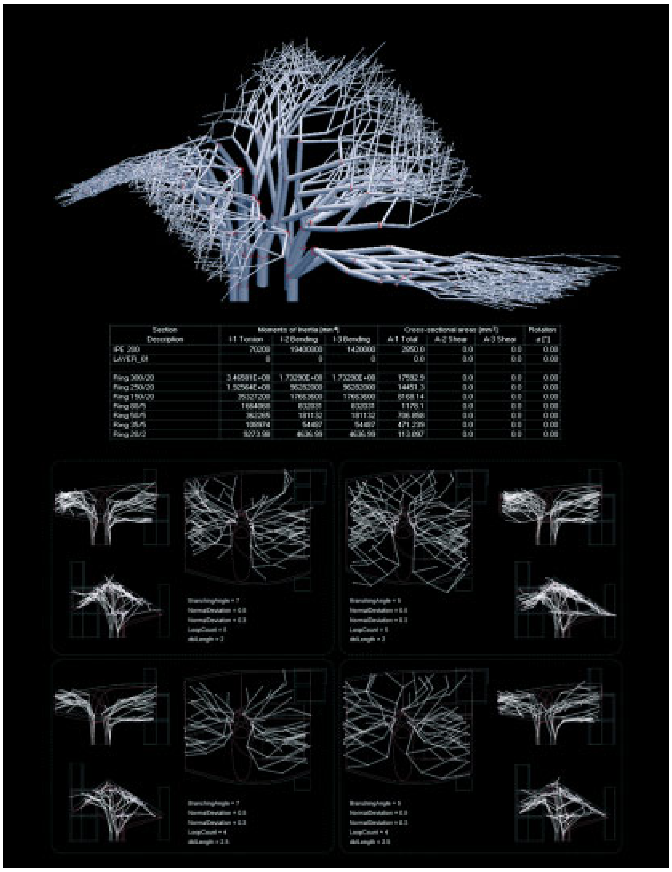
Reducing a building to its essential solid and transparent qualities requires an integral approach to all functional aspects so as to overcome the common separation of technical and structural systems. Thus the design development of the School of Management and Design results from the collaborative planning process incorporating the users, architects and engineers. Based on the initial architectural concept, the overall performance of the project evolved through the increasing integration of design, technological, economic and ecological aspects. Such an approach does not foreground the optimisation of single elements or systems. Rather it is based on the continual integration of design criteria of all involved disciplines and parties.

Lakehouse Patagonia, Argentina

Bollinger + Grohmann focus on integrating material capacities and anticipated forces within the digital design setup, replacing merely geometric description with models that represent the dynamic equilibrium of a network of building services, and structural and architectural parameters.

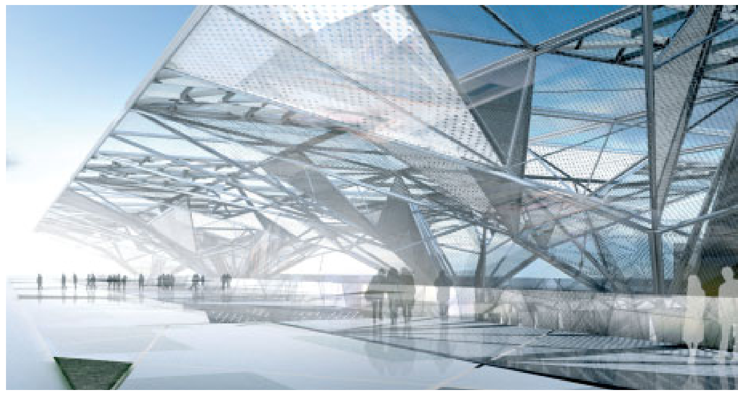
The Lakehouse Patagonia project by architects ArchiGlobe is an extension of an existing house in Argentina. The design process focused on developing spatial articulation through a roof structure that intrgrated functional and load-bearing characteristics. Based on Lindenmayer systems, a script-driven procedure generates a tree structure in response to the specific design context. The growth of the structure reacts to architectural criteria such as spatial volumes and views, and to structural aspects. The structure's gradual change in density interacts with the open space to create varied spatial qualities and atmospheres. The algorithmic process is implemented in the architect's design environment as a generative tool capable of deriving a large number of design iterations. Variation is driven by random modifications to parameters that influence the branching angle and branch length.

For subsequent structural analysis, the script also generates each individual's data set containing all relevant



ArchiGlobe, Lakehouse Patagonia, Argentina, 2007
Different versions of the Lakehouse structure are derived by a generative digital process driven by stochastic as well as arithmetic parameters.

z-coordinate within defined thresholds. A tube-like column folded out of the roof reaches the ground and acts as a support structure. To achieve cantilevering capacity and a minimum of node displacement just by folding the triangulated plane, the behaviour of the entire structure was simulated in RStab software. By encoding the z-coordinates of all nodes into a genome and using a genetic algorithm that allowed for crossover and mutation, the performance of the structure could be significantly improved over the run of 200 generations with 40 individuals each. As a fitness criteria, the displacement of the nodes under self-weight was calculated by the analysis software, the worst node defining the inverse fitness for each individual.

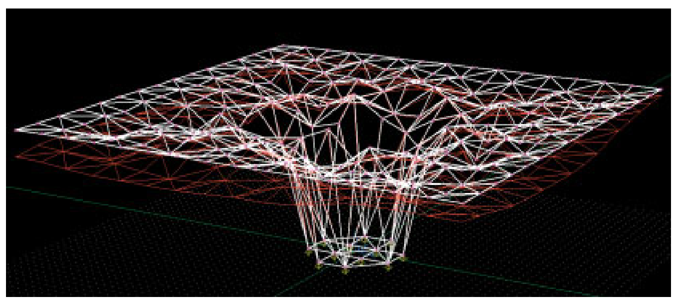


Dominique Perrault, Undergound station roof, Piazza Garibaldi, Naples, Italy, 2007
Competiton proposal for the differentiated branching structure.

digital information including coordinates, nodes and elements, and the related centre-line models. The evaluation of each iteration included both architectural as well as structural aspects, considering not only topological relations but also the related dimensioning of elements, as this has a substantial impact on the incidence of light and the views towards the surrounding landscape.

Undergound Station Roof, Piazza Garibaldi, Naples
Computational processes enable us to generate and evaluate a large number of possible structural articulations. During the design study for an underground station roof at Piazza Garibaldi in Naples by Dominique Perrault, entire populations of structures were evolved and individuals were selected through predefined architectural and structural fitness criteria. These processes evolved articulations in response to specific criteria without relapsing into *a priori* defined typologies.

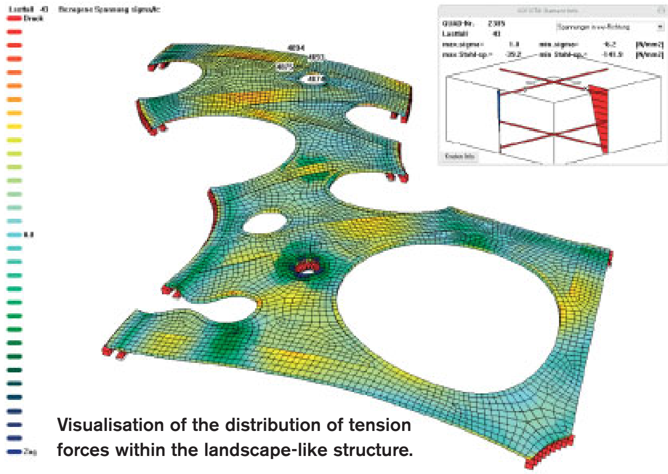
In collaboration with Fabian Scheurer of the ETH Zurich, we conducted a design study on improving the performance of the folded roof structure through genetic algorithms. Topologically the roof structure can be described as a two-dimensional plane based on a system of self-similar triangles folded in the third dimension. Each node is assigned a random



Analysis of the specific load-bearing behaviour of each individual branching structure derived through the evolutionary process.

Learning Centre, EPFL, Lausanne
We admire the elegance of Felix Candela's shells, the virtuosity with which he constructed these hyperparabolic structures and the breadth of his design repertoire. Ove Arup assumed the reason for the excellence of Candela's works was due to him combining architect, engineer and contractor in one person, with a clear dominance of engineering over architecture. He believed that the creative process needs to be synthesised in one mind that is aware of all aspects relevant to the success of a project.[6]

SANAA, Learning Centre, EPFL, Lausanne, Switzerland, 2008–
The artificial landscape of the new Learning Centre includes patios, openings and shell-like regions.



Visualisation of the distribution of tension forces within the landscape-like structure.

As this situation is extraordinarily rare, architecture is usually the product of a collaborative effort. Thus even a shell can integrate a wide range of design criteria far beyond just structural aspects. SANAA's Learning Centre project for the campus of the École Polytechnique Fédérale Lausanne (EPFL) provides different spatial situations through the undulations of the single-storey building. Containing the central library, service and study rooms, exhibition spaces, concert halls, cafés and a restaurant, the building will be the functional and visual centre of the campus.

From an engineering perspective, homogenous, idealised shells are elegant as they transfer forces without incurring bending forces and thus can be constructed with minimal material thickness. However, any incision in such an ideal shape as, for instance, a door, leads to fundamental, problematic changes in the structural behaviour. SANAA,s undulating landscape building includes patios, openings and various spatial qualities and thus results from a design process in which structural aspects were just one set of design criteria among many.

Rather than prioritising the idealised geometries of Candela's projects, here the work focused on analysing and identifying local areas of shell or arch behaviour, which were subsequently further developed and modified in an ongoing dialogue with the architects. Classic form-finding is superseded by processes of tracing performative capacities in the specific morphology. As the load-bearing characteristics vary across the landscape like articulation, no region represents a pure structural typology. The analysis also reveals problematic areas that would necessitate a disproportionate thickness of the concrete shell. Wavy tensile force progression, high bending movements and redirected forces combined with the lack of support points in the patio areas were addressed by redirecting the force flow between the shell perimeters through modification to geometry, size and location of the patios. Such an iterative process of tracking performance in collaboration with the architects entails ongoing design and evaluation cycles.

Conclusion

These evolutionary strategies depend on the fitness ranking, as selection constitutes the only control mechanism to direct the development. In nature individual fitness is evaluated on the phenotypic level as the likeliness for further reproduction.[7] Likewise, in digital processes each individual structure needs to be fully defined and modelled in order to be evaluated. Each evolved structure is based on the genetic information of a previous generation and has undergone further adaptation.

Thus the definition of the fitness criteria is critical for the quality of the building and its structure in that they control the direction of the evolving process. Our goal is the integration of such criteria for many different nodes within the complex network of requirements, to achieve performative and differentiated buildings and structures.

We assume there is similarity between these processes and the design methods of the aforementioned masters, who developed their structures through experience and observation of constructed buildings. This can also be understood as an evolutionary method, one that is not limited by the availability of calculation and analyses methods. Contemporary digital methods make possible the simulation of such processes, and thus enable us to refer back to the empirical methods of previous generations. AD

Notes

1. Hans Straub, Die Geschichte der Bauingenieurskunst, *Überblick von der Antike bis in die Neuzeit*, Birkhäuser Verlag (Basle), 1992.
2. David P Billington, *The Tower and the Bridge: The New Art of Structural Engineering*, Princeton University Press (New York), 1985.
3. Ibid
4. Bryan Lawson, *How Designers Think: The Design Process Demystified*, Elsevier (Oxford), 4th edn, 2006.
5. Klaus Bollinger, Manfred Grohmann, Daneil Pfanner and Jörg Schneider, Tragkonstruktionen der BMW-Welt in München, *Stahlbau* , Vol 7, 2005, pp 483-91.
6. Ove Arup, *Candela: The Shell Builder*, Reinhold Publishing Corporation (New York), 1963.
7. Ernst Mayr, *What Evolution Is*, Basic Books (New York), 2001.