The Progress of Geometry as Design Resource

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This essay tries to appraise how, in recent years, our discipline's problem solving capacity has been advanced, and might be further advanced, through the advancement of its geometric resources. While the design of the building's geometry, in distinction to the building's materiality with its tactile and visual-atmospheric values, does not comprise the whole of the design task, geometry is certainly centrally involved in most of architecture's relevant design decision tasks. Starting with Alberti architectural design has indeed often been identified with geometry – the distribution of lines and angles - in contrast to the builder's concern with material realisation. Le Corbusier is eulogizing geometry on the 1st page of his 'The City of Tomorrow and its Planning': "Geometry is the Foundation."

When we talk about the "geometry" of a space or building we are talking about (geometric) forms as aspects of the material world. These aspects have been abstracted and prepared for design manipulation via design media like drawings, or computational graphic models, via the mathematical science and technique of "geometry". We might therefore take account of various geometric repertoires and techniques as design media resources and appraise progress here in terms of the following valued dimensions of architectural problem solving: organisational as well as expressive versatility. The aspect of dimensional control and coordination for construction is something I have usually taken for granted and not thematised in my writings. However, mathematical geometric techniques that enable spatio-morphological conceptions aimed at organisation and articulation must at the same time meet the demand for controlling dimensional coordination for construction.
In the context of problem architectural solving - both with respect to technical and social tasks - we must look at drawings and models as simulations that

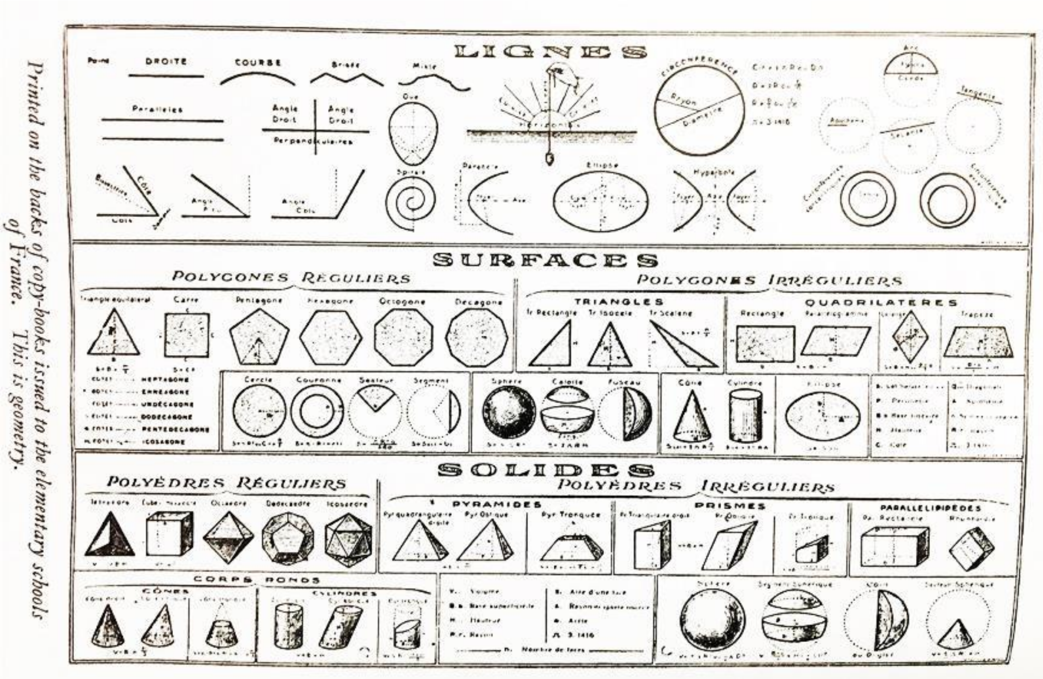
allow the designer to anticipate and ascertain key aspects of the designed building's performance.

This paper rehearses the recent geometric repertoire expansion called for by the increasing complexity of our tasks and made possible by the discipline's empowerment via the techniques of computational geometry leading momentous and impactful progress of geometry as crucial design resource. The repertoire expansion of recent years has been cumulative. Together these expansions signify a radical shift in relation to all prior architecture, including modernism, post-modernism and even deconstructivism. Historically, the geometrical resources of the discipline have advanced rather slowly with each successive style. However, the advances of recent years that align with the epochal transition from the mechanical to the digital age have been far more radical than any prior expansion. These geometric advances therefore participate and bear witness to the revolution in architecture that is on the agenda as Parametricism matures and proliferates as the new epochal style for design, architecture and urbanism. Twenty-five years into this process of cumulative transformation we can already discern several phases which we might designate and name as subsidiary styles within the epochal style and paradigm of parametricism, namely: Foldism, Blobism, Swarmism and Tectonism.

The Progress of Architectural Geometry

The use of geometry as such is the first stage in the story which therefore starts with ancient Egypt. The ancient Greeks achieved considerable advancement and refinement in both the science of geometry and its architectural application, but development slowed afterwards. Euclid's Elements remained a standard up to the 19^{th} century.

For most of its history architecture only used a very small and very simple subset of geometry's universe of possibility, even in relation to what had been available since antiquity. This geometric poverty lasted well into the 20th century when Le Corbusier was still able to convince the discipline that it was all about composing with the most simple platonic solids.

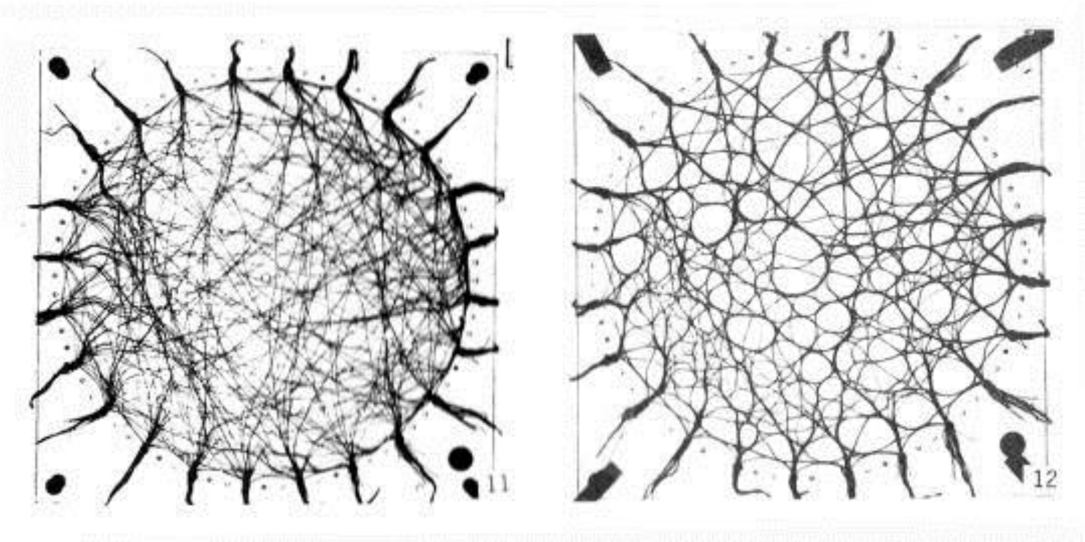


From Le Corbusier, The City of Tomorrow and its Planning, Foreword, Paris 1925

With the image above taken from a French elementary school book Le Corbusier closes the foreword of his treatise 'The City of Tomorrow and its Planning'. Le Corbusier gives a lot of credit to geometry here. He writes: "The age we live in is essentially a geometrical one"[i], and elaborates this by writing that "today our enthusiasm is for exactitude"[ii]. Le Corbusier thus still emphasises the original merit of geometry, namely its capacity of control, a capacity we should by now safely take for granted. Perhaps less trivial: For Le Corbusier geometry is the means of order, "the grip of man upon nature"[iii]. This fits my own premise, namely that the societal function of architecture is the framing and ordering of social processes. The key question then becomes in the context of geometry: which concepts of order is geometry operationalising and which ordering capacities it is thereby making available to the discipline's task.

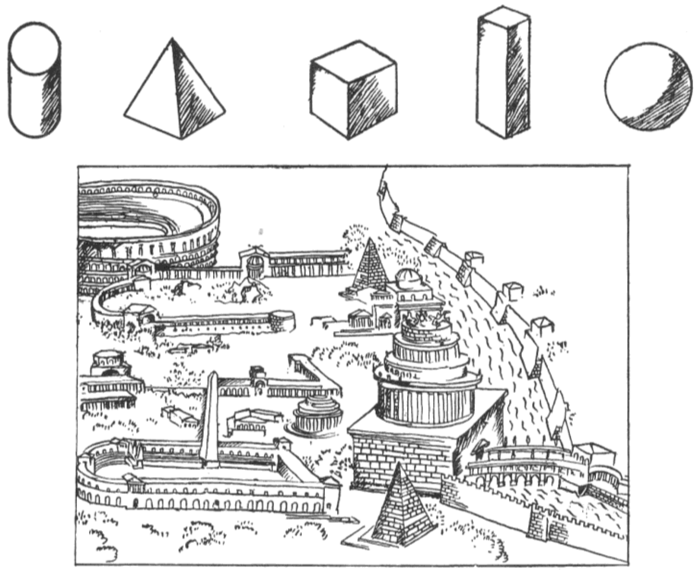
Le Corbusier's first great theoretical statement on Urbanism starts with a eulogy of the straight line and the right angle as means by which man conquers and goes beyond nature. The first two paragraphs of the book famously contrast man's way with the pack-donkey's way:
"Man walks in a straight line because he has a goal and knows where he is going; he has made up his mind to reach some particular place and he goes straight to it. The pack-donkey meanders along, meditates a little in his scatter-brained and distracted fashion, he zig-zags in order to avoid larger stones, or to ease the climb, or to gain a little shade; he takes the line of least resistance."[iv]
Le Corbusier admires the urban order of the Romans and rejects our sentimental attachment to the picturesque irregularity of the medieval cities: "The curve is ruinous, difficult and dangerous; it is a paralyzing thing."[v] Le Corbusier insists that "the house, the street, the town … should be ordered; … if they are not ordered, they oppose themselves to us."[vi] I agree, and yet I disagree with Le Corbusier's architecture: It is no longer adequate. Le Corbusier's limitation is not his insistence upon order but his limited concept of order in terms of classical geometry. Complexity theory (or chaos theory) in general, and the research of Frei Otto in particular, has since taught us to recognize, measure and simulate the complex patterns of order that emerge from processes of self-organisation and from evolutionary processes. Phenomena like the "donkey's path" and the urban patterns resulting from unplanned settlement processes can now be analysed and appreciated in terms of their underlying logic and rationality, i.e. in terms of their hidden regularity and related performative power that results from the consistent constraining pressures that have been underlying its process of formation.
Le Corbusier realized that although "nature presents itself to us as a chaos … the spirit which animates Nature is a spirit of order".[vii] However, his understanding of nature's order was limited by the science of his day. He lacked the concepts and computational tools that can now reveal the complex (geometric) order of those apparently chaotic patterns by means of

mathematically revealing and simulating their lawful “material computation”. A potent example of material computation is the physical simulation model made from a network of wool-threads that has been constructed at Fei Otto’s Institute for Lightweight Structures (ILEK) to compute optimised detour path networks. Depending on the adjustable parameter of the thread’s sur-length, the apparatus – through the fusion of threads – computes a solution that significantly reduces the overall length of the path system while maintaining a low average detour factor. The principles behind this “computation” have also been computationally recreated and are now in principle available to designers.



Marek Kolodziejczyk, Wool-thread model to compute optimised detour path networks, Institute for Lightweight Structures (ILEK), Stuttgart, 1991

Le Corbusier promotes the architectural use of elementary geometric shapes in his treatise ‘Towards A New Architecture’ in the chapter ‘The Lessons of Rome’. The chapter talks about the “spirit of order”[viii] and “fundamental, simple and unquestionable principles”[ix], and elaborates as follows: “Unity of operation, a clear aim in view, classification of the various parts.”[x]



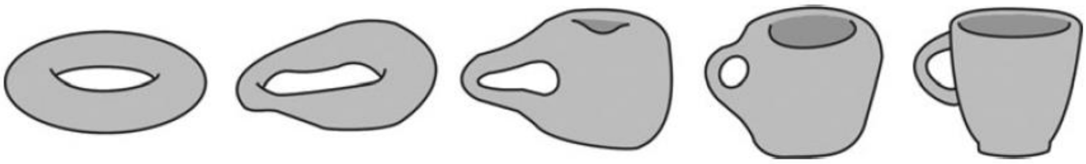
From Le Corbusier, Towards A New Architecture, p.159

All conscious architectural styles since antiquity, inclusive of Modernism, have thus been focussed on geometrical control via simple geometric solids like cubes, rectangular prisms, cylinders, pyramids and (semi-)spheres. Before modernism, their composition and subdivision were further controlled by symmetry and a system of simple number proportions. Since Modernism asymmetry and arbitrary proportions became viable. Postmodernism and Deconstructivism are aiming for more complexity but are still based on the same basic elements. However, these relatively recent styles allow for new ways of combining the basic elements via random agglomeration, intersection, and substraction.
This basic architectural ontology has only been decisively challenged more recently, in Parametricism.

A Revolutionary Transformation of the Discipline:
From Typology to Topology

The expanded geometric ontology of Parametricism includes the new (related) geometric entities of splines, nurb surfaces, and blobs, and allows for operations like lofting (morphing) and the compositional principle of affiliativeadaptive deformation. This radical ontological shift might be characterized as the shift from typology to topology.

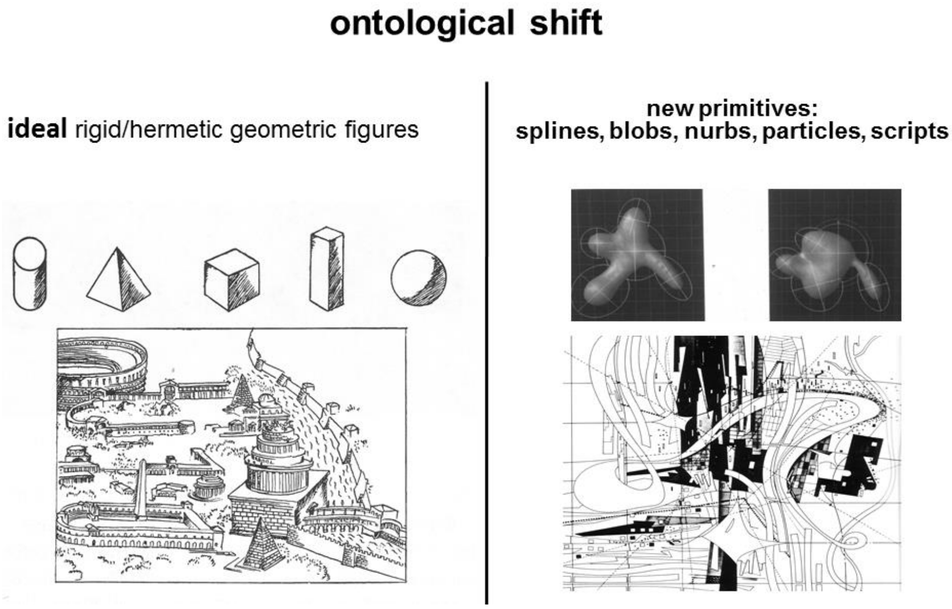
The slogan “from typology to topology” came to prominence in the 1990s within the architectural movement that was at the time referred to as Folding and which I later re-theorized as Parametricism. The slogan was meant to indicate that architectural design was now prepared to work with a much enlarged range of architectural forms that escape from the restricted repertoire that confined architecture to a handful of typical geometric figures like cubes or cylinders, and more generally that stereotypical solutions or standardized objects were eschewed for uniquely tailored solutions. Topology therefore stands here for flexible, adaptive variability rather than indicating that this new work relies or builds on the branch of mathematics called topology. In mathematics, topology is concerned with spatial properties that are preserved under continuous deformations of a surface without tearing or making new connections. According to this definition a doughnut and a coffee cup are topologically the same geometric object, or homomporph, i.e. the one can be deformed into the other without cutting the surface or attaching it to itself. The idea and animated image of such a transformation - as became a commonplace special effect within computer graphics at that time under the name of “morphing” - has been an inspiration in the early days of the movement of parametricism. Any two forms, however radically different, might be transformed into each other, as long as they shared the same topology. The analogical transference of this idea into architectural design was easy enough: the time sequence of the images of such an animation could just be laid out as spatial sequence transitioning between the two endpoints of the sequence.



Morphing series: Forms can be transformed into each other without cuts or discontinuities if they share the same topology.

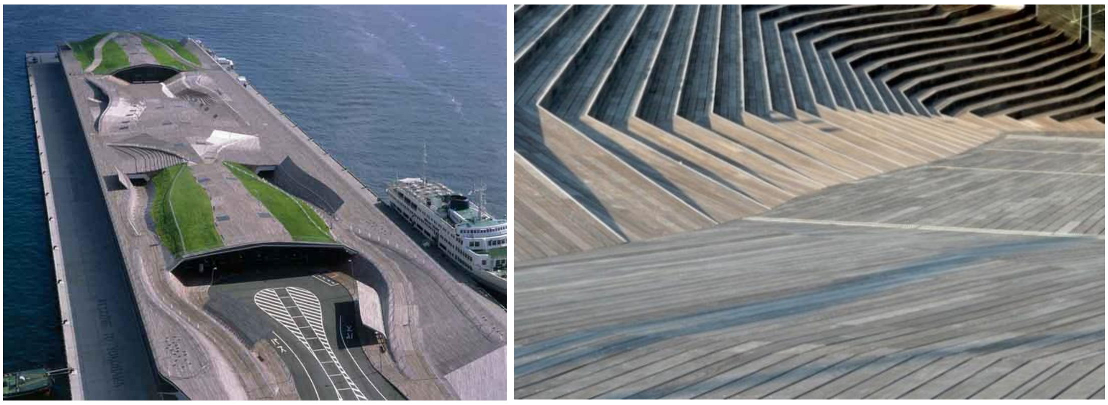
Mathematically this ontological shift is made possible by the introduction of algebra using variables, and calculus, i.e. working with infinitesimal increments and variations in quadratic, cubic or other polynomial functions as descriptions of complex curves with continuously varied radii, in contra-distinction to the classical repertoire straight lines, arcs and simple whole number proportions. Proportions in classical architecture were considered harmonic and beautiful. However, more basically they were required to control the construction process in terms of dimensional control, in the absence of decimal numbers (which were introduced in Europe only in the 17th century) and in the absence of a reliable standard measure like the meter (which was only established in the late 18th century in Paris). Calculus was developed in the 17th century. However, its geometric possibilities effectively arrived in architecture only in the 1990s, after the introduction of digital design tools based on calculus. The key new tool here was the *spline* in the form of the *Bézier Curve (after Pierre Bézier*) and its extension to surfaces called NURBS (for Non-Uniform Rational B-Splines). Pierre Bézier was an engineer and mathematician working for the French car maker Renault who worked out the mathematics of computing a smooth interpolation of a spline-like curve between any given points (control points).[xi]

An approximation of what became the mathematical-geometric spline had been used in ship building via the material computation of elastic planks bent over physical “control points”. Such curves when then also made available for drafting by means of so called ship curves or French curves. When I first joined Zaha Hadid’s studio in the late 1980s it was full of large sets of French curves and these were used routinely. In fact, all drawings were exclusively using these curves, while compass and ruler were largely eschewed.



The first CAD systems that included spline modellers and thus made Bézier's geometry conveniently accessible to designers via graphic user interfaces appeared in architectural schools and design studios in the early 1990s, notably at Columbia University, where digital design was promoted by the introduction of so called "paperless studios" in 1994. Splines and nurbs became the drivers for the expansive take up of a new emerging architectural style that then became known as "Folding ". This style progressed rather quickly together with the tools of computational geometry that developed equally rapid and was 15 years later, at a considerably more advanced stage, rebranded and generalized as 'Paramretricism'.
The new spline-based digital design techniques lent themselves to create much more varied and organic forms and allowed for smooth, gradual transitions between different forms via the "lofting" of spline-profiles. This allowed for a new kind of complexity that was based on the smooth integration of different forms into a seamless complex continuum in contra-distinction to the unmediated, rugged complexity of clashing forms achieved by the 1980s style of 'Deconstructivism'. The first compelling built result of the new style of

Folding was the Yokohama Ferry Terminal by FOA (Foreign Office Architects) designed in 1995 and completed in 2002.



Foreign Office Architects, Yokohama Ferry Terminal, 1995 - 2002

Shortly after spline- and nurb-geometries had been incorporated most prominently into the working tools of the new style and thereby expanding its repertoire and shifting its aesthetic values towards an embrace of complex variation and continuity, a new, related geometric tool became available within this milieu, namely isomorphic polysurfaces, offering a further expansion of the repertoire within the same system of aesthetic values. Isomorphic polysurfaces are dynamical design systems in which complex surfaces are defined by multiple “blob” objects that can deflect each other or fuse with each other depending on their relative proximity via simulated quasi-gravitational fields. The resultant complex surface geometry is defined by computing the contours where the composite field has the same (equilibrium) intensity – therefore the name isomorphic polysurfaces.
These objects are inherently relational, similar to the way the spline or nurb is relational relative to the control points the designer is shifting about with the mouse to shape the line or surface. However, a system of isomorphic polysurfaces can be much more complex and feels much more dynamic.

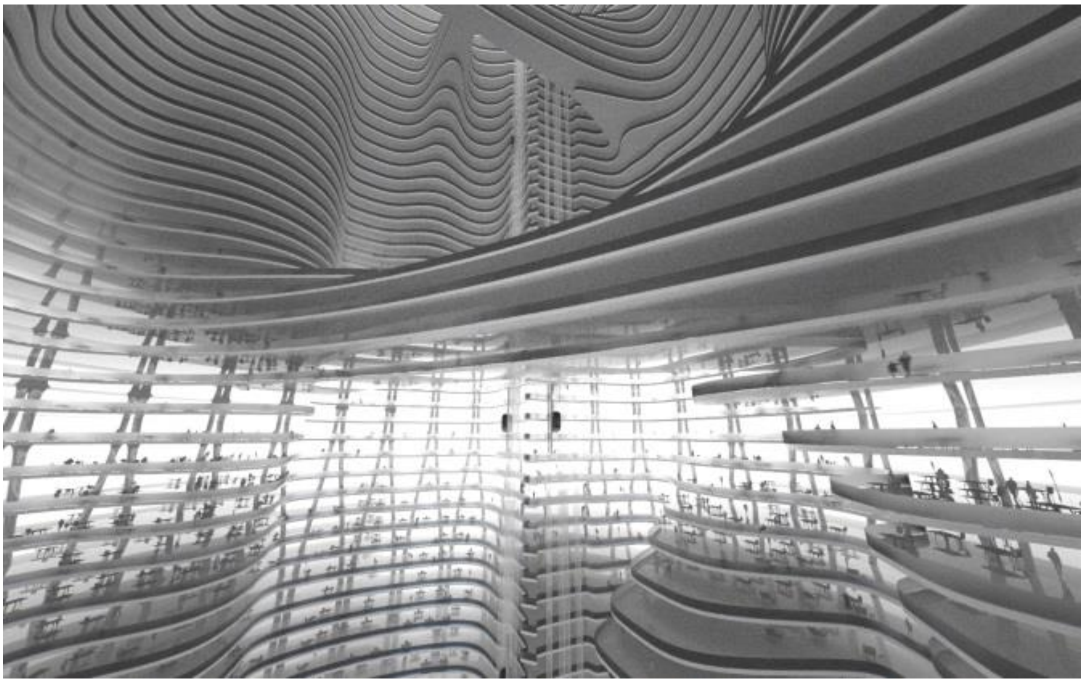
These new geometric opportunities entered architecture via special effects/animation software like WaveFront where the respective tool was called “meta-balls”.

Greg Lynn who prominently introduced these “Blobs” into architecture in his eponymous article from 1995 explains: “Unlike a conventional geometric primitive such as a sphere, these objects are defined with a centre, a surface area, a mass relative to other objects … and the surfaces are surrounded by two halos of relational influence – one defining a zone of fusion, the other defining a zone of inflection. When two or more meta-ball objects are related to one another, given the appropriate proximity of their halos, they can either mutually redefine their respective surfaces based on their particular gravitational properties or they can actually fuse into one contiguous surface that is defined … by the interaction of their respective centres and zones of inflection and fusion.”[xii]
Nurbs and blobs imply an ‘ontological shift’ not only by the new variability, nor only by their radically other, by traditional standards amorphous, anti-architectural shapes, but further due to the new aspect of inherent relationality, where every compositional action is now context sensitive and adaptive, potentially inducing a reaction in what had been placed so far, and generally implying a radical adaptiveness which offers new ordering capacities that allow to maintain legible order in the face of new degrees of freedom, versatility and complexity.
The blob (meta-ball) system gives much more morphogenetic scope to algorithmic self-organisation than nurb modellers that are manipulated via pulling control points. This trajectory of giving increasing morphogenetic scope to algorithms is an obvious dimension of methodological progress that also shows up in the increasing intricacy and rationality of the geometric results that are being achieved.

The meta-ball compositions also imply a new, more versatile and complex organisational logic, akin to fuzzy logic, similar to moving from crisp sets to fuzzy sets. Belonging together is no longer an either/or concept but comes in degrees. Also, it no longer requires nesting enclosure, nor alignment.

With blobs (isomorphic polysurfaces) architecture received its first instance of the general concept of associative logics.

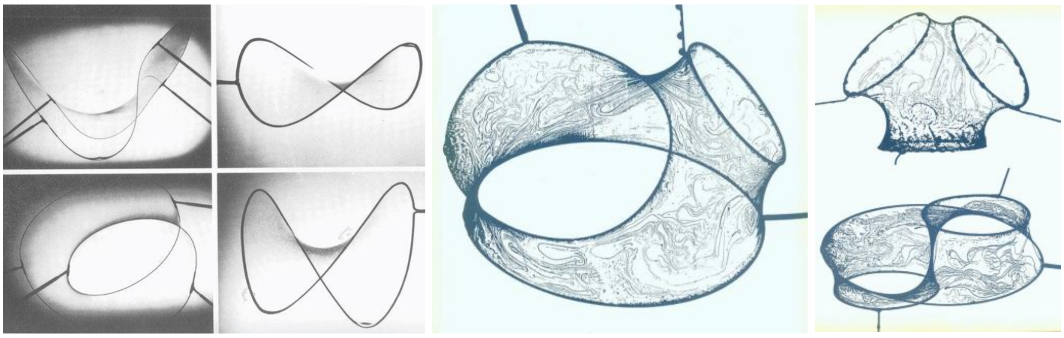
Zaha Hadid Architects, blob/meta-ball composition of massing, Soho Galaxy, Beijing



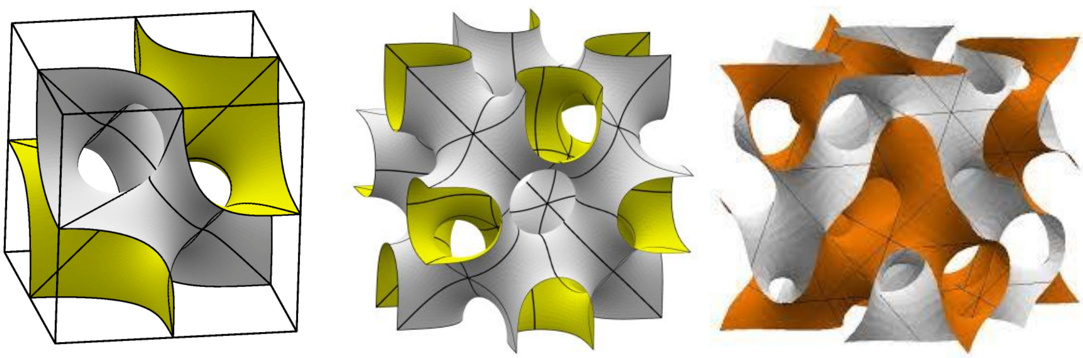
Zaha Hadid Architects, blob/meta-ball modulation of internal space, competition entry for a new Hyundai Headquarters, Seoul, 2015.

Minimal surfaces, which had been introduced a few years later into the architecture of Folding (Parametricism), fit into this trajectory of giving increasing morphogenetic scope to algorithms within the design process. 'Minimal surfaces' are surfaces of minimal surface area for given boundary conditions. They can also be defined as surfaces whose mean curvature is zero. The problem of finding the minimum bounding surface of a skew quadrilateral - a four-sided polygon not contained in a plane - was solved by Schwarz in 1890.

Frei Otto, the only true precursor of Parametricism, and indeed of Tectonism discussed below, had extensively experimented with minimal surfaces via soap films. He used these as morphogenetic engines, or material computations – in his language "form finding" – to discover optimal shapes for tensile structures relative to given or selected boundary conditions.



Frei Otto, Soap film experiments delivering Minimal Surfaces, Institute for Lightweight Structures (ILEK), Stuttgart



Triply Periodic Minimal Surfaces

The triply periodic minimal surfaces (TPMS) are infinitely extending, without self-intersections. These surfaces partition the space into two separate regions, each being continuous. The two colours in the diagrams above help to track the two domains. This topology thus organises and relates two interpenetrating networks of places. Toyo Ito has utilized this condition in his design of the Taichung Opera House, whereby – at least conceptually – the two domains were allocated to public foyer spaces versus performance spaces, obviously with occasional perforations of the boundary to allow for communication between the two domains.

Toyo Ito, Minimal Surface geometry, section, Taichung Opera House, Taichung, Taiwan

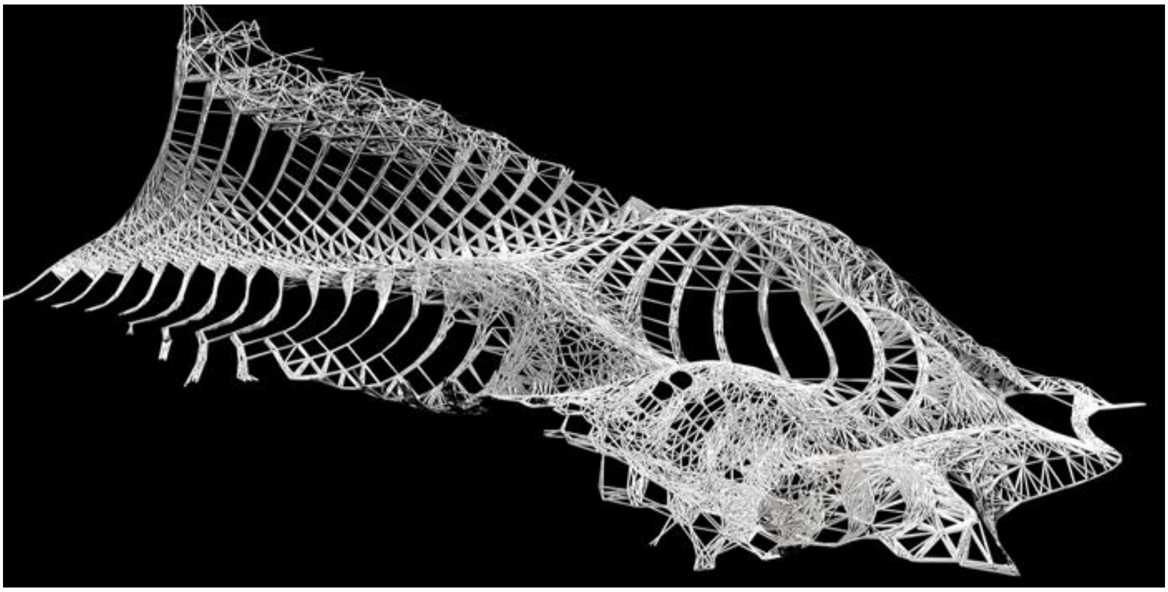

Toyo Ito, Taichung Opera House, Taichung, Taiwan

Swarmism and Multiple System Correlation

The principle of associative modelling is at the heart of parametric design. It implies the interdependency of the geometric shapes of all the components of a design. The crafting of these interdependencies – just like the variational range of each component - are calling for the designer's creativity. Interdependencies are not only concerned with geometric fit. They are in this sense non-trivial and can be freely chosen.
The design consists in the relationships that are maintained between the various elements of the composition. In fact the parametric design model is conceived as a network of relations or dependencies.
The essential identity of the parametric design resides in its topology rather than in its (momentary) determinate shape. This parametric malleability is advantageous both for the sake of continuous design adjustments as the design progresses, and for the sake of the generation of options and variations. The parametric model can be conceived as general building plan or *geno-type* for the generation of many different versions or *pheno-types* that might co-exist (rather than substitute each other as options). Optioniering thus leads to versioning. Mechanical repetition is being replaced by mass customization. Versioning might also be applied within a single building design via the versioning of components, via 'generative components'. The components adjust their individual shapes in relation to their placement within the encompassing model. These components are small parametric models, i.e. sets of interdependent parts with adjustable shapes. The component adapts to (and fits into) local constraints via the adjustment of its internal parameters. For instance an array of façade components - complete with glazed openings, frames and fixing details - might be made to populate the surface of a volume with changing curvature. The components are to be set up in such a way that they auto-fit to the surface. Each component will assume an individually fitted 'phenol-typical' shape, on the basis of the same underlying 'geno-type'. This results in continuously differentiated ***swarms*** of elements. The continuous

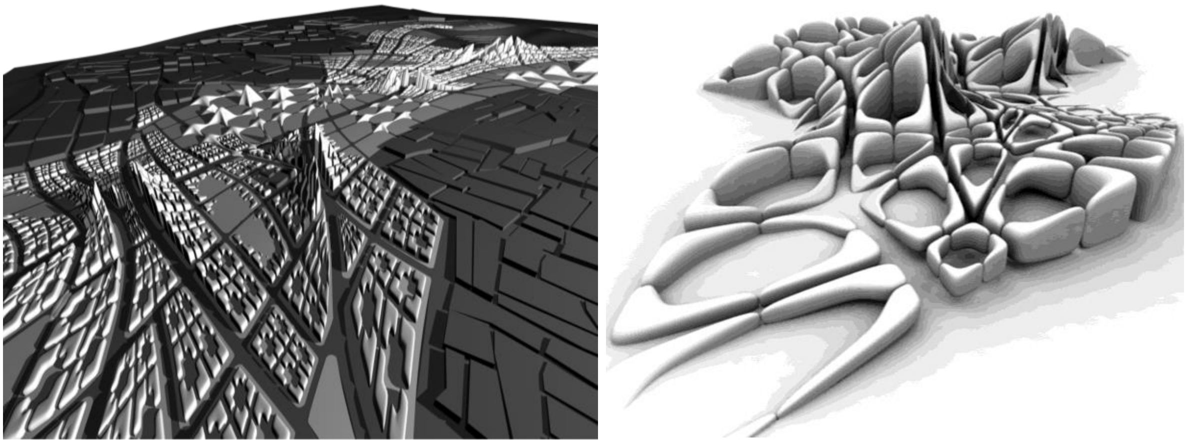
differentiation pertains both to the elements' individual shape as well as to their directional alignment and to the density of their distribution.

However, the potential for such differentiation is not confined to the achievement of scaling and geometric fit with respect to complex forms with continuously changing surface curvature. This kind of differentiation might also be driven by performance parameters like environmental or structural performance parameters, on the basis of external parameters like sun exposure or wind loads. For instance the opening within a façade panel or the shape of a shading element might vary according to the differential sun-exposure of a curved façade at each point of its surface. The parametric designer might set up the following dependency: the higher the sun-exposure of a certain surface patch, the smaller should be the opening of the façade component at this location. A sun-exposure map imported from an environmental analysis tool might then deliver the data input for the component differentiation. The sun-exposure map is thus being 'transcoded' into a differentiated field of façade panels that 'optimizes' the sunlight penetration within brackets set out by the parametric design. The resultant façade articulation is thus a function, mapping or indeed a representation of the façade's differential exposure to the sun. Similarly, a designed architectural volume might be structurally articulated via the transcoding of structural analysis parameters into differentiated geometric components. For this purpose the results of a finite elements stress analysis might become the input for a framing pattern that differentiates either member density or member size or both. Again, the result achieves a relative structural optimization (if compared to an undifferentiated framing pattern) and a thus differentiated structure represents the underlying stress distribution. Thus in a tall building a parametrically designed skeleton responds to and displays the differentiation of structural forces. Both compressive stresses due to the accumulating vertical loads as well as the moments due to horizontal wind-loads accumulate at the bottom of the tower which will thus be rather different from the middle and top of the tower respectively. The respective variation of performance parameters of the various subsystems of the building like envelope and skeleton thus translates into the morphological differentiation of these subsystems. The way performance parameters might be transcoded into morphologies is an open question that calls forth the creative designer. Further: These subsystems – each adaptively differentiated according to its own performance logic – also might adapt to each other's differentiation. We might talk about sub-system 'correlation'. To the extent that the envelope's differentiation is responsive to the skeleton's differentiation according to a rule it becomes its 'mapping' or 'representation'. The particular rule or mode of correlation is again open to design invention.



Network Pattern varies with Surface Condition, Maren Klasing and Martin Krcha for Zaha Hadid Masterclass, Vienna University of Applied Arts, 2009

The same principles of adaptive system differentiation and multi-subsystem correlation might be applied to urbanism which thus becomes ***'parametric urbanism'***. The initially considered subsystems here might be the circulation system (road network), the building fabric (massing) and the programmatic distribution (land use). The existing topography (topo-map) as well as the pre-existing roads might serve as underlying input data sets to be transcoded into a differentiated road network. The differentiation of the urban massing might initially follow its own logic of block differentiation, initially conceived as internal product variation without as yet responding to external data inputs. This internal differentiation could in a second step be ‘over-coded’ or correlated with the differentiation of the circulation network according to a certain rule. The fabric differentiation might be further adapted with respect to an agenda of morphological affiliation with the adjacent urban context. Each step requires the invention of a rule of differentiation or adaptive correlation. At the basis of these differentiations and correlations are the chosen geometric ‘primitives’ (or components build-up from those primitives) with their respective variables and respectively chosen degrees of freedom.

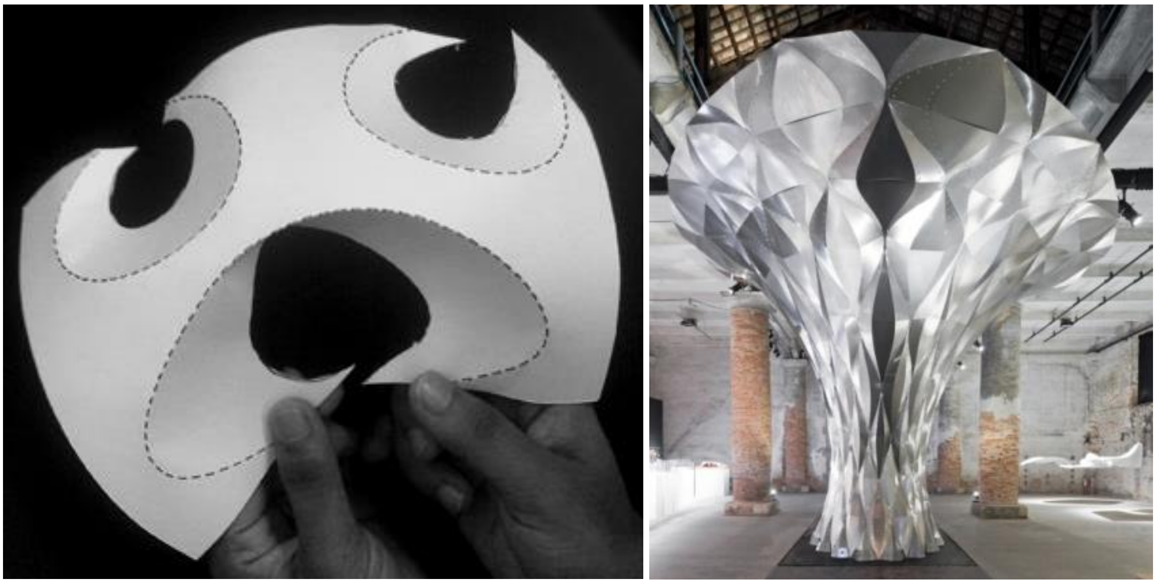


Zaha Hadid Architects, Kartal-Pendik Masterplan, Istanbul, 2007

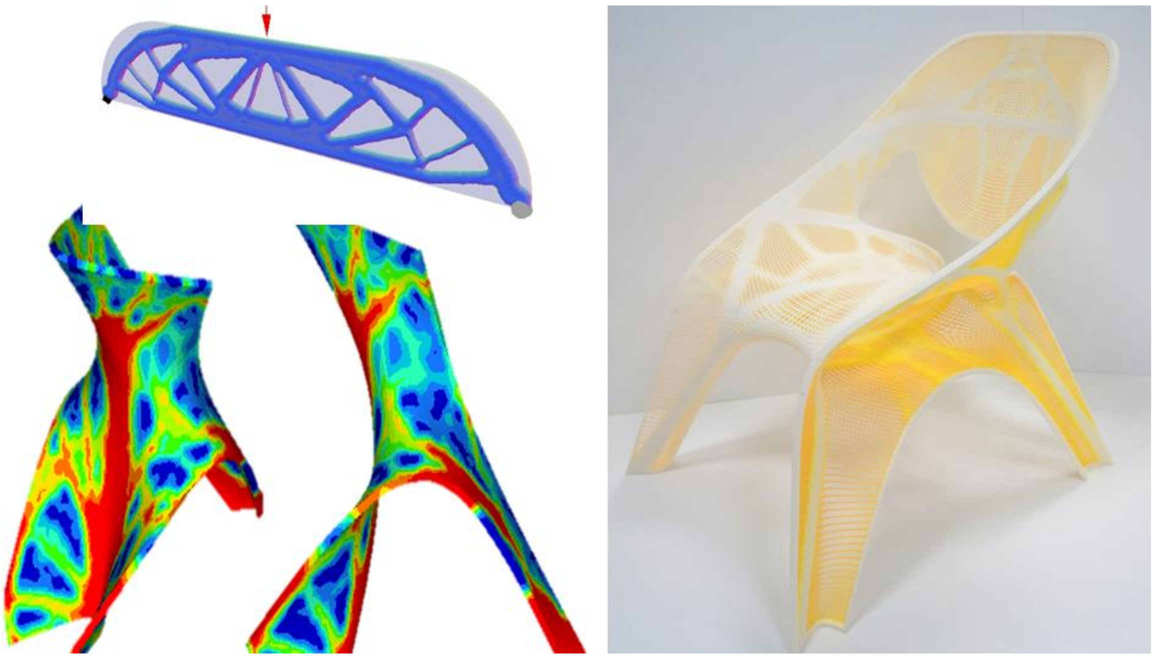
Geometric Simulations of Engineering Logics Deliver a New Expressiveness

By far the most widely used parametric design software is ‘Grasshopper’ developed by the David Rutten for Robert McNeel Associates and first released in 2008. Grasshopper is a freely available graphical associative logic modeler and algorithm editor closely integrated with McNeel’s 3-D modeling tool ‘Rhinoceros’. Grasshopper is a pertinent tool for the set up parametric models as described here (in the previous chapter) as networks of interdependent elements. The network of relations is set up and visualized graphically so that the designer can keep track of and intervene in the relational network he is designing.

During the last decade emerged a series of powerful plug-ins for Rhino/Grasshopper that bring a new level of algorithmically empowered geometric intelligence to designers. These plug-ins translate engineering intelligence into geometric constraints via so called ‘physics engines’, i.e. geometric simulations of physical behaviours of the kind Frei Otto had explored with his ‘material computations’ or physical ‘form-finding’ models. In this way new technical performance parameters can become parametric drivers for design while leaving sufficient degrees of freedom for designers to search for forms as design solutions in this pre-constrained space of possibilities. These drivers are now available to architects at early design stages via structural form-finding tools like RhinoVAULT (for complex compression-only shells) and physics engines like ‘kangaroo’ (to approximate shell or tensile structures), via analytic tools like ‘Principle Stress Lines’ analysis in ‘Karamba’ that can also be turned generative, and via optimisation tools like structural topology optimisation (e.g. available in ‘millipede’). Various fabrication- and materially based geometry constraints can also be embedded in generative design processes that are then set free to search the characteristic solution space delimited by the constraints. At ZHA CODE we are developing our own custom tools to model the particular constraints of particular fabrication processes, for instance for curved folding of sheet materials implying conic geometry, or for hot-wire cutting of moulds implying ruled surfaces.



Zaha Hadid Architects, CODE Group, Curved Folding, ARUM, with Buro Happold, Robofold, Venice Biennale 2012



Zaha Hadid Architects, CODE Group, Topology Optimization, for a sculpture in Mexico City, and for a 3D printed chair, printed by Stratasys, presented at ACADIA 2014

tectonic articulation orchestrated within a system of signification

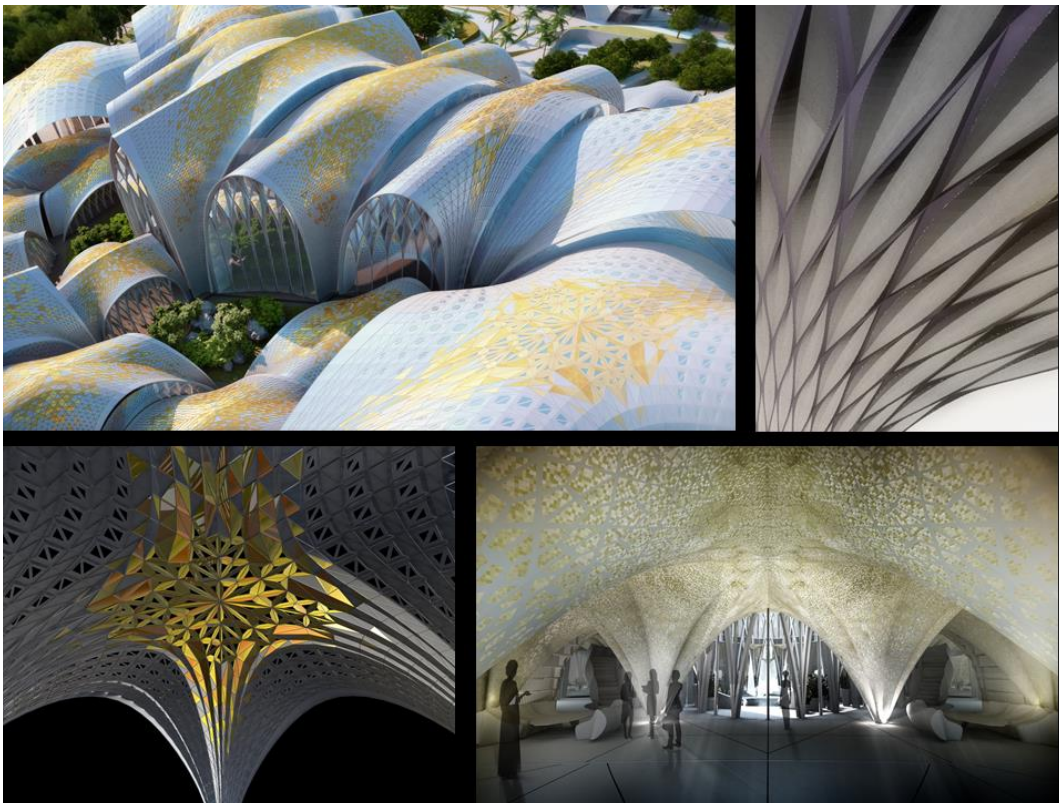
designing a semiological network of contrasts and similitudes

Four Pavilions, ICD (Prof. Achim Menges) witt ITKE (Prof. Jan Knippers), Architecture Faculty, University of Stuttgart

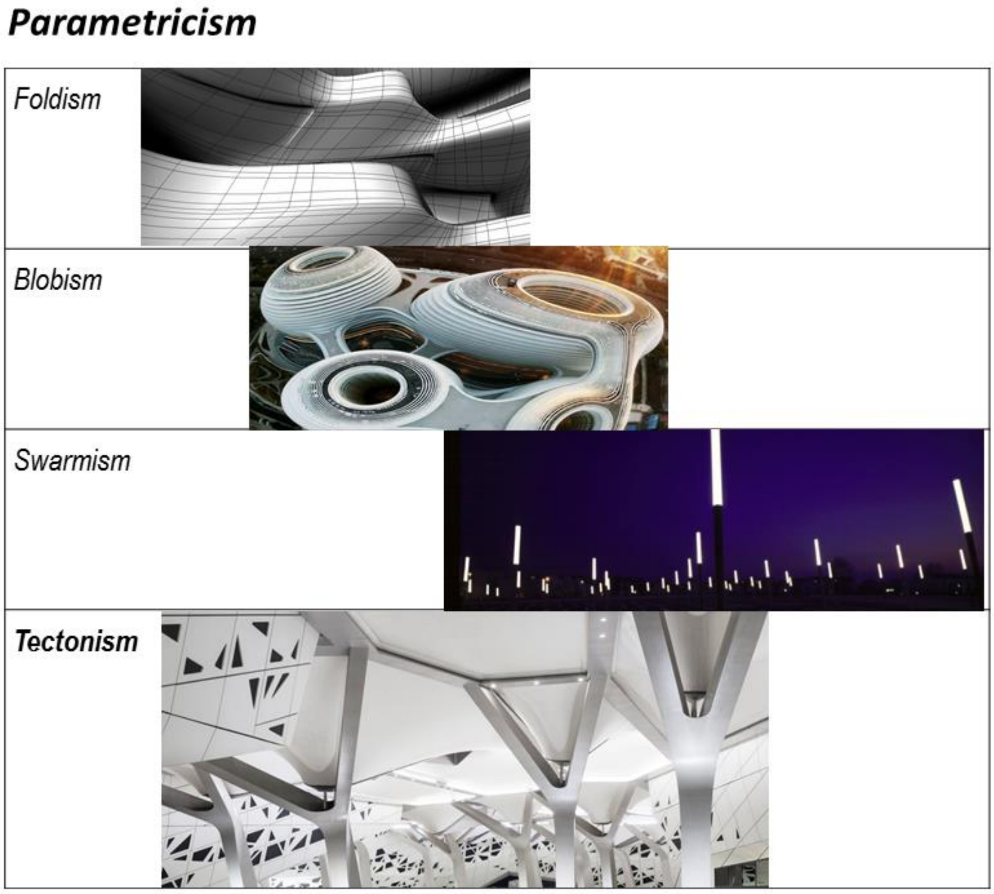
Each of these fabrication techniques imprints its unique, unmistakeable geometric character onto its products, including the shape-range of the overall form as well as the materiality and texture. This means that the concept of "faktura" is well alive in our era of robotics. (Faktura is the visual trace of the fabrication process in the artefact or work of art. It is seen as a positive, character sponsoring quality of the artefact or artwork. The concept emerged in the context of the Russian avant-garde art and design during the early Soviet Union.) The history of architecture abounds with examples where architectural elements and features with technical functions become the object of articulatory or "ornamental" endeavours. However, we need to understand the instrumentality of ornament, i.e. we need to grasp ornament not in contrast to performance but as a special type of performance: communicative performance.

The Latest Stage of Parametricism: Tectonism

This new diversity of form making potentials and aesthetic expressions affords a welcome expansion of parametricism's repertoire beyond the smooth nurb surfaces that had been prevalent previously. This fuels both programmatic invention as well as semiological articulation. The relationship between the technical and the articulatory dimension of the build environment leads to the concepts of tectonics, or more precisely ***tectonic articulation***, here understood as the architectural selection and utilization of technically motivated, engineered forms and details for the sake of a legible articulation that aims at an information-rich, communicative spatial morphology, for the sake of visual or tactile communication. This latest expansion of the discipline's geometric repertoire and thereby of the potential physiognomy of the built environment (and world of artefacts) merits the enunciation of a new style: ***Tectonism.***



Zaha Hadid Architects, Tectonism, Studies for a "Palace"



Stages and Subsidiary Styles of the Epochal Style of Parametricism

Tectonism implies the stylistic heightening of engineering- and fabrication-based form-finding and optimization processes.
However, this style does not spell a departure from parametricism. Rather, tectonism is the currently most prevalent and promising ***subsidiary style*** (sub-style) within the overarching paradigm and epochal style of parametricism. In retrospect we might distinguish tectonism from earlier phases of parmetricism like *foldism*, *blobism* and *swarmism*. These older sub-styles are still practiced, just as during the era of Modernism the earlier white Bauhaus style continued in parallel with the later Brutalism.
In contrast to these earlier sub-styles tectonism is embedding a series of technical rationalities that secure both greater efficiency as well as greater morphological rigour, while maintaining sufficient degrees of design freedom

to address programmatic and contextual contingencies. Since the principles tectonism utilizes are inherently plural and open ended, this additional rigour comes along with additional tectonic variety and thereby offers a new reservoir of morphological physiognomies. Â This empowers designers to give a unique, recognisable identity to individual projects. Tectonism delivers much more expressive variety than foldism or blobism, without descending into arbitrary form invention.

With the development of sophisticated computational design tools - within architecture, within the engineering disciplines, and within the construction industry - the scope for nuanced tectonic articulation has much increased. The realization of this potential requires an intensified collaboration between innovative architects, engineers and fabricators. Although there can be no doubt that architecture remains a discourse that is distinct from engineering and construction, a close collaboration with these discipline's as well as the acquisition of reliable intuitions about their respective logics are increasingly important conditions for the design of contemporary high performance built environments.

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[i] Le Corbusier, The City of Tomorrow and its Planning, Dover Publications (New York), 1987, translated from French original Urbanisme, Crès & Cie (Paris), 1925, p.xxi

[ii] Le Corbusier, The City of Tomorrow and its Planning, Dover Publications (New York), 1987, translated from French original Urbanisme, Crès & Cie (Paris), 1925, p.xxii

[iii] Le Corbusier, The City of Tomorrow and its Planning, Dover Publications (New York), 1987, translated from French original Urbanisme, Crès & Cie (Paris), 1925, p.xxi

[iv] Le Corbusier, *The City of Tomorrow and its Planning*, Dover Publications, New York 1987, translated from French original *Urbanisme*, Paris 1925, p.5

[v] Le Corbusier, *The City of Tomorrow and its Planning*, Dover Publications, New York 1987, translated from French original *Urbanisme*, Paris 1925, p.10

[vi] Le Corbusier, *The City of Tomorrow and its Planning*, Dover Publications, New York 1987, translated from French original *Urbanisme*, Paris 1925, p.15

[vii] Le Corbusier, *The City of Tomorrow and its Planning*, Dover Publications, New York 1987, translated from French original *Urbanisme*, Paris 1925, p.18

[viii] Le Corbusier, Towards A New Architecture, p.154

[ix] Le Corbusier, Towards A New Architecture, p.154

[x] Le Corbusier, Towards A New Architecture, p.158

[xi] For a detailed account of the context of this development in the 1960s and 1970s consult Carpo, Mario, *The Second Digital Turn: Design Beyond Intelligence*, The MIT Press, 2017

[xii] Greg Lynn, Blobs, Journal of Philosophy and Visual Arts, 1995, Reprinted in: Greg Lynn, Folds, Bodies and Blobs – Collected Essays, Bruxelles 1998, p.164