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From Cartesian to Topological Geometry: Challenging Flatness in Architecture

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Abstract
This paper argues that recent topological expressions of surface in architecture have an intellectual lineage to late-modernism. Several key developments of that era challenged the limitations of a simplified Cartesian understanding of form. This paper commences with a discussion of Cartesian geometry in Modernism, relative to innovations in the building industry that promoted constancy, repetition and standardisation. Despite the same logic being transferred to digital working platforms where the architectural elements are normally designed as geometric prisms and their immediate derivatives, an interest in computation has enabled architecture to bypass orthogonal regularity. Concepts investigated during late-modernism—such as adaptability, disequilibrium, and smooth transitioning—are now central to performance and parametric-based design, examined through the interaction with data inputs, further pointing at critical updates of common software production tools.

Keywords Topology · Flatness · Cartesian geometry · Soft architecture · Form-finding · BIM

Introduction

With the demise of expressionist plasticity, it is generally conceded that modernism, presented through the doctrines of the international style, tended to promote geometric regularity over *soft* topologies. In parallel, industry's preference for Cartesian resolution has aided standardisation and prefabrication, aligned with

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an engineering ideology directed towards mass-production, repetition, efficiency and quality control. In these models, surface was purified to its simplest shape as a rectangular plane to organise space horizontally and/or vertically, whereas to establish connections would require cutting the surface by following the geometry, construction logic and aesthetic principles of overall form. While this form of modernism dominated the architectural scene, there was another series of experimental works that challenged the limitations of its concurrent production standards in shaping imaginative thinking and so offering an alternate historical view about modernism, one that is more connected to topological surfaces computed with contemporary digital software. In effect, this paper borrows from earlier propositions on soft geometry developed alongside mainstream architecture to establish a connecting thread between recent developments and twentieth-century architectural discourse. Surfaces of late-modernism are compared with concepts that have emerged through the digital context. By taking advantage of the capabilities of computation, surface is translated to an elastic skin, whose shape is the result of data-driven real-time operations performed in a continuous and comprehensive manner to resolve space, structure and form. The historical framing addresses the influences of technology into architectural production and is presented prior to outlining the future aims of digital working platforms such as BIM, in order to better align the production strategies currently used with computational design's full potential.

Flatness

Concepts of flatness are symptomatic of a cultural condition present within spatial language, often exemplified by the phrase *level playing field* denoting a concept of fairness where there is an equitable chance of success. While it might also denote minimum standards, flatness also refers to the boundless space of deserts and other featureless landscapes associated with "emptiness, an absence of content and spatial clues" (Higman 2017). Central to this tenet is the notion of *tabula rasa*, or the ability to begin again, as in clearing a landscape to start without the remnants of the past which are seen as a burden.

Barry Higman (2017) observes that in architectural history "it is striking that the fundamental plane—the floor—remains defiantly flat, however topological and contorted the rest of the building's surfaces might be". This is in contrast to traditional vernacular building that might clear a relatively level surface but accept undulations and surface variability to adjust locally due to practical constraints. In their desire for horizontality, modern buildings demand precise measurements, points in space and lines that extend into planes. It is therefore safely assumed that the geometry of flatness aligns with the ideology of modern architecture, including simplicity and purity, and their associated symbolic conditions of being transparent, clean, efficient, standardised, predictable and equitable to all. This ideological position overtook other modernist notions, such as expressionist plasticity, and in consequence hegemonic modernism showed its preference for geometric shapes. Framed through both the Bauhaus ideology and Le Corbusier's vision, modernism's aesthetic and geometrical elegance was founded in the appropriation of Cartesian references. Under this conception, walls, roofs, floors and ceilings were defined as planar components possessing the same material consistency and constant thickness. Moreover, Migayrou (2002) argues that Cartesian geometric analysis assists in describing the edifice as a *true product*, an object entirely organized by a system of processes, finite, circumscribed, and valued in terms of cost and return on investment. Higman also suggests that the pervasive desire for *flatness* meant "profit for manufacturers, distributors and retailers. … From the bottom to the top—from flat files, to the smallest frozen food box, to the offices in the tallest skyscraper—space is divided into straight-sided units that can be fitted together" (2017: 157). To assist this process, surface was reduced to rectangular planes bounded and controlled by explicit geometries, and openings made by clear geometric subtractions. Such a mandate brings about manifold advantages, as for example the adoption of a common aesthetic language irrespective of ideology, culture, or feelings, and one that is portrayed as universal, since it carries within it symbols of values considered eternal and divine, such as harmony, timeless beauty, accuracy and order, being particular to Western thought.

Topological Surfaces of Late-Modernism

Although flat surface was widely aligned with modern ideology, several pioneering architects especially during late-modernism questioned its competence in meeting all design aims. For example, the works of Claude Parent and Paul Virilio (Virilio 1996), George Candilis, Alexis Josic and Shadrach Woods of Team 10 (Smithson 1968), Constantine Doxiadis (Doxiadis 1963) and late Le Corbusier in the 1950s and 1960s (Sarkis 2001) appear as focused attempts to break from sheer geometric homogeneity by defining surface as a dynamic element that unites various spaces together by responding to special requirements. Others such as Frei Otto argued that flat surfaces lack tectonic behaviour, as they promote rigid structures with large amount of material waste (Drew 1976). Despite their obvious differences, they all maintained that constant flatness was often inefficient particularly when programmatic and structural requirements could only be met by subtle manipulations such as gradual transformations and local adjustments.

In 1963, Parent and Virilio formed the Architecture Principe group with an aim to investigate a new architectural and urban order that emerged after their rejection of the vertical and the horizontal as primary generators of architectural space (Johnston 1996). They dismissed the two fundamental axes and proclaimed the end of the right angle, proposing instead oblique surfaces, which they believed would have the benefit of multiplying usable space. For Parent and Virilio, the *oblique* "was a new means of appropriating space … which promoted continuous, fluid movement and forced the body to adapt to instability" (Lucan 1996: 5). Among their priorities were to test the equilibrium and habitability of inclined slopes and to determine the best choice of angular spaces for different living conditions. To this extent, the oblique surface was a generator of activities and an engineered structure, rather than a purely aesthetic construct (Parent 1996).

Apart from its practical efficiencies, the oblique model introduced objectives that were fundamentally different to prevailing theories. Notions of disequilibrium and instability challenged "the anthropometric precepts of the classical era—the idea of the body as an essentially static entity with an essentially static proprioception—in order to bring the human habitat into a dynamic age of the body in movement" (Virilio 1998: 13). Parent and Virilio offered an alternative to the human body in homeostasis, and static proportioning systems that have governed architectural composition. In Virilio's terms, the oblique function offered new conceptions of urban space, through which he declared "the end of the vertical axis of elevation, and the end of the horizontal as permanent plane, in order to defer to the oblique axis and inclined plane. … [This contrast to modern verticality, would allow for] a 'reeroticization of the ground' as a sort of folded or pleated force field" (Rajchman 1998: 84). The oblique surface would encourage gravity awareness, establishing a tactile relationship between the body and the building and regaining their intimacy with the ground.

Greek architect and town planner Constantine Doxiadis' research from the late 1950s up until his death in 1975 was founded on similar principles, but followed a different trajectory. Drawing upon modernism's links with science, biological references were often employed to define the surface as an aggregate of units set in dynamic patterns. These units were designed to expand infinitely, and be embedded within each other to produce heterogeneity locally, while maintaining overall homogeneity. Various themes such as grid, cell, and hexagon became more than geometric references to subdivide a surface, irrespective of whether they represented the ground, a floor plan, a section, or the urban setting (Doxiadis 1966). Patterns were shown to grow externally and internally, while forming higher densities as needed, resulting in abstract continuums that led towards an all-systemic understanding about space.

Doxiadis related the various patterns through a structure described as *nesting* (Zavoleas and Tournikiotis 2014) (Fig. 1). Nesting is about compound systems derived from generic geometric schemes applied onto a plane to assist the arrangement of spatial units. Within this system, each unit is assessed relative to its positioning and by the way it is organized to accommodate other units. These abstract schemes are scaleless, and therefore applicable at any context, such as from the room-cell to the building, the block, the neighbourhood, the district, the city and outwards to describe regions, nations, continents, even the whole world seen as one compound. A spatial unit is classified externally according to its characteristics and size and is arranged in successive layers holding similar units as the system expands outwards. At the same time, it is broken down internally into a set of subunits similarly organised in layers. The result is a multi-layered system of grouping and syntaxing, where each unit influences, and is influenced by, the other units in a dynamic manner.

In Doxiades' work, surface is defined by nested patterns of varying densities, set according to the changing needs for resolution and detailing. Nesting manifests its organising purpose by connecting the units together in ways that their placement and function are in relation to each other. In effect, it presents an all-encompassing logic about spatial units in an early manifestation of layered organising and moreover, it

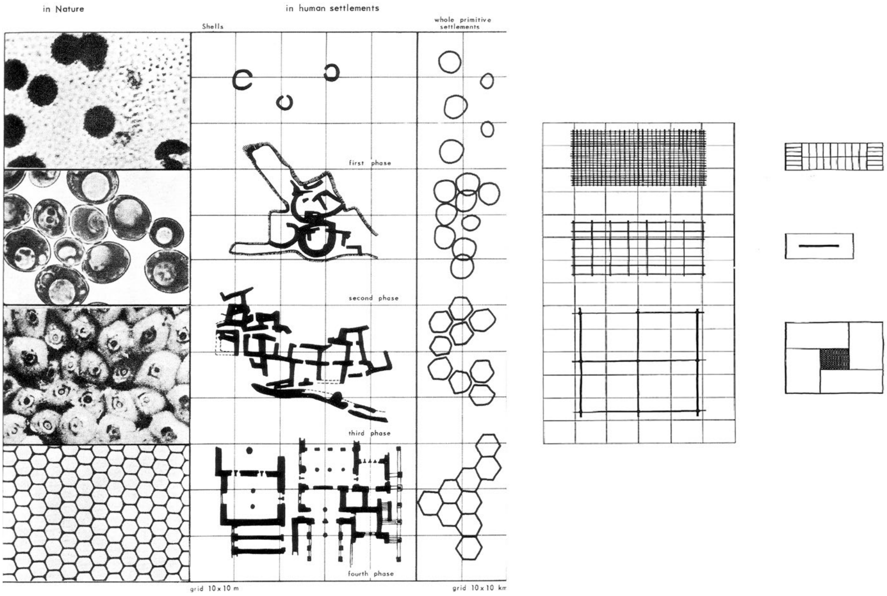

Fig. 1 Constantine Doxiadis, comparison of dynamic patterns in nature to ancient settlements (left), and the pattern codified to a rectilinear system deriving from the grid described as nesting (right). Source: Constantinos A. Doxiadis Archives. Constantinos and Emma Doxiadis Foundation

has enabled the subdivision of surface to interact with data by dynamically affecting its density and shape, an idea that has been eminent in parametric-based design software.

During the same period, a series of projects that employed similar dynamic patterns appeared under the guise of *mat building* which aimed to homogenize the building and the ground into one continuous surface structure. Mat building concerns a spatial envelope that expands mainly along the x/y plane, and, to a lesser extent, the z-axis. It creates an elevated terrain of varying thickness that duplicates the ground level while maintaining proximity and interaction with it, bringing together the versatile activities of the ground and the program. Mat-building's principal idea is evident in the competition entry for the reconstruction of the Centre of Frankfurt-Römerberg, designed in 1963 by Georges Candilis, Alexis Josic and Shadrach Woods (Tzonis and Lefaivre 1999) (Fig. 2). The scheme follows the general principles of the TEAM 10 group, concerning an architecture that readdress its links with society and corresponding socio-political impact to produce form through a brutalist yet intuitive sense of topology (Banham 1955). In this case, the design proposes a thick web structure placed above the historic part of Frankfurt that was severely damaged during Second World War. The web's grid pattern is set as a flexible system, made of cells of varying sizes that are either open or closed relative to circulation and activities, and it is also capable of adjusting to the remains of the urban tissue. The architects tested the same idea in their partially built proposal for Frei Universität, Berlin in 1963 (Fig. 3). An open scheme about a university that expands in all directions to accommodate change was in contrast to closed and finite

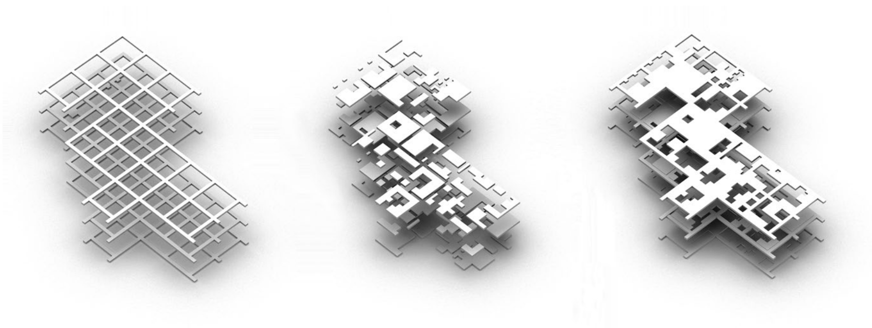

Fig. 2 Candilis-Josic-Woods, studies on mat building. Centre of Frankfurt-Römerberg, 1962–1964. Source: Yannis Zavoleas

Fig. 3 Candilis-Josic-Woods, studies on mat building. Frei Universität in Berlin, 1963 (below). Source: Yannis Zavoleas

building types. An intensive need towards flexibility and adaptability overrode any general wish for compositional completeness.

The above concept for an open-schemed solution that expands in all directions to accommodate change became popular among architects of the same era. As such, mat building presents a significant phase of Le Corbusier's recurring interest in open organising structures (Zavoleas 2013). Le Corbusier's related studies focused on grid patterns that extend over a surface to produce polycentric aggregates. Initially, he explored the idea on various occasions for Chandigarh, such as mural artworks, roof terrace layout and claustra façade patterns. One anecdote suggests that Le Corbusier had access to the drawings of the Centre of Frankfurt-Römerberg, provided to him by Shadrach Woods, who was a friend and former employee (Tzonis 2001). In the Venice Hospital proposal Le Corbusier designed between 1964 and 1965, a mat building structure is laid over the city of Venice as a lace of varying densities and voids to blend with the urban context.

Mat building unfolds as a high-genus topological surface. Its expansion in all axes suggests one structure of enormous size, but that dominance is subdued by a lack of massiveness in making the volume (Tzonis and Lefaivre 1999). A web-like scaffolding expands to support the parts and their linking with the greater setting, creating an abundance of experiences and connections with the urban fabric and nature, along with a potential to develop more density and expansion to support the fullest range of events. By adapting its shape and thickness, this topological surface manifests a field with higher order complexity to respond to future requirements as they arise.

Surfaces Pre-empting Digital Revolution

So far, this paper has demonstrated that alternative ideas about surface were propelled by topological studies that contributed to its conceptual shift away from a flat geometric element. The surface was subdivided by dynamic patterns interacting with forces, functions, organising modes and relationships set as data inputs of various kinds. The topologically defined surface bypassed geometric fixity and aesthetic determinism and incited a responsive attitude that formed a connecting system between edifice, dweller and environment. It is often claimed that these examples pre-empted data-driven computational approaches long before computers entered the workplace (Tzonis and Lefaivre 1999; Allen 2001; Wigley 2001). Their value resides in the fact that they contributed to updating architectural discourse not by suggesting another kind of utopia, but by being framed through the practicalities of the building industry. A quest on surface provided the context to overcome stylistic standards and typological rigidity in favour of dynamic architectural space and form; attributes, that would later be examined through the digital framework.

One of the most influential figures studying surface through new tools and techniques was the post-Second World War German architect and engineer Frei Otto. His focus was on structures that were a diagram of forces, where form-finding follows iterative evolutionary model testing that aligned with the laws of physics, as with natural structures (Drew 1976). Analogically, the biological operations of mutation and selection call for invention and optimisation through lightweight testing. An original architectural language is produced each time as the result of humans interacting with nature through technology and technique (Fig. 4).

The concept of prestressed tensile surfaces is attributed to experiments with high surface-tension soap film and linear spatial configurations to produce thin topological membranes. Stretched-skins of extreme clarity and captivating beauty would develop entirely in the search for structures with a minimum of building materials. These artificial terrains establish a surface topography subtly counterpointing that of the natural landscape, “the attractive identity between the surface relief of membrane and cable nets and the earth forms, one shaped by force and the other by the action of wind and water which erode and smooth out abrupt disconnections of form, assists in the organic integration of architecture with its natural setting” (Drew 1976). These lightweight tensile shapes become a measure of effectiveness for dynamic elements, since they are more robust, resilient and economical than those subject to bending.

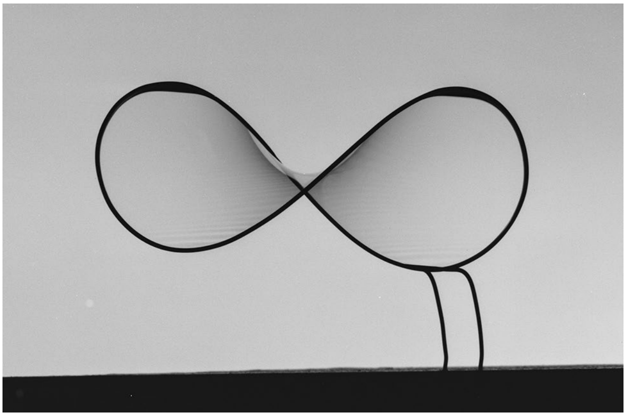

Fig. 4 Frei Otto, soap skin model. Photo: Atelier Frei Otto, Warmbronn. Source: SAAI | Südwestdeutsches Archiv für Architektur und Ingenieurbau, Karlsruher Institut für Technologie

Since the late 1980s, folding techniques based upon traditional Japanese origami have also offered ways to rethink surface as a topological entity that hosts diversity within its niches, while maintaining overall continuity. The main idea of folding is that surfaces such as floor planes and walls are joined together to form a single element, so that a continuous trajectory and a smooth experience similar to a landscape terrain traverses the building from the lower level to the roof. Folding becomes a strategy to build up and to manage complexity through iterative testing of folding techniques on soft surface materials, such as paper (Fig. 5). Even though folding registers as a very distinct effect, it is primarily an experimental process and a generative strategy that is "agnostic, non-linear and bottom up" (Vyzoviti 2003: 8), aiming to integrate disparate elements to "a heterogeneous yet continuous system" (Lynn 1993: 24).

Sophia Vyzoviti and Hans Cornelissen directed studies on surface topology through folding at Delft University of Technology between 2000 and 2003. They suggest that the paperfold, the outcome of a folding performance, is a diagram, operating purely by matter and function. Vyzoviti (2003) explains that the succession of transformations resulting in the paperfold artefact are a kind of genetic algorithm of form. The algorithm translates to a morphogenetic mechanism that creates spaces

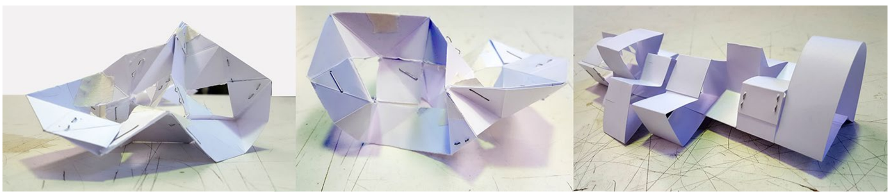

Fig. 5 Folding experiments. Time is recorded in the model through the use of rough materials to support iterations and testing to gradually increase complexity. Source: Yannis Zavoleas

through the voids of the paper fold during a dynamic generation process. These voids manifest a curvilinear form that cannot be exactly gauged at the outset. Form is produced directly from the iterations of paper-folding and therefore to define surface by its geometric characteristics alone seems irrelevant. Oblique planes dominate the horizontal and vertical, and the boundaries between surfaces and spaces are blurred. They appear to be constantly shifting, creating fluidity between slabs and walls, and bringing various levels into one continuum.

Technology as Facilitator and Inhibitor

A thread common to the above cases is that they all share a similar attitude about design as an experimental process, often using methods, references, tools and techniques from the scientific context. In an analogy to science's profound ties with technology to achieve progress (Winston 1998), a similar kind of evolution may be addressed about architecture's relationship with technology. Like science, architecture is also engaged with technological advancements in order to create, test and develop new ideas. In effect, technology conditions what is possible to imagine, design and create.

Although technology did support modernism's liberation from past practices, it has equally been an impediment to further progress. This is because fabrication processes tended to *regulate* any complex form to a set of geometrically defined elements that were more manageable and realisable, since the repetition of elements would render the structure cheaper and easier to construct. Variation, on the other hand, required customised design and fabrication of the components, advanced management, special ordering and tedious assembly, that were not thought suitable for low-cost production and as a result, challenging designs were often seen as unrealistic. To overcome this, many pioneering experiments devised unconventional solutions that proved costly and unprofitable. However, the solutions that were proposed often led to new techniques, production modes and, eventually, new aesthetics. The difficulty of building these forms meant that during the production process the curved surface was analysed into rectilinear systems, as a way to resolve structure and fabrication. This is evident, for example, in the designs of Parent and Virilio's designs, where the smooth terrain was translated into a triangulated system, and in Otto, Behnisch and Grzimek's tensile structure for Munich Olympic Stadium (1972), where a system of uniformed plastic sheets was developed as a solution to cover the curved surface roof.

This process is similar to that currently employed in most cases to construct forms that have occurred through fluid surface modelling, as a means to resolve soft topologies with conventional materials and techniques. For example, the same solution was chosen for the project for Eleftheria Square in Nicosia, Cyprus, an award-winning scheme designed by Zaha Hadid Architects in 2005. However, the aspiring proposal for a topological reading of the ground surface stretched to integrate traces of the past with those of the present, entailed challenging structural solutions. In fact, large parts had to be redone several times and in consequence, the project's estimated budget was dramatically exceeded. The fluid form underwent rectilinear analysis in order to construct it by using techniques familiar to the local building industry, but proved to be extremely expensive due to extensive manual labour and on-site monitoring.

The problem to rationalise a soft topological surface by a Cartesian system entails approximating a curve by an aggregate of points placed in proximity to each other and connected by straight lines therefore being easier to draw. When transferred to the digital interface, this approach sets the basis for point-based descriptions of curves being different to those generally defined as vectors. A point-based curve requires the position of every point to be calculated individually. A vector represents a parametric equation and can be stretched by a few control points normally residing outside its shape (apart from the first and last point and if the equation is above first degree). As a result, manipulating vectors happens by moving control points and so it requires fewer calculations, but it offers less accuracy compared to point-based curves. In 3D design software, vectors are referred to as NURBS (Non-Uniform Rational Basis Spline). As with vectors, NURBS shapes are controlled through parametric functions and fewer points, they respond to parametric inputs more efficiently compared to point-based ones, and therefore they can handle complex geometries much faster. For this reason, NURBS are suitable during form-finding, generative and bottom-up dynamic operations where raw data is given form (Lynn 1999; Lima 2014). In contrast point-based shapes, which offer more control are more applicable towards final construction and documentation phase.

Following processes similar to those applicable to pre-digital design, NURBS shapes may undergo rationalisation through Cartesian systems of analysis for more accuracy. This process of translating and analysing complex forms into Cartesian geometric shapes in the digital environment is often named as *geometricism* (Migayrou 2002) and happens through the *rasterising* process of triangulating and rectilinearising. Schematically, geometricism is about converting a smooth curve to a sequence of points and lines, or more specifically a NURBS shape to a cloud of points and polygons. As a result, a NURBS surface is turned into polygons and is approximated by a series of points connected through flat segments so that macroscopically its shape may still appear smooth. After a NURBS surface has been converted to polygons, depending on how complex it is, it may take considerably more time to manipulate it. Practically, polygonising NURBS surfaces is applied when form has been mostly decided and in order to facilitate final actions related to rendering, structural resolution and manufacturing. Consequently, the necessity for Cartesian rationalisation of NURBS shapes is attached to specific requirements during the later phases of production.

The introduction of CNC technologies to construction (Cache 1995) including 3D printing, robotic and drone fabrication, has enabled Cartesian rationalisation to be delayed until prior to construction. Currently, construction is commonly managed by BIM software. Since BIM is primarily devised as a construction tool, it is based on Cartesian shape analysis and so it reads any element as a polygon then linking it with its database. Due to its dependence on Cartesian geometry, any form-finding operation performed in BIM software is framed within Cartesian analysis, rather than NURBS-based or topological systems. The prospect, however, of integrating

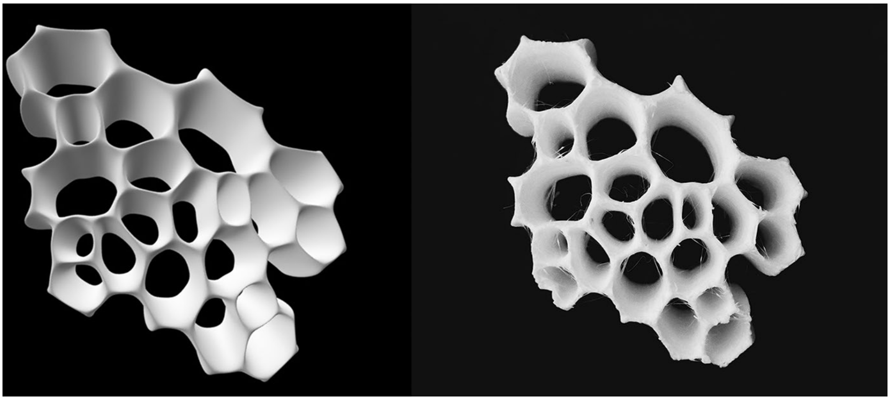

Fig. 6 3D digital rendering of natural reef structures (left) and 3D print (right). Project: RAW by Design. Source: Jenny Johnstone, Yannis Zavoleas, Peter Stevens, 2016

CNC into construction outlines a new aim for BIM to employ topological processes of shape analysis and effectively disengage all functions related to form-finding and early exploration from rigid geometric normalisations associated with production and data management (Aish 2013). As such, BIM will allow for more participatory modes of production and the complete management of the workflow from start to end directly applicable onto the digital model without any compromise for design (Migayrou 2002; Garber 2014). Form will be linked with the full flux of production including real-time databases and shared models aside from Cartesian references (Zavoleas 2016). Parametric data inputs can be applied straight onto soft structures (Spuybroek 2008; Lima 2014) that by virtue of CNC technologies are now equally feasible to construct. Therefore, it is suggested that CNC technologies are at the verge of bringing radical changes to the current practices of the building industry as the basis for BIM's future (Fig. 6).

Conclusion

This paper has attempted to establish a connecting thread between recent studies on soft geometry and twentieth-century architectural discourse. Specifically, it has linked together several late-modernist historical approaches to surface that questioned notions of flatness that abounded in the Cartesian-driven uniformity of early modernism. The examples suggest that the designers were seeking to capture, in a topological surface, the spatial complexities found in both observational studies and experimentation. What this led to was an understanding of topological surface as a dynamic element shaped through interactions with the parameters that describe the design problem. Far from early modernism's appropriation of flat geometries, the surface is conceptually transformed from a preoccupation with rigidity and stasis into a soft element that is malleable and extending. Furthermore, ideas drawn out of the history of modernism such as, distribution of densities and loads, dynamic patterns, local adaptations of thickness, smooth comprehension of structure, materiality and spatial fluidity, have re-emerged as the new agenda for design.

As this process is transferred into the current digital framing, topological surface may interact with the design variables in direct response to data inputs to produce iterative approximations of output shapes. Advanced computational tools have further enabled this aim, such that design has entered a new computation phase (Aish 2013) to become a data-driven problem of systemic nature. In a computational approach, design is analysed through data of various origin, similarly agents and their properties, represented by dynamic elements such as fields, forces and particles. Increased computational power supports generative techniques related to simulation, multi-agent inputs, data-tweaking and behavioural analysis to study relationships. Dynamic patterns integrate social, spatial, structural and aesthetic functions into one continuum, now appealing for an alternative to any of the geometric stiffness assumed by conventional production protocols. Structural efficiency is amplified through synergy among the participating elements to the point they become indistinguishable. Material properties are also entered as data activated through extended modelling techniques and linked with the database. Surface has become a hybrid, shaped by all of the influences about design related to structure, material, behaviour and resources (Vyzoviti 2013), favouring full openness, transitioning and unobstructed fluidity. The new topological surface sets a new paradigm exemplified through new geometries, new results, new vocabularies and new aesthetics.

Moreover, the emerging technologies of production and mainly CNC appeal for topological surfaces of greater complexity constructed within the same timeframe, energy, material and cost as with simpler geometric solutions. The introduction of CNC technologies has allowed postponing Cartesian resolution until final construction. As a result, from a practical point it is more feasible to work with NURBS geometry as the basis for the parametric model as a way to support more advanced interaction of the topological model with the database compared to polygonal ones. Starting with a topological surface loaded with elasticity, depth emerges as an answer to increased responsiveness to data inputs even in real-time. Consequently, it is proposed to employ data-driven modelling and topological analysis into BIM software so that creativity is released by limitations related to Cartesian rationalisation, which currently conditions the process from the beginning. Such a prospect presents with the potential to encompass all of the construction parts including walls, slabs, floors and pillars into one soft totality. In consequence, design will fully reflect the changes computation technology has brought into the field of architecture, further capturing the socio-aesthetic implications of space and form outlined in the recent decades.

References

Aish, Robert. 2013. First build your tools. In: *Inside SmartGeomtery: Expanding the Architectural Possibilities of Computational Design, eds.* Brady Peters and Terri Peters, 36–49. Chichester: Wiley.

Allen, Stan. 2001. Mat urbanism: The thick 2-D. In: *Le Corbusier's Venice Hospital, eds.* Hashim Sarkis, Pablo Allard and Timothy Hyde, 118–126. New York: Prestel.

Banham, Reyner. 1955. The new brutalism. *The Architectural Review,* 118 (December): 354–361.

Cache, Bernard. 1995. *Earth Moves: The Furnishing of Territories*. Cambridge MA: The MIT Press.
Doxiadis, Constantinos A. 1963. *Architecture in Transition*. New York: Oxford University Press.
Doxiadis, Constantinos A. 1966. *Between Dystopia and Utopia*. London: Faber and Faber.
Drew, Philip. 1976. *Frei Otto: Form and Structure*. London: Crosby Lockwood Staples.
Garber, R. 2014. *BIM Design: Realising the Creative Potential of Building Information Modelling*. Chichester: Wiley.
Higman, Barry W. 2017. *Flatness*. London: Reaktion.
Johnston, Pamela. 1996. *The Function of the Oblique: The Architecture of Claude Parent and Paul Virilio 1963–1969*. London: AA Publications.
Lima, Adriana. 2014. Topological surface and digital fabrication: A generative approach. In: *2nd International Conference of Bio-digital Architecture and Genetics (Barcelona),* ed. Alberto Estevez, 362–373.
Lucan, Jacques. 1996. Introduction. In: *The Function of the Oblique: The Architecture of Claude Parent and Paul Virilio 1963–1969*, ed. Pamela Johnston, 5–9. London: AA Publications.
Lynn, Greg. 1993. Architectural curvilinearity: The folded, the pliant and the supple. In: *Folding in Architecture*. *Architectural Design* 102, ed. Greg Lynn, 8–15. West Sussex: Wiley.
Lynn, Greg. 1999. *Animate Form*. New York: Princeton Architectural Press.
Migayrou, Frederic. 2002. Particularities of the minimum. In: *Archilab's futurehouse: Radical Experiments in Living Space, eds.* Marie-Ange Brayer and Béatrice Simonot, 15–18. New York: Thames and Hudson.
Parent, Claude. P. 1996. A critical modernity. In: *The Function of the Oblique: The Architecture of Claude Parent and Paul Virilio 1963-1969, ed.* Pamela Johnston, 14–15. London: AA Publications.
Rajchman, John. 1998. *Constructions*. Cambridge MA: The MIT Press
Sarkis, Hashim. 2001. *Le Corbusier's Venice Hospital*. New York: Prestel.
Spuybroek, Lars. 2008. *The Architecture of Continuity. Essays and Conversations.* Rotterdam: V2 Publishing.
Smithson, Alison. 1968. *Team 10 Primer*. Cambridge MA: The MIT Press.
Tzonis, Alexander. 2001. *Le Corbusier: The Poetics of Machine and Metaphor*. London: Thames and Hudson.
Tzonis, Alexander and Liane Lefaivre. 1999. Beyond monuments, beyond zip-a-tone, into space/time. In: *Free University Berlin. Architectural Association Exemplary Projects 3*. London: AA Publishing.
Virilio, Paul. 1996. Architecture principe. In: *The Function of the Oblique: The Architecture of Claude Parent and Paul Virilio 1963-1969, ed.* Pamela Johnston, 11-14. London: AA Publications.
Virilio, Paul. 1998. The overexposed city. In: *Architecture Theory Since 1968*, ed. Michael K. Hays, 540–550. Cambridge MA: The MIT Press.
Vyzoviti, Sophia. 2003. *Folding Architecture: Spatial, Structural and Organizational Diagrams*. Amsterdam: BIS Publishers.
Vyzoviti, Sophia. 2013. The depth of surface: An evolutionary paradigm for digital architecture. In: *International Theory of Architecture Conference ARCHTHE2013: Creativity, Autonomy, Function in Architecture* (Istanbul), 284–292.
Wigley, Mark. 2001. Network fever. In: *Grey Room* 4: 83–122.
Winston, Brian. 1998. *Media, Technology, and Society: A History from the Telegraph to the Internet*. London and New York: Routledge.
Zavoleas, Yannis. 2013. Digit mat(t)ers. Processes of normalization in architectural design. In: *Surface: Digital Materiality and the New Relation Between Depth and Surface*, *EAAE Transactions on Architectural Education no 48*, eds. Nikolas Patsavos and Yannis Zavoleas, 221–229. Athens and Brussels: Futura and EAAE.
Zavoleas, Yannis. 2016. Rethinking architectural vocabulary. Organic resolution via integrated BIM platforms. In: *Fifty Years Later: Revisiting the Role of Architectural Science in Design and Practice: 50th International Conference of the Architectural Science Association (Adelaide), eds.* Jian Zuo, Lyrian Daniel and Veronica Soebarto, 1–10.
Zavoleas, Yannis and Tournikiotis, Panayotis. 2014. Archetypes in-formation. Strategies of transition in architecture and urban design. In: *Cities in Transformation. Research and Design: Ideas, Methods, Techniques, Tools, Case Studies. Vol.II, eds.* Marco Bovati, Michele Caja, Giancarlo Floridi and Martina Landsberger, 1411–1417. Padova: Il Poligrafo.

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