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Artificial Nature (Towards a New Production)

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In a lapse of time of three different generations, the architects Antoni Gaudí, Richard Buckminster Fuller and Frei Otto, took nature as a reference, so as to bring its optimal form to architectural constructability. They all conceived design as an integrative non-linear process of translation, from the drawing to its physical construction; even if they did not have such an embedding and powerful tool as the one we have today: computation.
This essay will dissect, analyze and compare their technique, technology and tectonics by which they achieved such successful results, in terms of architectural form, material exploration and the structural performance, based on the natural paradigm.
If they brought such a novel approach to modern and postmodern architecture, feasible to construct, by the optimization of their contemporary means and resources within reach –each one in its own historical context–, this paper will explore how its legacy is being applied today since computation has embedded all phases of design into one. And what is more important, how the upcoming new model of production is already pushing architecture towards a new paradigm shift.

Artificial Nature.
Towards a New Production

Introduction

The formation of the word 'Architecture' comes from the Greek terms 'arché', which refers to the principles and theory, and 'techné' that in fact becomes the etymological root for what it represents: technology and technique, which are the principles for tectonics.
In a lapse of time of three different generations, the architects Antoni Gaudí, Richard Buckminster Fuller and Frei Otto, looked carefully at nature, in order to translate their designs close to optimal construction solutions. They pursued a natural approach in constructability, by the optimization of their contemporary means and resources within reach.
Each one in his own historical context.

If they all struggled in the pursuit of natural forms, by considering design as a non-linear process, in which they looked at technique, technology and tectonics at the same time; we now have the appropriate medium by which we can achieve it in a more efficient way, and it is computation. The architect Karl Chu, who has explored the codes of nature by means of computation, states that "*Buildability is an extension of the logic of constructability, which is now reformulated as a function of computability. (...) No longer is architecture to be construed as simply the art of putting two bricks together*".(1)

If these modern –or even postmodern– architects could achieve proficient architectural results, with this holistic approach, in a global productionist model, the new upcoming phase of capitalism (2) seems to bring with it a new production model based on computational novel means of fabrication and manufacture.

This essay will focus on Gaudí's, Fuller's and Otto's work, by considering their legacy in the pursuit for natural forms, in today's computational design.

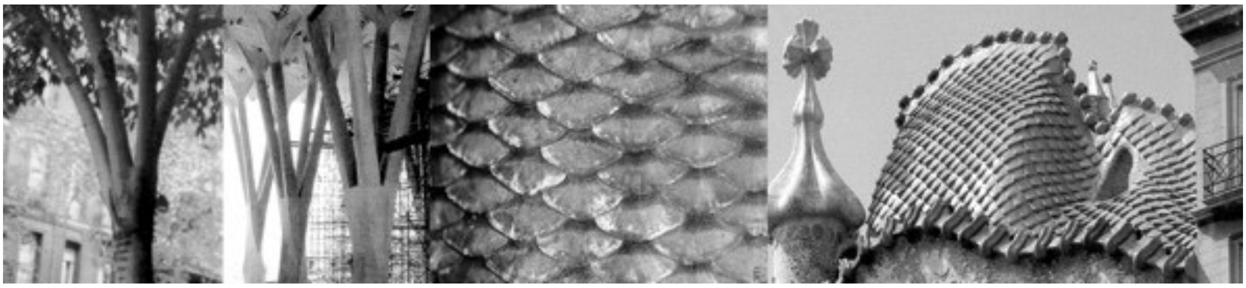


Fig. 01. Arboriform pillars in Sagrada Familia and scaley roof in Casa Batlló by Gaudí

Natural Forms

Either, in living and non-living nature, complex structures and behaviours emerge from simple rules and local material interactions, and thus, they can be astonishingly similar, as the British science writer Philip Ball claims (3). In a complete study in biology, natural history, mathematics, physics and engineering; in the book *On Growth and Form*, the Scottish zoologist D'Arcy Wentworth Thompson extensively explains how pattern and form arises in such a resemblance, in both, living and inert nature.(4)

It is in these terms, that Gaudí looked at nature. He noticed that, within the natural world, there were plenty of great solutions that could solve the problems architects often have to face when designing. As a result, Gaudí strived to achieve nature-based solutions to build arboriform pillars (5), mushroom-like chapiters (6,7,8), scaley roofs to properly drain out water (7), as well as efficiently resistant shell-like walls (8).

In the case of Buckminster Fuller, rather than giving great evidence for his interest in natural forms, as a technocrat, understood architecture as a science. In his attempt of pursuing cost and energy efficiency, he designed an optimal geometric structure, the 'geodesic dome', which minimized its surface and structure and at the same time covered a large space (9). If Fuller defined his architecture as 'design science' (10), he proofed it by considering his stable structures –even 'tensegrity' (11)– as natural forces, such as that of the geodesics, which in fact resulted to be the pure form of a molecule composed entirely of carbon. (12)
His proficient architecture lead him to a natural-based resolution.

Frei Otto, instead, showed his admiration for natural forms and structures already in his book *Natürliche Konstruktionen*, where he illustrates his quest for learning architectural and engineering solutions from natural studio cases. Otto tested architectural applications of cobwebs, hydros, shells or branches, and he tried to do so by using the most appropriate materials for them. (13)

They all proofed to achieve innovative and surprising results, by approaching to nature, from design, to materiality, in a non-linear process; by using the techniques that were within the reach in their contemporary times. They worked from the very beginning by pushing the materials to the limit, in a strife for getting the most of the tectonics, as a negotiation between their capacities and its structural and formal requests. Nothing is capricious, but everything in their architecture has a strong reason, just like in nature.

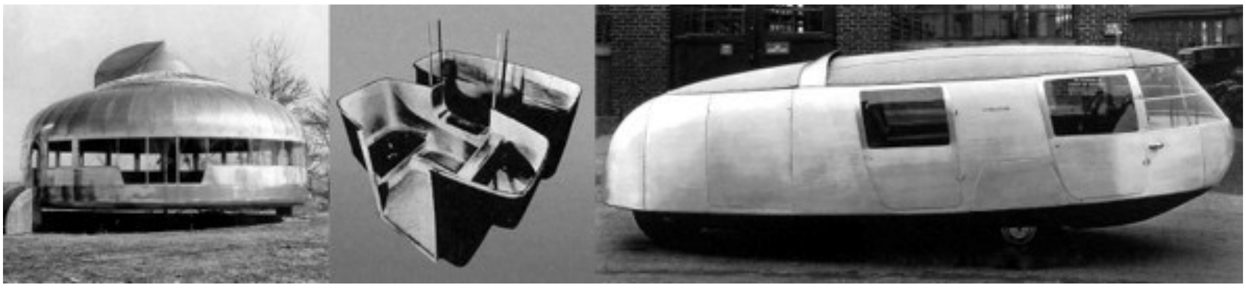


Fig. 02. Dymaxion House, Bath and Car designed by Buckminster Fuller.

Technique

Technique is defined as the procedure to accomplish a specific task. Here, the analysis of the techniques focuses on how construction solutions and materials were used by these architects to perform optimal results.

Gaudí,for instance, was more than aware of all the feasible materials within reach. He was living and working in–and for (14) the splendor of the Catalan Industrial Revolution, so he understood that his architecture had to respond to this local-scale industrial production model. As a result, most of his buildings worked with the natural stone –coming from nearby quarries, such as Montjuïch–, the monoresistant bricks produced by the contemporary industry and even to the novel mass concrete (15). He understood the possibilities of working with these materials and he took their structural properties into account. Their great resistance to work in pure compression worked perfectly in conjunction with his inverted catenary models –in which tension turned into compression– in an optimal structural behaviour (16). Notwithstanding, he rejected the use of steel –even in reinforced concrete– in his exploration of the natural structures, he worked with it in its malleable form (17).

Few decades later, the United States' economy had already brought the world to a fordist global mass production model. It is under these premises that Fuller conceived his architecture: he did not only embedded the standard materials of industry into his architectural designs, but also addressed his work to the vast society by conceiving its production in mass. This is the case of his Dymaxion (18) deployments -Fig. 02- such as the DDU Dymaxion Deployment Unit, the Bath or the Car, in which he tried to provide low-cost prefabricated designs for the post-war population living in such an emerging economy (19). He pursued the maximal human advantage by using the minimal energy and materials. In his words, the key was in "*'ephemeralization', doing 'more with less'*", in order to supply solutions for everyone, without being harmful to neither, the environment or the humanity itself (20).

The most recent industrial techniques, though, were used by Otto sometime after. He showed his interest in nature-based membranes, as they presented an optimal geometry, with a homogeneous state of stress all over its surface by using the minimal amount of material. Like Fuller, Otto understood how nature could efficiently offer 'more with less'.

He did his research on minimal surface membranes by modelling with soap, as he could produce agile and efficient simulations in many different variants. To translate his soap models into these novel architectural designs, Otto developed important basic shapes in tent constructions, and thus, he explored how these type of surfaces would behave by the effect of the real physical laws such as gravity -for which he had optimized the weight of the construction-, but also according to the external loads -like snow or wind-. Henceforth, he used tensile fabrics and extensively studied how they behave, from the relation with its edges to either its support were linear or planar. Besides his tensile exploration on fabrics, he later researched on prestressed wire nets, or even steel branching structures that had to support bending and compression forces (21).

Albeit all their work on the contemporary techniques has to be highly acknowledged, they all actually outsourced them to their contemporary production models -according to different stages and local conditions of the capitalism- rather than embedding them. Instead, these techniques were applied as much as they could in this natural pursuit but, by those times, any architect could take the entire responsibility and control on them, as they were usually applied by coordinated specialist manufacturers. In fact, Gaudí spent a lot of time in the workshop at *Sagrada Família* just to survey the proper construction of the temple, in a quest to achieve optimal results.

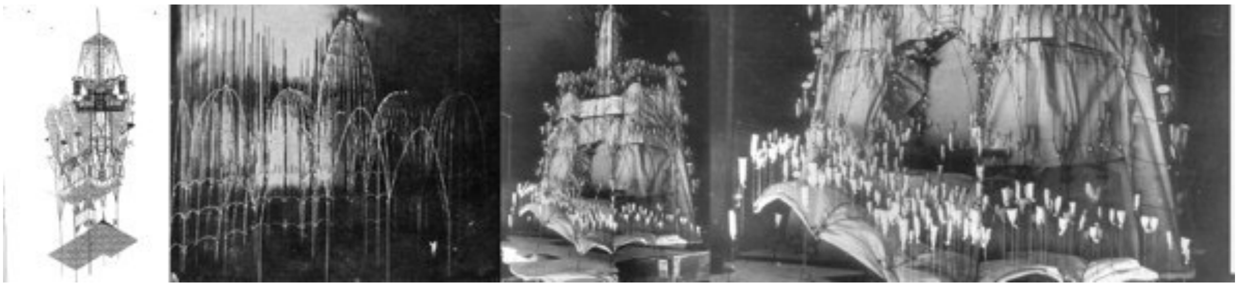


Fig. 03. Funicular models used by Gaudí for simulation.

Technology

Technology is the use and knowlegde by which techniques and tools –including machines– are applied in order to provide solutions. It is technology that links technique with tectonics and, therefore, allows the translation of architecture into real.

In Gaudí, all his technological contribution has to do with his great skills in simulation and modelling. As machinic –and obviously, also computational– technology was out of his reach, his stress and deformation analysis on the form were tested in his workshop, for which he used many methods, including his so-called catenary models –Fig. 03–.

With the use of his anti-funicular method, he turned pure tension into pure compression, which made very coherent the application of techniques such as monoresistant masonry or even mass concrete. There was no need to include tension-resistant materials, or even use buttresses in the structural design of both, the basilica of *Sagrada Família* and the church of *Colònia Güell*, as equilibrium was guaranteed (22).

The Catalan architects Carles Buxadé and Joan Margarit exposed *"in the stress analysis of Gaudinian structures, it can clearly be seen that the mass is accumulated where the plexus is most dense, that the openings are situated in areas of no stress away from the flows of axial stress, and that the rigid nucleuses, towers, bell towers, etc. are always found in the most unfavorable directions of the horizontal stresses"* (23).

Thus, this anisotropic geometry of the structure was designed and tested on one side, to present openings, and on the other, to respect the path of maximum stress, in a surprising manner that reminds us of the designer and professor at MIT Neri Oxman, when she enhances the ability of bones and sponges *"to design and fabricate building components with varied properties –density, elasticity, translucency– supporting the integration of functions such as load-bearing and natural ventilation"* (24).

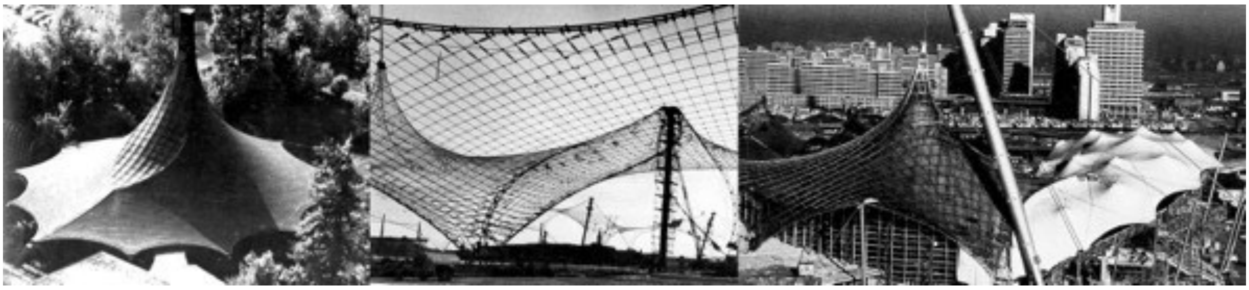
In the case of the church of *Colònia Güell*, we can find a shell-like exterior wall, which warps in a combination of bricks and basalt stone masonry, to achieve optimal performance over resistance. The basalt stone confers great resistance on the most critical structural lines, once again in a resolutive anisotropic behaviour of the surface, inherited from the knowhow of nature. Gaudí explained his architecture as a result of a 'constructional sincerity' (25).

In a similar way, Fuller said that his 'science of design' was lead by 'truth and inspiration' (26). Probably, this is the reason for which he achieved structural forms in equilibrium, such as his model for geodesic domes, which also appear in the molecular structure of C_{60}, or the tensegrity model, which was also found in molecular biotensegrity –and performs the perfect equilibrium halfway between tension and compression– (27).

In Fuller, technology was already conceived in a global industrial production context. In 1928, as part of his fourth dimensional approach (28), Fuller wrote the manuscript *4D Timelock*, in which he stated that technology applied in a proper manner could provide higher living standards for all the global population. He promoted autonomy, selfsufficiency and independence in his technocrat architectural approach to face the future. In fact, he struggled for it during the next thirty-five years (29). In his article for the *New Yorker*, the art critic Calvin Tomkins highlighted Fuller's perseverance and belief in a real revolution in this 'design science': "*Fuller proposes a worldwide technological revolution (...) carried out primarily by what he calls 'comprehensive designers' (...) Fuller thinks that there is still time, but he also thinks that time is rapidly running out for humanity, and it is this belief that keeps him in virtually constant motion around the world, talking to students and training them to think comprehensively*" (30).

Otto, like his predecessor Gaudí, based his studies in physical models. Even, he also worked by inverting suspended chain structures, although the avoidance of tensions and bending forces would allow him to orient this model for light weight structures. The fact that Otto was born two generations after Gaudí, allowed him to start experimenting with what we understand today as technology. That is, he started modelling with the 'soap film machine' from the *Institute for Lightweight Structures*, for his research on optimal tensile structures. As a result, his great-spanned tent structures achieved an excellent equilibrium (31). The architect Achim Menges, who has preserved and extended the legacy of Otto, in fact admits that "force-driven material systems, as, for example, pretensioned membrane structures, require physics-based design approaches, especially if they consist of multiple levels of hierarchy and many different tensile elements, as they do not follow predictable geometric or mathematical patterns" (32). Menges was probably talking under computational terms, in return, his words become even more meaningful when considering Otto and his models.

In reality, all of them showed to have their own efficient technological means, in an effort to integrate them in the design-process. Thanks to them they could simulate and test their experiments, and consequently achieve optimal nature-



based structures which provided tectonic equilibrium.

Fig. 04. Otto's Peak tent, for the Institute for Lightweight Structure and the Munich Olympic Stadium.

Tectonics

Tectonics concerns the construction and the structure of either, a building or the earth. Actually, there may be no distinction between both.

The Catalan architects Josep Lluís González and Albert Casals define Gaudí's ruled geometries 'relatively easy to construct'. Actually Mark Burry, executive architect and researcher at *Sagrada Família*, says that these geometries were certainly often very well explained; from several informational coordinates many straight lines could be traced to link them and generate the surface. However, he goes further and states that in fact, unlike construction, "*surface has impossible thinness*" and thus, "*pure geometry is, of itself, becoming a misrepresentation of the facts, thus when forming any architectural surface it will probably be compromised by the stuff of building*" (35). Apparently Burry noticed Gaudí's disregard of the geometric substantiation, in his translation from the drawing to the tectonics of *Sagrada Família*.

In Fuller, his optimal design geometries eased the assembly of lightweight industrialized prefabricated components, as he would have probably considered this from the very beginning. Efficiency was not only applied in the geometry of his designs, but also in its built form, from the small scale of a construction component, up to the whole built product.

In both scales, there was a special concern in that global mass production model, by which, his designs were addressed to everyone.

Otto envisioned his designs, such as the tent for the *Institute for Lightweight Structure*,IL; or the *Munich Stadium* -Fig. 04-, in lightweight structures, like Fuller, and thin materials the 'smallest amount of material' (36), unlike Gaudí. Therefore, Otto's architectural work in thinness eased the translation from the design into its construction, despite of its pretensioned structure.
Their struggle in the architectural form, the material exploration and the structural performance, through its analysis and simulation in a nonlinear process of design –and thus, based on the natural paradigm–, brought a novel approach to modern and postmodern architecture.
Their integrative conception of the design process, though, presented few inconsistencies as they had not the powerful tools that today computation offers.

Since computation has been embedded in the design process, and a new production model is about to emerge, architects are urged to exert all its potential and push it to a new scenario in architecture. Just like these architects already did in their times.

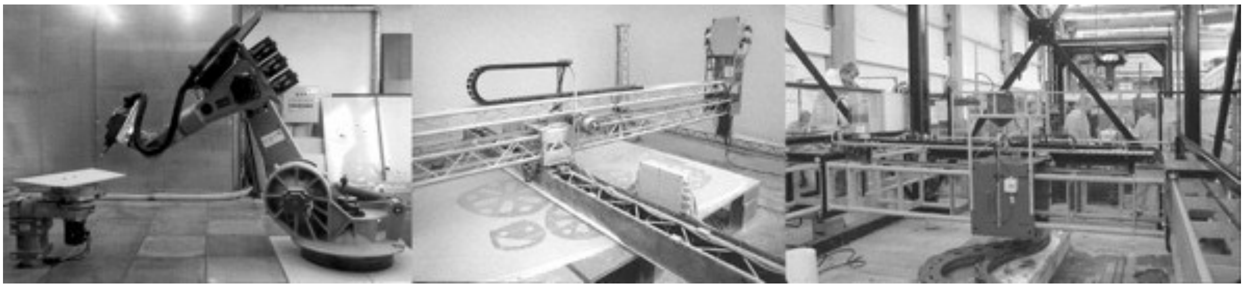


Fig. 05. Digital fabrication and manufacture: six-axis robot, CNC and AMC.

A New Production

Karl Chu states that a new phase in capitalism is about to come (37), and the American architect Jesse Reiser becomes more precise onto saying that, together with it, a new production model is near to arise: "*we stand at the brink of radically expanded fields whose horizons are restricted only by our own material imaginations (...) the sublime has arrived; not in the lineaments of some latter-day metaphysics, but instead as a material fact*" (38).
The big paradigm shift is now becoming feasible, by our pursuit for natural solutions through computational artifices.

Chu claims that *"the concept of buildability, be it that of architecture or otherwise, is an extension of the logic of constructability, which is now reformulated as a function of computability"* (39).

Gaudí, Fuller and Otto, were well aware that technological means were crucial for design, to analyze, simulate and bring it into tectonics. Even, if they somehow felt *"subordinated to conventional notions of building"* (40). The French Philippe Morel urges architects to incorporate this computational paradigm into practice, although he poses a great challenge when he says that *"non-standard production lies in the meeting between what is calculable –i.e. digital programmable machines– and what is non-calculable –i.e. matter, object, etc.–"* (41).

Computational design not only allows us to consider matter in the design, as Burry noticed, but also to design its form, behaviour and responsiveness (42), by analysis and simulation. Architects are now responsible for providing new technical solutions, according to the design. These solutions are not outsourced any more to a certain production model or a specialist manufacturer, as they are now embedded in the computational design and thus, it is the duty of the architects. Achim Menges affirms that *"design computation provides the possibilities of integrating physical properties and material behaviour as generative drivers in the architectural process (...) thus, architectural form, material formation and structural performance can be considered syncronously"* (43).

Material is now capable to be computational, embed information, and use it. These materials can perform artificial natural-like properties and capacities, by the use of the new production technologies -Fig. 05-: on one side, open-ended fabrication generic machines, such as the six-axis robots, that already exist in the fields of automotive and aeronautic engineering (44), or on the other side, those for specific manufacture, such as the additive manufacturing –AMC– or the computer numerically controlled machines –CNC– (45).

The MIT's designer and computer scientist Skylar Tibbits goes further and says that *"rather than taking raw materials, sending them through a machine or process that is inherently fighting tolerances, errors and energy consumption, to arrive at a desired product, we should directly be embedding assembly information into raw materials, then watching as the materials assemble themselves"* (46).
In any case, the importance of computation is in its power of embedding all the processes of design, which leads to an optimized architectural result. Achim Menges says that, like in nature, computational architecture can provide maximal performance by minimal resources (47).

Morel infers that, in fact, optimization is inherent within computation: "*with optimization, architecture is not just 'geometric', (...) it also demands an algorithmic description*" (48). To Morel, algorithms are the 'true machines' (49); while Chu says that even algorithms themselves have to be optimized: "*'Less is more' is a minimalist manifesto that is also the unspoken assumption of all algorithmic programming*" (50).

Computation is definitely the most powerful tool we have within reach, which allows us to integrate all phases of design into one, and open new scenarios for an optimized, social and sustainable production.

Gaudí, Fuller or Otto, looked at technique, technology and tectonics in an integrative attempt to bring the 'techné' back with the 'arché', and recall the actual meaning for architecture. They understood there was a need to learn from the nature and give it back a response within the same principles, which they somehow computed –without computers!–, but with their own simulation and design tools, methods and techniques. The three of them, in three different generations and contexts, became a great precedent for computational architecture and revealed a need for change in constructive methods and the productive model.

Computational design and the novel means of digital fabrication are today taking architecture and buildability towards a new paradigm shift. There is a pursuit for optimization, just like nature does. And our journey towards a new production, is also an approach to design and build a new realm of *artificial nature*.

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IMAGE CREDITS

Fig. 01
Arboriform pillars in Sagrada Família and scaley roof in Casa Batlló by Antoni Gaudí
Giralt-Miracle, Daniel (2002), 'Gaudí, Exploring Form. Space, Geometry, Structure and Construction', ed. by Lunwerg Editores, pp. 105, 152.

Fig. 02
Dymaxion House, Bath and Car designed by Buckminster Fuller. Fernández-Galiano, Luis (2010), 'Fuller Abridged', in AV Monografías, ed.
by Arquitectura Viva SL, 143, pp. 9, 10, 11.

Fig. 03
Funicular models used by Gaudí for simulation.
Giralt-Miracle, Daniel (2002), 'Gaudí, Exploring Form. Space, Geometry, Structure and Construction', ed. by Lunwerg Editores, pp. 50, 51, 99.

Fig. 04
Otto's Peak tent, for the Institute for Lightweight Structure and the Munich Olympic Stadium.
Kullmann, Ernst (1975), 'L8. Nets in Nature and Technics', ed. by Institute for Lightweight Structures, Stuttgart.

Fig. 05
Digital fabrication and manufacture: six-axis robot, CNC and AMC. Schwinn, Tobias (2012), 'Manufacturing Reciprocities', in Architectural Design, ed. by Wiley and Sons, 216, p. 123.
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NOTES

(1) Chu, Karl (2002), 'The Unconscious Destiny of Capital. Architecture in Vitro / Machinic in Vitro', in Designing for a Digital World, ed. Neil Leach, Chichester, p. 131.

(2) This part of the essay refers to Chu, Karl (2002), 'The Unconscious Destiny of Capital. Architecture in Vitro / Machinic in Vitro', in Designing for a Digital World, ed. Neil Leach, Chichester, pp. 127-133.

(3) Menges, Achim (2012), 'Material Computation: Higher Integration in Morphogenetic Design', in Architectural Design, 216, ed. by Wiley and Sons, p. 17.

(4) Ball, Philip (2012), 'Pattern Formation in Nature: Physical Constraints and Self-Organizing Characteristics', in Architectural Design, 216, ed. by Wiley and Sons, p. 23.

(5) i.e. the structure for the basilica of Sagrada Família, Barcelona.

(6) i.e. the towers of the Parc Güell, Barcelona.

(7) i.e. the roof of Casa Batlló, Barcelona.

(8) i.e. the crypt of Col nia Güell, Santa Coloma de Cervelló, Barcelona.

(9) This part of the essay refers to Fernández-Galiano, Luis (2010), 'Fuller Abridged', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 16.

(10) Zung, Thomas TK (2010), 'Houses for the Future', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 51.

(11) 'Tensegrity' is a concept coined by Buckminster Fuller, that comes from the words 'tension' and 'integrity', as it is referred to a structural model that performs the perfect equilibrium between tension and compression

(12) Zung, Thomas TK (2010), 'Houses for the Future', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 50.

(13) This part of the essay refers to Rohan, Thimothy M (1978), 'Natural Forms - Architectural Forms', in The Work of Frei Otto and his Team 1955-1976, pp. 17-30.

(14) Antoni Gaudí's patron was Eusebi Güell, a Catalan entrepreneur whose profit was basically made from the local industry.

(15 Giralt-Miracle, Daniel (2002), 'Gaudí, Exploring Form. Space, Geometry, Structure and Construction', ed. by Lunwerg Editores, p. 48.

(16) Ibid, p. 50.

(17) Ibid, p. 59.

(18) 'Dymaxion' is a term coined by Buckminster Fuller, to join the concepts 'dynamics', 'maximum' and 'tension'.

(19) Fernández-Galiano, Luis (2010), 'Fuller Abridged', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 6.

(20) Chu, Hsiao-Yun (2010), 'A Biographical Sketch', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 33.

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(27) This part of the essay refers to Fernández-Galiano, Luis (2010), 'Fuller Abridged', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 4-25.

(28) Fuller coined the term 4D since he included time in his projects.

(29) Chu, Hsiao-Yun (2010), 'A Biographical Sketch', in AV Monografías, ed. by Arquitectura Viva SL, 143, p. 33.

(30) Ibid, p. 35.

(31) This part of the essay refers to Rohan, Thimothy M (1978), 'Natural Forms - Architectural Forms', in The Work of Frei Otto and his Team 1955-1976, pp. 17-30.

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