eCAADe 2017

ShoCK!

Volume 2

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Proceedings of the 35th International Conference on Education and Research in Computer Aided Architectural Design in Europe

20th-22nd September 2017
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Theme

ShoCK! – *Sharing of Computable Knowledge!*

The theme of the 35th eCAADe Conference is *Sharing of Computable Knowledge! – ShoCK!* so, we have invited eCAADe community, members of Sibling Organizations and CAADFuture friends to face this exciting theme.
Why such a strong theme? Mainly for three reasons.
The first one, is that we live in a city that has been witness of several revolutions of the conceptions of architectural space: most turning points of space perception are present here by means of architectural masterpieces as Bruno Zevi stated. I like to quote Rem Koolhaas: "It is a platitude that the presence of history in Rome is detriment to the development and display of modern art. But if that were true, Rome – *a city of successive modernities* – would never happened.".
Secondly, as my DaaD research group states "Rome is an open-air museum of architectural avant-garde masterpieces of an *uninterrupted history* where styles are juxtaposed, intertwined and *stratified* other than culturally also physically…" This concept is very close to the modern concept of cognitive sciences: to think by means of several abstraction levels of intelligence.
And the third reason is that we live in a Faculty founded in 1817 – right two centuries ago - has always had a multidisciplinary approach to understand and solve problems: from the outset Architecture, Civil engineering, Bridge construction, Topography, Geometry and Mathematics subjects were present. As a matter of facts this approach it is not limited to technical aspects as – most importantly – the Faculty, now Civil and Industrial Engineering, lives in *Sapienza* University of Rome – established in 1303 – a university that pursuits the "universal" approach where each discipline enhances the others.

Going back to the theme, it involves in turn several subjects: Internet of Things, pervasive nets, Knowledge 'on tap', Big Data, Wearable devices and the 'Third wave' of AI, ... All of these disruptive technologies are upsetting our globalised world as far as it can be predicted henceforth.
So, academicians, professionals, researchers, students and innovation factories… are warmly invited to further shake up and boost our innovative and beloved CAAD world – we already are in the post-digital era – with new ideas, paradigms and points of view.
I said "*CAAD world*" as I think that it contains and involves several disciplines but it is a new subject it its own that overcomes the former ones.

The underlain idea of this International Conference is that as a catalyst of creative energy it pursuits with determination founders' purposes and to be a shocking vanguard, a melting pot of novelties, in words: to become an “incubator” of innovative and seminal ideas, to generate enthusiasm, to be an occasion for new friendships and to facilitate the establishment of effective researches’ networks. The title of the conference reflects well these intentions:

Sh o CK! – Sharing of Computable Knowledge!

So the aim of the Conference was to knock our habitual design activities out, to compare the various methodological and technological trends and to disseminate the latest research advances in our community. Will our fine buildings and design traditions survive? Or, will they ‘simply’ be hybridized and enhanced by methods, techniques and CAAD tools? Obviously, computation is needed to match the ever-growing performance requirements, but this is not enough to answer all these questions we have to deal with the essence of problems: *improve design solutions for a better life*!
Obviously, ***computation*** is needed to match the ever-growing performance requirements, but this is not enough... As life is not a matter of single individuals, we need to increase collaboration and to improve ***knowledge*** and ***sharing***. This means going back to focusing on human beings, and involves the humanistic approach, and the long history of architecture... from handicrafts to thinking to technology... to handicrafts again.
A large spiral of the *architectura* as *eternal* as our city.

A.

Antonio Fioravanti
eCAADe 2017 Conference Chair

* This second volume of the conference proceedings of the 35th eCAADe conference contains 81 papers grouped under 14 sub-themes; both volumes contain altogether 155 accepted papers. The Conference was held at the Faculty of Civil and Industrial Engineering, *Sapienza* University of Rome, Rome, Italy, in via Eudossiana 18, Rome, on 20th – 22nd September 2017.
In addition to the accepted papers, the first volume contains *Keynote* speakers’ contributions concerning the themes of their keynote lectures and the *Workshop Contributions* including the contents of workshops given; the second volume furthermore includes the *Poster Session* contents.

All the papers of these proceedings will be accessible via CuminCAD - Cumulative Index of Computer Aided Architectural Design, http://cumincad.scix.net

Acknowledgements

Authorities, colleagues, researchers, professors, students, professionals all of you are welcomed to the 35th eCAADe conference, in Rome the *eternal city*.

It has been a long time ago – 31 years – since the previous eCAADe conference was held in this Faculty, hosted by our University - “La Sapienza”.
That time, Gianfranco Carrara, one of the eCAADe founders, chaired the 4th eCAADe conference in 1986. That time on, there was only one eCAADe conference in Italy precisely in Palermo in 1995 chaired by Benedetto Colajanni and Giuseppe Pellitteri. This Faculty – now Faculty of Civil and Industrial Engineering – inspired by Parisian and Austrian models, is quite old as it was funded by Pope Pius VII in 1817, so now it celebrates its Bicentennial!

But it is quite young compared to our mother University “La Sapienza” that was established by the Pope Bonifacius VIII in 1303.

The original idea of bringing the eCAADe conference back to Rome goes rather back in times, I remember it was in 2009 at eCAADe conference in Istanbul. You know things take their time in Italy, so only in 2013 my Faculty approved and on 21st March 2015 eCAADe Council granted us the permission to organize the 35th conference. Over the last years several people have helped us to make this conference happen. We thank the former Dean of Civil and Industrial Engineering Faculty, Prof. Fabrizio Vestroni and especially the present Dean, Prof. Antonio D’Andrea for their supports.

During the process of organizing the eCAADe 2017 we have had the privilege to experience the supportive, collaborative and frank atmosphere of eCAADe Council, whose members, no one excluded, have helped us with all organizational aspects.

Let us be touched in remembering for his humanity the former eCAADe President, Johan Verbeke, who recently passed away. We all are sad in this moment thinking is no more physically with us now, but at the same time we are grateful to have met him and exchanged ideas on equal terms as his habit. In spirit, he is present so we can tell him: Johan, special thanks for your open-minded support, we warmly thank you! We miss you, and we do not forget you!

How cannot we mention Joachim Kieferle a friend, who is also the eCAADe President, for his encouragement and unswerving support during the last years and his ability to cut up dead-

locks into pieces. A special thanks to the great Bob Martens for his ability in organizing complex tasks and simplifying processes – Dutch origin helps – his daily support was precious and helped us relentlessly. And a "suuppper" thanks to a "super" friend as Gabriel Wurzer for his optimism and silent help in difficult issues.

Also, we wish to thank all the other previous conference organizers, Henri Achten, Rudi Stouffs and Emine Mine Thompson, for sharing their experience and knowledge. A special thanks to more recent conference organisers Bob Martens, Gabriel Wurzer, Thomas Grasl, Wolfgang E. Lorenz and Richard Schaffranek together with Aulikki Herneoja, Toni Österlund and Piia Markkanen!

Quality is the vital issue concerning conference proceedings.

To improve it we used different means: *OpenConf* conference management system that easily ensured that none of the reviewers came from the same institution as the authors; through special relationships between Liverpool University and eCAADe thank to Martin Winchester's support we were able to overcome program bugs; a second and handcraft check of interest conflicts among authors and reviewers was made during the reviewing phase; a double-blind peer review process; and an accurate reviewers' selection. The selection was fair, and only extended abstracts with high grades were admitted to full paper phase.

Quality means also typographic quality control in two ways: for printing results and for respecting author's layout; so, thanks to the well-known *ProceeDings* formatting management system eCAADe could fulfil these two needs.

Authors uploaded their extended abstracts (length of 1000 to 1500 words, two optional images, 5 to 10 references) by 1st of February 2017; each abstract was evaluated anonymously.

Altogether, we received 309 extended abstracts from 46 different authors' countries, shortly after 5 were withdrawn. Each extended abstract had three blinded peer reviews so 912 reviews were accomplished in a short time and 165 papers were accepted for full paper submission, 21 of these were withdrawn and eventually 154 papers were published in eCAADe 2017 Proceedings.

Let us express our very grateful appreciations for all the 132 reviewers from all over the world for their constructive and thorough comments for each author. A special thanks to reviewers who spent their time to review more than 8 extended abstracts – Joachim Kieferle and Anand Bhatt - not to mention members of "Joker Reviewers' Team": Stefano Cursi, Salma Elahmar, Paolo Fiamma, Silvia Gargaro, Gianluigi Loffreda, Wolfgang E. Lorenz, Davide Simeone, Gabriel Wurzer and me that were able to review abstracts during the last days to accomplish missing reviews on time.

We thank and congratulate all authors for their hard work and support on using the ProceeDings tool and finalizing their full papers carefully in time. In this last phase of editing full papers we want to thank for his "extra-ordinary" work Gabriel Wurzer, the Master of the ProceeDings and Wolfgang E. Lorenz and Ugo Maria Coraglia, who with high sense of responsibility worked with us and to successfully produce high quality proceedings.
We also continued the practice started in eCAADe 2015 conference in Vienna of having all the session chairs to give prospective comments of the papers and to evoke the discourse at early stage between the author and session chair for the 27 sessions of the conference. All the session chairs also participated the peer review process of the extended abstracts.

We owe great gratitude to the session chairs for their commitment and their long-term contribution to the process until the final paper presentations.
We thank the keynote speakers and their contribution of writing the keynote papers concerning their lecture themes: Gianluca Peluffo, Chair in *Exhibition Design* and *Art & Architecture*, IULM - International University of Language and Media; John Gero, Research Prof. in *Computer Science and Architecture*, University of North Carolina at Charlotte and Krasnow Institute for Advanced Study George Mason University; and Gernot Riether, Director of *School of Architecture*, NJIT – New Jersey Institute of Technology, Editor of *DCA Journal*.
Workshops are part of eCAADe conferences, so we thank all the organizers for their workshop and for their contribution of short papers (non-peer reviewed) about the contents of their own workshop.

We are also grateful to Wolfgang Dokonal and the eCAADe Council for organizing the traditional PhD workshop for young researchers and supporting the grant winners with a subsidy for traveling to Rome.

We recovered an old tradition of previous eCAADe Conferences bringing poster session to life again, so during the conference we had 4 free lectures on interesting themes.

This year for the first time we launch an international competition linked to the Conference, the "eCAADe2017 Logo Contest" that helped in disseminate the spirit and values of eCAADe in new areas. We thank the International Jury that was made up by Antonino Saggio (President, Chair in *Information Technology applied to Architecture and Urban and Architectural design*), Eleonora Fiorani (Vice president, Chair in *Cultural Anthropology and Sociology of Innovation*),

Henri Achten (former eCAADe President, Chair in *Computer Aided Architectural Design*), Maria Argenti (Chair in *Architectural Composition* and Editor in chief of *Rassegna di Architettura e Urbanistica*), and Antonio Fioravanti (Chair in *Architectural Engineering*). Two Winners and three Honourable mentions were awarded (see on website https://www.daadgroup.org/result/).
We would like to express our gratitude for the administrative help in organizing this conference to eCAADe council and especially Nele De Meyere that has provided us valuable input and lessons learned from past conferences.

We have also had support from DaaD*group* for managing the conference services, ranging from the registration process to the actual on-site registration services. A big thank you goes to PhD students Ugo Maria Coraglia and Francesco Rossini for their extra-work in critical situations.

Thanks to the sponsors we were enabled to organize an international conference as eCAADe is. Financial supports, apart Sapienza University of Rome, was generously provided by A-Sapiens, AT Advanced Technologies, Autodesk; 3TI Progetti and Bentley Systems International Ltd. Technical support was provided by Epson Italia, Gangemi Editore, Geores, it solution, Noumena and ProceeDings.

We wish to also thank Gangemi Editore in person of Giuseppe and Fabio Gangemi for their very fast and accurate printing process and the high quality of both volumes.

As a special form of sponsorship, all members of the Organizing Team and students of Architecture-Building Engineering M. Course that donated their time to help prepare and organize this conference. Thank you all !!!

Rome, 1st September 2017

Antonio Fioravanti

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Angelo L.C. Ciribini, Gabriele Novembri and Armando Trento

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Contents

Form is Matter

Triply periodic minimal surfaces structures by digital design tools

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Architecture and biology teach that the shape affects mechanical behaviour of structures therefore geometry is the basic concept of design, with an ethic responsible and sustainable approach, following the nature's organic model. Industrial design may apply formal properties of elementary shapes and basic design rules to manage the ``geometrical behaviour'' of new structural surfaces. The research aims to apply digital tools to the design of surface structures that maximise the matter efficiency in the development of ``solid fabrics'' with parametric controlled geometry.

Keywords: *Minimal surfaces, Parametric and generative design, Shape and form studies, Digital fabrication*

INTRODUCTION AND RESEARCH GOALS

Architecture and biology teach that the shape affects mechanical behaviour of structures, therefore geometry is the basic concept of design, with an ethic responsible and sustainable approach, following the nature's organic model. Industrial design may apply formal properties of elementary shapes and basic design rules to manage the "geometrical behaviour" of new structural surfaces. In facts nature's objects have been fundamental model since antiquity and the concept of Nature as a design model drives the theory of Architecture and the man's reference to natural forms a recurring statement in literature and it incorporates many basic design concepts, but the affirmation of digital technologies is changing the concept of *organic design*. Actually nature's patterns solve several project requirements, as it fulfils Alberti's *concinnitas* and the main architecture requirement, meaning Vitruvio's triad of *firmitas, utilitas, venustas*. [1]

Arts applied the reference in different ways: the first was the bare imitation in the pattern of ornaments and decoration, due to the admiration of the beauty of harmony and perfection in regular conformation in natural phenomena. Then Architecture applied skeletons' and trees' model to structures, imitating nature's balance in the proportioned relationship of building elements. Later it was the connection of parts in machines. Finally the imitation is fulfilled in the process of growth, which is the expression of life. In its digital procedures, the responsive Design copies vital process of life. Rules of basic shapes evolved in growth and form-finding processes.

The late development of digital technologies allows an important leap in the organic reference of design, improving the evidence of organic forms in design. *Imitation* is still the first way of learning, but *to imitate* does not mean *to copy*. In design it means *to reinvent*, therefore to understand and transform. Thus the imitation requires the very knowledge of form finding processes, which are due to a careful observation.

In the classical world the formal beauty was linked to a recognizable law that order the multiplicity in the unity: *symmetry, proportion* and *direction* resume rules that generate the shape starting from a *module*. Together they express the *eurythmy*, which in 1860 Gottfried Semper referred to in treatise *Der Stil*, as a '*concatenated sequence of spatial ranges, similarly shaped*'.

Everybody know what module means in architecture, and its importance about measurement, that is just ratio between quantity and unit; so this concept is directly connected with modular grids to control composition and proportion: thus design means measurement, which is geometry. The basic rules of form apply the same simplest operations of arithmetic and geometry: *addition, multiplication* and *division*. Growing and living processes implies *transformation*, that is changing in dimensions without changing topological ralationship in between elements, and/or responsive adaptation to external inputs. In computational design the concept of *module* plays the living principles of cell in organic fabric.

The biologist D'Arcy Thompson gave a wide explication of the geometry's evidence inside natural phenomena and architectures. Nature finds a static force balance in the symmetry of structures but in living beings it plays with different rules due to asymmetrical forces of growth, which imply dynamic transformation. He just stressed that life is tied to asymmetry and continuous transformation. [2] His work was fundamental to several architects, who pursued organic concept in architecture, such as B. Fuller and F. Otto. The first one applied the study of surface balance in cells to geodesic domes and the second designed light structures from the minimal surfaces' study with soap sheet and bubbles.

Minimal surfaces offer a great attraction to many disciplines. Some reasons for the common interest lie in the deep problems, which open up during closer investigation of their properties, and others in the widespread possible applications of minimal surfaces in completely different areas of research. Configurations of minimal surfaces have been found in a wide variety of different systems: from the arrangement of calcite crystals that form the exoskeleton of certain organisms to the theories that explain the nature of astronomical phenomena.

In design-building research, structures derived from minimal surfaces have led to the design of various typologies, such as tension-active roof structures, compression-active shells and large-scale architectural systems. This is, however, only one in between all possible uses. But in architectural structures, minimal surface structures remain rather unexplored for their suitable applications in design. Frei Otto in undoubtedly the main reference in the experimental development of minimal surfaces in light architecture, imitating self-formation processes in nature. He tried successfully application of the same efficient concept to different typologies of light architectures: tent structures, net constructions, pneumatic constructions, suspended constructions, shells, branched constructions and umbrellas as example of convertible constructions (moving and transformable). Actually Otto didn't *copy* the nature, but he referred to explaining it through technical developments. He stated that "*Technical object for which self formation process occur to a high degree form the natural border between natural and artificial*". [3]

Such as Frei Otto applied minimal surface theory in quite simple aggregation to architecture, as well mathematicians developed a larger set of surfaces from different boundary constraint with their further aggregation in modular lattices. *Triply Periodic Minimal Surfaces* (TPMS) are probably the ones that have the most interesting characteristics, including for design purposes. They are called periodic because they consist of a base unit that can be replicated, theoretically ad infinitum, in Cartesian space in three dimensions (triply), thus creating a new surface seamlessly and without intersections.[10]

Triply Periodic Minimal Surfaces, as it is visible in many natural systems, have a great potential, due to their structural efficiency thanks to overall area minimization, and efficient material distribution. Actually they comply Otto's requirements for *natural architecture*, because they apply/follow the nature's teaching in the balance of forces. [5] This is ethical and ecological approach, because it minimize the energy waste, saving material. [6]

Probably, despite at a theoretical level, the properties of Triply Periodic Minimal Surfaces have been investigated, the complexity of morphology has so far limited their use to manufacturability and design purposes.

The research aims to apply digital tools to the design of surface structures that maximise the matter efficiency in the development of "solid/permeable fabrics" through parametric controlled geometry.

This paper focuses on both the form-finding and the fabrication related to the geometric properties of TPMS. The aim is understand how the translation from the virtual three-dimensional space to the built artefact could be embodied into a computational process, which would also solve the issues within the fabrication framework

METHODOLOGY

The research follows two different paths, concerning basic topics:

- first, the definition of *computation tools*, meaning the selection of design parameters and the scripting of the digital form-finding process,
- next, their *design experimentation*, testing mechanical properties of different TPMS fabric.

Main computational design tools are:

- drafting formal and mechanical features according to shape;
- drawing basic shapes, by developing formal geometry features, starting from different minimal surfaces in a 3D modular lattice and developing modular aggregation by symmetrical repetition;
- selecting basic shapes that optimize the use of materials (minimal surfaces);
- defining tiles' parameters and lattices' aggregation rules, then to script formal codes and their transformation range;
- modelling selected modular lattices from basic geometry.

The design experimentation regards:

- to check formal behaviour of new structures in plane and in curved surfaces (flexibility, permeability, stiff movement and elastic responsiveness) and their adaptability to morphological transformation;
- to verify mechanical properties on printed prototypes (strength, lightness);
- to stress shape effects according to parameters variations, then optimize application range to different cases study.

The further development will inquire topics related to practical applications to case studies in design of printable objects, evaluating the adaptability to the object's shape, to their function and use as well to production requirements.

DESCRIPTION AND GENESIS OF MINIMAL SURFACES

A minimal surface is a surface whose mean curvature is always zero. This definition answers to the Plateau problem[11] proposed by Lagrange in 1760: if a closed polygon or oblique plane is assigned, then there is always a system of surfaces, including all possible surfaces that touch the frame, which are able to minimise the area. The minimal area of the soap film's surface of is one of the many examples that illustrates a well-known physical principle governing

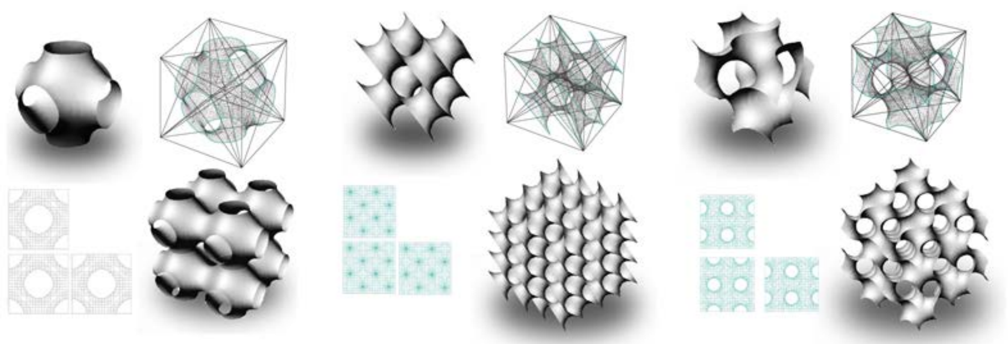


Figure 1
Triply Periodic
Minimal Surfaces

forms and motions of natural objects: the principle of least energy waste (or least action). It states that any physical configuration assumes its state or path in such a way that the energy requirement is minimal. In soap films, the shape minimizes the potential energy balancing the intermolecular force. Therefore this energy is directly proportional to the surface area of the soap films (assuming that the thickness of soap films is uniform) and, as a result, the soap films achieve minimal area.

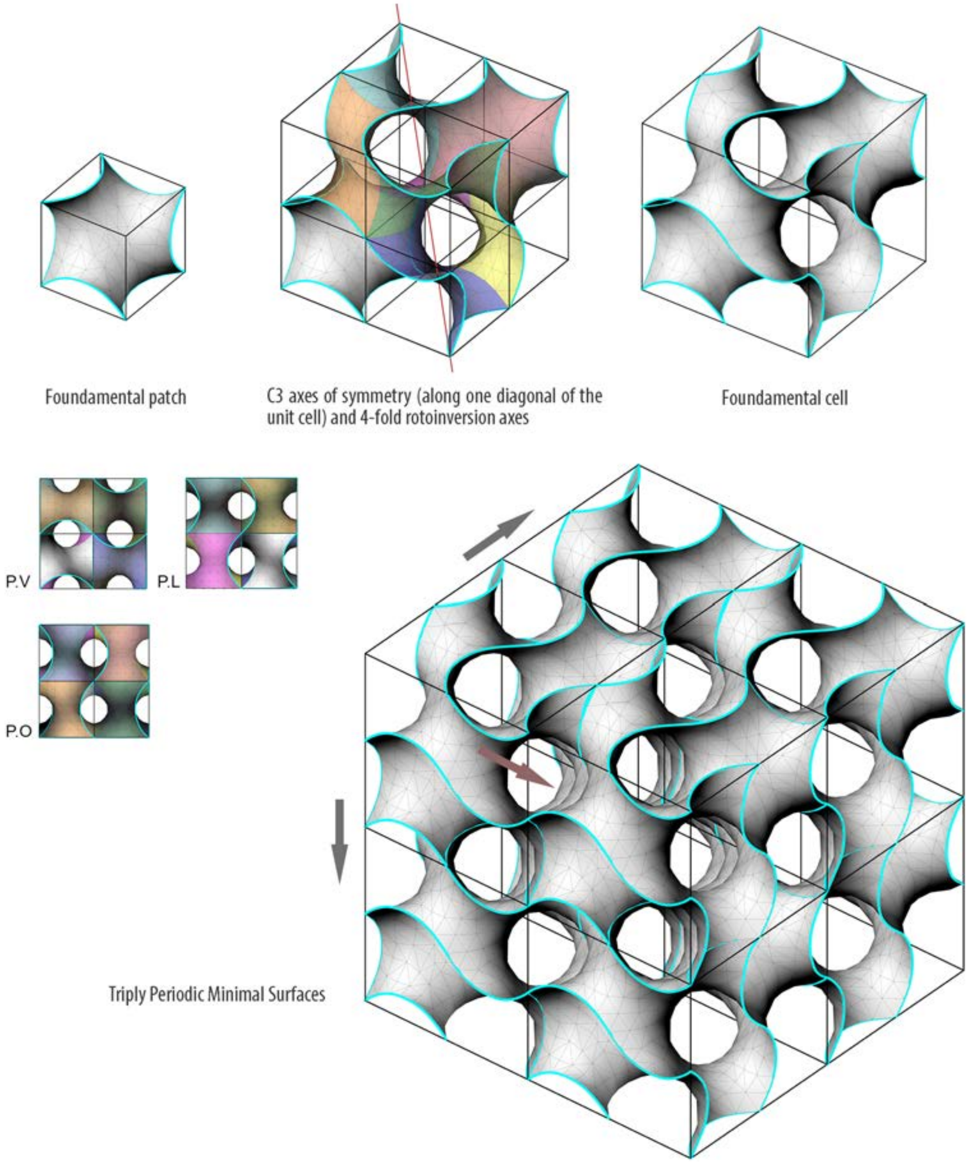
This means that minimal surface combine structure and material in a very efficient manner by aligning force and geometric form in an organic shape.

A triply periodic minimal surface (TPMS) is a minimal surface, which is periodic in three independent directions (Figure 1). TPMS are described in terms of a fundamental patch or asymmetric unit from which the entire surface may be built up by its symmetry elements. A single minimal surface is characterised by different curvatures: in other words, some surfaces are flatter than others. It follows that not all points of the surface support any concentrated loads equally well. If the same surface is, however, associated with a periodic distribution the physical iteration between the modules causes a compensatory effect that greatly increases their structural efficiency.

Because of that, the study of TPMS for design purposes is particularly fascinating (Figure 2). These surfaces may be made by defining and evolving their fundamental region, which is usually very simple due to the high symmetry, and then displaying many suitably transformed copies. Several fundamental regions are one of Coxeter's kaleidoscopic cells. Many of these surfaces were described by Alan Schoen in a famous NASA report. [10] The first step was to find a way to generate and control the TPMS in digital environment. The computation played an essential role in the simulation and modelling process of such complex phenomena. It was used Grasshopper, a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools in order to create an algorithm able to describe and to control various types of TPMS.

This research applies minimal surfaces that can be described by implicit form, typically a linear function of three variable, $f(x, y, z) = 0$. The trigonometric form is appropriate to the digital description because it allows the handling of the large number of elements that characterize TPMS, without overload the calculation process and also does not allow self-intersections. Using Grasshopper it's possible to define algorithms that are able to describe with good approximation any minimal surfaces directly from its implicit formulation. The algorithm translates the algebraic equation into a finished form that can be studied, manipulated and replicated.

Figure 2
Construction principles of TPMS based on gyroid



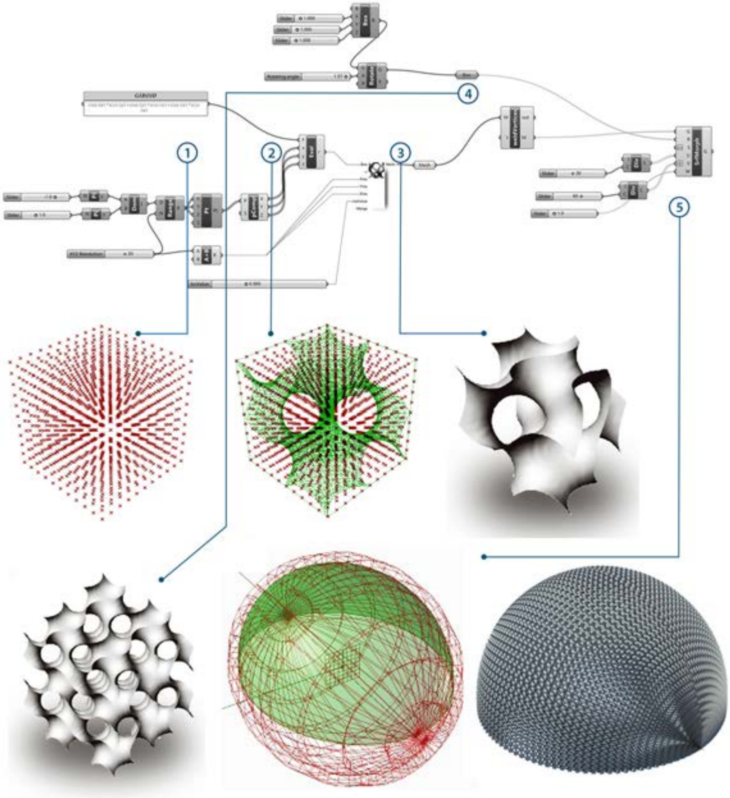


Figure 3
Step of the algorithm: 1) Definition of points in the fundamental cell; 2) Triangulation creates the surface; 3) Gyroid surface ; 4) Invariant translation to create a TPMS based on Gyroid; 5) Discretization of the hemispherical dome to obtain a surface composed by Gyroid.

The process can be conceptually simplified imagining that, in the domain of Cartesian space, the equation "selects" points, belonging to the surface you decide to represent (Figure 3). The next algorithm's instruction connects them by triangulation creating the surface. It is now possible to exploit the symmetry characteristics of the single unit by replicating it in a symmetrical cell, which is suitable to further replication in a modular lattice and to study the processes of adaptation to any required morphology. [7]

TPMS ANALYSES

The testing strategy applies the algorithm to a standard triply periodic minimal surface and it identifies the efficiency of the algorithm testing the level of accuracy in generating the geometry, comparing the two porous structures generated by *Gyroid* and *P-Surface*, in comparison with a solid bar.

To investigate the mechanical behaviour of different minimal surfaces structure, numerical simulations were also conducted. The model was implemented into finite element software code (COSMOS), which allowed the simulation and predicted the deformation characteristics of the designed porous structures and its mechanical behaviour, depending on the thickness changes.

A stress test was carried out (Figure 4). The application of 1kgf (10 N) was then evaluated on an iron parallelepiped sized 10x10x100 mm and compared the result with two equivalent-sized structures with different thicknesses, composed respectively of the P-surface and the Gyroid.

Table 1 summarizes main results.

This analysis leads to some data, which stress two main interest focuses.

First, in minimal surfaces element, even for very thin thicknesses (0.1 mm), the bar does not break even though it deforms considerably. This is because the stress does not focus on one point, but it is distributed among the different units that work in synergy: overall performance improves that of individual parts.

Second, the behavior changes with increasing thickness. When thick is 2 mm thick the deformation decreases considerably: if the solid iron bar deforms 1 mm, the one articulated in P-surface deforms 2 mm, while the Gyroid bar is deformed by 1.6 mm. The interesting aspect is that the two bars weigh, respectively, ten (P-surface) and eight times (Gyroid) less than the solid one, while maintaining good stress resistance properties.

Table 1
Stress test results

		THICKNESS (mm)	DISPLACEMENT (mm)	STRESS (Kgf)	WEIGHT (g)
	SOLID		0,00005	0,031	780
P-SURFACE	a	0,1	0,013	2,36	4
		0,5	0,0012	0,273	19
		1	0,0003	0,111	37
	b	2	0,0001	0,044	74
GYROID	c	0,1	0,016	1,1	5
		0,5	0,0008	0,40	25
		1	0,0002	0,115	49
	d	2	0,00008	0,055	98

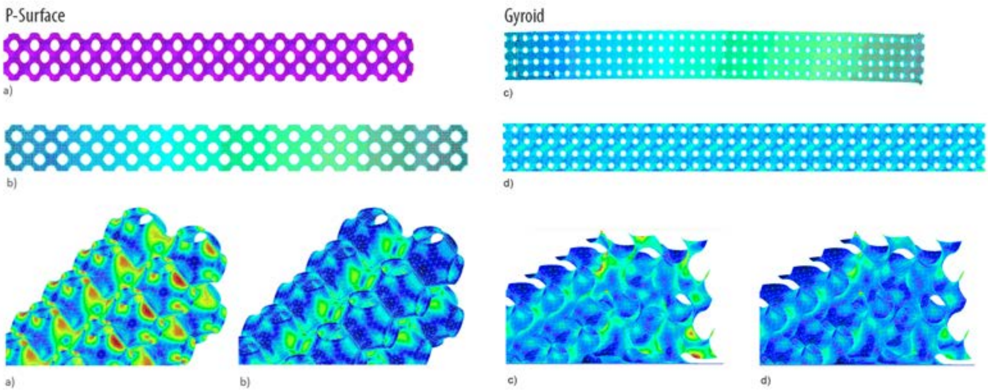


Figure 4
Stress test results

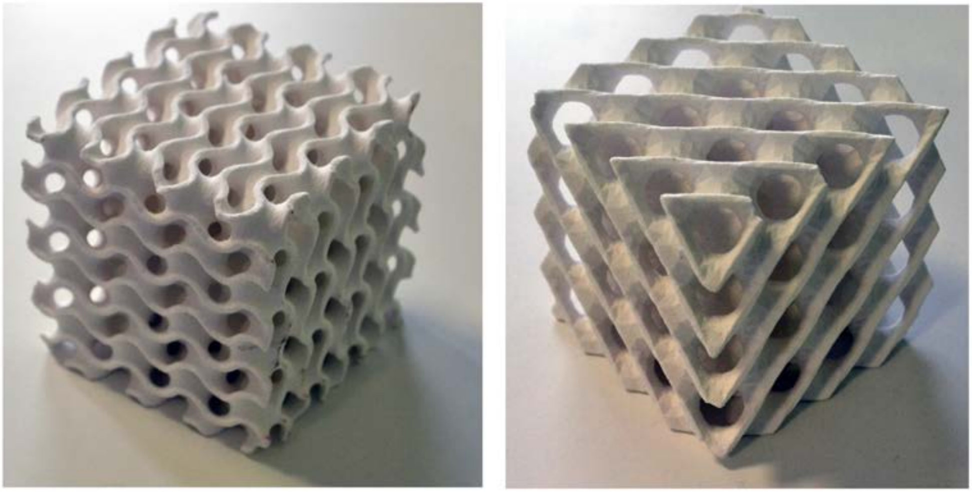


Figure 5
TPMS based on Gyroid and Diamond Surface manufactured by 3d printing process

FABRICATION AND TEST OF TPMS

The possibility of designing TPMS would be pointless if they couldn't then be created.

In recent years there has been a convergence towards the digitalisation of production processes thanks to machines able to construct, either in whole or in part, the designed object, starting from its digital model. This process is known as *Digital Fabrication* and does not require any additional interpretations to that of the designer, as the file is planned and the object can be fabricated without the involvement of other intermediaries. With other words, we could say that the scripting is both the *design representation* and the *making input*. Furthermore this new manufacturing permits the creation of forms and structures that were once considered extremely complex (Figure 5).

After assessing the cost-benefit ratio and research intentions, the first experiments were conducted with the *Z-corp Spectrum Z510* plaster-based 3D Printing. Considering that printers deposit layered material, moving vertically, usually it is necessary to provide the most correct arrangement to support the protruding parts to prevent the structure's collapse during the printing. It is worth noting that structures created using TPMS do not require additional support. If we consider that even in nature they are in processes where the generation takes place by layering, they are likely to be self-supporting body. This property makes it particularly suitable for 3d printing technologies, allowing a considerable saving of the production times and the construction material.

TPMS APPLICATIONS

A design application comes from an ergonomics research carried out simultaneously to this work: a study about safety of construction workers has shown as, especially in the summer, many operators do not wear helmet due to the weight and heat [7]. Furthermore, the three marketed sizes are not sufficient to meet the anthropometric variable, increasing the discomfort of many users. The example in figure 6 shows how, via computational modelling, it is possible to integrate the properties of the minimal surfaces into a protective artifact capable of solving these problems. After comparing the different minimal surfaces we chose to use the Gyroid-based Tpms. In nature, these structures are present where you need strength and lightness, such as in the sea

Figure 6
Comparison between the different Tpms and the ultimate safety helmet

urchin exoskeleton or butterfly wings. Stress tests performed (See TPMS analysis) confirm that the Gyroid is a structure that optimizes the ratio of used material, lightness and mechanical strength. These features, associated with the breathable characteristics due to the porosity of TPMS, make Gyroid particularly interesting for the design purposes proposed.

It has previously been explained how the algorithm allows to digitally describe the Tpms. It is now necessary to continue with scripting to adapt the fundamental cells to the protective helmet morphology

The helmet model was solved with a NURBS surface, discretized in parallelograms coinciding with the lower base of the pyramid trunk in which each single Gyroid will be recalculated. The limit of this procedure is the anisotropy of the fundamental cells that the hemisphere geometry involves. The mesh elements are more elongated in correspondence of the poles of the hemispherical dome. For compensation effects already mentioned, and for the small size of individual cells, this is not a problem from a structural point of view.

Assuming that future production costs for 3d printers will decrease,[7] it would be possible to obtain a helmet customized on anthropometric characteristics of the user, and that it is also lightweight, strong and which allows the circulation of air.

CONCLUSION

The study focuses on Triply Periodic Minimal surfaces and their structural system as a suitable manufacturing method. However, the potential of the suggested generative tool is not limited to these solutions, as the geometry could reach higher levels of complexity by exploring the design possibilities of all known periodic minimal surfaces or even to explore new types of surfaces or hybrid typologies.

The purpose of the research is to open a new direction within the computational design methodology, as part of design process, involving a multiple purpose design strategy, which takes into consideration various constraints, as part of an articulated parametric system.

Porous surfaces generated by TPMS could be interesting to various applications at different scale, from architecture to reach the level of industrial design artefacts, furniture or installations. Due to the cellular logical structure of the system, in correlation to the fabrication method, a feasible field of applications could include even fashion and textiles design.

So far is the beginning, concerning lightness and strenght, because several interesting properties are still to be tested: permeability, optical effect on color, sound absorption...The research must go on.

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