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PRO-INNOVATION

PROCESS PRODUCTION PRODUCT

edited by

Giuseppe De Giovanni

Francesca Scalisi

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2

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Edited by Giuseppe De Giovanni and Francesca Scalisi

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INTRODUCTION

The beginning of the third millennium has marked a period of unprecedented change for cities, architecture and product/visual design. Over the last two decades, economic, social and environmental causes have stimulated and conditioned research and production, directing them towards substantial paradigm changes, proposing new challenges to create more smart, more resilient, more responsive and adaptive, more efficient and more sustainable urban systems, buildings and objects – from nearly Zero Energy Buildings (nZEB) to Positive Energy Architecture (PEA) – designed and built faster, with lower costs and with a positive effect on the environment, society, health and productivity: more innovative, in a nutshell. It is a common knowledge that innovation is, now more than ever, the tool needed to recover from the global economic crisis, to aim for economic prosperity and quality of life improvement, to increase productivity, to foster competitiveness, to support the challenge of globalization and environmental sustainability, both at an 'incremental' level (improvement of an already existing production process) and 'radical' (to create a new unmatched method or production system).

Innovation concerns Process issues, i.e. sequence and organization models, management and control of the process stages, operating methodologies (ideational, design, productive, operational, management and of disposal of the work/product) of the whole life cycle of the artifact, regulations, new professional experts and technical skills, ways to involve professionals and users in the several decision-making stages, etc. Production can also be affected by innovations involving tools suitable for the optimization of the different stages of the production process including machines and robots for digital manufacturing (CNC milling, laser cutting, 3D printing, etc.), for prototyping and for prefabrication, relating to analysis and design/simulation software (also with virtual reality) CAD and CAM, BIM, digital, parametric, algorithmic and generative, environmental, structural, energetic and thermal; installation and assembly techniques and technologies, etc. Finally, Innovation can also deal with smart, advanced, composite, recyclable, sustainable, nanostructured, shape-memory, phase-change, self-repairing, responsive, adaptive, low-cost and high-performance materials/components/objects with a low environmental impact, automation, detection, management and control equipment for performance optimization, 'passive' technologies for efficient casings, including natural ventilation and cooling systems, water collection, storage and recycling, and off-grid renewable energy production. In this regard, the publication 'Pro-Innovation: Process Production Product' collects essays and critical thoughts, research and experimentation on the subject of Innovation in the building and design industry, which can provide some starting points for debate for the international scientific community or show successful examples of innovation, sustainability and social inclusion. The papers are grouped into two sections (Architecture and Design) according to the scientific field they are referred to.

On the link between Shape and Structure, Bellini and Ruscica's paper is worth mentioning. They highlight how the potential of construction systems based on structural conceptualization and respect for static equilibrium, with reference to reciprocal structures and tensegrity systems, can help to teach the importance of the control of shape and structure, activating a fully unitary process. While on the links between Structure and Plants, Quadrato observes how the structural elements, in the Italian architecture of Marco Zanuso and Aldo Favini, between 1950 and 1975, while preserving an internal system of topological and tectonic relationship, they became technical tools capable of ensuring not only a static, spatial and figurative validity but also a technological one. On Prefabrication as a possible (flexible and adaptable) response to the housing emergency, Ruggiero critically describes a housing construction program underway in the City of London (based on the implementation of off-site production principles), outlining its aspects on technological innovation and questioning the potential and problems of a new building culture.

On the subject of Digital Manufacturing, Vacanti, Ferrari Tumay and Vian talk about the Fab Labs not only as places of experimentation and research but, above all, as joints of a network that, over the last few years, has succeeded in starting collaborative processes between geographically distant places, highlighting how the Ma(r)ker, co-producer and co-designer, hybridizes new technologies with traditional production systems, manufacturing artifacts that have symbolic values of belonging to a specific territory. On the potential applications of 3D printing, we mention Inzerillo's paper which describes some experiments, as a result of the relations between research and real actions of companies – design-oriented – which invest in their own territory, developed in Palermo and whose innovation is focused on the market of Carbon fibre reinforced plastic and the integration of digital production processes.

Also Conato and Frighi deal with innovation, analysing the relationship between Buildings and Intelligent Materials, highlighting how these product innovations can define process innovations in the organization, management and control of every step of the life cycle of an artifact, allowing the creation of tailor-made buildings oriented towards a more efficient architecture. And Baratta, Calcagnini and Piferi's paper has a critical reflection on the subject of innovation in the sector of Brick production, a more traditional material, identifying the more recent and interesting solutions on process, product and process innovation that have enabled this material to efficiently respond to an increasingly strict regulatory framework and to meet contemporary formal and market needs.

Other aspects of innovation in the building sector are dealt with by Rogora, Carli and Trevisan who propose the Role Play as a way to interact between designers, citizens and public administrations to favour common decisions in the processes of transformation of the built environment in a sustainable way with a method that enables to verify the effectiveness of the achieved results. Angrisani and Orsini investigate the innovative potential of the Parametric Design Process, applying it to three case studies on an urban, architectural and technological scale, by checking how it can favour smarter, more resilient, more adaptive, more sustainable cities, buildings and components, in the context of new design processeses managed by algorithms that provide solutions and improvements on efficiency, performance, choice of materials and cost optimization. While Cianfanelli, Pelosini, Tufarelli and Malpelo report an experimentation of these new devices applying generative design to evergreen Made in Italy products, with the aim of understanding how these new procedures can be used to provide valid solutions and if they are destined to replace the role of the designer. On the roles and skills of the Professional Designer, Bisson, Pizzolato and Palmieri's paper should be noted. They consider how this role is evolving, with reference to the collaboration with the industry world, asked to offer new skills in operational contexts sometimes unexplored.

Regarding the subject of environmental sustainability, it is worth mentioning: Sposito and Scalisi, identify in the Environmental Product Declaration (EPD) or Type III Environmental Label a useful tool to guide the professionals and users in the choice of low environmental impact building materials and with equivalent functional requirements, analyse and compare the records of wood products (for building systems and components) on the market in relation to their end-of-life; Buoninconti, De Joanna and Vaccaro present the ongoing research at the CITTAM of the University of Naples 'Federico II' for the development of a product evaluation methodology, which can be integrated with the BIM, guarantees sustainability certification and, in fact, contributes to the digitalization of the executive project; Clemente, Altamura and Cellurale, within the Italian building regulatory framework recently characterized by the definitive implementation of the Environmental Minimum Criteria (CAM) for the building industry (Ministerial Decree 11/10/2017), compare two architectural design experiences for training, highlighting how the same CAMs can represent a perfect driver for the recovery of an economic sector that is struggling to restart; Cannaviello focuses on the subject of energy redevelopment of logistics services and on the nZEBox System capable of responding both to the need to optimize not only energy-environmental quality, and aesthetic and communicative quality of the traditional building site monobloc.

Other research integrates the overview about innovation. On the basis of a study carried out by Confcooperative Habitat, Mastrolonardo, Di Dio, Spataro, Sala and Schillaci describe research aimed at improving how to work actively on communities for a tangible social impact capable of offering a model that knows how to enhance common urban spaces within the interventions, through a procedural model proposed and modulated on an evolved platform. For the creation of a Simulation Centre aimed at providing education and training in the medical field, Bisson, Ianniello and Palmieri propose guidelines and toolkits, capable of combining traditional tools with virtual reality technologies, to create complex, more realistic systems, useful to build an effective and targeted training, fostering the horizontal collaboration among the many operators, even geographically distant. Vignati and Terenzi report the experimentation of a new Innovative Product both to respond to the specific need of children in preschool age and from the technological point of view, capable of encouraging and facilitating their motor skills through games and digital technologies. Finally, Zappia and Morozzo della Rocca, as part of the new subject dedicated to the History of Nautical Science, Nautical Heritage, describe the studies and results achieved in defining guidelines and methods for the conservation and restoration of historic boats.

The papers collected in this publication provide a summary, obviously not exhaustive, of the Innovation that is characterizing the beginning of this century, presenting many proposals and new points of view of the process, of its management and of the building production that indicate new paths to thread and new professionals.

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SPATIAL RECIPROCAL FRAMES AND TENSEGRITY
PRELUDE TO FORM-FINDING

Oscar Eugenio Bellini [a], *Giuseppe Ruscica* [b]

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Abstract
If the dualism between form and structure, which appeared with the scientific and technological progress, has allowed to explore new frontiers in the construction field, the consequent disciplinary specializations have increased the separation of the knowledge related to the project. The architect and the engineer, who were the same figure in the past, have progressively begun to separate, increasingly distancing themselves from one another. This essay investigates the potential of building systems based on the structural conceptualization and stability, referring to reciprocal frame structures and tensegrity systems. From a didactic point of view, they can help understand the importance of the control of form and structure, starting an absolute unitarity of process.

Keywords
design, process, spatial reciprocal frames, tensegrity, form-finding

The establishment, in 1671, of the Académie Royale d'Architecture – promoted by Louis XIV and inspired by Jean-Baptiste Colbert – confirms on a symbolic level the reciprocal self-determination of architecture and engineering and the formalization of two autonomous and independent scientific sectors among the transformative processes of the built environment[1]. From that moment, specific contents and expertise of architects became formally established, and they are considered as the individuals appointed to the control of the compositional and formal aspects of the building. In a similar way, engineers are considered the repositories of building construction techniques. To the former, 'artistic' skills are referred, while from the latter more 'executive' skills are requested. A role separation which has been further consolidated in 1794 with the establishment of the École Polytechnique, which would definitely establish not only the conditions for an increasingly pronounced cultural and scientific contrast between architecture and engineering, but also the formalization of different ways to interpret the processes which modify reality (Deswarte and Lemoine, 1980). This duality implicated, on a process level, the creation of a contradictory, or perhaps ambiguous, project culture. This led architecture and engineering to become apparently separated entities, while they are actually bonded by a reciprocal correspondence and correlation aimed at finding, through the project, moments of discussion and blending. Occasions that in history proved to be a 'common ground', a space to explore and where a 'border epistemology' can be experimented (Morin, 1993, p. 67). A dimension where alternative ways can be promoted in order to create correspondence in the contents that an architectural project has to express; situations where a dialogic relationship between architecture and engineering can be reinforced and the mutual role of the two disciplines can be legitimated, also defending their character and function. From a phenomenological point of view, Campioli (2015, p. 67) writes: «Architecture and engineering, in a dialogic point of view, are not merely juxtaposed, but are one essential to the other. This allows maintaining duality within unity, through the association of two terms which can be considered complementary and antagonistic».

In recent history, with the occurrence of a lack of the self-referentiality that architecture and engineering can reach, the more interesting outcomes have been celebrated. Situations where it has been possible to reach, through the project phase, new expressive forms, promoting innovative actions related to the complexity of construction. If, on the one hand, the history of modern architecture is characterized by unbearable divergences between architectural and engineering knowledge[2], on the other it is marked by numerous occasions when the final quality is the result of the explicit contamination between these two disciplines. Moments in which architecture demands have become one with engineering reasons, reaching – if not a true symbiotic relationship – at least a construction unitarity.

The search for form and structure is attributable to high-value intellectual and scientific figures: Robert Maillart, Pier Luigi Nervi, Eduardo Torroja, Eugène Freyssinet, Félix Candela. Designers. Designers who had the undeniable merit of bringing to the attention of the project discipline the expressive potential of the static and constructive components, the new materials and innovative technologies, thus promoting the importance of pursuing, through the design and process action, the maximum interaction between formal identity and construction technique (Margolius, 2002). These hybridizations are present in some paradigmatic interventions which left their mark on the history of construction, like Jørn Utzon's Sydney Opera House in 1957, whose construction was made possible thanks to the unique role of Jack Zunz, an engineer at Arup & Partners, or the Parisian Centre Georges Pompidou in 1971, designed by Renzo Piano and Richard Rogers, where the involvement of Peter Rice, also an engineer at Arup & Partners, turned out to be decisive for the realization of the building[3]. Occasions on which it was possible to cross the disciplinary borders, proposing new formal narratives and figurative expressivities between technical experimentation and linguistic research. Design outbursts which produced advancements in the conception and definition of architecture and reformulated the creative and generative process intended for the morphological research together with the static analysis. In the interaction between architecture, engineering and industry, Richard Buckminster Fuller and Konrad Wachsmann led the discipline towards a prolific debate about the topics of mass production. The former did it through the experimentation related to unification and prefabrication, as can be seen in the Packaged House System's patent of 1942. The latter experimented, in the Dymaxion House of 1929 and in the Geodesic Dome of 1954, the potential of reticulated space structures, tensegrity systems and large-scale industrial production.

In the specific field of the structural expressiveness of thin-shell systems, the morphological experimentations carried out in the Kresge Auditorium by Eero Saarinen in 1955 stand out. The Auditorium was realized in Cambridge, on behalf of MIT and in collaboration with the New York-based Ammann & Whitney engineering firm. There were also the Deitingen Service Station by Heinz Isler in 1968 and, among the infrastructures, the Musmeci's Basento Bridge in 1971: works where form and structure achieve a complete constructive synthesis, according to the specificity that Giò Ponti (1955, p. 2) described with great lucidity in an article appeared on Domus and entitled Engineering and Architecture: «They belong to engineering those forms which are generated and developed […] by the repetition of identical elements and which could […] extend and grow, […] in theory forever. Not having a dimension of their own – that is, a finite and closed form – they are not architecture. These forms, I thought at the beginning, belonged to the construction industry, to building: today I think it is more correct to say that they (some of them appearing beautiful to me) belong to something higher, something that can be sublime too, but that is not architecture: today I think it is more correct to say that they belong to Engineering, a demanding and beautiful discipline which distinguish itself from Architecture (art) because it (Engineering) is progressive and Architecture, art, is not. Engineering is eclectic, Architecture is not: engineering accepts, experiments and absorbs […] the best that technique and production can offer […], creates technical works, repeatable, multipliable and superable, one subsequent to the other, continuously getting better». On an educational level, the dimension of structural data can be promoted by experimenting some constructive systems which, through their simplicity, force a student to think about forces and weights. Tensegrities and spatial reciprocal frames, ancient but still modern systems, are the ones that, more than others, can transform into useful preparatory tools for a 'form-finding' education.

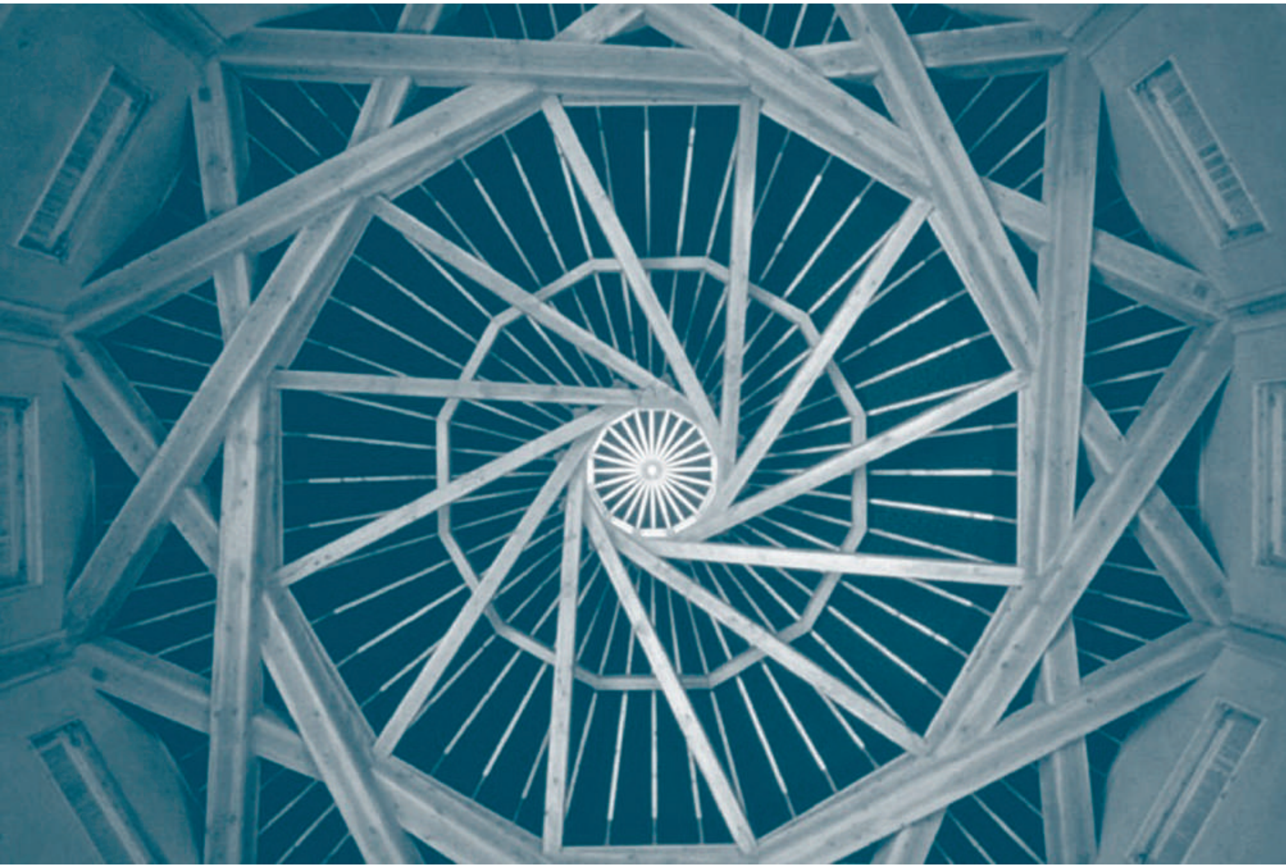
Reciprocal frames – Reciprocal frames are spatial systems composed by three or more beams that hold each other, forming a closed circuit. Their arrangement, mainly of the grid type, allows to span over long distances without using intermediate supports, and that is the reason why they are historically used for planar roofs. Their configuration allows spanning lengths greater than the dimensions of the single beams constituting the whole, thus making it possible to bypass the technological and constructive limits of the traditional systems. The use of reciprocal frame structures had already been documented by authors like Villard de Honnecourt and, later, Sebastiano Serlio (1978, or. ed. 1566) and Leonardo da Vinci himself, in the Codex Atlanticus (Gioppo and Redemagni, 2000). In the last years, this structural system has been studied in a more organic way by John Chilton (Chilton and Choo, 1992; Chilton, Choo and Popovic, 1995) and Olga Popovic Larsen (1996, 2008), who analyzed its geometric, constructive and structural principles.

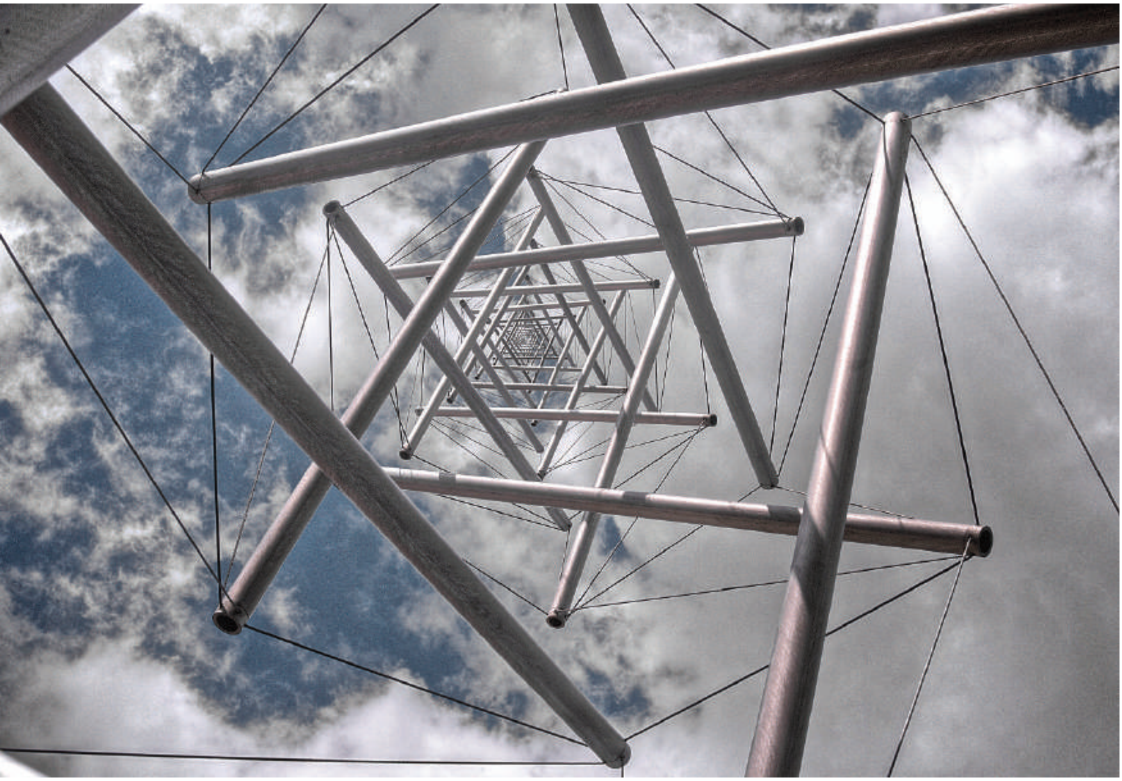
The main criticality of reciprocal frames is their structural robustness. Because of the reciprocity principle itself, in fact, there are no predefined paths for acting forces, as happens in traditional frame structures. Every element supports and is supported at the same time, in a circularity of forces and weights, as stated in other studies (Pugnale and Sassone, 2014). The lack of a hierarchy between elements and the consequent lack of structural redundancy can lead to a collapse of the system, especially when a single component suffers a structural failure. These aspects should be taken into account when reciprocal frames are going to be studied and used. In relation to this, noteworthy are the studies and the experimental tests carried out at the University of Bergamo by the research group of Attilio Pizzigoni (2008). During this research, a 'short beam' profile to be adopted in reciprocal frame roofs has been perfected. Starting with a modular element, several tests have been conducted to determine the breaking strength and the ultimate resources available to the entire system, in order to demonstrate the feasibility and practicability of such design solutions. In literature there are several examples of reciprocal frame roofs, like the ones used in 1952-53 by Louis Kahn for the Mill Creek Public Housing Project in Philadelphia, which was unfortunately demolished. Visually stunning is the Japanese Seiwa Bunraku Puppet Theatre (Fig. 1), designed by Kazuhiro Ishii in 1992. In this case, the reciprocal frame structure is clearly visible in the elegant roof over the exhibition hall, with structural elements having a length of about 8 meters, where the wooden beams, intersecting each other, reveal the basic principles of reciprocity. More recent works can be seen in some temporary pavilions, like Shigeru Ban and Cecil Balmond's Forest Park Pavilion and the renowned Serpentine Gallery Pavilion by Álvaro Siza, Eduardo Souto de Moura and Cecil Balmond (Fig. 2). In this last case, the wooden elements constitute the pavilion's envelope, which seamlessly goes from the roof to the walls.

Tensegrity structures – Tensegrity systems share several properties with reciprocal frames, like circularity and recursivity. Recent studies by Biagio Di Carlo (2008) show their analogies and similarities. This kind of structures, adopted for several years in installation art (Fig. 3), is making an increasingly frequent appearance on the international architecture scene (Dal Co, 2018). Sculptor Kenneth Snelson defined them as 'floating compression structures', in a way recalling their equilibrium form, which shows the lightness, both visual and structural, that so fascinates contemporary architects. Among the engineering studies, several definitions of tensegrity structures have been provided, starting with R. Buckminster Fuller, Kenneth Snelson and David G. Emmerich, who claimed its authorship. It was through Kenneth Snelson's first tensegrity models (Fig.

Fig. 1 - Next page. *Kazuhiro Ishii,* The reciprocal frame structure of the exhibition hall roof in Kazuhiro Ishii's Bunraku Theatre complex, *Seiwa, Japan, 1992 (credit: The Architectural Review).*

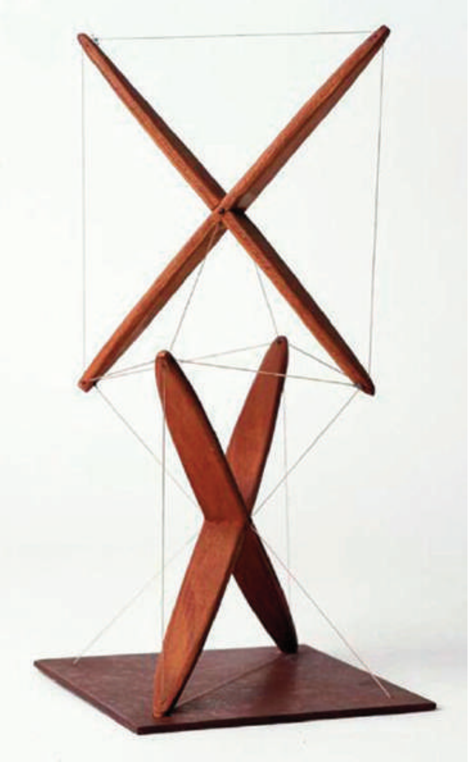
Fig. 2 - Álvaro Siza and Eduardo Souto de Moura with Cecil Balmond, Serpentine Gallery Pavilion, *London, 2005 (credit: Arup Photograph 2005 S. Deleu).*





4) that R. Buckminster Fuller developed the concept of tensegrity. The term derives from the contraction of the words ‘tension’ and ‘integrity’, meaning ‘tensional integrity’. The mesh of the elements in tension makes the entire system deformable, so that, if a certain pressure is applied on one or more elements, the structure experiences a deformation and then returns to its initial configuration as soon as the perturbation stops.

One of the main characteristics of tensegrities is that, before being subjected to external loads, they are already prestressed: compression elements put in tension the other elements, and vice versa. In this way, the structure assumes a geometry deriving from the continuous balance of opposite forces. There is no unique definition of a tensegrity system. As a general rule, this system can be defined as a set of discontinuous compression elements which interacts with a continuous set of tensile elements, in such a way to define a stable volume in space. Bin-Bing Wang and Yan-Yun Li (2003) speak about tensegrity systems as self-supported reticulated structures, stiffened by a state of self-stress, where a set of cables is tensioned by a discontinuous set of compression members. René Motro (2003) provided a comprehensive definition: a tensegrity system can be intended as a system which is in a stable self-equilibrated state composed of a discontinuous set of compression elements inside a continuous net of tensioned components.



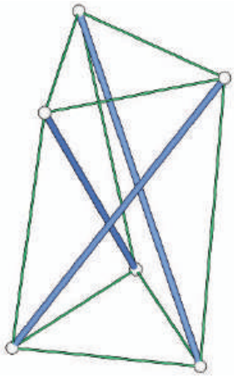


Fig. 3 - Previouse page. *R. Buckminster Fuller,* Neddle Tower *(credit: C. Shonkwiler via Flickr Licence CC BY 2.0).*

Fig. 4 - Kenneth Snelson, The X-piece*, 1948.*

Figg. 5, 6 - Tensegrity T-prism; Gerkan, Marg und Partner (Architect) and Schlaich, Bergermann & Partner (Structural Design), Tensegrity Tower, *Rostock, 2003 (H.G. Esch, Hennef-Stadt Blankenberg).*

Considered the great variety of achievable configurations of a tensegrity, several researches categorized them over time, identifying sets and subsets.

Anthony Pugh (1976) was the first to propose a classification, enumerating the ways of connecting more systems in order to get more extended configurations. Among simple tensegrity units, the best known is the triangular tensegrity prism (Fig. 5), also called simplex or T-prism, generated by a right prism where cables are horizontal or vertical and bars are diagonal and connect vertices of two different levels. If a relative rotation between the upper and lower polygons is introduced, the corresponding tensegrity prism can be obtained. In order to achieve an equilibrium configuration, this rotation cannot be arbitrary, and depends on the number of bars. The very first structure realized following tensegrity concepts is The Skylon, a tower symbol of the Festival of Britain in London, built in 1951. Designed by Hidalgo Moya, Philip Powell and Felix Samuely, it presented a steel frame structure, with a shape resembling a cigar. The base of the mast was about 15 m from the ground, while the upper part was 90 m high. The main element, visible at a great distance, was supported by three cables, giving the illusion of being floating with no support, according to a characterization already proposed in Kenneth Snelson's tensegrities. The prestress applied to the cables was meant to stabilize the structure, reducing its inevitable oscillations.

In 2003 another tower-symbol was proposed: the Tower at the Fair of Rostock, in Germany (Fig. 6), designed by the architecture firm Gerkan, Marg und Partner and engineered by Schlaich Bergermann und partner. It is a structure of relevant size, composed of six simplex tensegrity modules about 8 m high, with a steel needle placed on top. Another realization is the Blur Building (Fig. 7), a temporary pavilion designed by Diller Scofidio + Renfro on the occasion of the Swiss Expo 2002 in Yverdon les Bains. The building appears impalpable, and looks like a suspended air and water cloud on the lake Neuchâtel. Inside, there is a tensegrity steel structure, designed by the Passera & Pedretti engineering firm. The building presents an elliptical plan, while the base is a bipyramidal tensegrity module (Fig. 8) obtained by reworking a study of Bin-Bing Wang (1996).

For the unity of the design process within the designer's education – What tensegrities have in common with reciprocal frames is the strong correspondence between form and structure. Their geometry is related to acting loads and the type of modules forming the structure. This forces the designer to rethink and reinvent the possible process approaches that are connected to their design. A traditional structure allows for a certain freedom to work on forms, transferring the analysis of the structural system to a second phase, according to a 'cascading' unnatural process. This implicates the separation between the figures contributing to the design of the building and the denial of the much desired 'integrated design'. The study of reciprocal frame and tensegrity systems can help, on an educational level, increase the student's awareness of the importance of the unity of form and structure within the design process. The experience promoted at the Faculty of Building Engineering of the University of Bergamo during the Architec-

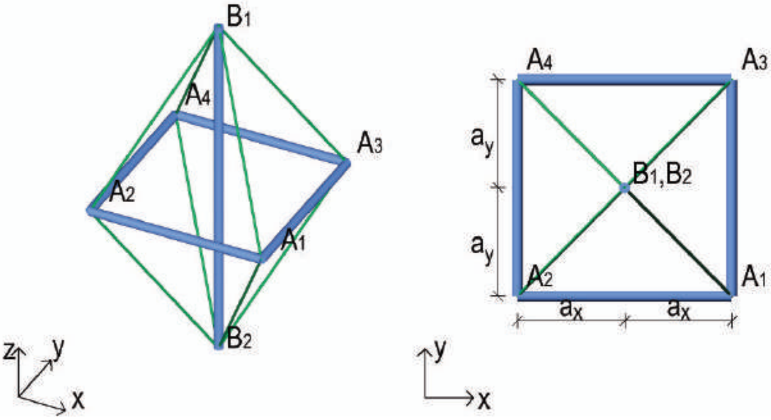


Fig. 7 - Diller Scofidio + Renfro (Architect) and Passera & Pedretti (Structural Design), Blur Building, *Yverdon-les-Bains, 2002 (credit: DS+R).*

Fig. 8 - Axonometric and top view of an octahedral tensegrity module.

tural Design course held by Attilio Pizzigoni is a valid proof of this method (Ruscica, Micheletti and Pizzigoni, 2010). Engineering students, always used to a mechanistic and software-dependent structural design, were asked to study in a conceptual way the structural geometry of reciprocal frames and tensegrities, preventing them from adopting pre-established traditional structural systems. This forced the students to search for innovative structural morphologies and, at the same time, allowed them to optimize the materials used, which today is an important issue, according to the new environmental sustainability requirements.

Due to the geometrical and mechanical peculiarities, tensegrity systems cannot be studied through a traditional calculation system, but they have to be designed empirically and experimentally, with an approach that imposes a preliminary conception (it is not a simple frame). It's an approach which stimulates the students' ideational potential, making them think without any 'information technology intermediary' and without any preconception about the identity between form and structure, while defining the static and structural behaviour. The making of scale models of the structures conceived allows the student to observe and intuitively understand the way to reach an equilibrium configuration, highlighting the zones where the stresses are higher and where weaknesses may appear. Only when the relation between form and structure is understood, it is possible to take back that sensitivity which in the past allowed to build structural systems, even complex, where materials were adopted with real constructive and mechanical peculiarities and where intuition and experience helped achieve the magic which merges architecture and engineering.

This proves once more that, within the discipline, it is becoming increasingly important to achieve unitarity in the disciplinary knowledge of the engineer and the architect, experimenting an education that promotes the innovation of process and product, starting with an improvement of the design culture, opposing the disintegration and separation of knowledge, like Karl Popper (1958) did when speaking about the salvation of science and philosophy. During some lectures at a postgraduate course, Pier Luigi Nervi hoped for the creation of an ideal school, where it could be possible to teach 'structural architecture', which, according to his opinion, 'was a necessity, and not a trend'. He asked himself if it would be more appropriate to teach structural architecture in a school of architecture or of engineering or, even better, in an ideal school which architects and engineers could attend together, with the belief that the first who did it 'would have earned points'. This hope still presents a certain novelty.

Our times are witnessing the crisis, if not the decline, of the polytechnic culture; step by step, the disciplines, especially those related to the construction of architecture, seem to have lost their connection with reality, changing into simple guardians of a 'theoretical elsewhere'. The same theoretical elsewhere that in 1999 Edoardo Benvenuto highlighted while speaking about teaching related to the structural dimension of buildings: «our Structural Mechanics teachers are not to be blamed, because those poor guys only know a little bit of the theory of tensors, and only that; their hearth lies in this elsewhere: inside the scientific knowledge; a magnificent elsewhere coming from the theoretical spaces of mathematical analysis» (Benvenuto, 1999, pp. 609, 610). «The essence of the matter» – wrote Pier Luigi Nervi – «lies in the degree of static and constructive competence and comprehension by designers and, in order to discover its origin, in the efficiency of the Faculties of Architecture», adding thereafter: «One of the most serious mistakes is to suppose that an architect may need a less knowledge of static-constructive matters than an engineer». In order to make the design popularization of great works and current architecture surrender to the success of an innovative culture of construction: «a comprehension of concepts so deep that these ideas (constituted by physical premises, mathematical theorems and experimental data) are merged in one synthesis and transformed in a spontaneous, almost unwitting sensitivity is necessary». Because «it is precisely the ability to feel and sense a structure as one feels a relationship between proportions or colors that constitutes the essential basis of structural design» (Nervi, 1955, p. 156).

Final considerations and possible future developments – The present notes aim to be a consideration on how the study of tensegrity systems and reciprocal frame structures can provide the preparatory bases to improve the skills and critical attitudes through which the unitarity between form and structure and the complexity of other paradigms that contemporary design culture requires can be managed within the form-finding context: lightness, essentiality, sustainability, reversibility, effectiveness, efficiency, harmony, rationality, tension, temporariness, dismantleability, etc. Solutions that, on the level of both image and the rational use of resources, make students interrogate themselves about research and the use of innovative materials, capable of achieving maximum efficiency with minimum energy consumption. Lightweight or super lightweight structures that, with their astonishing forms, promote the innovation of the formal and technological progress in construction, opening up to Non-Standard Architectures issues (Migayrou, 2003), feasible through the study of the parametric management of the project and the numerical control, according to what is identified as file-to-factory or, more recently, digital crafting.

The challenge that Architecture schools must try to win is the overcoming of a positivist matrix linear process and an instrumental use of technologies. The project embodies a very high ‘technological level’, risking to uncritically consuming itself only within the practical reasons of an articulate range of sectional solutions, without recollecting back together in a unitary or summarized prospect. The simple ‘practical approach’ – based on the pragmatic culture that ruled the processes of industrial revolution, the transformation of nature and a radical innovation of the social production relationships – is not sufficient anymore. Architecture and Engineering Schools seem to be the natural places where designers can be educated to the belief that these two disciplines have to be reciprocally essential, while preserving their identity within the unity of the design process, in order to consider the union of two academic disciplines which can be considered complementary to one another, but antagonistic at the same time.

The question is not to educate hybrid figures, as is happening in several Italian Universities (Engineering-Architecture degrees), but to create the best conditions so that these two worlds can better talk to each other, communicating and, in the best case, mixing and complementing each other, creating a common ground where experience, skills, expertise, different languages can converge in order to generate elective affinities, because only when architecture and engineering manage to merge along disciplinary boundaries, it is possible to achieve the most interesting and innovative results. The attempts implemented in the Italian Schools do not seem to ensure any success; the academic entrenchments are still too rigorous to be able to open up to a real debate and renewal. It is not yet time for a project culture capable of assuming an attitude similar to the one already occurring in human sciences, and indicated as 'collective intelligence', a common, enhanced and organized intellect, capable of leading to a deployment of expertise and skills in order to provide, without any simplistic reductions, well-structured answers to complex questions.

The need to consolidate the relationship between form and structure should be redefined, because «if we adapt to a more sensitive understanding of the most subtle relations between engineering and form – if we conceive composition with engineering, rather than through engineering – if we work together rather than moving away from each other, we could achieve a relationship between form and engineering that has a broader meaning for the future architecture…» (Contini, 1958, pp. 61-63). In the contemporary architectural culture it is necessary to go back to one of the main assumptions of the project research, that is the natural aesthetic expressiveness of a good constructive solution. In the project, the beauty of the structural component is proposed as the truth of the natural laws and as a measure of space. A clear concept for Pier Luigi Nervi who, while speaking to the students of the faculty of Architecture, used to ask this challenging question: «What is beauty in architecture? It does not start with a relation between masses and voids. It starts with a fundamental truth: the structure is the truth. An architecture made of masses and voids has no meaning without a truthful structure» (Einaudi, 2010, p. 139), because, in architecture as in poetry «Beauty is truth, truth beauty, — that is all/Ye know on earth, and all ye need to know»[4]. A research which was perfectly clear to Eduardo Torroja, for whom «The best work is the one that is sustained by its own form, and not by the hidden resistance of its material. The latter is always easy, while it is the former that is difficult. In this lies the merit, the fascination of research, and the satisfaction of discovery» (Pierini, 2016, p. 47).

NOTES

1) «In the construction industry the current trend is to remain inside the first category of problems (inside disciplines) or even to fragment the construction world within the single disciplines. For each of them there is only one problem to be solved: that concerning their own discipline. So, for urban planners, for structural engineers, for architectural technologists the project is always and only an urban project, a structural project, a technological project. In this way, architecture as a discipline left behind and locked up inside its purely formal logic» (Monestiroli, 2005, p. 76).

2) In 1964 Christopher Alexader wrote «The modern designer relies more and more on his position as an ‘artist,’ on catchwords, personal idiom, and intuition – for all these relieve him of some of the burden of decision, and make his cognitive problems manageable. Driven on his own resources, unable to cope with the complicated information he is supposed to organize, he hides his incompetence in a frenzy of artistic individuality. […] the real work has to be done by less gifted engineers, because the designers hide their gift in irresponsible pretension to genius» (Alexander, 1964, p. 10).
3) Ove Nyquist Arup, founder in 1946 of Ove N. Arup Consulting Engineers and in 1963 of Arup Associates, commented about the architect’s proficiency: «with his possible technical expertise he cannot know by himself all the implications of the modern technological advances which today are involved in the construction of a building. He is therefore unable to identify by himself the right solution and he is in the grip of the various commercial interests supporting their products. The problem is the same in our field as in other fields of human activity, where the richness of new knowledge, new materials, new processes has expanded the fields of possibilities so much that they cannot be adequately analyzed by one single mind. Together with this development of means, there are new requisites to be satisfied. Our needs grow together with the means. Standards have got higher, new services have been introduced. This situation produces the specialist or the expert, and the consequent common problem of how to create the organization, the ‘composite mind’, so to speak, that can achieve a synthesis well-balanced by the richness of the available details. This, I think, is one of the essential problems of our time». (Arup, 1942, pp. 19-26).
4) Verse taken from John Keats’ poem *Ode on a Grecian Urn*, 1819.

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UTENSIL-STRUCTURES
THE LANGUAGE OF INSTALLATIONS AS AN ITALIAN TECTONIC TRAJECTORY (1965-1975)

Vito Quadrato [a]

section
Architecture

typology
Essays & Viewpoint

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Abstract
The technological issue of the relationship between mechanical services and structural research in the architecture of 20th century became certainly one of the most important lines for development and innovation of Modern architectural style. With respect to this topic, the paper analyses, as a key of interpretation, the role of installations to determine the relationship between envelope and structural layout in the construcitve logic of the framework. In this sense the paper highlights on the type of single-storey factories built in Italy between 1950 and 1975, analysing some built works by Marco Zanuso and Aldo Favini through the archival records. These works show how this type of building gain to paradigmatic innovations, transforming the tectonic joint into an integrated device, whose form was the result of the definition of the mechanical components as technical writing.

Keywords
form and structure, mechanical services, tectonic, prefabrication, reinforced concrete

From the end of 19th century to date, the technological apparatus of the mechanical services has become increasingly pervasive within the architectural design. The current effect of the cost of system equipment on the cost of a conventional building ranges «to 30% of the total building cost-and in some cases more than 50%» (Paricio, 2016, p. 117). Today, this clearly emphasizes the importance to develop strategies that turn a logistical and economic issue in a technical and figurative potential for the architectural expressiveness. Despite the advent of technological systems dates from the early Modern (Giedion, 1970), the available literature on the relationship between architectural and plant design is quite minimal, compared to the current importance of the issue. Actually, the notion of comfort intertwines with the origin of sedentary living, as underlined by Reyner Banham: «The mankind started with two fundamental methods of environmental control: the first one, avoiding the problem and hiding under a rock, a tree, a tent, a roof (this conducted to the end of architecture which we know), the second one, struggling with the place weather, usually through a camp fire» (Banham, 1974, p. 138). It is in this connection that the issue of the mechanical services based on the ontological relationship between the mankind and environment, thus to the way in which the man interpreted the oppositional dichotomy between construction and nature.

In the first half of 20th century, the evolution of the concept of comfort spawned the process of the mechanization of the building environment described by Siegfried Giedion (1970) and Reyner Banham (1994). This more and more bulky presence of the mechanical services was going hand in hand with an architectural research on the «spatial continuum» which was to correspond to a «thermal continuum» (Prieto, 2016, p. 63). However, the two needs of continuity engendered two different languages: one mechanical, consisting of pipes, cabins and ductworks, the other consisting of the architectural elements, such as walls, pillars, ceilings and windows. In order to avoid any figurative conflict, it is inevitable that the architectural language should face with the 'language of installations' (Cocito and Frateili, 1991). Can this dual conflicting language turn to a possibility for Modern Architecture innovation? Finally, if the coexistence between architectural and 'mechanical vocabulary' is possible, how this aspect can influence the evolution of architectural language?

On the basis of these questions, the paper suggests a reflection on the emblematic cases in which one can identify the milestone of Modern architectural language innovation and evolution, in the equipment problem. The aim is to help demonstrate that the Modern architecture provided for best practices examples in which air conditioning, lighting and drain systems are not additional elements 'a posteriori' with respect to the architectural design, but they play a substantial role in the technical-figurative innovation. In order to investigate this matter more thoroughly, the paper would assess the impact of mechanical services in the relationship between structure and envelope (Fanelli and Gargiani, 1999). As the use of the framework becomes more and more diffuse in the structural layout of modern building, the complexity of the envelope grows at the same pace (Beccu and Paris, 2009). In this context, the idea of well-tempered environment plays a fundamental role in those cases in which the architect chooses to turn the obstacle of the installations to a creative component, favouring a correlation to the definition of the envelope or the structure.

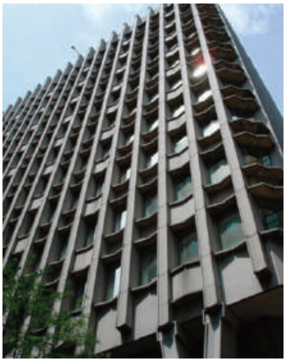
Focusing on the relationship between structure and well-tempered facilities, the paper investigates more deeply the type of the reinforced concrete single-storey factory in Italy, during the period between Fifties and Seventies of the 20th century. It can be established that this type is precisely that which shows the most interesting innovations in the relationship between the structure and mechanical services. Indeed, the architects and engineers focus on the design of tectonic joint beam/pillar that becomes an integrated device that consider the apparatus for the comfort in the factory as a «technical writing» (Graf and Marino, 2016, p. 10) which favours the expressiveness of the construction. Therefore, the paper will focus on a comparison between two authors' design methodologies – Marco Zanuso and Aldo Favini – which explore the issue of the essay through several built works. Hence, one will propose critic drawings which analyse the process of definition of the architectural order, shaped by utensil structural elements of the framework.

The language of air-conditioning system as determiner of the envelope in the framework structures – For focusing on the proposed issue, it is necessary to point out the modalities through which mechanical services turns into deliveries of the building. Welcoming the belonging of installations to the well-tempered devices of the building, it is possible to cover two types: active deliveries and passive barriers (Banham, 1994). Active deliveries are the apparatus of mechanical services that produce environmental benefits through a direct impact (ventilation system, artificial lightning, air conditioning etc.). For passive barriers, one intends any architectural element that controls the environmental shifts between indoors and outdoors, in order to preserve or, on the contrary, facilitate the modification of the inner thermal condition (solar shading systems, opening and closure systems etc.). From the beginning of 20th century, the active deliveries raised two groups of problems for the designer: «the first group regarded changes to the building apparatus – especially the research for a space to arrange mechanical services and the necessary modifications to the construction.

The second group regarded the constructional modifications made easier by the installation of the new deliveries, especially the freedom to do not yet adapt the construction in order to provide to environmental qualities» (Banham, 1995, p. 67). Whereas, on one hand the presence of active deliveries raised new spatial integration needs, on the other hand it offered new possibilities for shaping architecture and structural language. The inner comfort of the building, that at the end of the 19th century worked with a passive barrier effect, thanks to the thermic inertia generated by the thickness of the perimetral walls, have been replaced by the transparency and thinness of the Modern structure, ensured by the active deliveries.

The most important consequence of this phenomenon was the separation between structure and envelope (Frampton, 1999). The control of the mechanical services played a fundamental role to determine this relationship, because it became an unavoidable aspect of the Modern building. In this sense, it seems to be interesting refer to the question of the control of air conditioning within the design of the façade in the multi-storey buildings. Indeed, this issue affected especially office and store buildings which provided for a diffuse inner compartmentalization, thus a widespread indoor air quality.

The need to equip this kind of building with a centralized system of ventilation, created a network of ducts, ramifying from a central cabin and branching the whole building. Starting from Fifties, one of the most common air-conditioning system was the dual duct that combined cooling and heating tubes: the first one was linked to a chilled water circuit, the second one to a heated water circuit. The ‘dual duct’ system has been used in two iconic Modern buildings as the Rinascente (1957) designed by Albini & Helg (Fig. 1), and the Blue Cross and Blue Shield Building (1956-60) by Paul Rudolph (Marino, 2016; Fig. 2). In both cases the ventilation system was «octopus-shaped, […] coming from the top and encircles the whole building» (Rohan, 2007, p. 100). The air conditioner mechanicals were placed on the rooftop and the ductworks branches to the perimeter, engendering a visual interference with the grammar of the façade. However, both designers saw the limitation of air-conditioning system for the façade expressiveness as an opportunity to discover new Modern



Figg. 1, 2 - Franco Albini, La Rinascente*, Roma 1956, Paul Rudolph,* Blue Cross and Blue Shield buildings*, Boston 1956 (credits: www.rchidiap.com; Sean Khorsandi).*

architectural languages, intrinsic to the 'accidentalità tecnica' (Marino, 2016).

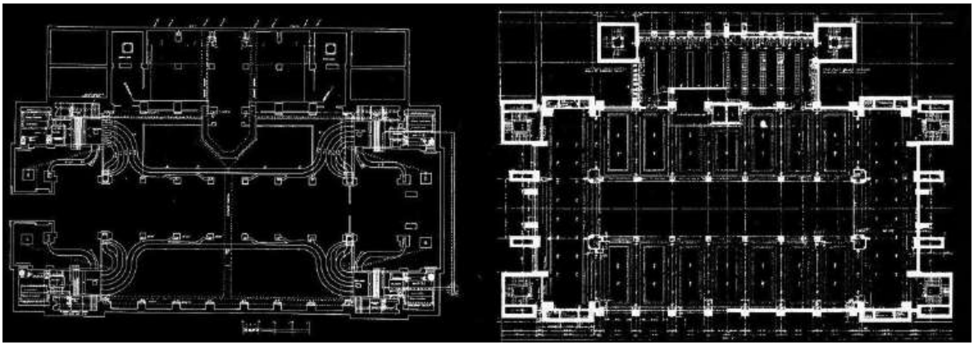
The Albini & Helg's design strategy identified the cladding system of the steel framework as the element to put in representation the 'services language'. Working on the thickness of the envelope, Albini designed wrinkled prefabricated panels which hided the ductworks and pipes within them. As Banham said, «the finally crimped envelopes are thus a dual role: passive barrier against exterior climate conditions, and active delivery vehicle for indoor environmental comfort» (Banham, 1995, p. 256). Paul Rudolph created through precast prefabricated panels a 'dummy exoskeleton' which replicates largely the grammar of the structure in order to put the hot and cold air ducts in the space in between, minimally they added secondary elements to the façade as the attenuation boxes under the windows and the mullions that housed the return air duct. Through these elements «On each floor, hot and cold air mixed in an attenuation box located between the columns and was then blown inside. A third non-structural pier, which was not backed by a steel I-beam, contained the air-return duct that sucked used air back up to the thirteenth-floor mechanicals» (Rohan, 2007, p. 99).

Whereas this first approach showed the possibility of mechanical service to create a façade grammar in a structural framework, the second approach adopted the strategy to consider the installations as spatial elements of the design. Thus, in this second approach, the mechanical services were no longer considered as linear elements, rather as three-dimensional and volumetric places. As Banham said, the idea of mechanical services as servant spaces stem from the traditional concept of chimney and water ducts as «intervention in plan and in section view of the building» (Banham, 1995, p. 13).

For understanding how developed in Modern history this traditional spatial idea of mechanical services, it is possible to refer to two authors: Frank Loyd Wright and Louis

I. Kahn. In the Larkin Building (1902-05; Fig. 3) Wright wrapped a brick wall envelop to a steel framework in order to impede to the surrounding factories emissions to reach the office building workers. For the same reason, the architect introduced in the corner of the building four ventilation towers (Fig. 4): sucking outdoor air from the top, the system makes it flow to the basement; here the air was cleaned and pumped in the building through the hollow pillars of the central hall. Hence, in this case, the question of the mechanical services turned in to a monumental effect of the building, that increases in massiveness through its envelope.

This possibility of the ‘pochè’ was developed by Louis Kahn putting the perspective of the relationship between installations and envelope to a new dualism between installations and structure. Whereas the structure engenders the space, the mechanical services assists in determining the shape of the structure. The case in point are the tetrahedral-shaped ceiling of the Yale Art gallery (1951-53), in which the structural cavities were needed to hold lightning and air-conditioning system (Fanelli and Gargiani, 1999, p. 594); the brick shaft towers of Richards laboratories (1957-64) that, similarly to Larkin building, hold the outdoor air ducts. The most interesting solution for the issue of this research is the preliminary proposal for the Salk Institute laboratories (1959-69). In this project the form of the structure corresponds to the Arcaismo Tecnologico of the



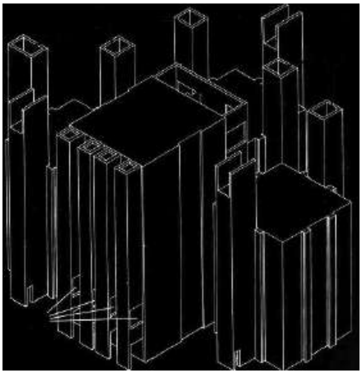


Fig. 3 - Frank Loyd Wright, Larkin Building plan, Buffalo 1902-1905 *(credit: by the author, based on a picture published on Fanelli and Gargiani, 1999).*

Fig. 4 - Louis Kahn, Ventilation towers layout in Richards Laboratories*, Philadelphia 1965 (credit: by the author, based on a picture published on Banham, 1995).*

Richards laboratories towers[1]. Here, the beams became «pipe spaces» that «carry the mechanical services in an underbelly designed for easy servicing and linear distribution» (Leslie, 2012, p. 783). Therefore, Kahn transformed the relationship mechanical services-envelope-structure in the constructive logic of the framework. Even if in the Albini and Rudolph's buildings this relationship became a stratified envelope that encircled the exoskeleton, in the case of Kahn the mechanical services were synthetically absorbed by the 'system-structure'. This system of «hollow stones» corresponds to a «whole range of essential bodies to constitute the shelter and making the space habitable» (Fanelli and Gargiani, 1999, p. 436). Both these trajectories may be established as milestones for some Italian built works.

The framework in the reinforced concrete single-storey factories as scope of trial. The 'system-structure' in Italy between 1950 and 1975 – After the second post-war, in Italy, the industrialisation of building radically renovated the places of production. The coming of prefabrication and prestress in reinforced concrete technology transformed the idea of framework which, in the specific field of single-storey factories, allowed to architects and engineers new degrees of freedom and, at the same time, this innovation invited them to rediscover the classical meaning of 'trabeated' structure. The monolithic continuity typical of the Maillart and Hennebique's reinforced concrete structures was replaced by the discontinuity of prefabricated components which generated an 'atomisation' of the typical reinforced concrete framework and created a conceptual proximity with steel framework solutions. Thus, in the manufacturing of foundations, pillars, beams and decks, the architects researched an expressiveness of each one element[2]. This new kind of framework had to fulfil the request of the programme for a bulky equipment service, which must ensure to the worker the necessary comfort for the production.

These aspects quickly showed that «a building made by components is precisely at ease in the field of installations, because of favourable requirements, commencing with the industrial production of structural elements» (Cocito and Frateili, 1991, p. 87). As demonstrated by Albini and Rudolph, the possibility to predetermine the design of structural elements, offered by the prefabrication, allowed to optimise the interaction with structural layout and services layout. Thus, the 'system-structure' proposed by Kahn, which brought static and mechanical components in a unique shape, can be applied to the reinforced concrete single-storey factory. This implies that «the structure was not shaped with abstract criteria, without first being carry to a research on mediated combination with installation needs» (Cocito and Frateili, 1991, p. 90). The key architectural tool of this process is the bay, through which the second post-war Italian designers created as a question-answer mechanism (Gubler, 1985) the structural form according to the service apparatus. Indeed, the bay embodied a flexible and repeatable spatial-structural cell, which established a system of relationship between architectural components (namely the structural joint) and the control of the inner environmental comfort. In this way, the structure hid a network of canal-

Fig. 5 - Marco Zanuso, Comparison between the originary shape of the beam (with the air conditioning cabin) and the current state of conservation which reveals the structural hollow, Necchi Factory *in Pavia, 1965 on the left and 2019 on the right (credit: F. Ferrarese, 2019).*

isations, acquiring the typical proportions of the structural classicism: «solid in appearance but hollow in construction» (Graf and Marino, 2016, p. 30).

Each bay, as a 'spatial genome', was shaped as an environmental apparatus which had to equip the building with passive barriers (water-draining system, natural lighting system) and active deliveries (air conditioning system, artificial lighting system) for every unit of space. However, the dimensions and the key role, which these deliveries play in a general factory program, is such that each structural element was no longer simply the container of ductworks, skylights or channels, but the trabeated structure was shaped complying with a complex installation requirement. Thus, «the pipes enhanced trilithic horizontal and vertical elements that does not confine itself to support bending forces but brings the lifeblood of the architecture. The 'impianto-struttura' results in a new order» (De Giorgi, 1999, p. 19).

Marco Zanuso and Aldo Favini. The Utensil-structure in the Necchi and Kodak factory (1965-75) – Between Sixties and Seventies, Marco Zanuso and Aldo Favini proposed the most relevant experiences on the idea of system-structure, working on a new expressive architectural order related to the prefabricated reinforced concrete framework. The comparison between the two authors is the more interesting because they analysed this issue from different points of view: Zanuso was one of the most prolific architects of the second post-war Italy and Favini was a leading figure of Italian school of engineering, belonging to the 'concezione strutturale'.[3]

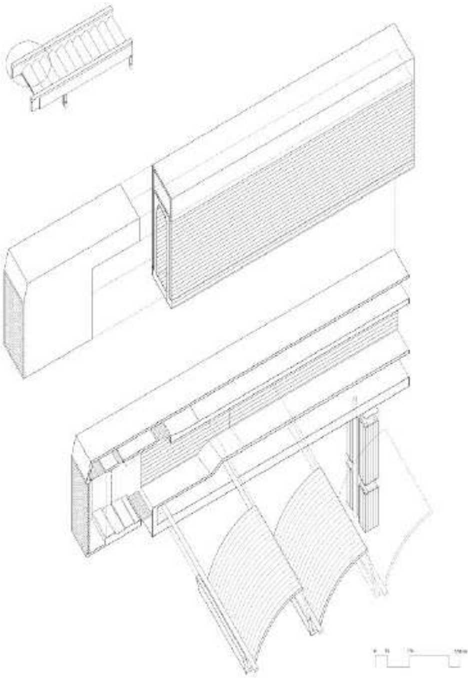
Marco Zanuso, as Kenneth Frampton underlined, was the Italian 'designer to industry' (Frampton, 1999). Since the early Fifties, he developed a design method for the factory, called 'progettazione a posteriori' (Guiducci, 1959), which created the Adriano Olivetti's confidence. According to Zanuso, in architecture the form is a result of «adherence to technical reality», within « the structure becomes architectural expression to the extent that it was conceived with the whole building […]. It exists an object, a form that drives […] from the definition of the joint […], to the distribution of a mechanical services» (Zanuso and Vittoria, 2013, p. 178). Roberta Grignolo affirmed that, «in his single-storey factories, the structure had not only a load-bearing role, but became in each case something more: a support for the lighting systems, a device for water draining and air conditioning systems, or a vehicle for the energy transport. In this way the Zanuso's sequence of projects can be read as a progressive complexification of the pillar/beam system, which incorporates several facilities» (Grignolo, 2013, p. 39).

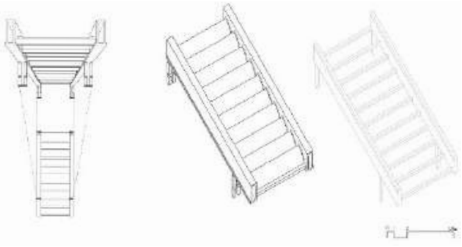
In this way, we would consider the Zanuso's gradual process of innovation: starting from Cedis factory in Palermo (1956) to the Olivetti's prototypes tested in the Scarmagno, Crema and Marcianise production plant (1967-72). In this process, the beam assumed the role of «genetic code of the building» (Faroldi, 2007, p. 34), providing for the external water draining and inner reflection of natural sunlight (in the Cedis Factory). In the Olivetti factory in Merlo the same structural element became a duct-beam, incorporating in the hollow section the pipes for air conditioning system. In Scarmagno, Crema and Marcianise, the primary and secondary beams were shaped on the basis of the grid of the ventilation system, working in a multidirectional way. However, the Zanuso's radical innovation consisted of transforming each beam in an autonomous air conditioning system. This approach would mean that the centralised ventilation system, as one saw in Albini and Rudolph work, was replaced by the introduction of local conditioner for each beam of the structural layout. From the perspective of structural language, this strategical choice generated, an interesting consequence: the beams were no longer simple containers of the installation's ductworks, as the Kahn's principle of integration between systems and structure, but Zanuso disclosed their utensil role exposing the crankcase of the ventilation box. This device gave to consider mechanical service as the ornament of the architectural language. The outcome was a calibrated balance between unveiling and concealment of the mechanical facilities, interchanging the principle of integration with juxtaposition between structure and systems.

This operational concept reached an interesting conclusion in the Necchi factory in Pavia (1965): the considerable dimensions of the structural bay, stood 7x28 meters (Fig. 5). The bay consisted of two cyclopic duct-beams (m 3,80 high x m 83,60 long), ten vaulted sheds, four pillars hinged both on the centreline and on the top. The programme requested by the customer was specifically complex: «The structure needed to be efficient for the placement of air conditioning system, possibly with differentiated treatment and it must provide for the distribution of all complex equipment such as, cold and hot water, lubricants, acetylene, electric energy, vapours» (Zanuso, 1965, p. 103; Fig. 6). This explains that «the roof framework consisted of great hollow rectangular-shape beams, capable to house inside the ductworks for water draining system, the pipes for air conditioning system and on the head, the cabins of ventilation» (Zanuso, 1965, p. 103).

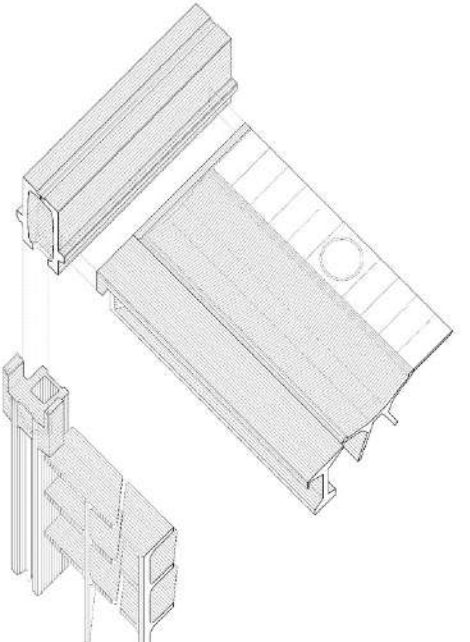
With respect to the design for Olivetti factory in Merlo praised by Banham, the clip-on solution of the ventilation nozzle was transformed in a shell which enveloped the outline of the beam, creating a unique continuous form (Fig. 7). The presence of the air conditioning cabin within the horizontal structural element, was exposed on the façade through the grill of the nozzle, as an ornament of the beam head. In addition to the reasons set out above, the Zanuso's design choice moved in the direction to create a «technological dolmen» (Prina, 2007, p. 70), giving a cyclopic outcome of the trabeated structure, amplified by the hidden installations.

Aldo Favini – Gustavo Colonnetti's collaborator at Lausanne Polytechnique during the second war Italian emigration in Switzerland – is considered as one of the most important interpreters of the prefabrication and prestress technique in the reinforced concrete system. In the context of the architecture for industry, the Italian engineer focused on the research of concrete prefabricated components for elementary structural layouts, in which «the research of an essential design» was due to the «simplicity of execution and set up» (Molina, 2004, p. 11). Favini started his career as designer to single-storey factories and warehouses in the mid-Fifties. Through the collaboration with Carlo Rusconi Clerici, the engineer's structural alphabet developed in the direction to resolve the issue of mechanical





Figg. 6, 7 - Marco Zanuso, Necchi Factory, *Pavia 1965: Graphic analysis of the prototype; Section of the Beam (credits: interpretative drawings by the author based on some microfilm accessible in FMZ – Archivio del Moderno, dell'Accademia di Mendrisio, 2019).*



Figg. 8, 9 - Aldo Favini, Perugina Factory*, Perugia 1962, and Aldo Favini with Gianluigi Ghò,* Kodak Factor, *Marcianise 1972-75: Graphic analysis of the prototypes (credits: interpretative drawings by the author based on the panels available in FAF – Archivi storici del Politecnico di Milano, 2019).*

deliveries. Indeed, Rusconi Clerici built up considerable experience in the management of the installation in architecture, through the experience collected during the design of the Pirellone (1955-60) and the Siemens headquarters in Milan (1955-57).

The long cooperation between the two engineers started from the late Fifties in the occasion of the Perugina factory commission in Perugia (1961) and the FIMI factory in Rescaldina (1961). These buildings had the same typical plan and structural layout: the main roof framework consisted of prestressed box-beams, 2.40 meters in height, the secondary framework consisted of sheds shaped as parabolic-vaulted, already experienced in Dormelletto (1950), four pillars V-shaped, hinged on the foundations (Barazzetta, 2016). From the analysis of the Perugina factory's drawings, kept in the Polytechnique of Milan historical archives, one can recognise the form of a typical structural element in the work of Favini, such as the duct-beam. On the lines of what was done by Kahn and Zanuso, the beam became a spatial structure, in which the hollow section contained in the upper part the ducts of air conditioning system, in the lower part the water draining system.

The structural gigantism of this element not only created a servant space for mechanical services, but it implied that the beam-duct became an accessible technical plan. This invisible space housed on the inner side the air conditioning cabin that encircled all the spatial unit through the ductworks placed in the U-shaped beams of the sheds. These two frameworks, as hollow stones, were carved out in the upper part, in order to place the ventilation nozzles which ensured to the work a thermal comfort; in the lower part the rain-ducts crossed the secondary roof framework and engaged in the vertical strut contained by pillars. Thus, in this case, the issue of installations overturned the relationship between structural thickness and utensil thickness of the components (Fig. 8), generating, in the field of trabeated structure, a new expressive architectural order, based on archaic proportional dimensions. In the Max Market factory (1965), the water draining system became itself a structural system, gaining the role of tectonic mechanism. Indeed, the strut of the rain-duct, incorporated in the pillar became the tenon of the joint between beams and supports and ensuring the structural continuity and stiffness.

In this way, Favini initiated a process of tectonic assembly production, through a gradual refinement of design solution, leading to an interesting conclusion embodied by the commission of the Kodak factory in Marcianise, designed with the architect Gianluigi Ghò (1972-75). In the report of the project Favini declared that the form of each element of the bay came from the need to employ for static purpose the contours coming out from technological systems (ventilation, water drainage etc.); these equipment are strictly demanding, due to specific internal needs » (Biraghi, 1976, p. 653). The plan view of the pillar was asymmetrical H-shaped, in order to «on the external side, placing the drainpipe, incorporated in the capital on the top of the pillar […]. In the inner side, the pillar housed the air conditioning ductwork»[4]. The main beams were double C shaped, according to the reinforced concrete box-beam typology. This shape was due to the provision in the hollow part of the beam (1,50 x 1,20 centimetres), of an «[…] hidden pipe of air conditioning with entrance and exit holes on the lower face of the beam» (Fig. 9).

These ducts were linked, as the same technological octupus-shaped system described by Rudolph, to the air conditioning cabin placed in a upper volume in the center of the building. The 'copponi' (this term was used by Favini to indicate the secondary roof framework elements, supported by the main beams) were X-shaped, reflecting the static necessity to resolve the bending moment already experienced in the Church of Baranzate. Furthermore, this kind of section allows to optimize the inner flow of the air and turned to a rectangular shaped section near the support base, forming the lateral partition of the eaves drain pipes. The boarder beams were double T-shaped, in order to avoid the dripping on the façade; through a concrete lift which consent the continuity of water draining system. The envelope system worked as passive barrier in order to shade the building from the hard sun of the South of Italy. It consisted of five brise-soleil, prefabricated on-site, consisted of a strut with fixed size and three shelfs which changed grade on the base of their solar exposition.

The tectonic trajectory of the Utensil-structure – In conclusion, it is possible establish methodological consonances, in the restricted field of single-storey factory, between Zanuso and Favini. For the two authors, the structure, as spatial system which responds to all the needs of the human habitat, constituted a common field of research. However, the Zanuso and Favini's hollow architectural orders gain a new perspective, implementing the formal research with the adherence to the technical reality in which they work. In this sense, the issue of mechanical system is not separable from the structural concept of the architectural organism, but rather it is both part of the reinforced concrete structural language and the topological definition of the elements of the bay. In other words, the two authors designed utensil-structures: «Whereas the scientific research abstracts from particulars and investigates the rule which dominates and gather them, the technique, on the contrary, deals with natural elements in any of their parts, in order to achieving a synthesis of the purposed scope. Thus, the builder recognises in each stone of his building an individual, identified by a name with reference to the function. At the same time, the technician turns his attention to the purpose: the utensil must satisfy all the needs and processes of use. Thus, one looks beyond the construction (not the utensil in itself but the work it must to do)» (Dessauer, 1933, p. 17).

This kind of technical building can reach to architectural expressiveness, if the designer recognises its 'utensil nature' that resolve the issue of installations avoiding the genericity of the prefabrication. In the displayed designs, the structural elements, preserving their topological and tectonic relationships, turned to technical utensils, capable to fulfil a static, figurative and technological solution in a unique shape. The bay, as the control device of the element's relationships, become a mechanism that responds distinctively to the multiplicity of the architectural demand. In this regard, there is a still true tectonic trajectory for the technological innovation.

NOTES

1) The expression Arcaismo Tecnologico was coined by the section ‘selearchitettura’ with reference to Richards laboratories. See *L’architettura: cronache e storia*, anno VI, n. 6 (1960), pp. 405-411.
2) Looking at the Angelo’s Mangiarotti industrial buildings, in the Sixties and Seventies, it is clear how the leit motif is embodied by the tectonic joint, made by the assembly principle. See: Graf and Albani, 2015.
3) The term indicated the renovation of the technical expressiveness, during the second post-war in Italy. See: Desideri et alii, 2012.
4) The description comes from the unpublished report of the project, written by Favini and kept in the Historical Archives of Polytechnic of Milan – Fondo A. Favini.

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LONDON CALLING
OFF-SITE BUILDING STRATEGIES FOR HOUSING DEMAND: THE UK CASE

Roberto Ruggiero [a]

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Abstract
Today, a strong re-proposal of building prefabrication is at the basis of the new housing policies that can be detected in main evolved industrial contexts. Off-Site is the word through which the theme of prefabrication seems to recur under new auspices. Among the Countries of the European continent more involved in this new challenge, Great Britain offers several insights, considering its consolidated culture in the field of urban development and its historically dynamic real estate market. Great Britain and its capital, in particular, represent an ideal point of view to understand the potentialities and the criticalities of this new building culture, in the UK explicitly supported by specific housing policies. Starting from the author consolidated interest for technological innovation applied to housing issues and coherently with the historical attention that the same author has over the years perpetrated for the British social, economic and productive context (considered as an advanced context), the paper critically illustrates an innovative housing program underway in the City of London (based on the application of Off-Site production principles), questioning about new prefab housing potentiality.

Keywords
off-site, made-factory, housing, production, innovation

The idea that in the main European Countries since the 1960s, building prefabrication would solve the problems connected with the housing emergency caused by the II world war first, and the industrial development later, has been a ‘dream’ that has rarely been reflected in reality. Often presented as an innovative way to create a new generation of high-quality housing and to solve quickly a large housing demand, the prefabricated systems generally failed their task. Actually, they allowed building, in the space of some decades, with relatively contained costs and high profits, a huge low-performance housing stock, generally unfit to satisfy inhabitants’ needs and their aspirations. Some Countries in particular, such as the UK and French, were the ‘driver’ of what we can now consider a ‘betrayed revolution’, in relation to some enthusiastic position spread in those years in many European political environments. In the UK, the Country on which this paper is mainly focused, Richard Crossman, Labour Minister for Housing and Local Government between 1964 and 1966, declaring his idea to ‘forge’ a new Britain in the ‘white heat of technology’, stated that «the new factory-built housing can be just as good as production-line cars […]. The only thing is to make sure they are done by good architects and well landscaped, that will get over any danger of monotony; the main thing is you standardize the production» (NLA Research Report, 2018, p. 5). Today we know that, in most cases, the result of this idea was a large stock of prefab housing made by gigantic, monotonous buildings and shoddy architectural figures, really far from local living cultures. The twentieth-century productive culture, based on the standardization of industrial components, produced, even in the best examples of innovative and 'illuminated' design, a large number of neighborhoods which became, after few years, a social, urban and technological emergency.[1]

Nevertheless, the 'idea' to combine the promise of an industrialized building with the dream of a popular mass-market for architecture «has exercised a magnetism over architectural culture» that continues still today (Smith and Quale, 2017, p. 77). This is also demonstrated by the recent Robin Hood Gardens controversy (Fig. 1), the querelle about the famous (cult object for many architects) residential complex designed in London by Alison and Peter Smithson in the late 1960s which, despite the tenacious opposition of a significant part of Anglo-Saxon (and not only) architectural culture, will soon be demolished[2]. In any case, in Europe the word 'prefabricated' has never recovered its bad reputation in public opinion. The failures of the 1960s building policies have been a huge setback that, still now, makes many people associate the prefab housing to an idea of bad quality and speculation.

A new technological scenario – In the last decade the technological scenario has changed. Referring to building production in advanced industrial contexts like Sweden, Netherlands, the UK and, outside the European continent, the USA and Japan (i.e. high-industrialized countries with a consolidated culture in building prefabrication), we can notice how the 'dream' of a high-quality prefab housing is now not far from becoming a reality. Unlike the 60s, when concrete was almost the only material available and the Henry Ford production system was the main reference model, today a greater variety of materials, structure, cladding and, above all, tools and production methodologies are available (Figg. 2, 3). This explains the birth of a new concept of prefabrication applied to Architecture, supported by digital technologies and capable of supplying high-quality products: efficient, sustainable, flexible, i.e. adequate to the current standards and, in the field of housing, to the users' expectations. If the first wave of building industrialization was dominated by a logic based on the repetition of a small number of different elements produced through mass production, the second wave of industrialization is coming, characterized by advanced IT technology and high-tech manufacturing processes.

This development is often named New Industrialization and both as a concept and as a production process, it derives from an advanced concept of industrial production,

Fig. 1 - Previous page. Robin Hood Gardens, *London (Alison and Peter Smithson, 1972).*

Fig. 2 - Factory production line.

Fig. 3 - Transport operation of a façade component, all factory-assembled.

supported by new computer technology and new business models. In particular, the widespread of Building Information Model (BIM) and the software connected to this approach matches perfectly with this new industrial production mindset. Indeed, working in BIM environment, it is possible to provide a complete, shared digital model of a project, down to the detail of every component. This not only enables much more comprehensive collaboration between different design and production operators but allows more efficient monitoring of information and workflows, according to the typical industrial process of production. As a consequence of the Digital Revolution, this New Industrialization is not only concerned with efficient production but also with establishing new organizational patterns and structures of collaboration between the many different actors engaged in construction. These changes are primarily based on technological, organizational and collaborative dimensions, not on architectural visions. Nevertheless, they do have a decisive impact on the way architecture is conceived.

Off-Site construction: prefab housing is back – To better understand this new ‘wave’ of prefab housing it is necessary to explore the multitude of terms today used to describe it. The terms vary between Countries as well as across industry, academic and policy domains, but generally the word Off-Site (followed by building or construction) can be considered the current translation of the original term Prefabricated. In particular, in the USA, the spectrum of applications where buildings, structures or parts are manufactured and assembled remote from the building site prior to installation in their final position is described as Off-Site Construction Techniques (OSCT). Differently, in the UK the expressions Off-Site Manufacturing (OSM) or Off-Site Construction (OSC) are used to refer to «the process of planning, designing, fabricating, transporting and assembling building elements for rapid site assembly to a greater degree of finish than in traditional piecemeal on-site construction» (Blismas and Wakefield, 2009, p. 72).

As seen, this change of name to describe prefabrication derives not only (but also) from a question of brand (in relation to the reluctance, in particular in European context, to use the term Prefabricated because of negative connotations resulting from postwar failures); it depends also on the new philosophy of intending buildings and, then, Architecture, as a manufacturing activity; a mindset due evidently to a new technological background. If ‘quantity’ was the driver of the first prefab construction, ‘quality’ seems to be the new password of Off-Site Construction, meaning for ‘quality’ not only the intrinsic quality of the final product, but also the process quality, i.e., between others, the speed of delivery, construction health and safety, energy in use, whole-life carbon footprint and reduced transport pollution. «Housing not only faster but better, to avoid to repeat the mistakes of the past», this is the new promise connected to Off-Site Construction.

Refusing the ‘one-size fits all’ approach, typical of the first age of mass prefabrication, and using the current technological ‘know-how’ based on the digitalization of design and production processes, the Off-Site approach, in many current experiences, has demonstrated to succeed in providing a new generation of housing, characterized by a huge range of different solutions and innovations that can be adapted to different conditions and requirements. In this way, housing can be conceived as a ‘tailor-made’ industrialized product, very close to other kinds of evolved industrial products like cars (Figg. 4-6). This second chance for prefab housing derives not only from the digital upgrade of design and production processes. It is also the answer to the construction industry to a new, large, housing demand, which involves today many countries and certainly most of Europe. To this market ‘pressure’, that in some areas of our continent is becoming a real emergency, generally, the building industry has not been able to reply, also because of structural weakness. In his report, entitled Modernise or Die, Mark Farmer, CEO of Cast Consultancy for the UK Construction Leadership Council, in 2016 used a medical analogy to define the British construction industry crisis, common to many Countries. In particular, Farmer stigmatized the motivations of the crisis indicat-

Figg. 4, 5 - Building site as ‘assembly’ place; Prefab housing module, just before to be ‘plugged’.

Fig. 6 - 18 Floors in Wood: Student Residence in Vancouver designed by Acton Ostry Architects and Schwarzach’s Hermann Kaufmann Architekten.

ing, among others, low productivity, fragmented leadership, lack of collaboration and shortage of investment in innovation. At the same time, he indicated in Modern Methods of Construction and, in particular, in Off-Site Construction, the best cure (Farmer, 2016).

The UK in the international context – Japan and Sweden have long been established as leaders in this field. Up to 90% of single-family homes in Sweden are 'factory-built', while available figures from Japan showed that the Off-Site manufacturing sector has in recent decades resulted in up to 160,000 properties per year or about 14 to 20% of the annual total. Other countries such as Germany and the Netherlands, which have been identified as having highly efficient traditional or 'craft-based' house-building industries, also have significant levels of Off-Site production. The USA and Australia sit alongside the UK as countries where manufacturing has been employed less frequently, generally to ten per cent or less of total housebuilding (Smith and Quale, 2017). In terms of the future global picture, a 2016 study forecast that worldwide demand for prefabricated housing would increase 2.7 per cent per year to 3.4 million units in 2019, with advances in overall housebuilding – as well as greater take-up of factory-made systems and components – likely to occur in the Asia/Pacific region, Africa and Middle East, and Central and South America[3]. In these regions, demand will likely increase for both low-cost, multioccupancy housing units and high-quality homes for more affluent residents, especially in urban areas with high population growth. China is also taking a lead in cutting-edge construction techniques: in 2015, Chinese company Broad Sustainable Building, for example, reportedly completed a 57-storey skyscraper housing 800 apartments alongside office space in just 19 days, using modular Off-Site construction methods (with more than 2,500 individual modules) to complete three-storey daily (Steinhardt and Manley 2016).

Among the Countries today more focused on this point there is certainly the UK, a strong-industrialized Country where a rooted culture of 'transformation' of the urban environment matches with a traditionally dynamic real estate market. The UK and its capital, in particular, represent an ideal and original field of observation to better understand the potentialities and the criticalities of this new culture of factory-made Architecture, in the UK explicitly supported by specific policies, that would be welcome in other countries like Italy, for example, where building production and new housing market are too feeble to create new development conditions. Over the last 20 years, the economic productivity in the UK has risen by over 30% and productivity in the manufacturing sector has grown by over 60%. In contrast, productivity in the construction sector has increased by just over 10% (WPI Economics Report, 2017, p. 6).

That's why the UK government has identified Modern Methods of Construction (MMC) and, in particular, Off-Site Construction as a key vision for meeting the UK housing needs, considering that the UK expresses today, in the main urban areas, a strong housing demand. In this regard, the recently published government White Paper (February 2017), reports how the UK needs 225,000-275,000 or even more homes to be built per year to keep up with population growth. This indicates as to what the Off-Site market size could be[4]. The White Paper summarizes in some points the new UK housing strategy. Some of those points seem to be particularly relevant to our focus: «an expanded and more flexible affordable homes program, for housing associations and local authorities, with £7.1bn of already announced funding; smaller building firms will be given assistance to expand, including support for Off-Site construction, where parts of homes are assembled in a factory». The White Paper was followed by the Construction Sector Deal announced by the Department of Business, Energy and Industrial Strategy (BEIS) in July 2018, in which the Government promised to invest £420 million in 'bytes and smart mortar construction' through the use of digital design, new manufacturing technologies and Off-Site manufacturing, as well as procurement. In this delicate phase of UK policy, where the Brexit makes impossible a serious forecast on the country future economic asset, the developing of Off-Site Building is, on many sides, seen also as a new export opportunity for the post-Brexit economy that would be possible just through the modernization of the sector in the Off-Site direction.

London policy – The lack of housing to accommodate a growing population is one of the most challenging issues that London is facing. To reach the Mayor's target of delivering more than 60,000 new homes in London each year – and indeed the UK Government's overall target of 300,000 nationally per year – radical new approaches in housebuilding are being sought to accelerate the pace of delivery, at a time when local Authorities have been demanding targets for completion. Factory-Made and Off-Site housing are now being explored and advocated by National and Mayoral policy as one of the key potential solutions to meeting acute housing demand, not only in London but across the UK (Mayor of London Report, 2018). The objective of this new policy is not only referred to the determination to satisfy so large housing demand. In London, the recent Grenfell Tower tragedy raised urgent questions about the safety and quality design of some existing buildings so as new building.

On this regard, the Mayor's London Housing Strategy is the reference document where the current London Administration sets out its vision for housing, declaring the aim to invest over £4.8bn of affordable housing up to 2022[5]. In this document Mayor explicitly promote the new technological opportunities linked to Off-Site construction, also informed by an influential report by the London Assembly[6]. This urged the Mayor to galvanize the sector by measures such as developing and adopting a Manufactured Housing Design Code that would generate a component standardization 'catalogue' approach that can then be configured in multiple combinations as part of a specific design response. The Mayor report explicitly refers to the need for supporting and promoting the modernisation of London's construction industry through more precision manufacturing of homes, but also «working with the housing industry to promote greater standardisation of precision-manufactured homes, […] negotiating a share of the Accelerated Construction Fund to be used flexibly in London to support the shift to more precision manufacturing of homes, […] making the shift to more precision manufacturing of homes a key priority for investment in London's skills system» (Mayor of London Report, 2018, p. 84).

After declaring his general strategy for London housing problem and adopting a clear position on behalf of Modern Method of Building, according to a Factory-Made and BIM approach, in April 2018 the Mayor commissioned Cast Consultancy (Real Estate & Construction Consultancy) and Bryden Wood (a multidisciplinary design group) a survey focused a digital toolkit with design principles and guidance to assist designers and clients in understanding where and how different Factory-Made e approaches can be applied. On those bases, London's built environment industries are now developing and delivering innovative and high-quality Factory-Made housing in a huge variety of contexts, forms and tenures, from individual houses on small sites to large-scale developments in major areas of opportunity (Figg. 7-10).

London experiences – Manufacturing processes are not only being applied to the construction of large-scale housing but are also disrupting the conventional market for individual detached, semi-detached and terraced homes, especially through customization and self-build. Companies are developing a 'vertically integrated' approach to design, manufacture and construction – often including the building or acquisition of factories – which therefore offers greater control over the production process from beginning to end, and makes the customization of individual homes more viable by offering different permutations around a core, repeatable manufactured element.

Many examples of innovative Off-Site individual homes in London could be done. Robinson Court[7], for example, consists of five houses from the townhouse range of the Urbane toolkit. Each house is manufactured in a day, and installed in a day on site. These homes follow a clear concept: 'customize the visible, standardize the invisible'. A flexible yet standardized toolkit of homes, developed with their manufacturer, enables all projects – from detached homes, terraces, townhouses to apartments – to surpass national policy and building regulations. All homes are created around a series of pre-designed and easily transportable components – these consist of pre-clad SIPS panels, roof and floor panels, to kitchens and bathrooms. In this example, speed, quality and cost of building, combined with the flexible yet standardized layouts, made up of relatively small components, produces an agile business model which can operate effectively on the full range of challenging London sites from the micro to macro sites. This could be considered a paradigmatic experience in London, imported, in its principles, from Urban Splash's Town House[8] concept based on the customer purchasing a home by space rather than the number of rooms. In the Town House the core element is a standardized shell with a stair, kitchen and bathroom pod, from which the purchaser can select sizes, living spaces and layouts, again in an enormous variety of possible arrangements to suit their needs and lifestyle. The complete home can be produced in the factory and delivered to site or the purchaser can choose to fit out the shell themselves. In other examples, at-

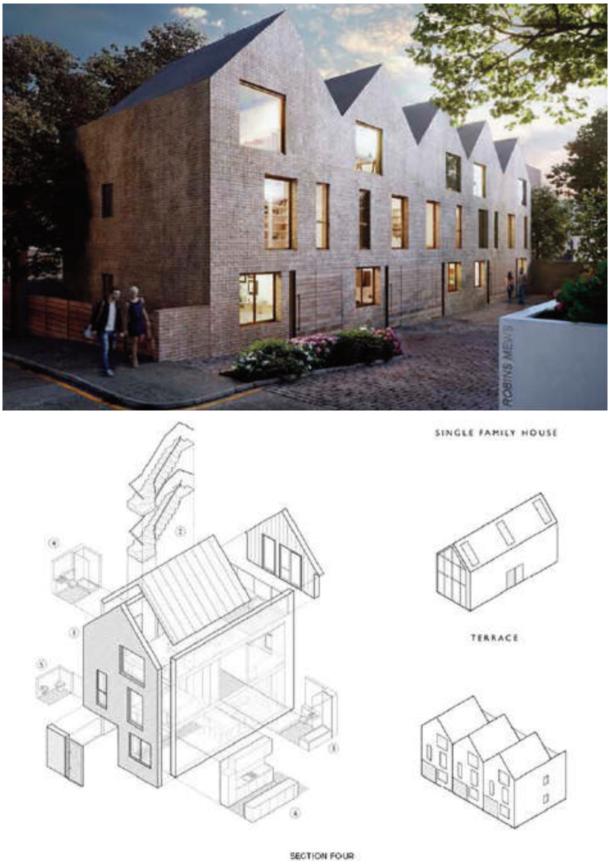

Fig. 7 - Town House *in new Islington, Manchester (Shedkm Architects, 2016).*

Fig. 8 - Robins Court *in London (Surface to Air Architects, 2019).*


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tention has been focused recently on how innovative manufactured homes can be suitable for constrained and infill sites. Cube Haus[9], is working to deliver high-quality customized CLT homes for small urban sites with simple material palettes manufactured in the UK; these will be commissioned and installed by the company or available as a self-build solution.

Being quicker to build, reducing noise, waste and pollution on-site, and offering flexibility and adaptability on site through the use of repeated elements, Off-Site housing has seen its biggest take-up to date in London for larger-scale apartment blocks, hotels and student accommodation. This has emerged alongside the rapid growth of the build-to-rent sector. Employing prefabricated modules and fit-out materials such as CLT for such developments enable design and construction to be completed, sometimes up to a year earlier than those using traditional methods, as in HTA's Apex House[10], a 29-storeys the tallest modular building in Europe. Faster completion times mean that residents can move in earlier and the building's owner or operator can make a return on investment more quickly. Yet the sophistication and customization of prefabricated systems and building elements available today mean that these high-rise developments, while often containing stacked units, can respond to local context and character effectively through distinctive massing, choice of materials and facades, quite unlike the uniform towers of the modernist era; just one recent example is the green terracotta-clad Mapleton Crescent designed by Metropolitan Works for Pocket Living. Using frames, panels and modules produced Off-Site can not only result in fewer deliveries but easier and quicker installation in constrained areas, making them especially appropriate for infill sites and the drive to support housing growth through the intensification and densification of places in and around London's town centers and transport hubs. In the same way, the lighter weight, adaptable configurations and need for minimal foundations mean that prefabricated systems can be especially suitable for opportunities to build over rail and tube lines and on top of existing structures. One of the most significant recent examples is Waugh Thistleton Architect's Dalston Works[11], the world's largest CLT building for affordable and private rent; constructed over the proposed Crossrail 2 line, it weighs only 20 per cent of a similar structure in concrete.

Factory-Made housing can provide innovative and high-quality temporary as well as permanent solutions to urgent housing need in areas undergoing long-term regeneration and/or for brownfield sites. The Y:Cube project[12] designed by Rogers Stirk Harbour + Partners for YMCA London South West in Mitcham, completed in 2015, is a pioneering example of affordable housing comprising self-contained factory-made units with services already incorporated, that can be taken down and reconstructed in other locations, and to which additional units could be added. Y:Cube Housing is a modular system

Figg. 9, 10 - Previous page. *Prefab housing 3D module assembly;* Ladywell *in Lewisham, London (Rogers Stirk Harbour + Partners, 2016).*

using volumetric technology that enables the factory-made units to stack easily on top and/or alongside each other, making it completely adaptable to the size and space available and therefore perfect for tight urban sites, creating semi-permanent communities. It is not designed to provide long term accommodation, but to act as a transition between temporary accommodation and market housing.

Conclusions – Using Off-Site methods primarily to design and build any type of new home on any scale requires a complete rethink of established attitudes to commissioning, procurement, finance, design and construction. Off-Site building put in crisis the conventional construction industry and represent an opportunity to explore new and flexible building typologies adapted to living and working in the 21st century, and to take full advantage of innovations such as digital planning to make decision-making quicker and more agile. That is what is now experienced in some advanced Countries with a strong industrial production tradition. In this context, the City of London is an exceptional case-study, where the speed and the variety of the urban, social and technological processes is pushing innovation in building towards a new and unexplored target. London and other experiences show as, today, Off-Site Construction methods come with a wide range of potentially large productivity, economic, social and environmental benefits. Between its current key-benefit, we can mention some main questions that emerged clearly from the example previously showed and from a larger analysis of current London experiences.

Speed and Reliability of Delivery. It has been estimated that Off-Site housing can be built 30% more quickly with 25% lower costs. Normally, on-site methods are impacted significantly by the weather, site conditions and access conditions (Oliveira et alii, 2018).

Reduced Costs. Although it is a controversial point, some observers state that the increase in quality in building deriving from off-site construction methods implies a reduction in building costs (linked to the simplification of construction phases) and, above all, in the maintenance (linked to the increased level of quality of the buildings). Off-Site housing (especially for high rise social housing) could be more expensive than traditional in-situ construction. Although, some observers found that it could achieve lower overall costs by incorporating the construction time reduction because of lower material and labour cost in the place of production (Jaillon et alii 2009).

Improved and More Consistent Quality. These benefits typically arise from the fact that the factory environment facilitates the use of tighter controls and more consistent and standardized processes. Vastly improved materials and quality control within the factory can exponentially reduce variation and potential defects, as well as provide quality assurance and rigorous testing on aspects such as acoustic and fire performance, durability and structural resilience. As well as the obvious benefits of improved quality, this drastically reduces the need (and associated costs) of re-design and re-work.

Improved Safety and Workforce Satisfaction. Off-Site Construction has the potential to significantly reduce the risk of accidents and ill health. The HSE[13] list a range of potential advantages, including that it provides a controlled, clean and warm environment, uses production line techniques and standards, reduces the need to work at height or below ground and reduces exposure to UV rays.

Reduced Environmental Impact. The principal new force bearing on construction is the climate crisis. Improved performance and quality certainly lead to reduced energy costs and waste. Furthermore, by reducing traffic flows to and from the construction site, there are significant benefits in terms of congestion and, by implication pollution in the local area. Recent research based on case-studies has suggested that projects using Off-Site construction can deliver a reduction of between 20% and 60% in metric tons of CO_2 associated with project transport. Likewise, the energy use associated with the completed assets can also be lower. This is a result of the fact that Off-Site construction is generally associated with higher and more consistent building quality, for example, leading to improved air-tightness. Estimates suggest these savings could be as high as 25% over the asset life.

Flexibility and Customization. The variety of systems and materials in use means that there is a solution for almost every site and scale of project, and the interchangeability of many components can allow a greater diversity of form and typology. Modular constructions especially can be assembled and de-constructed for relocation and reuse. This focus has been successfully employed both from the market and from some advanced research. As an example, in the first case, the urban developer Urban Splash in Manchester (UK) gives consumers different options through selected combinations, with a focus on space instead of rooms. Rather than selling homes on the number of bedrooms, as is usually done, Urban Splash idea is to encourage the customer to work out how much space they want and then how they want to use it to suit their family circumstance, their lifestyle and their budget. This gives our customers the ability to curate their new homes to suit how they actually want to live. With regard of research experiences, at the Advanced Manufacturing Research Centre at the University of Sheffield, pick and place robots can assemble a stud wall in one operation, and with changes in automated tools, they can produce many design variants with flexible fixturing.

Offering a really flexible and adaptable product to different needs is probably the more attractive result of this new kind of prefabrication. It also can allow Off-Site Construction to better compete in the housing market. In this way, it is possible to imagine a real tailor-made housing stock but at affordable prices. This new concept can be defined of course as ‘standardization’, but with controlled and researched variations (options!) in relation to client requirements or aspirations for their housing units. As final result of this essay – that however represents the first outcome of a research path undertaken by the author in the field of innovative housing processes in Europe, with particular focus on the UK – there are two questions involving the figure of Architect that is here considered strategic and that deserve to be developed in the research prosecution.

The reported positive consequence of Off-Site method needs of a new design and building approach that not only concerns, as already said, digital technologies and design tools, but also the operators of the construction (modifying their conventional roles) and the logistics of the building site. Where traditional construction is characterized by waves of trades passing over the site in alternating sequence, in the new model the workflow foresees the contemporary development of the different construction and design phases. In this scheme, the specialized workers (electricians, plumbers, cabinet makers, wall finishers, ironworkers) and, crucially, the architects and engineers all collaborate side-by-side, sharing information on a single digital model, learning from each other in real-time. About the crisis of the traditional role of the architect in the professional market, considering buildings as an industrial advanced product, it is also possible to imagine a new and more central role of the architect in this process. If, for architects, the role of 'shape creator' seems to be relinquished, Off-Site Construction defines a new process where the architect should integrate his traditional expertise with new skills, particularly in terms of ability to deal with complexity and industrial dynamics, to initiate open processes and to create a characterful, strong architecture on industry's terms. In this scheme, 'design' and 'management' should be the new pillars of architects' expertise.

NOTES

1) In the UK, when the failure of the 'prefab way to housing' had already become explicit, the 1968 collapse of Ronan Point gave the definitive 'coup de grace' to the idea that prefabrication could have been the solution to housing problems. A 22-storey tower in east London felt down killing 4 people and injuring 17. This tragedy dealt a deep blow to public confidence in prefab house and has profoundly shaped perceptions which endure to this day.

2) The interest of architectural culture for prefabrication has its roots also in a previous and noble history which goes from the first half of XX Century pioneering experiences (Gropius, Mies, Le Corbusier, to mention just a few), to the late and heterogeneous experiences of Buckminster Fuller, Jean Prouvé, Konrad Wachsmann, Charles and Ray Eames, Paul Rudolph, Moshe Safdie, and Metobolists in Japan (always just to mention a few). Those and many others explored – sometimes in provocative form, if not always in method – the implications of prefabrication and its corollary, i.e. modularity, in the construction of housing.

3) For more details, see Global Wood Markets. Info on the website: https://www.globalwoodmarketsinfo.com/prefabricated-global-demand/ [Accessed 18 January 2019].

4) One of the slogans of the White Paper is: «planning for the right homes in the right places». This strategic document also reports that «where communities have planned for new homes, we want to ensure those plans are implemented to the timescales expected […]. As of July 2016, there were 684,000 homes with detailed planning permission granted on sites which had not yet been completed. Of those building has started on just 349,000 homes».

5) For more details, cfr.: London Assembly Report, (2016), *Designed, sealed, delivered: the contribution of offsite manufactured homes to solving London's housing crisis*. [Online] Available at: https://www.london.gov.uk/sites/default/files/london_assembly_osm_report_0817.pdf [Accessed 17 January 2019].

6) This vision underpins the five priorities of the Mayor's London Housing Strategy: building homes

for Londoners; delivering genuinely affordable homes; high-quality homes and inclusive neighborhoods; a fairer deal for private renters and leaseholders; tackling homelessness and helping rough sleepers.
7) The building is about to be completed with a cost of 150 pounds per sq ft. Address: 85 Kings Avenue, Clapham, LB Lambeth, London, SW4.
8) Town house was completed in 2016 with a cost of 1,000 pounds per sqm. It is allocated in Manchester, new Islington, M4.
9) Cube house is in London, Forest gate, LB Newham, E7. It will be completed in June 2019.
10) Apex house has been completed on August 2017 with a total cost of 46 million of pounds per 16,600 sqm. It is in Fulton Road, Wembley, LB Brent, London, HA9.
11) Dalston Works consist of 121 new affordable homes alongside 3,500 sqm of commercial spaces. It has been completed on October 2017 and is situated in Dalston Lane, LB Hackney, London EB.
12) The Y:Cube units are 26 sqm one-bed studios, for single occupancy, that arrive on site as self-contained units. Y:cube Mitcham is the first Y:Cube development, made up of 36-units and the first residents moved into their homes in September 2015.
13) The Health and Safety Executive (HSE) is Britain's national regulator for workplace health and safety. It prevents work-related death, injury and ill health. HSE is an executive non-departmental public body, sponsored by the Department for Work and Pensions.

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CONNECTION MAKING
ANALOGUE-DIGITAL SYNAPSIS BETWEEN FABRICATION HUBS

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Abstract
The paper intends to apply the emerging theories on network science to the production chain of contemporary society, hyper-globalized and hyperconnected, to provide an alternative point of view aimed at the multilevel development of a given territory/context. The subject of discussion will be the Fab Labs, specifically those belonging to the Fab Charter, framing them not only as places of digital fabrication, experimentation and research, but, above all, as nodes of a network that in recent years has expanded to connect realities geographically very far from each other. With the analysis of case-studies we will investigate the dimension and importance of planning and designing these systemic processes to lead to the onset of an organizational culture oriented to 'sensemaking' and with the aim of optimizing collaborative processes of the Fab Lab network, demonstrating the social value of 'glocal' production.

Keywords
fablab, network, hub, amplification, glocalization

Fabfoundation.org describes the Fab Lab network as such: «The Fab Lab Network is an open, creative community of fabricators, artists, scientists, engineers, educators, students, amateurs, professionals, of all ages located in more than 78 countries in approximately 1,000 Fab Labs. From community-based labs to advanced research centers, Fab Labs share the goal of democratizing access to the tools for technical invention» (fabfoundation.org, 2019). These places of digital fabrication, experimentation and research are considered in this paper as nodes of a network that in recent years has expanded to connect realities that are geographically very distant from each other. By applying the emerging theories of network science to the production chain of contemporary, hyper-globalized and hyper-connected society, we want to provide an alternative point of view aimed at the multilevel development of a given territory/context (Fig. 1).

Network science – Starting from the first problem of graph theory formally discussed and solved by Euler in 1736, the so-called 'problem of Königsberg bridges', this discipline of mathematics is concerned with studying graphs, as schematizations of an immense variety of situations and processes. Demonstrating that there is no solution that allows the citizens of Königsberg to cross the city by crossing each of the seven bridges only once, Euler highlighted how each network possesses peculiar properties given by

Fig. 1 - Official logo of the Fab Lab program.

the geometric distribution of the connections between its nodes, which influences the way in which the same networks can be used. Considerable steps forward in the understanding of the behavior of complex graphs have been made thanks to the theories of Paul Erdős and Alfréd Rényi, who in 1959 defined the random graph model, later questioned as not explanatory of foundational processes of the birth of a real network (Barabási, 2003). Their contribution to the discipline was fundamental for understanding the dynamics that underlie the formation of a community: once the nodes of a graph are connected by a number 'n' of links such that each node has on average even a single connection to the rest of the network, a cluster emerges, an entity in which it is possible to move from any of the nodes that compose it to all the others. Erdős and Rényi (1959) hypothesized that the addition of links to each node followed the principle of randomness, but this approach cannot explain the complex dynamics underlying the immense variety of natural and social phenomena that are studied in graph theory.

However, the study of the clustering phenomenon has allowed us to understand a fascinating characteristic typical of real networks: these are 'small worlds' closely interconnected, in which each node is incredibly close to the others, in the sense that only a few steps are needed, in relation to the total size of the network, to reach any node that belongs to it. The birth of the 'small world theory' can be traced back to the famous experiment by Stanley Milgram (1967) made at Harvard, known as the '6 degrees of separation' experiment; examining the average length of the path between any two subjects belonging to the social network of American citizens, Milgram obtained an average of 5.5 passages between one individual and the other. His experimentation became famous in the public imagination thanks to the homonymous theatrical work presented on Broadway in 1991 and to numerous subsequent studies that have expanded and supported the theories behind it.

Recently, it has been shown that there is an average of 19 steps between any two URLs on the World Wide Web, a growing network of billions of nodes. Mathematically, this phenomenon was explained in the article Collective Dynamics of Smallworld Networks by Duncan Watts and Steven Strogatz (1998), who postulated that a social network falling under this paradigm must have a high global clustering coefficient, or measurement of the degree to which the nodes of a graph tend to be connected to each other. In most real-world networks, and in particular in social networks, nodes tend to create strongly united groups characterized by a relatively high density of connections;

the clustering coefficient of the real networks therefore tends to be greater than that of the graphs in which the links are randomly generated. The greatest breakthrough in understanding the topology of real networks came about with the definition of scale-free networks by Albert-László Barabási and Réka Albert (1999). Their analysis stems from the empirical observation of the World Wide Web network; observing the presence of hyperconnected nodes, or hubs, characterized by an extremely higher than average number of links, it was understood that this network, like most of the other real networks, cannot be based on the random model of Erdős. In a scale-free network, following a power law, a hub tends to become more and more connected with respect to any node, but above all it contributes to making the graph a 'small world' acting as a bridge between very distant nodes and creating short paths from one node to the other that in the absence of its presence would require many more steps.

Overview of community sociology – The term 'hub', very dear to the academic sphere, in literature finds different definitions even in disciplines of humanistic and social mold; in fact, among the first to focus his research work on social interactions we find Georg Simmel, who can be considered one of the fathers of modern sociology, together with Weber and Durkheim. The key concept of his thinking is interaction, the Wechselwirkung: society is characterized by the incessant interaction of its individual elements; social relations define it and form a 'new entity', not simply deriving from the sum of its parts. Sociology is thus a 'formal' science, devoted to describing the forms that reciprocal relationships (interactions) assume in different times and places, through the formation of groups or social circles. The ideal place in which these relational ramifications manifest themselves, or better, are naturally the place where by definition there are large concentrations of individuals, the big cities. The expansion of the group coincides, for Simmel, with the development of individuality, even if the differentiation of individuals is in turn necessary for the development of the group itself (Simmel and Jedlowski, 1995).

These concepts are the basis of the ideologies and methodologies of the famous Chicago School, founded, among others, by Robert Ezra Park (1864-1944), a student of Simmel, who identifies four fundamental interactive processes in urban space: competition, in the Darwinian sense the most elementary form of social interaction ('biotic order' of the city); conflict, a consequence of competition, concerns the actions of the individual and determines his position and his social status, dominant or subordinate; agreement, which involves the cessation of the conflict and the stable assignment of positions and statuses of power, defined and consolidated by laws and customs; assimilation, a process of interpenetration and fusion that can follow the agreement. The latter, according to Park et alii (1967, or. ed. 1925), is characteristic of the city that succeeds in integrating the various migrants and its various social components economically and culturally, even if all retain their identity and status. Park believes that the city is something more than a group of people, institutions, services, administrations, more or less organized: the city is a state of mind, a set of attitudes and feelings organized in customs, traditions and ways of behavior. According to Park, in the diversified and cosmopolitan city the individual can choose ‘with whom to stay’, he is not obliged to follow the tradition but he can attend people more congenial to him and their ‘company’ will provide him with moral support and justification of behavior chosen by him. The city is thus divided into a multiplicity of moral regions (that of vice and bourgeois, bohemian, working class, that of singles, etc.), but not always the company is ‘chosen’; often we find ourselves living there and it fits us. This naturalistic approach presupposes the existence of an urban space left to laissez-faire and to the mechanisms of the market, as well as linked to a strong division of labor and social roles. And the almost total absence of urban planning. The perspective is no longer that of the theoretical view from above, but that of the vision from within (Manzini, 2015).

In this framework, transposed in a contemporary key, the theories of the pedagogy of catastrophes and degrowth, of which Latouche (2008) is the ‘putative father’, are inserted: a crisis can be an opportunity to regain awareness of one’s own resources and one’s limits, defining them as foundations and perimeter values and perimetrals rather than as constraints. It is extremely important in this historical period to focus on the concept of the Hegelian ethos, or the perception of being part of a community and a social morality where the realization of good takes place through institutional forms such as civil society, to face today’s urban problems. The human, economic, ethnic and environmental processes that manifest themselves in urban centers systematically escape plans and projects, maps and building logics, never as today, democracy is played in the public space, in the streets, on the sidewalks. Urban planning and design, on the other hand, are still trapped in an eighties vision, which mitigates passivity to the detriment of the needs and trends of reality. What is needed today, argues La Cecla (2015), is a new science of cities capable of guaranteeing a decent life for all – a basic concept of the ideology of the need for degrowth at local level – focusing on how to develop policies that promote this trend.

Fab Lab as hubs – The Fab Lab program was born in 2001 thanks to US professor Neil A. Gershenfeld, inside the Boston MIT Center for Bits and Atoms. From the beginning, the aim of the project was to teach future generations how to design and produce technological artefacts autonomously, favoring the dissemination of bottom-up experiences and products designed specifically for the community and the territory in which they will be used, according to logics that are far from those dictated by the globalized market but oriented to a democratization and widespread accessibility of the means of production offered by the individual laboratories, especially to communities with poor access to education or technology (Lena-Acebo and García-Ruiz, 2019). A Fab Lab is generally equipped with a series of tools (including mainly numerical control machines, printers for rapid prototyping and various tools) freely usable by those visiting the laboratory (Menichelli, 2016). After the birth of the project

Fig. 2 - Map of Fab Labs worldwide (credit: fablabs.io, 2019).

in MIT the program was widely spread all over the world, starting from Vigyan Ashram, India, the second Fab Lab ever, born in 2002 (Fig. 2).

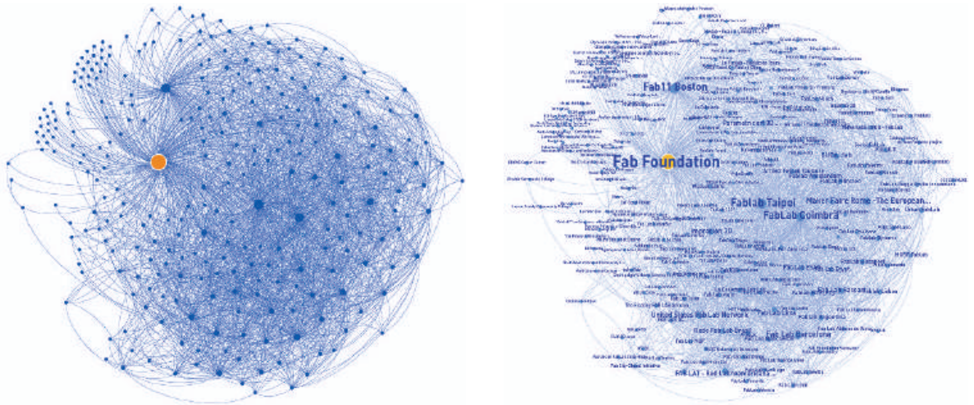
MIT has supported the birth of these laboratories through the official registration at the Fab Foundation. Since 2014, the list of all official Fab Labs has been maintained and updated through the fablabs.io site, a reference point for the open source community. To date, the site has registered 1458 Fab Labs spread across all continents, with the exception of Antarctica. Analyzing data extracted from fablabs.io immediately emerges the evidence that this closely connected community is not evenly distributed on the planet: of the more than 1000 Fab Labs registered at the Fab Foundation, 720 are located in Europe, 406 in the Americas, 262 in Asia and only 70 in Africa and Oceania. We are talking about a strongly western community. Specifically, 202 Fab Labs are based in the US alone, that have a population of 327 million inhabitants; France and Italy follow closely, with a widespread distribution in the territory, respectively 191 and 138; here, however, the Fab Lab per capita ratio rises dramatically: in fact in Italy there are 434,000 inhabitants for each Fab Lab, while in France the ratio is 350,000 inhabitants for Fab Lab. India and China, despite being countries heavily devoted to industry, are not yet included in the dynamics of sharing of the maker movement: in the Chinese state there are only 22 Fab Labs compared to a population of over a billion people, in India instead there are 53 laboratories. In Europe, Germany and Spain travel in the order of 60 laboratories, in the Iberian state, however, Fab Lab Barcelona stands out in the field of research; it is managed by IAAC (Institute for Advanced Architecture of Catalonia). In the rest of the world, especially in African countries, less than 10 Fab Labs per state are active.

Network visualization has been exploited to capture the image of how effectively the Fab Labs belonging to the system are interconnected. Taking advantage of the Netvizz application, it was possible to download the 'friendship between pages' network of the Fab Foundation Facebook page. This is the network that connects this page to all those that followed it, plus the relationships between them. The Gephi open source software was used to perform a basic statistical analysis of the network in question, allowing to obtain a graph in which the nodes are organized in groups of 'greater mutual relationship'. The 281 nodes (the Facebook pages analyzed) are connected to each other by 2431 links; the diameter of the graph, defined as the shortest path between the two most distant nodes that build the network, is only 5 steps: we are observing a 'small world' in which the pages of the Fab Labs of the entire planet have a strong reciprocal relationship , a world in which projects and ideas travel rapidly across the globe, in compliance with the values expressed by the open source community (Fig. 3). A first look at the topography of the graph shows that most of the nodes form a rather united community, while in the upper left there are smaller, more isolated clusters, held together by the hub represented by the Fab Foundation page (node indicated in yellow; size of the nodes is proportional to the number of followers of the given page: Fig. 4). Adding the labels with the names of the pages shows that, in principle, the less connected nodes are external to the Fab Lab community: these are mainly Colleges and technical institutes. On the contrary, in the right and thickest part of the graph connections there are laboratories from all over the world, from Genoa to Tokyo to Latin America.

Territorial cluster – We have so far described the Fab Labs in relation to each other within the global community of participatory planning and the open source community. In this sense they operate as bridges, minimizing the geographical distances between individuals and societies with a similar mentality. Going down to a lower level, we need to analyze the relationships that the Fab Labs are able to create and feed within the specific territory in which they operate. Two radically different and contrasting case studies were analyzed to highlight criticalities and opportunities offered by the Fab Lab model. Firstly, the small reality of the Genoa laboratory, included in the Lsoa Buridda Social Center, was studied. The analysis of the 'friendship between pages' graph gives an extremely poor result, indicative of the scarce activity of the Facebook page: it is connected only with the nearby Fab Lab Alessandria and with the page, much more active and followed by users of the social network (it counts more than 10,000 followers), of the aforementioned Social Center in which Fab Lab Genoa is based (Fig. 5).

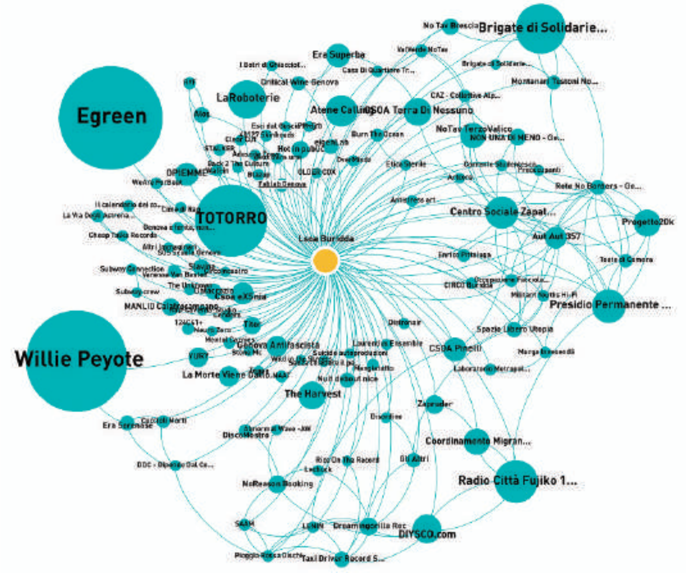
In order to better observe the community that revolves around the Genoese laboratory, the network of the Lsoa Buridda page was therefore analysed, consisting of 113 nodes and 222 links. In this case, we immediately notice how the graph is much less cohesive than the one generated around the Fab Foundation; not surprisingly, even though it is a much smaller network, the diameter is 6. It means that the Lsoa Buridda page follows and is followed by a very heterogeneous group of pages, which have few relationships among them. Specifically, the network is composed of numerous pages of collectives, social centers, occupied spaces, music labels and independent artists; connections with cultural institutions, museums and schools in the city are totally missing. Likewise, there are no connections with open source communities related to rapid prototyping and technological projects and innovation (Fig. 6). Buridda calls itself a self-managed occupied social laboratory, born on 11th May 2003 with the occupation of the headquarters building of the former Faculty of Economics of the University of Genoa, abandoned for several years. The Fab Lab, one of the very first born in Italy, immediately took up residence in the building. Following the eviction in 2014, all the activities have so far been moved to the former Magisterium owned by the University in Corso Monte Grappa (Fig. 7). The evidence of the network analysis accompanied by the reading of the vicissitudes of this center paints a picture in which the political convictions of the founders unfortunately acted as a deterrent to the creation of an active community really involved in the cultural panorama of the city of Genoa.

The opposite and much more positive experience is that of the Fab Lab Barcelona, already mentioned in this paper as one of the most active in the world in terms of research. Part of the Institute for Advanced Architecture of Catalonia, the Fab Lab supports



Figg. 3, 4 - Graphs of the interactions between Facebook pages that follow the Fab Foundation page (credits: A. Vacanti, 2019).

Fig. 5 - Graph of the interactions between Facebook pages that follow the Fab Lab page in Genoa (credit: A. Vacanti, 2019).


Brigate di Solidarie...
Ere Superba
Egreen
LaRoboterie
Critical Wine Genova
Atene Calling
CSOA Terra Di Nessuno
NoTav TerzoValico
NON UNA DI MENO - Ge...
Rete No Borders - Ge...
TOTORRO
Centro Sociale Zapat...
Progetto20k
Aut Aut 357
Teste di Camera
Presidio Permanente ...
Willie Peyote
Genova Antifascista
CSOA Pinelli
La Morte Viene Dallo Spazio
The Harvest
Coordinamento Migran...
Radio Città Fujiko 1...
NoReason Booking
DIYSCO.com
Taxi Driver Record S...
Era Serenissima
Discomostro
Zapruder
Gli Altri
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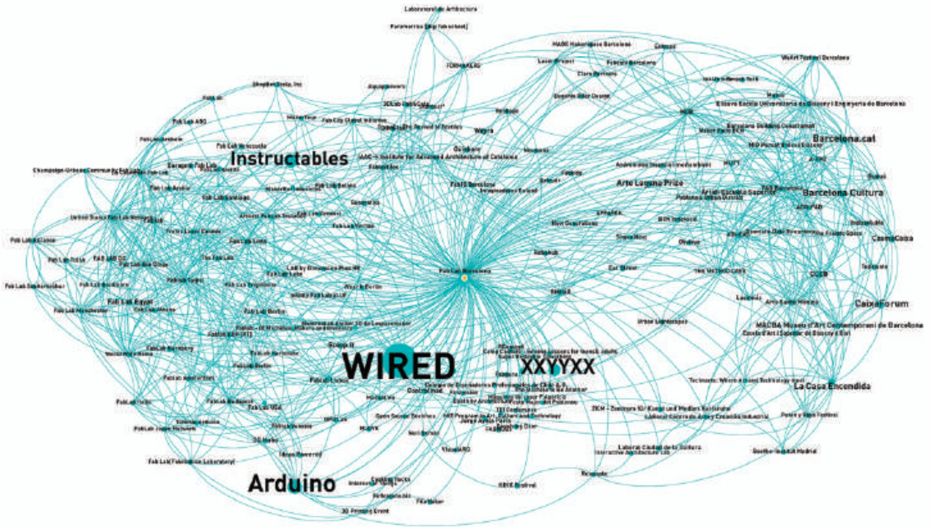
Instructables
Barcelona.cat
Arts Santa Monica
Barcelona Cultura
CaixaForum
MACBA Museu d'Art Contemporani de Barcelona
WIRED
XXYYXX
La Casa Encendida
Arduino
Fab Lab Barcelona
Fab Lab Berlin
Fab Lab Egypt

various educational and research programs related to the multiple scales of human habitat. It is also the headquarters of the global coordination of the Fab Academy program in collaboration with the Fab Foundation and the MIT Center for Bits and Atoms; the Fab Academy is a distributed education and research platform in which each Fab Lab operates as a classroom and the planet as the campus of the largest University under construction in the world, where students learn the principles, applications and implications of digital production technologies. Here, projects such as Hyper Habitat IAAC (official selection for the Venice Biennale XXI) or Fab Lab House (Audience Award in the first Solar Decathlon Europe in Madrid; Fig. 8) have been developed. The friendship graph of the Fab Lab Barcelona Facebook page (about 12,000 followers) consists of 174 nodes and 902 links, with a network diameter of 5. It is also far from the cohesion level of the Fab Foundation graph, however the qualitative analysis of the nodes that compose it depicts a much brighter panorama of the Genoese experience: in the network there are numerous global Fab Labs, from Bolivia to Berlin to Venice, some pages of important realities such as the innovation magazine Wired and Arduino. Above all, there are many pages related to affirmed realities in the cultural panorama of the city of Barcelona, such as Museums, Cultural Centers, Schools and Universities (Fig. 9).

Glocalized heterotopia – In 2014, Barcelona became the protagonist of a concrete experiment: in the historic industrial district Poblenou of the Catalan city: for a week, an area of about one square kilometer was transformed into a Fab City. Here a circular model for the city was born, capable to reuse waste and to create new objects and re-enter them in the production cycle. Craft shops, technology experts together with scholars and designers have shown that it is possible to create a circular system within a large urban center by creating connections and synergies. For example, making fabrics produced from plastic collected on Spanish beaches, or producing eco-leather from pineapple leaves. This initiative carried out by MIT, IAAC and the Fab Foundation aims to transform cities into places of local production and global connection in which citizens are a fundamental part of change (Diez, 2018). What Bauman and Bordoni (2014) defined as 'glocal': a neologism that indicates a reality that combines globality and locality together, as well as a communication addressed to the global context while taking into account the specificities of the individual local cultural realities. In the world, every community has its own social and cultural values that express the identity of that territory: by globally sharing these values with other communities, the local culture is enriched and becomes a 'glocal' culture. For this reason Fab City is

Fig. 6 - Graph of interactions between Facebook pages that follow the page of Lsoa Buridda (credit: A. Vacanti, 2019).

Fig. 7 - Facade of the new occupied headquarters of Lsoa Buridda in Genoa (credit: L. Buridda).

Fig. 8 - Students at work at Fab Lab Barcelona (credit: Fab Lab Barcelona).

Fig. 9 - Graph of the interactions between Facebook pages that follow the Fab Lab page (credit: A. Vacanti, 2019).

collegial, multidisciplinary and co-designed, it moves in a fluid context, in which different actors collaborate depending on the projects: engineers, designers, architects, urban planners, public offices, artisans, shops, associations, informal groups, small and large companies (Nike and Ikea are partners).

Ma(r)ker as minimum unit – We can affirm that for a balanced and self-sustainable urban development, declined in the economic-productive and socio-environmental sectors, different stakeholders of the same urban network can play a vital role. The creation of a circuit is essential to widely disseminate this systemic approach; in this cross-linked structure, the hubs, the connection nodes, can be the Fab Labs that work increasingly alongside the Administrations and in partnership with large and small companies, but remain focused on people, in a place where citizens are perceived not only as consumers but as producers capable of performing this function by accessing digital tools for manufacturing and creating culture. In this scenario, the activators/catalysts of these practices that operate in these places, the makers, create what MacCannell (and Lippard, 1999) defines as a 'marker' – an artefact capable of giving identity and recognizability to the construction process of the image of the territorial reality to convey and to represent the complexity of its material and symbolic characteristics. They therefore undergo a sort of further semantic upgrade, qualifying as the Ma(r)ker: co-producers and co-designers, who hybridize new technologies to traditional production systems, fabricating artefacts that carry symbolic values of belonging to a given territory.

Conclusions – According to Buckminster Fuller (1972), in order to teach a community a new way of thinking, we must neither impose it nor teach it, but rather set the conditions for the community to have the tools to be able to build its own. This way the conclusion of the paper can be summarized: in the current delicate socio-political world situation, to overcome the shortcomings caused by increasingly complex global dynamics, it is necessary to bring to light a collective conscience that transcends geographic boundaries and points out the real ones and specific needs of each territory; to obtain this, it is essential to create the conditions that make these objectives possible, increasing participation in bottom-up mechanisms guided by figures with skills and attitudes that allow the right structuring of connective systems.

Fab Labs can be seen as organizations born for 'sustainability', in the different meanings that this word brings with itself: a social sustainability, an environmental sustainability and an economic sustainability. However, these laboratories are still a rather new and little studied research context. For example, there is no knowledge on how the organization and management of their activities are carried out and what challenges the Fab Lab managers have to face in translating these types of sustainability into action in specific social contexts (Galuppo et alii, 2019). Very often the main problem of laboratories is finding and managing economic flows, so the relationship with companies and large industry is essential to ensure the survival of these places.

The research and development processes that characterize companies often refer to consolidated technology partners and suppliers that belong to a rather closed system. Those who work in spaces of innovation such as Fab Lab and makerspace often do not fall within the relational sphere of companies and therefore remain outside the frequencies intercepted by the antennas of small and medium-sized enterprises. This highlights a limit on both sides. If on the one hand companies often fail to enter into open innovation logics and abandon their traditional supply networks, on the other hand makers tend to form closed universes that do not relate easily to the surrounding economic environment. Despite various virtuous exceptions, we need to work towards greater integration between the two worlds (Schiavo, 2017).

The case studies analyzed have in fact highlighted how two Fab Labs, although belonging to the same program and guided by the same values, have an extremely different impact on the global system and above all on the region in which they operate; among the many factors that distinguish the two experiences, we believe it was fundamental for the positive development of Fab Lab Barcelona the relationship with a reality linked to a project such as the IAAC, which was able to guide the development of the laboratory and tie it to achievements, experiences and innovative research in the world of design, technology and architecture. Fab Lab Genoa, on the other hand, did not know how to network on its own territory, which in any case presents greater challenges than a big city like Barcelona, and let other realities and stakeholders hybridise their experience, thus remaining a phenomenon that is mainly isolated and not tied to the world of innovation and project. The tool of Network Visualization allowed, in this paper, to immediately highlight the differences and the specificities of the two case studies examined. In the future we propose to continue this type of analysis by finding larger datasets that are able to shed more light on the phenomenon of participatory design in general and makerspaces in particular.

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SMART MATERIALS
TECHNOLOGICAL INNOVATIONS IN ARCHITECTURE BETWEEN PRODUCT AND PROCESS

Fabio Conato [a], *Valentina Frighi* [b]

section
Architecture

typology
Essays & Viewpoint

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Abstract
The revolutions that affected the construction process have traced a precise path also for the whole building sector, in which the innovation of materials and components become a priority. The construction of sustainable buildings was thus accompanied by new challenges: the development of a new generation of smart buildings fits into this context. In this transition, the building envelope certainly plays a significant role thanks to the possibilities that new intelligent materials opened up in this field. The present contribution intends to investigate this domain, with the aim to demonstrate how these product innovations can determine process innovations in the organization, management and control during all the phases of building's life cycle, allowing the construction of tailor-made constructions towards a more efficient architecture.

Keywords
smart materials, smart building, building envelope, building materials and components, architectural technology

Recent transformations that occurred within the construction process, resulting from the distortion of already consolidated practices due to new emerging needs, led to an actual paradigm shift, fostered by the availability of new materials equipped with unconventional features and assisted by highly-automated and industrialized productive processes whose results generated increasingly daring experimentations. Augmented reality, Internet of Things and large amounts of data available allowed us to develop extremely targeted design and management processes, endorsed also by innovative materials and products with ever-increasing performance, and with reduced dimensions and fast and effective application modalities. Therefore, the contamination with the digital world seems to give an unprecedented acceleration to the transformation of some systems into real interfaces that allow users to interact with the building organism, making them 'prosumers'[1] active in this transformation process (Gaspari and Busacca, 2017).

However, in view of this enormous potential, the need for a radical transformation of the design process and, with it, of a new design philosophy (Di Salvo, 2015), capable of maximizing the effectiveness of these innovations, is simultaneously and implicitly affirmed; formerly in 2002, Tatano (Sinopoli and Tatano, 2002) recognized the beginning of a different and unconventional relationship with the architectural project if compared with the past, due to the introduction of such new techniques. The planning horizon that emerged at the opening of the last century indeed, even if still valid in terms of method and reference procedures, turns out to be inadequate to describe the context that design technological culture has to deal with (Campioli, 2017). The diffusion, in common language as much as within the 'specialist' lexicon, of terms like 'advanced', 'innovative', or simply 'new', to define building materials, components and systems is a clear expression of this necessary change towards the possibilities of material transformation, that are going to open new routes in the field of development and creation of new materials (Lucarelli, Mandaglio and Pennestrì, 2012).

Therefore, the present contribution aims to briefly outline the role played by such technologies and, above all, their intrinsic abilities in bringing innovation within the construction process, addressing both the scientific community and those who 'design technology' (Torricelli, 2017, p. 23) not with synthesis purposes – difficult due to the extent of the state of the art on the subject and, especially, of its continuous update – but rather with the desire to provide new insights within the specific reference framework, which is that of building envelope technologies, today free from their traditional role to become bearers of new issues. Moreover, the present discussion is deliberately not limited to the analysis of a specific class of technical elements but rather it considers as reference domain the class of technological units represented by building closures, considered as the category with the greatest potential both on a formal and a performance level.

Smart Buildings' Era – The changes caused in today's society by lifestyles' modifications, on one hand, and by the so-called fourth Industrial Revolution, on the other, contributed in the creation of a rather precise path even in architecture, making research in the field innovative materials and components a priority of the industry, thus bringing the technical and aesthetic conception of building envelope to evolve accordingly, thanks to new and in appearance unlimited possibilities introduced by such novelties (Ajla, 2016; Conato and Frighi, 2018b; Fig. 1). The construction of sustainable buildings, with low environmental impact and almost zero consumption, has now been accompanied by new challenges, driven by the desire to foster this change towards a general improvement of life and environmental quality. The development of a new generation of intelligent buildings, resilient towards change, thus means capable of adapting to it, perfectly fits into this framework (Fig. 2).

However, if we often have the tendency to 'simplify' such systems, associating them with buildings only equipped with automations and network connected, thus able to guarantee their occupants a remote control of devices installed within them (like the so-called BMS[2]), for the purposes of the present dissertation, with the term Smart Building we intend a complex architecture, in which heterogeneous materials and components interface each other to achieve a dynamic performance response – in the broadest sense of such definition – conferring to the building thus obtained the ability to trigger dynamic interactions as a whole and with the external environment. Indeed, Kiliccote et alii (2011) suggest the conception of a Smart Building as a con-

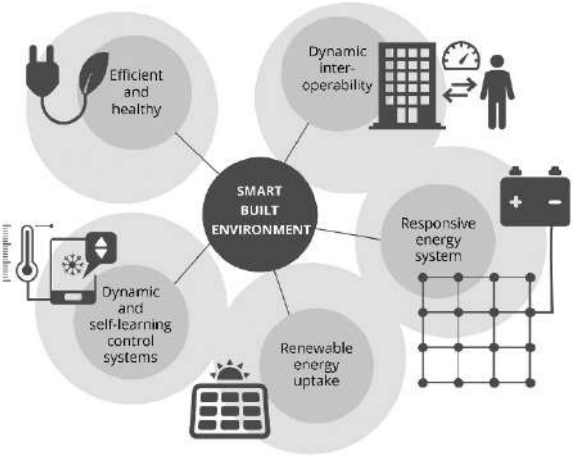


Fig. 1 - Foster and Partners, Ateliers Jean Nouvel and PTW Architects, Hanging gardens of One Central Park, *Sydney 2013 (credit: www.flickr.com, 2014).*

Fig. 2 - Buildings' evolution (credit: the authors, 2019).

Fig. 3 - Five pillars of a smart built environment (credit: authors' editing on BPIE' analysis, 2017).

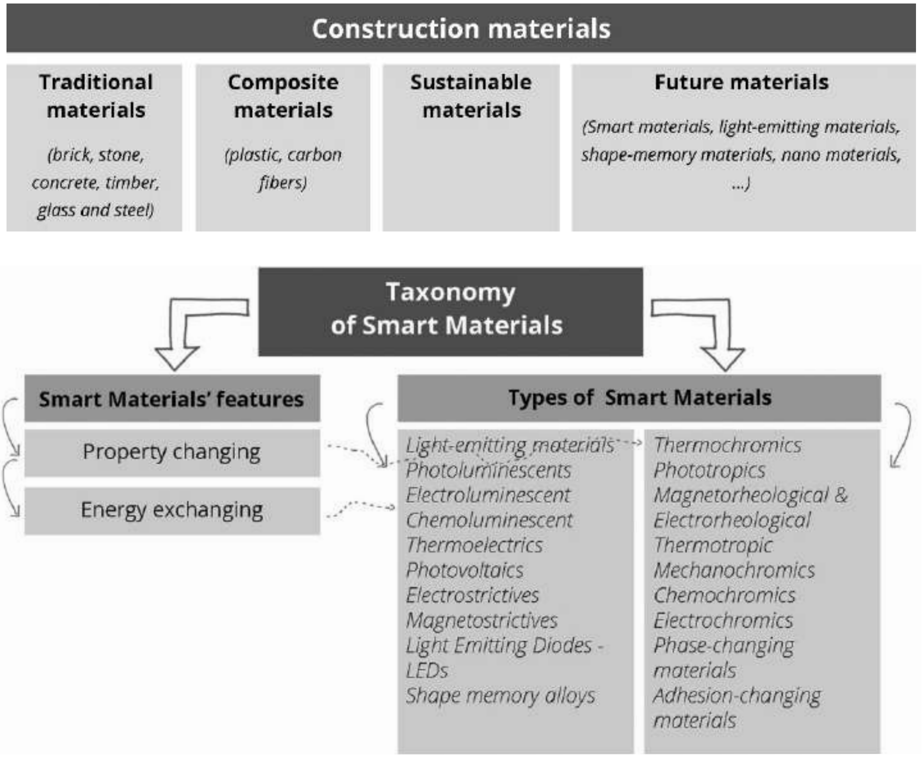
scious organism, possibly equipped with the chance to use intelligent sensors to operate within the following domains: i) different perception of individual comfort during the day and the year; ii) changes in building use; iii) variations in occupancy features; iv) changes in external weather conditions.

Therefore, after these assertions, we can define a Smart Building as a building equipped with technical solutions capable of providing high performance in terms of comfort, energy efficiency and environmental sustainability, able to interact with the surrounding and to acquire data and other useful information aimed at a continuous fine-tuning of its operation, also through users' interaction (Fig. 3). In this transition from a 'traditional' building to a fully automated 'smart' building, it is clear that the building envelope plays a significant role, both as element conceived to guarantee certain comfort conditions within confined spaces, as well as responsible for the interactions (in terms of heat, matter and light fluxes) between inside and outside. However, although their enormous potentials, technical applications which involve the use of intelligent materials, components and systems within this domain remain, even today, only marginally known and explored.

Smart Materials: towards a shared definition – If, in the past, building materials were mainly selected on the basis on their performance, economic, formal and aesthetic features – accepting their limits as well as criticalities intrinsic in their nature – starting from the 21st century, also thanks to the possibilities offered by new technologies regarding the optimization of the various phases of the process, which started to allow shapes and applications previously unthinkable, the relationship between materials' science and architecture evolved accordingly, finding its maximum expression in the so-called Smart Materials (Fig. 4). This term is conventionally referred to all the materials considered intelligent, thus means equipped with innovative features and/or more selective and specialized performances if compared with traditional materials. In this group fit all materials with variable properties in reaction to external inputs of various nature, as well as apparently traditional materials but actually able to provide an intelligent and adaptive behavior, thanks to the acquisition of such characteristics through mutual interactions (such as, for instance, those among different elements within the same building component or in the relationship among several heterogeneous components).

Because of the multiple interpretations that can be given to the term Smart Materials, a shared definition, conventionally accepted by the scientific community, is actually difficult to be formulated, as stated also by Addington and Schodek (2005). Indeed, they repeatedly stressed the fact that the term Smart Materials, as a concept that can be interpreted according to different meanings, can be used without a precise definition of its meaning since this appears surprisingly difficult. However, analyzing recent scientific literature on the subject (Scalisi, 2010; Sadeghi, Masudifar and Faizi, 2011; Rossetti and Tatano, 2013; Casini, 2016; Abeer, 2017; Ritter, 2017; Frighi, 2018; Juaristi et alii, 2018a; Abdullah and Al-Alwan, 2019; among others), it is possible to assert that, with this term, we can identify all those highly engineered materials, capable of responding in an intelligent way to the context in which they are inserted, changing their performance, chemical-physical or morphological features in a reversible way, assuming different functions in relation to stimuli of various nature or, again, in response to transient needs. Therefore, when speaking of Smart Materials, we conventionally refer to materials with a dynamic response, naturally opposite to 'traditional' materials generally equipped with mainly static performances (Conato and Frighi, 2018a).

Which and how many: definitions and classification criteria – The main characteristics that distinguish a Smart Material from a 'traditional' material can be summarized as follows (Addington and Schodek, 2005): 1) immediacy, intended as the ability to respond to real-time stimuli; 2) transiency, defined as the ability to respond to more than one environmental state, due to the fact modifications which occur are transitory; 3) self-actuation, since the control capacity is intrinsic in the material and does not depend on external actuators; 4) selectivity, since the reactions of different materials are distin-



Figg. 4, 5 - Building materials; Taxonomy of Smart Materials (credits: authors' editing on the basis of Mohamed, 2017).

guishable and predictable due to their characteristic properties; 5) directness, since the performance response is a direct expression of the event or input that generated it and, therefore, to it directly connected. Because of this, several different criteria can be suitable for the classification of these materials, for instance as a result of their intrinsic properties (such as material nature, chemical composition, physical-mechanical properties, etc.), or on the basis of the performances that the material is able to guarantee, subdividing them among materials with fixed performances[3] and materials with variable performances, or, again, according to their mode of operation, marking them as passive (if activated following temperature or brightness changes), active (if electrically regulated, therefore by artificial stimuli), or intelligent (if able to self-adapt to the surrounding environment), combining both the aforementioned modalities.

One of the main classifications, which, as a matter of fact, derives from the previous considerations, is that which distinguishes Smart Materials according to their fundamental abilities, subdividing them into two categories: on one hand those that vary one or more of their performance characteristics in direct response to an external stimulus – the so-called Property Changing Materials – and, on the other, those materials which, following impulses of various types, convert energy from one form to another – the so-called Energy Exchanging Materials. The first category includes thermo-chromic, electro-chromic, mechano-chromic, chemo-chromic, phototropic, thermotropic, shape memory, phase change and adhesion materials. In the second category instead, fit light-emitting materials, photovoltaic materials, electro-strictive and/or magneto-strictive materials, LEDs, piezo-resistive and thermo-responsive materials and thermoelectric and piezoelectric materials (Fig. 5). In both cases, the reactions are direct and totally reversible, triggered by luminous, thermal, pressure, electrical or electromagnetic stimuli. However, if in the first case materials undergone an alteration of their molecular structure, in the second, the material does not change because it is only the energy that is converted into another form.

The Smart Materials in the architectural project – It is known that a technological innovation, in architecture as much as in other disciplinary areas, occurs when «a process of change reaches a critical mass that overcomes the inertia of the classical system» (Di Salvo, 2015, p. 109); however, within this specific domain, due to the structural conception of the ‘system’, it is still suspiciously perceived and very slowly recognized before being able to modify practices consolidated over time (Sinopoli, 2002). This is extremely true especially in relation to the technologies presented so far, although it must be said that, despite the fact that most of such systems seems very complex in terms of concept – due to a high level of engineering – it is also true that, often, a good part of them can be integrated into building envelope design without excessive complications. Clearly, even because the still limited existence of real examples that can be taken as design references, it is currently difficult to formulate and provide adequate technical information concerning their design and operation (Juaristi et alii, 2018b).

However, it must be said as well that, starting from them, it would be possible to develop a wide variety of technologies functional to different purposes. Therefore, referring the concept of 'smartness' only to building materials sounds actually rather reductive since, especially in the domain of building envelope, an architecture constitutes a very complex organism in which a multitude of heterogeneous materials, components and systems must interface each other to provide a response suitable for the application context in which it is inserted. Hence, even apparently conventional materials, already fully included in current construction practice, if capable of providing an intelligent and adaptive behavior, possibly establishing unprecedented interactions with other materials and components, can be defined 'smart' as well.

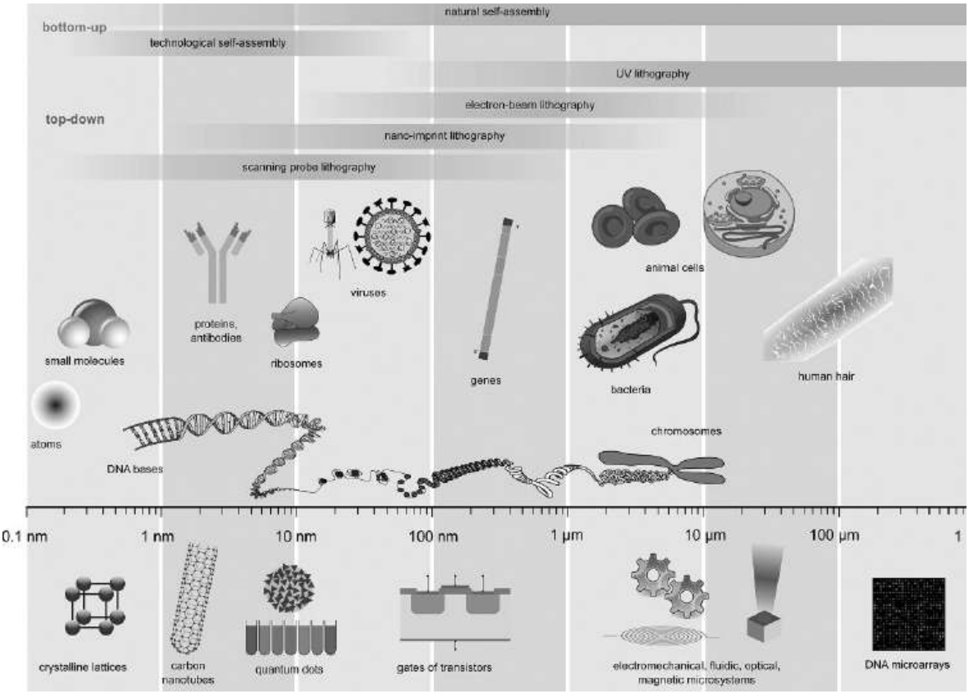
Existing technologies and their application potential – The recent innovations, in terms of both product and process, have led the technological industry towards the development of increasingly advanced materials and components, with a particular attention towards the environmental sustainability and considering the significant constraints with which the designer has to deal with during design and construction phases, as well as dimensions and installation fine-tuning. Among the most interesting materials lately developed, there are undoubtedly inventions such as the well-known Aerogel[4] (Fig. 6), the nanotechnologies[5] (Fig. 7), the Phase Change Materials[6] (Fig. 8) or the so-called chromogenic materials (Fig. 9), able to change their optical features in response to external stimulations. The application of such technologies has allowed, in recent times, the development of Smart Windows, active building envelope components, kinetic devices and more.

As a matter of fact, materials, components and systems definable 'smart' constitute a very heterogeneous sample, difficult to be catalogued especially following the extension of such concept in relation to what stated above. For this reason, wishing to provide a general overview of the possibilities provided by these technologies, in the present contribution some of the existing products (on the market or, more frequently, still in the development phase) have been identified and presented; they have been choice among those considered most significant and distinguished according to their performance in: fixed performance materials and variable performance materials.

Within the first category, one of the most interesting products is certainly the 'translucent wood' (Fig. 10), developed in 2016 by researchers of the Royal Institute of Technology in Stockholm (KTH)[7] and comparable in the appearance to a common polycarbonate sheet, while retaining the original properties of the basic wooden support. Its development has been possible thanks to a particular chemical process through which the lignin was removed from wood, making it almost colorless. The product thus obtained was subsequently impregnated with a transparent polymer which made uniform the optical properties, making it usable in replacement of glass in transparent building components or to increase the efficiency of solar cells in photovoltaic components. The high production cost of this technology as well as its laboriousness, combined with the difficult

Fig. 6 - The Aerogel, discovered in 1931 but remained practically unknown until 1970s, has a density equal to three times that of air but it is able to support significant loads, being at the same time an excellent insulating material (credit: Addington and Schodek, 2005).

Fig. 7 - Nanoscale: a comparison of the size scales of various biological assemblies and technological devices (credit: G. Paumier; components from P. Ronan, NIH, A. J. Fijałkowski, J. Walker, M. D. Jones, T. Heal, M. Ruiz, NCBI, User: Liquid_2003 on Commons, Arne Nordmann and Tango Desktop Project, 2013).



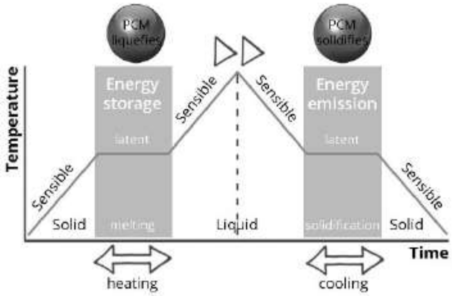


Fig. 8 - How PCM works (credit: authors' editing on the basis of Pazrev, 2014).

Fig. 9 - Thermochromic fabric.

Fig. 10 - Transparent wood prototype developed by the KTH's researchers (credit: P. Larsson, 2016).

to obtain large-format panes, does not yet make it suitable for commercialization.

Equally significant but perhaps less surprising are products developed starting from metal supports, such as composite steels or shape memory alloys. Among them, a special mention deserves the 'boing microlattice', an artificial structured material with electromagnetic properties function of its particular molecular structure – with open cells, consisting of metal nano-tubes with polymeric matrix – as well as of the characteristic shape in which it is generally employed. This metallic foam, extremely light (even more than the Aerogel, with a density lower than 1 mg/cm^3), has actually an extraordinary capacity to absorb mechanical energy, making it ideally suitable for different architectural purposes. However, to date, the only known applications are those related to the aerospace field, due to the extraordinary performance features of such material. Finally, even among polymeric products there are significant advancements, thanks to several experimentations aimed at developing materials with greater resistance, insulation capacity, durability and maintainability. The fabrics produced by Sefar AG[8] could be taken as example; they are obtained, in general terms, through the combination of metallic and polymeric fibers can be used to generate heat, illuminate, detect physical parameters or, again, for the construction of transparent conductive electrodes, such as those employed in OLEDs, solar cells, electroluminescent devices and electrochromic glass, albeit with very high costs.

On the other hand, concerning variable performance products, it is possible to assert that the most significant innovations certainly fall within the domain of ceramic-based materials, even only because of the great variety of products that this field groups together. Relevant are also the experimentations on metallic or polymeric supports, such as shape memory alloys or polymers, magnetostrictive or photomechanical materials or dielectric elastomers. An interesting prototype, with passive operation mode, is the device developed by a group of students of the Institute of Advanced Architecture of Catalonia, in Barcelona[9], consisting of clay modules and hydrogel spheres able to absorb an amount of water comparable to 400 times their volume, reducing indoor temperature up to 6 ° C by exploiting the evaporative cooling principle (Fig. 11). Even the self-repairing cement, developed within the Technische Universiteit Delft[10], is a noteworthy product. In it, the presence of bio-chemical additives containing sleeping bacteria – capable of producing limestone on a biological basis – and organic compounds, wrapped in porous expanded clay particles, allows the triggering of self-repairing mechanisms able to seal cracks lower than 1 mm.

Furthermore, numerous experimentations are still in progress on glass-based products, due to the always present need of implementation of the basic material. The strategies implemented within this field range from the development of systems with static abilities, to control incident solar radiation, to dynamic products, with variable performance function of various kinds of inputs. These systems generally exploit chromogenic technologies to vary the optical, transparency and brightness properties of the glass pane due to stimuli of various nature. Clearly, there are also researchers aimed at integrate transparent photovoltaic systems[11] into glazed building components or high-performance materials (such as PCM), to increase building insulation properties, or, again, those conceived for implementing their physical characteristics and mechanical strength, such as composite materials which combine the advantages of glass with resins' resistance[12]. However, it must be said that, although these devices have significantly evolved over the last decade, reducing the main criticalities related to their operation, their application in current situations is still sporadic, mainly due to the high costs that justify their adoption only in interventions of particular relevance

Fig. 11 - Hydroceramic *prototype developed by the IAAC's students within the course of Digital Matter Intelligent Constructions (credit: Pensamento Verde, 2015).*

or size. Moreover, the aforementioned technologies generally present a high environmental impact as well as they are scarcely on-the-market available as they are frequently still at a prototype stage (Pacheco-Torgal, 2014).

Conclusions and future perspectives – Downstream to these considerations it is therefore easy to understand how product innovation has actually very scarce success without a project able to understand its potential and to maximize its effectiveness (Lucarelli, Mandaglio and Pennestrì, 2012); the interaction among the various technical elements – in the mutual features that characterize the complexity of an architectural project – necessarily requires a minute and accurate design, capable of bringing together «at the same time very distant [...] technologies» (Campioli, 2011, p. 64) towards a single purpose. In fact, as stated by Maria Chiara Torricelli (2017, p. 23) «the acceleration of technological innovations from other scientific and industrial environments has shifted the role of technological skills from those who systematize and design technology to those who know how to interpret, finalize, use and make it works in the complex design system».

The buildability of the assemblies deriving from the technical solutions here presented, focusing on building envelope's domain, is not obvious at all, but rather it constitutes an important starting point for developing a new approach towards the project, which takes into account the existence of such innovative technologies but, above all, offers potential design solutions capable of adequately respond to the constantly changing needs of modern society. However, the question is still open as most of the technologies and materials above mentioned is still suspiciously considered. This is aggravated by the existence of critical issues both under a theoretical and an applicative point of view, which have to be added to the limits already highlighted; on one hand indeed, reduced knowledge or workers in building sector reluctant towards the adoption of unknown technologies prevent their spread; and on the other, different barriers to their diffusion are still present, such as excessively high costs, difficulties in integrating them with the so-called 'traditional' components, critical issues in the management of the production chain and in the dialogue among different operators or, again, lack of consolidated and recognized reliability for some products as well as difficulties in the effective monitoring and on-site certification of their performance.

Therefore, to let the product innovations here presented to become a milestone towards significant process innovations, it is necessary to continue, from one side, the researches and experimentations in this field, and, from the other, to raise as much as possible the awareness among professionals in the field about the potentials offered by such technologies in each phase of the complex process of design and management of an architectural work, pushing it towards a new level, capable of promoting an adaptive interrelation between different skills and resources. Product innovation must then be confused with process innovation (Campioli, 2011), expanding the scope of different stakeholders thus promoting a synergistic interaction among them, aimed at implementing the mutual supply chains throughout the whole building life cycle, allowing in this way the creation of tailor-made constructions towards a more efficient and sustainable architecture.

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NOTES

1) Term obtained by merging the words ‘producer’ and ‘consumer’, introduced for the first time in: Marshall, M. and Barrington, N. (1972), *Take Today: The Executive as Dropout*, Harcourt Brace Jovanovich, University of Michigan (USA).
2) The initials are the acronym of Building Management Systems.
3) Fixed performance materials can be, for example, structural advanced materials, thermo-structured materials or functionalized surfaces materials.
4) Siliceous based solid mixture made, for the 99.8%, of air, which makes it one of the lightest materials in the world. Its lightweight as well as its insulation capacity is comparable to graphene’s properties, discovered more recently and considered one of the most promising future materials thanks to its extraordinary strength (200 times greater than that of common steel employed in construction) and unusual physical characteristics.
5) In general, all the materials equipped with improved physical-structural characteristics thanks to the molecular manipulation at the nano-scale, which gives them properties completely different than those common in the solid state.
6) Already diffused as integration of building components to increase their inertial and thermal insulation capacity, or to improve the performance of technical solutions.
7) For more details, see the website: https://www.kth.se/en/forskning/artiklar/kth-forskare-har-upp-funnit-genomskinligt-tra-1.638511 [Accessed 7 April 2019] and Li, Y. et alii (2016).
8) For more details see the website: https://www.sefar.com/it/818/Product%2BFinder/SmartFabrics2.htm?Folder=6935656 [Accessed 7 April 2019].
9) About Hydroceramic, for more details, see the website: https://iaac.net/research-projects/self-sufficiency/hydroceramic/ [Accessed 7 April 2019].
10) For more details see the website: https://www.tudelft.nl/en/ceg/research/stories-of-science/self-healing-of-concrete-by-bacterial-mineral-precipitation/ [Accessed 7 April 2019].
11) Such as the prototype developed within the MSU, capable of absorbing sunlight without compromising the transparency of the system; for more details, see the website: http://www.sunwindenergy.com/photovoltaics/transparent-solar-windows) [Accessed 7 April 2019].
12) Developed by Nippon Electric Glass, it is an ultra-thin laminated glass that covers a resin film on one or both sides by means of an adhesive agent. The material obtained is lighter than a traditional glass with the same thickness and has greater resistance to abrasion, scratches and shocks, offering better sound insulation and greater resistance to bending compared to the resin singularly employed. The maximum achievable size is 1200x2400 mm in a range of thicknesses ranging from 1 to 20 mm.

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