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PRO-INNOVATION

PROCESS PRODUCTION PRODUCT

edited by

Giuseppe De Giovanni

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2

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Edited by Giuseppe De Giovanni and Francesca Scalisi

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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-

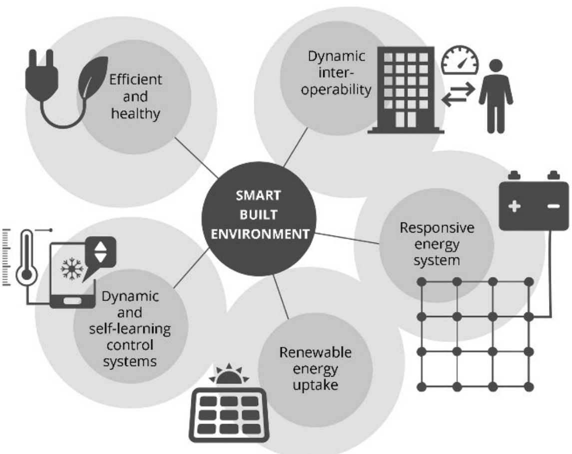


Fig. 1 - Foster and Partners, Ateliers Jean Nouvel and PTW Architects, Hanging gardens of One Central Park, *Sydney 2013 (credit: www.flickr.com, 2014).*

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

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

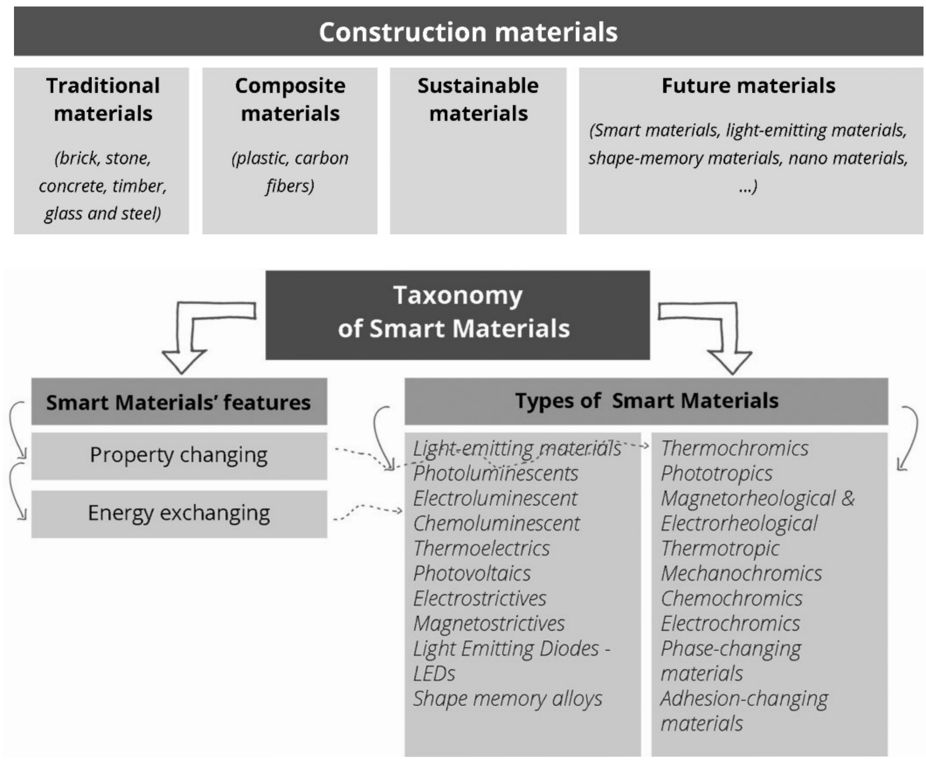
scious organism, possibly equipped with the chance to use intelligent sensors to operate within the following domains: i) different perception of individual comfort during the day and the year; ii) changes in building use; iii) variations in occupancy features; iv) changes in external weather conditions.

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.

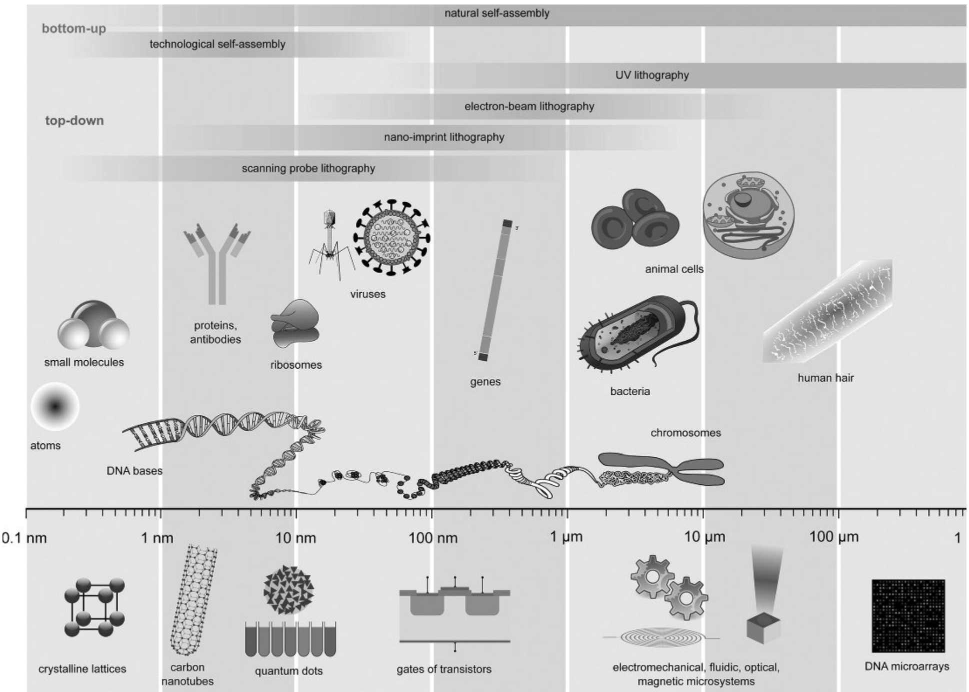
Existing technologies and their application potential – The recent innovations, in terms of both product and process, have led the technological industry towards the development of increasingly advanced materials and components, with a particular attention towards the environmental sustainability and 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).



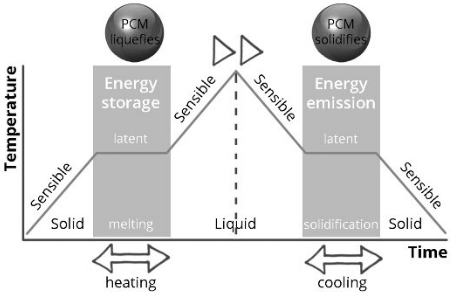


Fig. 8 - How PCM works (credit: authors' editing on the basis of Pazrev, 2014).

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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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).

In this regard, the book 'Pro-Innovation: Process Production Product' collects essays and critical thoughts, researches and experimentations 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, and 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.

Giuseppe De Giovanni, Architect and Full Professor of Building Construction at the Department of Architecture in Palermo (Italy), he is the Scientific Director of Agathón | International Journal of Architecture Art and Design, member of the Scientific Committee of the EdA Series | Examples of Architecture, member of the Italian Society of Architectural Technology, Chair of the Scientific Committee of INSA (National Sustainable Architecture Institute), Chair of DEMETRA Ce.Ri.Med. He carries out researches on transformation of the traditional approach and the study of technology, of traditional and innovative materials; temporary architecture and its many applications in the field of emergency, health and 'pleasure'; technological and domestic design of homes for elderly people with neurodegenerative diseases; design of products for the Design for All.

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