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# Smart Materials in Architecture: Useful Tools with Practical Applications or Fascinating Inventions for Experimental Design?

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**Abstract.** For at least several decades smart or so-called intelligent materials, being the result of great advancements in material engineering, appear in architecture in different applications. Most of them are called “smart” because of their inherent properties: a real-time response to environmental stimuli. There are also those considered to be “smart” due to smart design: their original structure or the composition of their materials are in nanoscale, providing them with unique properties. Colour changes, physical states, temperature or shape –always repeatable and reversible – make these materials attractive to architects, both from a visual and a practical point of view. Their spectacular applications often inspire architects, scientists and artists to create, for instance, city displays revealing various shapes and figures according to daily weather conditions; thermochromics urban seats that reflect peoples’ presence; wallpaper with organic patterns that glow in darkness, and many others. On the other hand, more practical projects are being developed, such as “switchable” partition glass walls (that is, we can turn them on and they change their transparency while switching on or off: electrochromic glass is a good example). Other concepts include self-cleaning building envelopes; self-repairing concrete; phase-changing materials diminishing cooling loads in the buildings; energy-generating highways; materials that harden at the moment of impact thus withstanding exceptionally great forces; shape memory alloys playing the role of actuators-opening and -closing façade louvers or thin polymer films mimicking the function of living skin, adopted as a building envelope. All those projects result from the fascination of designers with the possibility to create materials and, in effect, a complex environment that is active, “flexible”, and adapts to changing conditions and users’ needs and is compatible with real, natural environments. Smart materials that serve this purpose make such projects not only more unique and beautiful but, as their inventors claim, their application may bring real environmental and financial gains in the future. This article presents the most crucial, selected examples of such materials and examines what benefits they could offer.

## 1. Introduction

It may be stated that up to the 19th century materials in architecture were used, first of all, according to their functional properties, and secondly, because of their aesthetic features. Throughout history, in most cases, materials were rather subordinate to architecture. They followed the structure and function of the buildings. For centuries building technologies and construction methods were improved, but the materials used in projects were mostly traditional: stone, brick, wood, etc. Only since the Industrial Revolution took place may we observe an unprecedented change in the “world of materials”. Thanks to new manufacturing methods, mass production, the development of laboratories and the birth of material engineering as a new field of science, a vast realm of new materials appeared, and among



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them, “smart materials”. According to researchers they are “highly engineered materials that respond intelligently to their environment,” born as a response to the 21st century’s technological needs [1]. Building materials today are expected to be more multifunctional, having more selective and specialized performances, because architects are aware that ‘new science’ may provide it. In effect, designers do not have to accommodate to a material’s limitations but may choose high-performance materials that are “changeable and responsive to transient needs”, [1]. Most of such materials must have special, unique properties, which is why they are commonly called “smart.”

There are several definitions for smart materials, establishing that smart materials are those “that remember configurations and can conform to them given a specific stimulus (NASA);” “have intrinsic or embedded quick response capabilities;” “are designed in a way to have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields [2].”

More common definitions find them as materials and products that have changeable properties and are able to reverse their shape or colour in response to physical and/or chemical influences, e.g. light, temperature or the application of an electric field. There exists also the definition of semi-smart materials as those “that may change their appearance or shape in a response to a stimuli but only once or a few times [3].” Finally there is also a group of materials that are called “smart” not because of their ability for immediate reaction, but because of their “smart” design, the composition of their components, in most part in nanoscale.

Similar to smart materials are materials called “intelligent,” defined as “those materials which sense any environmental change and respond to it in an optimal manner (Rogers 1988).” They can be defined as “materials with one or more properties (e.g. mechanical, thermal, optical, or electromagnetic properties) [4] that can be varied in a predictable or controllable way in response to external stimuli, such as, for example, stress, temperature, moisture, pH and electric or magnetic fields (Mark Saxton 2010).” The term “intelligent” comprises the ability to respond intelligently and autonomously to dynamically-changing environmental conditions. What is emphasized in this concept of material intelligence is “seamless quickness- immediate action for specific response, [1].” Not every smart material has such abilities; that’s why we usually use the term “intelligent” to the structure that comprises actuators, sensors and a control system. The technologies encompassed by intelligent materials are very diverse and include: “fibrous materials, ceramics, photonics, micro sensors, microactuators, signal processing, piezoelectric, dielectric elastomers, biomimetic, shape memory alloys, neural networks, nanotechnology, conducting polymers, liquid crystals, biotechnology and information processing and many, many others[4]”.

To summarize those definitions, the term “smart materials” concerns both a set of molecules, a material, a composite, an assembly or a system and, as scientists declare, can be best characterized by their specific behaviour and the character of their response; this response should be immediate (they respond in real-time), transient ( they respond to more than one environmental state), self-actuated (intelligence is internal to rather than external to the ‘material’), selective (the response is discrete and predicable) and direct (the response is local to the activating event)[1].

Smart materials are seductive for architects and designers especially because, as it was mentioned, they react in a way that materials have never done before, in an active, reversible manner, presenting new properties and possibilities. We have high-tech “super alloys”, unique ultra-durable textiles, biopolymers or advanced glass technologies, colour or phase-changing materials and many others. Are they really what they promise? Which smart materials and solutions have validated, exist on market and are included into architects' practice? Which bring tangible benefits? Is the aesthetic potential of smart materials being exploited?

## 2. Smart materials-practical approach

The application of smart materials in architecture may bring real benefits. As scientists claim, the use of smart materials optimizes energy and matter flows [5], contributes to extending lifespan of building materials, and makes possible the creation of high-strength ultra-light structures. It would be very

fruitful to use them within many building solutions. Although it took a long time before smart materials “got away” from laboratories to architectural practice, now we can point to some ready-made smart solutions that have a great potential to become popular market products.

Interactive sun protection façade systems are one of the most popular projects that involve smart material solutions. This is the effect of the larger need to design more energy-efficient buildings that save energy, usually consumed for the most part by HVAC systems. The first sun shade facades appeared a few decades ago; just to mention two pioneers of this, we have le Corbusier with his brise-soleil at the Salvation Army Hostel in Paris or Fullers’ Geodesic Dome for EXPO 1967 in Montreal equipped with a complex system of shades used to control internal temperature. The second project was very sophisticated at that time, because it was driven by a computer and the textile shading hexagons were changing the position according to the trajectory of the sun. Afterwards, many other practical, stable or movable sun shade solutions appeared. Horizontal, vertical, manually actuated by users or equipped with sun sensors – all of them became common solutions in architecture.

Nowadays, we can observe that more and more shade systems, first taking the form of traditional sunscreens and blinds, are now being created using smart material solutions, relying on their inherent properties. One such system is the Homeostatic Façade System by Decker Yeadon that automatically adjusts to changing outside temperature or the amount of sunlight [6]. The smart solution in this case is based on the use of dielectric elastomers: polymer material that can be polarized by applying an electrical current delivered by silver electrodes coating the core polymer material. This set of materials is a smart composite in the form of a ribbon that is placed between two layers of glass and deforms when there is too much sun outside, thus helping to regulate temperature inside the building. This solution can be compared to “artificial muscles.” Movement is being provoked by the charge in the silver layers. Then, the core bends, similarly to muscles, pulling the elastomer material to one side, “closing up” the façade, thus controlling solar heat gains. This solution has a few positive aspects: it tries to reduce the need for energy-intensive, mechanical systems of artificial cooling, is energy-efficient (its dielectric elastomers consume very little power and are also flexible) and presents original design.

Another self-regulating shading system that potentially could play the role of a building envelope is an experimental, 20-foot tall installation by Architect Doris Kim called “Bloom” [7]. It takes advantage of another smart material, thermos-bimetal, also a composite consisting of different metals laminated together. As the temperature changes, the metals curl up or down - expanding at different rates, reminding one of a bird's feather. When opening or closing according to changes in temperature and light, the structure may play the role of sun shades or a ventilating system. Although this project is experimental the author is already working on integrating thermobimetals into various building components, like glazing or bricks. The essence of this project is a composite smart material made of two different metals laminated together, that enable the structure “to breathe”, and if it was a building envelope, to adapt to the environment through self-ventilation.

Most smart technologies perform at the molecular level, at nanoscale like among others, high-performance glass solutions. For instance, polymer films are anti-reflective, thermo-chromical, electro-chromical; mirror film, conductive polymeric film and many others are more or less common in the design and glass industry. But, still, under research are new functional solutions that could make glass facades an intelligent barrier able both to control heat losses and prevent overheating, all due to innovative, smart projects. One of them is a kind of glass composite that contains nanocrystals, small particles that react in a special way to light [8]. It helps to let through a window more warmth than common glass does while keeping it transparent. Nanocrystals are covalently bonded into an amorphous structure; thus in one material we have two functional components: tin-doped indium oxide nanocrystals and glass (niobium oxide glass: NbOx). The resulting material enables the dynamic control of solar radiation transmittance through windows by varying the applied electrochemical voltage over a range of 2.5 volts. These transparent films can block near-infrared and visible light selectively. Such glass splits heat and visible light which can be controlled by the user.

“Smart” pertains not only to materials and composites but also to whole structures. Popular smart structures in architecture often take the form of dynamic, responsive façade solutions focused on sun protection and solar gains (relying on solar sensors that detect UV radiation and interactive systems that actuate movement of shade louvres). Although many smart façade solutions have been already created, research is conducted all the time to make the whole building more energy efficient and more symbiotic with the environment. Such experimental façades composed of “integrated concentrator solar modules” have been developed by architects at Materialab, an interdisciplinary research firm from Rensselaer Polytechnic Institute in Troy, New York [9]. The lenses integrated into an inverted pyramid track the trajectory of the sun to catch the largest amount of sun rays. Solar concentrators that are transparent comprise Fresnel lenses and photovoltaic cells. They are mounted in vertical arrays and assembled between two panes of glass to protect them from damage. The system of pyramidal lenses tracks the movement of the sun, capturing more sun rays than traditional photovoltaic cells do. These high-tech solar cells convert 30 percent of the sun’s light to electricity and absorb 50 percent of its energy in the form of heat, far more than traditional solutions. Research tests show that such a “system could supply as much as 50 percent of the energy for a building’s operational needs”. Thanks to the integration of innovative technologies the absorption of energy optimises and is ready to become a part of an ecological HVAC building system. A key issue in such projects is multidisciplinary work. In this case it was necessary to integrate emerging technologies from the field of nanotechnology, electrical engineering, mechatronics and others. As a result, one hybrid ‘smart’ system working harmoniously with the changing climate conditions and users’ needs was achieved.

Thanks to such scientific research in various fields it became possible to create a Hybrid Solar-Thermal Façade that also relies on linear concentration, instead of pyramidal elements comprised of thin plastic with Fresnel lens curved in a plastic sheet, integrated with the glass layer [10]. A Hybrid Solar-Thermal Façade is a kind of “light farm” that serves to collect light rays which are transformed into heat or electric power by CPV photovoltaic cells. CPVs are highly efficient, multi-junction (MJ) solar cells that make use of solar trackers. An active tracking system is comprised of active solar sensors deployed on the louvre surfaces, with drivers and actuators of very low energy consumption. The great advantage of this system is high efficiency (min 50% combined heat and electricity) and, what is worth mentioning, aesthetic aspects (ordinary photovoltaic panels are unified and black). Because Fresnel Lenses that are used for this structure as a kind of magnifier, they are unable to achieve original optical patterns on the building envelope. By placing a small design motif around the focal point of the lens it is possible to create original optical illusions or any other façade patterns [11].

Analysing smart material's practical applications, within glass, translucent, and ephemeral materials, we may distinguish them from a strong group of “hard”, cement-based materials that have undergone serious and effective research. The same criteria concerns both: tensile and flexural strength and aesthetic features. Because concrete and other cement-based composites comprise one of the largest groups of building materials in the world, there is a great effort made to improve its properties to make it more 'smart'. One of the most well-known effects of this research is self-cleaning concrete, which has become a common, very useful and practical commercially-available solution [12]. What's so smart in this invention is the use of photocatalysts: Titanium oxide (TiO<sub>2</sub>), that decomposes organic and biological materials and pollutants (soot, grime, oil breaks, mould, algae and bacteria, volatile organic compounds and tobacco smoke), and breaks them down into molecules that are “either beneficial to or have a benign impact on the environment.” Because Titanium oxide is a semi-conductor, “the energy from light causes the TiO<sub>2</sub> to create a charge separation of electrons, which disperse on the surface of the TiO<sub>2</sub> and react with external substances, decomposing organic compounds.” What is also very practical in self-cleaning concrete is that its white colour reflects the sun thus helping to reduce heat gains and the use of air conditioning, making buildings more energy-efficient. The latest research developed by TU Delft is the wide Self-healing Materials research programme at the Delft Center for Materials (DCMat) together with the Biotechnology section at the Faculty of Applied Sciences and the South Dakota School of Mines in the United States, informing about calcite-precipitating bacteria that could help repair cracks in concrete, especially where the



structure is in the ground or retains the water [14]. The potential application of self-healing concrete would also contribute to the reduction of steel reinforcement. Meanwhile the research team is working on creating the right conditions for the bacteria to produce as much calcite as possible, and on optimizing the distribution of food for the bacteria, as they examine their behaviour during temperature fluctuations or other mechanisms during deterioration that may affect them [13].

Lots of efforts related to concrete are being made to improve its physical and mechanical properties, its toughness and versatility. Control of the composition of water-to-material ratio, the analysis and invention of special additives, the methods of mixing and moulding – all that makes concrete look and perform in a way newer than it did before. Such materials as Ductal concrete, ECC (Engineered Cement Composite), bendable concrete or Litracon transparent concrete – all of them are called “smart” not only because they are able to respond in real-time to external stimuli but very often because of their smart design and unique internal structural design based on nanotechnology achievements. Such a material is Ductal [14], ultra-high-performance concrete. Its unique properties are both strength, ductility, durability and aesthetic design flexibility, achieved mostly thanks to the high carbon metallic or poly-vinyl alcohol (PVA) fibres blended into the concrete mixture. Ductal concrete strength is 6 to 8 times greater than that of conventional concrete. Its longevity is 2 to 3 times longer than that of conventional concrete because it is much more resistant to external aggressions (abrasion, pollution, weathering, scratching) than traditional concrete. Thanks to these advantages load-bearing elements can have thinner sections (comparable to the steel sections), curvilinear, sophisticated shapes may be achieved, and some spectacular curtain wall, latticework, and bridge walkways may be designed. The smart design of Ductal also contributes to reduced global construction costs, form works, labour and maintenance-extended usage life.

Searching for new ultra-light and significantly strong materials other than concrete, researchers are investigating the use of graphene [15]. The problem is that although graphene is thought to be the strongest of all known materials, being a 2- dimensional form of carbon, it was problematic to design graphene 3D structural systems. But now it may soon seem possible thanks to researchers at MIT who have developed a 3D form of graphene that can be ten times as strong as steel, but much lighter. Researchers realized this idea of a 3D model by compressing small flakes of graphene, using a combination of heat and pressure. The resulting structure of curved surfaces being the geometric arrangement of the graphene flakes under deformation, designed similar to natural coral formations, is very strong and stable. Once again it may be repeated that term “smart material” concerns not only a single material but also a structure, whose design is considered to be “smart” – as it is in this case of the spatial conglomerate of graphene flakes.

As we may observe many smart materials may be very useful for building structure, interior design, and façade solutions, but the research is also moving forwards, to include them into public spaces and infrastructure. Researchers have developed innovations – smart materials embedded into roads that would collect data, for example, asphalt informing about cracking, pavements generating electricity, highways signalling about changing weather conditions and other applications. Scientists from the Delft University of Technology are working on Radio Frequency Identification (RFID) sensors that could be used to monitor and keep relevant composition, construction and performance data. The aim of TU Delft was to examine if RFID are small and robust enough to use it as a part of an asphalt structure and “if they could withstand high asphalt mix temperature, heavy pressured roller compactors and resulting shear stresses between aggregates.” They began their research on temperature and pressure sensors, but the objective is to monitor data during asphalt construction as well as during a typical life cycle, to have information available “on the spot.”

Another smart road solution concerns the idea of creating an interactive highway that would include “smart lighting, energy harvesting strategies and traffic signs that adapt to changing road conditions.” Working together on the Smart Highways project, designer Daan Roosegaarde and the Dutch infrastructure company Heijmans are developing proposals for roads that would be comprised

of glowing-in-the-dark road markings, interactive street lights, battery-charging e-lanes, illuminated weather warnings, and much more [16]. Their goal is to make the road more sustainable and interactive by the application of smart materials and smart technologies. One idea is to make green photo-luminescent markings, charged by sunlight during the day, and painted onto the road surface as lane indicators and emergency shoulders. Photo-luminescent paint would improve the visibility of road signs at night. Another option is the use of thermo-sensitive paints that would reflect strong weather conditions through snowflakes appearing on the road when the temperature falls below the freezing point. There are also more extreme ideas as, for example, road surfaces made out of solar cells, not only providing electricity but also melting winter snowfall (thus reducing road accidents) or priority highway lanes that can charge battery-powered cars in motion by using underground induction coils. These ideas have already been implemented on a small scale: on footpaths and cycle paths which are in the test phase at the moment.

### 3. Aesthetic potential of smart materials

Smart material solutions present a great realm of new aesthetic effects and make a tempting and inspiring field of inspiration for architects, designers and artists. They change colour or appearance, are able to emit sound and odour, reveal refined patterns (see Fig.1b), change shape, and are able to produce kinetic movement or display interactive images. With their special aesthetic features they attract the attention of building users and public space participants, being more noticeable than other more functional smart solutions. There are more of these kind of solutions in architecture, art and design because they are more simple and require less effort to make experimental surfaces or sculptures than laboratory-tested smart products for mass use. An important aspect in favour of the creation of aesthetic smart projects is that historically artists were always willing to search out new methods of expression that were not exploited before [17].

One of the first projects involving smart materials was light-emitting art such as the Schattenwand mit Blitzelektronik by the German artist Konrad Lueg, involving phosphorescent paints. The project was in the form of a screen excited by a flashgun which made it phosphoresced. In addition, objects or people passing between the screen and the flashgun could “leave” their shadow. Another early “smart” artistic project was a colour-changing wall made by Sigmar Polke for the Biennale in Venice, Italy in 1986. The author covered the conch of the pavilion of the Federal Republic Germany with hygro/hydro-chromic paint consisting of water-bonded cobalt chloride. Colour changes depended on the degree of air humidity and oscillated from lavender-blue in the unsaturated state, to purple, then to red in the saturated state [17]. There are many modern artistic realizations making use of similar technologies, just to indicate a few; for example, luminous wallpaper – Filigree Wallpaper designed by Julite Quintero, painting a solution made of egg whites, icing sugar, hot water and phosphorescent pigments; light installations in the Hotel Teufelhof in Basel (1994) representing artistic interior drawings created from a mixture of fluorescent and phosphorescent pigments; or Starpath elasto-meric coating with additives that absorb and store energy from ambient light during the day, and releases this energy at night. The latest smart paint solution is interactive paint called WallSmart by designer Jonas Enqvist, that allows changing the colour of the walls in the home with a smart phone due to nano-particles added to the paint. Thanks to those nano-particles and RGB LEDs connected via Bluetooth to an Arduino, the user has the ability to change the colour of a surface by selecting an alternative colour through a WallSmart application [18].

Light-emitting smart materials that become excited by the effect of energy, light or an electrical field to perform make use of various phenomena such as photo-luminescence, bio-luminescence, electro-luminescence, chemo-luminescence and others. But, there is also a large group of architectural projects that involve a very interesting class of smart materials that undergo optical changes or colour changes, which may be a result of a chemical reaction inside the material structure or just depending

on the view angle. Although the second group of materials are not really “smart” because they stay static, their internal structures remain unchangeable, and they present aesthetic effects which are worth mentioning, becoming popular in architecture. These are, for instance, dichroic, holographic materials and polymer films that in the recent years are often included into façade solutions. The most spectacular projects of this kind are the Harpa concert hall and conference centre in Reykjavík, Iceland, the La Defense office building in Almere, Netherlands, the façade with holographic glazing at Augenfeuer in Bonn (see Fig.1a), and the Dichroic Light Field's installation of glass fins in New York.

One of the most spectacular and aesthetic smart solutions in architecture are interactive facades that emit light either by reacting to external stimuli or from physical movement. The first group are often called media façade because they display various refined animations or low resolution patterns both during the day or night. The second group are kinetic structures: 3-dimensional, textural building envelopes. Both of them are being designed all over the world constituting a strong group of realization that dynamically respond to the environmental impulses coming from both the surrounding natural environment (changing weather conditions) and impulses “emitted” by a living city

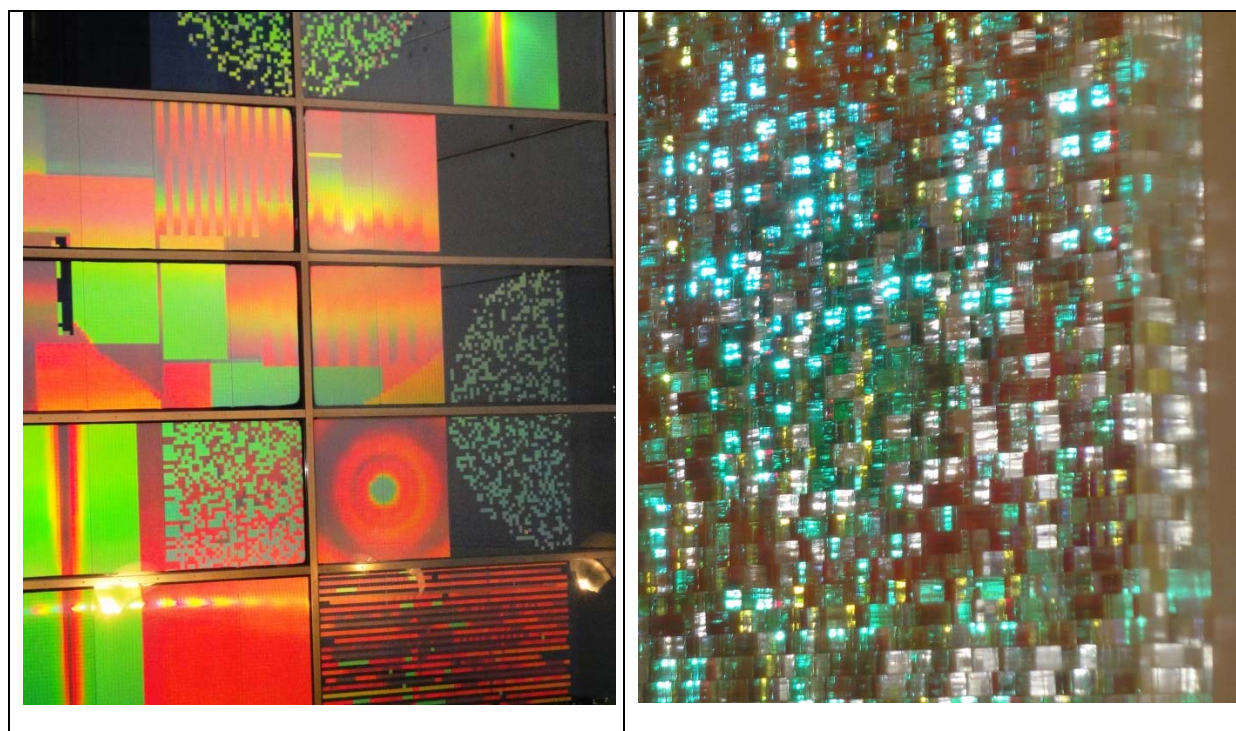


Figure 1. a) Façade with holographic glazing Augenfeuer in Bonn. b) Sensitiles system light reflective polymer panels.

### 3. Conclusions

Smart materials constitute a large, heterogeneous and still widening group of materials in fields of interest to architects and designers. Greater possibilities that bring the development of nanotechnology result in an increasing number of new and arriving smart architectural solutions. As specialists we claim those materials may change the future of buildings, making them more efficient and sustainable, making them more “intelligent” and adaptive to the environment we live in. They become more specialized, invisible and also more multifunctional. On the other hand, materials being one of the richest sources of innovation today, they are no longer intended for practical use alone but are “playing an important role in taking aesthetics forward [19].”



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