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Current Trends And The Future For Intelligent Facades: A Review

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Abstract
Buildings play a significant role in shaping the lives of people around the world and research on how to make them healthy, comfortable and sustainable is central to scientific research in the past decades. Driven by recent evidence about climate change and the global energy crisis, buildings are identified as an important consumer of energy and resources worldwide. In this context intelligent buildings have been put forward as an alternative to introduce high efficiency and effective use of resources, by making use of the latest technological developments, collaborative design and organizational conceptual methods. This paper focuses on intelligent building facades as the main multifunctional element of the building filtering light, heat, air, water, and offering connectivity, adaptation and aesthetical pleasure from the inside and the outside. The latest trends in intelligent façade design worldwide are presented through a series of built example buildings, including kinetic adaptive façades, interactive facades, bio-facades. The issues addressed are the role of nature in design, the use of renewable resources, the methods of adaptation and interaction between buildings, occupants and the environment. Opportunities and challenges related to the future development of intelligent facades are analyzed and a direction for future research is proposed.

Keywords
Intelligent facades, Adaptive, Interactive, Kinetic, Biofacades

1. Introduction- Methodology

The concept of intelligent buildings that use technologies, design and organizational conceptual methods to optimize the use and energy performance of buildings is identified by several researches during the last decades as a driver for the future of buildings. A significant amount of research on intelligent buildings the past few decades is focused on intelligent facades, as the main multifunctional element of the building providing the filter of light, heat, air, water. This paper aims to identify different approaches and trends in the field of intelligent facades, focusing mainly on the design concept, and to offer the opportunity to the reader to follow the ideas from scientific research to actual architectural projects adapted to a particular framework (site, climate, use). As technical details of built projects are often not publicly available or published in academic literature, this paper includes also information gathered from architectural journals, conference proceedings, video portals, designers and scientists' websites, interviews and e-mail correspondence of involved professionals with the author.

2. Definition

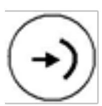
Several researchers in the field of intelligent facades presented and analyzed methods to define, categorize, and evaluate intelligence; and identified it in different aspects of the building's life, from the perception to the maintenance and use. Continuous changes in the context of intelligence over time and space explain the range of definitions and their divergence, depicting different aims, backgrounds, beliefs;

according to Wigginton and Jude's research (2002) there are 30 different definitions of intelligence in buildings.

Intelligent is one of the terms used to describe a concept that is referred to with a wide vocabulary, including a multitude of different terms; smart, digital, cyber, sentient, sustainable, green, adaptive, interactive, responsive, advanced, dynamic, kinetic, automated, high-tech, integrated; and is practically considered a progression from these concepts and an umbrella concept for them. This range of used vocabulary is introducing great difficulties in researching for the application and development in the area of intelligent facades, classifying and comparing the performance of built examples. An analysis of intelligence is provided by Himanen (2004 as cited in Clements Croome, 2004) who identifies specific characteristics derived from characteristics of human intelligence and human sciences: building self-recognition, an 'understanding', with the building identifying its status, building- connectivity, a 'language' to communicate with the user including control systems, music and linguistics, building logic, with monitoring and 'learning' by embedded sensors, and building kinaesthetics, the active, moveable structures that offer the adaptation of the building function in response to different requirements and stimuli. Ochoa and Capeluto (2009) define intelligent facades as those that respond dynamically to demands posed by outside environment and inside occupancy, following energy-conscious principles and maintaining user comfort.

For the needs of this paper we define intelligent façade as following: "Intelligent façade is one that is designed to use in the optimum way the combined functional and physical characteristics of its components, active and passive, in order to recognize its status and adapt to environmental conditions and performance requirements; aiming to achieve higher user satisfaction and quality of living, in building and city scale, and better use of energy and resources during the whole building's life cycle."

Intelligent facades systems and technologies have been classified by researchers under different terms according to general characteristics and properties like thermal, mechanical and optical or according to the innovative systems and technologies they incorporate (Loonen, 2010; Wigginton & Harris, 2002). This paper uses the following four key ideas to describe the concept of intelligent facades and evaluate intelligence in the level of design intention for the presented examples:

Adaptability  Self-recognition- Interaction, 

Combination- Synergies,  Energy generation- Total Sustainability. 

Figure 1. Symbols of main characteristics of intelligent facades. Author 2013.

3. Adaptability

The first idea described here, adaptability, is fundamental in recent research and is defined by Ferguson et al. (2007 as cited in Loonen 2010) as 'the ability of a system to deliver intended functionality considering multiple criteria under variable conditions through the design variables changing their physical values over time.' Developments in the field of intelligent adaptive facades are in different scales, the macro-scale, the micro-scale and the nano-scale. A great source of inspiration for the development of intelligent facades is nature, where adaptation to the environment is achieved with numerous different ways and in different time scales, including color and shape change, hierarchies, integration of elements, optimization by trial, evolution and growth (Gruber, 2014; Zari, 2010). A significant role is also played by recent developments in sensor technology and electronic control.

In the area of built-examples that provide sophisticated adaptive behavior the majority of the systems identified in academic literature, architecture journals and websites are kinetic in macro-scale with centralized control systems. This method introduces moveable parts that provide dynamic control of daylight, ventilation and insulation properties (Gruber, 2011). Several researchers have identified numerous examples of this type worldwide, with the most well-known probably being the Arabe Institute du Monde by Jean Nouvel in Paris. A representative example of this approach is the One Ocean Thematic Pavilion in South Korea by SOMA architects, incorporating an innovative kinetic shading façade system to control the daylight levels and the solar gains inspired by nature (fish gills). (Knippers, 2012, figure 2). In the classification of adaptive systems of this kind special attention should be paid to avoid presenting examples where the design idea is derived from exclusively morphological criteria and is not adapting either to the environment or the occupant behavior and preferences therefore doesn't meet the criteria of intelligent facades definition given here. Examples of this trend in building fabric design are the Hemispheric by Santiago Calatrava in The City of Arts and Sciences in Valencia and the London Aquatics Centre by Zaha Hadid.
On the other hand there is the micro-scale of materials when no observable motion is detected and the adaptation is based on the changes of the materials' characteristics (thermophysical, color, texture) for example the photocromic glass that changes color according to the radiation. The developments in material science led by nanotechnology, 'the study of the control of matter on an atomic and molecular scale' offer yet unexplored potentials of embedded nano-devices into materials, phase change materials, breathing walls, graphene, photochromic, thermochromic and electrochromic glass (Pacheco-Torgal & Jalali, 2011). Built examples of adaptive behavior in micro or nano scale are less in number and size and mainly restricted to pilot studies and installation of "smart" glazing of different kinds. One example of such application is the U.S. General Services Admin in Washington, DC by Shalom Baranes Associates where electronically tintable glass was used in the façade and the atrium glass.

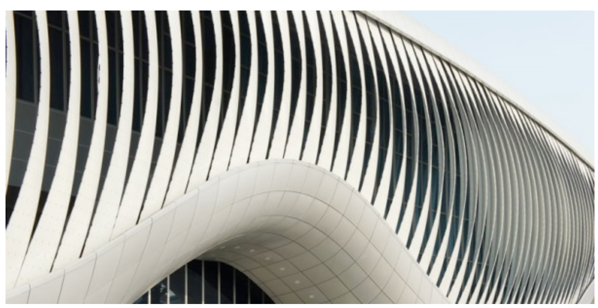


Figure 2. Kinetic system concept. (Knippers & Speck, 2012)

4. Interaction- Self-recognition- Learning Ability

The origin of the term "façade" is derived from "facies" (lat. face), which implies convertibility, adaptability and responsiveness to external influences, like it is the case for human faces (Sauter, 2008). Interaction in façade level is usually associated with media facades, advertisement and art. According to Schmidt and Wachlowski (2011) the interactive media facades are categorized in four types according to the way they act and interact in urban spaces: 1) Sender-Recipient-Mode / it displays certain pre-defined contents, mostly for marketing purposes. 2) Interactive-Mode that allows direct communication with the façade via a mobile phone and aims to attract the public audience and involve them in their life program. 3) Environment Mode / Reactive Mode that presumes the media façade to react actively to external triggers like weather, traffic, temperature and light, using sensor technology. 4) Organicistic Mode that postulates an "intelligent skin", which might be driven by a kind of artificial intelligence, is collecting various parameters from the surroundings and could also create connections between buildings.

In the context of intelligent facades communication between the users, the façade and the environment are the most important types of interaction. Several examples of interactive media facades are identified in literature: one of the first was the "Tower of Winds" in Yokohama a 21 meter high ventilating that transforms measured wind-strengths into various light animations on its surface (Wachlowski, 2011). More recent examples are the GreenPix zero energy Media Wall by ARUP, incorporating PVs to generate the energy used by the LED media façade (Menzel 2012, and the Homo Lumens MMVII by László Benczúr, Péter Sugár, and László Kara in Hungary (Wachlowski, 201). The penetration of information and communication technologies (ICT) in everyday life, makes now possible the organistic mode, where a central system collects data by environmental and personal monitoring, use wireless sensor networks to communicate and respond to conditions in order to create more comfortable, interactive and energy efficient spaces, based on personalized data and preferences.

Figure 3. Front view. Anon(2008b)

5. Combination- Synergies

An important aspect identified by several researchers in the definition of intelligent buildings is the fact that they should not just be a collection of smart technologies, but an integrated sustainable system that 'combines the resources of a number of individual systems so that when controlled cooperatively and work together, they achieve more than the sum of their parts' (Ochoa & Capeluto, 2009). This idea of introducing synergies in the design is highly dependent on the successful communication and collaboration between professionals of different disciplines. They require interdisciplinary and multi-industrial engineering, the combination of 'architecture, structure, building services, information technology, automation, facility management' (Vallero & Brasier, 2008). The new approaches to design and modelling, including thermal analysis and energy behavior affect the core processes of design and architecture and the increasing role of teamwork and the rapid development of collaboration design tools (Building Information Modelling) will provide the frame for the future synergetic- collaborative projects. Although the true potential of these tools is yet to be unfolded, in the time being several projects worldwide became possible by the use of collaborative and energy modelling tools offering the opportunity of international design teams of experts and estimations of benefits of different ideas. An important example between these is the Bio-Intelligent Quotient House in Hamburg Germany by Splitterwerk architects and ARUP that is going to be described in detail in section 7.

6. Energy Production- Total Sustainability

Sustainability is identified as a fundamental idea related to building's intelligence by several researchers and it is defined as good resources management, in terms of energy, materials, water, waste, human resources, as well as social, cultural and economic viability, and whole life-cycle analysis and the performance evaluation (Clements- Croome, 2013). The building façade plays a significant role in the amount of energy balance of the building by means of control of daylighting, and ventilation in the building and is also providing the maximum opportunities for energy production on site via integrated to the building fabric systems based on renewable resources (sun, wind, water, air). The technology of façade integrated photovoltaic cells has been used in several buildings and is now considered mature. Several examples are identified in literature and one of the most characteristics combining kinetic system with integrated photovoltaics is the EWE arena by ASP Architekten in Oldenburg, Germany where the integrated photovoltaic shading system creates a temporary double skin façade that moves around the building to the location where it is desired (Weller, B. and Jakubetz, S, 2008 as cited in Loonen 2010). A relative new idea related to energy production at building level is integration of façade components using biotechnology to produce energy, like the Bio-Façade in the Bio-Intelligent Quotient House in Hamburg described below.

7. Example- Synergies- Collaborative Design- Energy - Bio-Intelligent Quotient House

The first built example using biotechnological elements as an energy source at building scale is the Bio-Intelligent Quotient House in Hamburg, Germany. The 5 storey residential building is a result of a two-stage competition to design innovative projects for the International Building Exhibition (IBA) in the district Wilhelmsburg. The winning solution 'Smart Treefrog' by the design team of Splitterwerk architects, ARUP, Strategic Science Consult (SSC) and Bollinger und Grohmann proposed the use of microalgae bioreactor technology to filter light and produce energy, introducing synergies with building services systems like space and hot water heating (Roedel & Petersen, 2013). Part of the original idea was to use the bioreactors in front of openings to control the daylight, however it was abandoned due to the risk lying with occupants' perception. In the center of the conceptual idea are the intelligence of the natural processes and nature as inspiration and unlimited resource, and the dynamics of the natural cycles (ARUP,2013). Microalgae were selected due to their quick response to environmental conditions, offering an almost direct response to the changing transmission of radiation. The façade system consists of 129 flat panel uplift algae bioreactor units mounted to a structurally independent steel frame (figure 4). Each unit is a multiple monolithic glass system that provides space for the growth of microalgae and it is connected to a closed loop central management system. When the sun hits the bioreactor units two energy cycles begin: Firstly as the flat panel bioreactor absorbs the sunlight, it heats up to 35°C, this heat is extracted by a heat exchanger and the thermal energy is used for solar water pre-heating and space heating or stored in the geothermal bore-holes' buffer storage of the building or the district heating scheme. Secondly the algae multiply and produce biomass, that is collected, filtered, stored in temperature-controlled collection tanks and transported to the local heat and power plant were it is used to produce biogas with efficiency 70-80%. After the microalgae are harvested the medium is returned to the bioreactor unit and a new cycle begins.

Figure 4. BIQ. Southeast facade. Author (2013)

The required high levels of control to the internal conditions in the bioreactors for the survival of algae, and the need to integrate the biofacade with the building services and other energy systems to achieve the synergies described above introduced the need of a sophisticated central building management system (Rockwell SPS). This almost fully automated system monitors and controls all the bio-chemical processes, the algae cell density, the temperature in the culture medium, and the orientation of the elements towards the sun, provides the necessary nutrients, compressed air to generate water flow and turbulence of high velocities and CO2 in the form of fuel gas, and harvests the microalgae. The high level of monitoring and control of the system introduces opportunities for an optimization process that can offer benefits to both users and facility managers but also imposes a high risk of failures due to the complexity (Summer 2013, Author observation, SSC 2013). The use of materials, that can be recycled at the end of their life and can be easily disassembled and transported to different locations for the bioreactor façade system, works towards a sustainable whole life building cycle. Two fundamental issues for the design of intelligent facades were identified in the design process as it was described by the involved professionals (SSC,ARUP, 2013): The first is the collaboration between scientists of different disciplines, architects, biologists, energy consultants, façade engineers, and the effective communication. The second is the importance of initiatives promoting innovative projects and the competitions to achieve the optimum result and challenge designers to exceed their limits.

8. Some Future Developments

Following this brief analysis of the fundamental ideas identified in intelligent facades research and the description of built examples, the focus of this paper is transferred to prototypes and ideas that have yet to be developed but offer a clear indication of how the future for intelligent facades might look like.

In the field of adaptation there is a great amount of new systems and ideas that are coming to light suggesting an expanding field of research and indicating a change towards smaller scales of units and adaptation at material level. The ideas of shading elements are combined with phase changing materials and PV's to provide more efficient systems like in the case of the proposal in Solar Decathlon, named Eclipsis shutter shade which is filled with aerogel, providing shading and insulation. Smart glazing and breathable walls inspired by nature are in the centre of new ideas: Representative examples of these concepts are: For smart glazing, GlassX crystal that integrates four functionalities into a single unit: transparent insulation, overheating protection, energy conversion and thermal storage, by using a phase change material in the glazing panel (Ritter, 2007). For the breathable walls concept are the examples of the Stomata inspired skin and the Bionic Breathing Skin that use physical properties of material and piezo-electric actuators respectively to increase and decrease air flow though the façade (Gruber, 2013).

The current trends in energy production at building level include a)exploring already established ideas like building integrated PV's and wind turbines in different scales and combined with kinetic systems; and b)introducing different energy producing systems like algae. Microalgae technology is an important trend identified in several new building designs and concepts and it can introduce several synergies from its use in industrial and commercial buildings design or large scale applications (district level) (ARUP,interview 7/8/2013). A similar approach to energy generation in the building facade level is the development of a hydral bioreactor to produce hydrogen. The artificial leaf project, firstly produced by Dan Nocero at MIT (now at Harvard) in 2011 is a simple catalyst-coated wafer of silicon, that when put in water and exposed to sunlight, breaks down water into its components, hydrogen and oxygen that can be collected and used as fuel to produce electricity in fuel cells (Nocera, D.G. 2012). Clement Croome (2013) proposes the placement of a series of artificial leaves in a water wall that similarly to the algae façade will use daylight to produce energy.

In the field of interactive facades and learning abilities, recent research focuses on aspects like the kinetic elements and the interaction with the user and the environment. At MIT, Harrison Hall, Rogen Lonergan, Kent Larson and Shaun David Salzberg has developed a robotic facade that interacts with the user and the environment to save energy and meet the users lighting requirements (TED, 2012). Research on similar direction includes the Paratonic facades of the Yazdani Studio that introduces sensors that vary there aperture level according to temperature and solar radiation (Yazdani Studio, 2014); and the Flare façade, environmental reactive type, reflecting the ambient and direct sunlight and controlled by individually controllable pneumatic cylinders (Klooster, 2010).

9. Discussion- Conclusion

This paper established a definition of intelligent facades and reviewed and critically presented built examples and presented scenarios for future developments in the field of intelligent facades. To summarize it is important to keep the concept of intelligent facades separate from the idea of smart facades, suggesting a more wide definition that includes revisions and synergies between well-known tested systems with proven benefits like green facades, double facades and PV's and innovative systems like microalgae bioreactor technology and façade embedded devices, aiming to achieve the highest benefits in building performance and user satisfaction. Recent developments in communication, designing software and sensing technologies and material science are identified as important drivers of change for the future of intelligent facades. Although research in this field is rapidly expanding there is still little evidence and publicly available data on the actual performance of these systems and very few applications of the ideas described above in real projects.

The importance of bridging the gap between the design professionals and the scientists is fundamental for the development and expansion of intelligent facades' concepts in practice. Therefore it is necessary to form multi-disciplinary teams that will be able to develop new ideas and optimize existing, inspired by nature and recent scientific developments, and provide a comprehensive guide for designers presenting full concepts with technical details of systems under a classification system that follows design ideas and intentions. The four ideas used in this paper could offer a base for the classification of projects and the development of a guide for the researcher and designer to test their ideas and compare them to different concepts. This guide in the form of a global platform-database needs to be open to public, and provide easy to understand visual information.

Taking into account the method of realizing the prototype built examples, especially the close connection with public research funding, it is fundamental for the development of intelligent facades to secure the support of governments globally. This support is necessary from the conceptual stage to the application of these ideas in order to mitigate the risk related to applied innovation in the built environment. Initiatives like the International Building Exhibition (IBA) in Hamburg give great opportunities to designers to develop a vision for a different way of living and apply their ideas away from the limitations opposed by the conservative traditional construction market.

An important aspect influencing the future of intelligent adaptive facades is the matter of occupant control and satisfaction. Although occupant dissatisfaction related to automated control of thermal conditions, lighting and shading has been identified by several researchers as one of the most important risks in the operational phase of buildings with intelligent adaptive facades there is very limited evidence in literature of proved negative or positive results. Most of research is associated with automated blinds and suggests high intolerance to fully automated systems with no control override (Bakker, Hoes-van Oeffelen, Loonen, et al., 2014). Therefore there is a need for further research and a design process that aims to simplicity in the façade actions movements and controls to facilitate the operational phase.

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