

Dynamic Adaptive Building Envelopes – an Innovative and State-of-The-Art Technology

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Abstract: The building envelope has a key role to play in achieving indoor comfort for the occupants and building energy efficiency. A dynamic, active and integrated solution -- able to achieve the optimum thermal performance, harness energy from renewable resources and, integrate active elements and systems -- is the most promising and innovative strategy for the building envelope of tomorrow. To achieve an effective and sustainable building envelope with a dynamic behaviour, considerable efforts in research and development are necessary. This paper endeavours to present a broad review of design, research and development work in the field of Dynamic Adaptive Building Envelope (DABE). Based on detailed studies, the characteristic features, enabling technologies, and the overall motivations that have tendered to the advancement of DABE are discussed. In spite of its positive aspects, the study reveals that the concept of DABE has not yet been well-applied and needs much more exploration. Various challenges need to be resolved and advanced research undertaken to bring it to maturity and acceptance.

Keywords: Dynamic Adaptive Building Envelope; Building Management System; Kinetic Façade; Actuation

1. INTRODUCTION

Since the Stone Age, human beings have sought shelter that would protect them from the external environment and offer comfort conditions. Initially the concern was safety and security but soon it was realised that this shelter can be an effectual measure to achieve thermal comfort inside. To improve this function, it became necessary to focus on the building envelope considering the fact that this building element, which further consists of a set of components, separates the outdoor from the indoor. The basic thought was to create a

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protective cover which is capable of shielding the building, its occupants and its contents, from the extreme and sometimes hostile climate outside. As an outcome, optimisation of the ‘separation effect’ became the primary objective of architects and engineers, as it has been for centuries [18].

The building envelope, or ‘skin’ as it is also known as, is that part of the building which encloses space, separating the inside from the outside. It, thus, comprises those elements which are constructed to divide the internal from the external environment and, consists of structural materials and finishes and include doors, windows, walls, floor surfaces, and roofs -- the transparent as well as the opaque elements. The basic function of the envelope is to balance the building requirement for daylight and ventilation while taking care of moisture and thermal protection pertinent to the micro-climate of the place where the building is located. The design of building envelope plays a major role in determining the operational energy usage of a building during its lifetime. Moreover, the embodied energy and the overall environmental life-cycle impact of various envelope materials differ significantly.

Climate is the one of the primary factors which affects the design of building envelopes. Different climates will suggest different design strategies and solutions, and, for a given climate, specific designs and materials are required. Therefore, keeping in mind the need for designing the whole building as a single unit, the architect should integrate the envelope design with other design elements like proper natural lighting and other passive solar design strategies; appropriate selection of materials; heating, ventilation and air-conditioning (HVAC) and passive cooling techniques; energy saving measures; and project performance goals [2].

It is time to have a closer look at the impact that buildings have on the environment and how we can make good use of new technologies to create more adaptive building envelopes. Today, we have facilities for appropriate designing of building envelopes that can reject or accept free energy available from the external environment, thereby reducing the costs required to achieve a comfortable, internal environment [9].

2. DEFINING ‘DYNAMIC ADAPTIVE BUILDING ENVELOPE’

Dynamic Adaptive Building Envelope (DABE) is a nomenclature used in building science and engineering to include the roofs and the façades which relate with their variable environment in a dynamic way [4]. There are several variants of the terms ‘dynamic’ and ‘adaptive’ such as ‘intelligent’, ‘kinetic’, ‘smart’, ‘active’, etc. Although the exact meaning of each term differs, they are often used interchangeably.

Loonen, *et al.*, explain the concept and characteristics of DABE as: “A *dynamic adaptive building envelope has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.*” [13].

3. THE NEED FOR ‘DABE’

Conventional buildings, having static building envelopes, cannot respond to the continuous environmental changes outside and the requirements of the occupant inside. On the contrary, dynamic buildings are designed to adapt to the continuous changes of the external environment. These changes can happen on a daily basis or on an annual basis. For instance, a retractable shading device may be designed to retract when it is cloudy and extend when it is sunny. Conversely, the same is retracted in the winter and extended during the summer, similar to a deciduous tree. The dynamic feature can be either moderate or dramatic -- moderate, as in retractable shading device, and dramatic, as in a rotating building that tracks the sun. Dynamic buildings will not only offer better performance than static buildings, but will also give an exhilarating aesthetic, the *aesthetic of change* [11].

3.2 Special Shading Strategies

Most external shading devices are variations of the horizontal overhang, the vertical fin, or the egg-crate. However, some interesting exceptions do exist [11].

The geodesic dome designed by Buckminster Fuller as the U.S. Pavilion for the Expo '67, created an artificial climate for the structures within (Fig. 1). To prevent overheating inside the clear plastic dome, the upper panels had vents and special roller shades. Each of the glazed hexagonal structural units had six triangular roller shades that were operated by a servomotor[11].

A completely different approach is to rotate the building with the changing azimuth of the sun. an example of this approach is the revolving house built by Richard to enjoy the panoramic view of his Connecticut property(Fig. 2). A rotating building specifically designed for its solar benefits is the “Heliotrope” built in Freiburg, Germany, by the architect Rolf Disch as his home (Fig. 3). The building, like a heliotrope flower, tracks the sun. In the winter, the triple glazed windows face the sun, while in the summer the building exposes its blank insulated wall to the hot sun. The balcony railing consists of a vacuum tube solar hot water collector. Rotating separately on the roof, the PV array generates much more electricity than the building needs. Thus, the Heliotrope is better than a ‘zero-energy building’ – it is an ‘energy-plus house’[11].

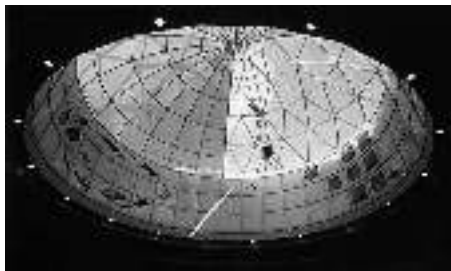
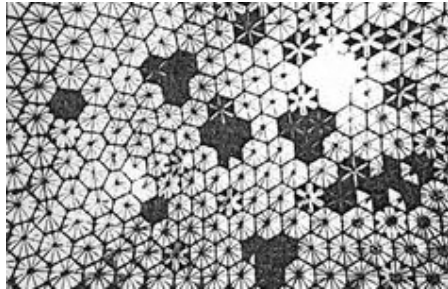


Figure 1 (Top Left): Geodesic Dome by Buckminster Fuller, Montreal, Canada (Image Source: - <https://www.pinterest.com>)

Figure 2 (Top Right): Round House by Richard Foster, Connecticut, USA. (Image Source: - <http://takesunset.com/>).

Figure 3 (Left): 'Heliotrope' by Rolf Disch, Freiburg, Germany (Image Source: <https://upload.wikimedia.org>).

Figure 4 (above): Tanfield House by Michael Laird Architects, Edinburgh, UK. (Image Source: - <http://www.edinphoto.org.uk>)

In another instance, the Tanfield House uses a triangular parasol to shade its glass domes (Fig. 4). The solar blind is a spherical triangle that moves on an indoor circular track in order to block the sun when appropriate. The domes are used for daylighting, natural ventilation, and space heating[11].

3.3 Building Energy Efficiency Many of the new materials and technologies, that have been evolved in the building industry, have found application in building envelopes in the form of curtain walls, shading systems, double-skin façades, etc. Also, with the advancement in computer technology, building management systems (BMS) that control mechanical and electrical equipment in buildings have become commonplace.

Though the initial purpose of BMS was to monitor and manage the buildings' energy demands, their reach quickly extended to building envelopes that began to incorporate kinetic components that would affect a building's thermal performance, i.e., its heat loads. With greater innovation in BMS (such as electronically controlled, mechanically activated shading and ventilation systems), came the kinetic or dynamic façades, active and high-performance building envelopes. The main idea behind these new systems was that buildings should respond in dynamic fashion to constantly changing environmental conditions and should do so in energy-efficient ways. Buildings thus became adaptive, with building envelopes playing a key role in how they adapted, i.e., responded to the ever-changing external environment. The key focus in designing adaptive envelopes is better management of energy flows, both from the exterior environment into the buildings and from the interior spaces of the building to the outside, with the overall goals being the improvement of the building's performance and the user-comfort inside the building.

The adaptive behaviour of the envelopes can be visible or invisible or both. In addition to components that move literally, such as the shades or vents, air or water would move as directed, and thermal energy would flow through different materials as designed. The visible adaptive behaviour could lead to an urban spectacle that can add performative dimensions to the project that go beyond the scale of the building. While the literal movement of components is not an end in itself, in many building projects that include climate adaptability, it is frequently exploited to give a vibrant appearance making it “alive” [10].

Therefore, the basic way to save energy and control occupant comfort is to design the building envelope. The architect is now able to design an envelope that maximises indoor environmental quality, including acoustics, daylight, air quality, humidity, security, and thermal control; while minimising operational costs by controlling daily temperature variations as well as by making use of solar and wind energy. The building envelope is part of the BMS, an active system competent of responsiveness and self-adjustment for the reduction of energy use and the control of indoor environment conditions [7].

4. MECHANISMS OF ‘DABE’

The building envelope can act as a “living” part of the building – its “skin”, a semi-permeable membrane that mediates between the building and the environment. It is a layer – or more precisely a set of layers – where architecture and environmental engineering intersect as disciplines. Whereas the focus is traditionally on blocking heat gain or heat loss – effectively creating energy barriers – the new façade designs attempt to harvest energy

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from the environment and channel it to where it is needed. For example, in double skins, the air contained in the space between the two layers is heated by the sun during the winter months; conversely, in summer months, cold air is drawn in at the bottom of the cavity and as it heats up, it is exhausted at the top using natural convection. The dynamic control of energy flows (manifested as light and heat) is at the centre of innovation in adaptive building envelopes. It is facilitated by new materials and the latest advances in sensing, control, and actuation systems.

To imbue building skins with dynamic, changing behaviour, their elements need to be actuated, i.e., moved, rotated, expanded, shrunk, twisted, etc. so that the desired performance objectives are met. What differentiates adaptive building skins is not so much as what is actuated (though that matters greatly), but how that actuation is produced. There are essentially four different methods of actuation in building envelopes: (1) motor-based; (2) hydraulic; (3) pneumatic; and (4) material-based. Most of the automated adaptive façade systems deployed to date rely on motor-based, i.e., mechanical actuation. Recently, we have seen increasing use of pneumatic actuation, primarily with patterned, multi-layer ETFE (ethylene tetrafluoroethylene) based systems in which hermetically sealed air chambers can be inflated or deflated to create different shading densities. There are also ongoing experiments in material-based actuation, which offer the promise of “zero energy” dynamic building envelopes, though these are years away from large-scale commercial applications [10].

4.1 Mechanical Actuation

Motor-based actuation, as stated, is the most common type of actuation used in dynamic facades. The most commonly used motor-based dynamic facade system includes use of motorised venetian blinds system installed in double skin facades. These blinds can significantly reduce glare and solar heat gain. These blinds are often automated. A central BMS tracks the location of the sun and monitors the light conditions and can adjust the blinds as and when required. The blinds are housed between two layers of glass, one on the outside providing protection from the elements, and the one on the inside protecting it from potential damage or interference with its operation. The KfW Westarkade in Frankfurt, Germany, designed by Sauerbruch Hutton (Figs. 5a & 5b), features such a system[10].

Another example of mechanical actuation is Jean Nouvel’s Institut du Monde Arabe, completed in 1989 in Paris. The envelop of this building is a technological interpretation in glass and steel of a traditional Arab lattice screen called *mashrabiya*, and is composed of some 30,000 photosensitive

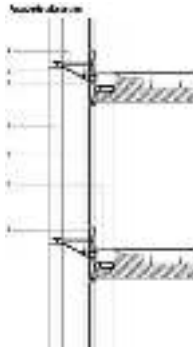


Figure 5a and 5b (Above Left and Right): KfW Westarkade in Frankfurt, Germany designed by Sauerbruch Hutton (Image Source: - <http://www.archello.com/>)

Figure 6 (Left): Institut du Monde Arabe in Paris, France designed by Jean Nouvel (Image Source: - <http://paris.stouring.fr/>)

diaphragms that control light levels and transparency in response to the sun's location (Fig. 6). It is the first significant, large-scale building to have an adaptive envelope[10].

A recent and noteworthy example of mechanical actuated external adaptive shading system is the Al-Bahr Towers – the twin 29-storey buildings in Abu Dhabi, UAE, designed by the London-based AHR studio and completed in 2012. The responsive façade here is also based on the *Arabmashrabiya*. These “mashrabiya” consist of a series of transparent umbrella-like components that close and open in response to the path of the sun. Each individual tower comprises over one thousand shading devices which are regulated through the BMS, thereby creating a smart façade. Every unit includes a sequence of stretched polytetrafluoroethylene (PTFE) panels that gradually close and open once a day and, is operated by a linear actuator. It functions according to pre-determined calculations that prevent striking of direct sunlight on the façade and keep the direct solar gain within a maximum limit of 400 watts per linear meter. In the event of overcast conditions or high winds, a variety of sensors that protect the entire installation will open the units (Figs. 7a, & 7b). The effects of this system are inclusive of improved

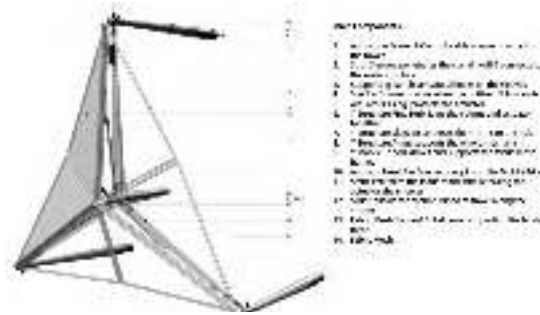


Figure 7a (Left): Al Bahr Towers in Abu Dhabi, UAE designed by Aedas Architects (Image Source: - <http://al-ahwal.blogspot.in/>)

Figure 7b (Above): Section showing the fixing of shading device (Image Source: - <https://s-media-cache-ak0pinimg.com/>)..

daylight penetration, reduced glare, less dependence on artificial lighting, and over 50 percent reduction of carbon dioxide emissions by 1,750 tonnes per year [6].

4.2 Hydraulic Actuation

Hydraulic actuators typically include a piston inserted in a hollow cylinder. A force is produced that can move an external object when an unequal thrust is applied to the piston. The mechanical motion, thus produced, provides an output in terms of linear, rotary or oscillatory motion [12].

REX architecture studio in New York has recently designed a couple of ultra-thin, stone-clad media towers at an undisclosed location in Middle-East which have ‘blooming’ *Mashrabiya* sunshades that protect against excess solar gain (Figs. 8a, 8b & 8c). Measuring about 15 metres in diameter, these sunscreens can be swiftly set out from the cavities embedded between floors, converting the glass façade of the building, within minutes, into a “blossoming” shaded tower [19]. The courtyards surrounding the building also feature deployable umbrellas that are automatically retracted when the courtyards are in the shadow of the building or, conversely, expanded when exposed to sunlight[10].

Yet another example of the type is the external adaptive shading system used in Melbourne’s ten storied Council House 2, or CH2, as it is called. Completed in 2006, the CH2 is Australia’s foremost building to have received a rating of six stars from the Green Building Council of Australia [3]. The principal design architect of the building, Mick Pearce, covered the west

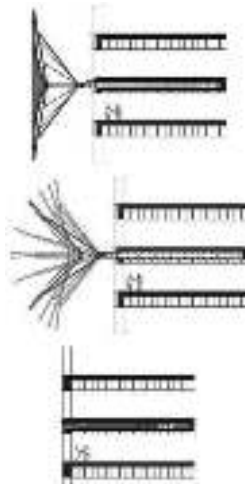


Figure 8a (Top Far Left): Eastern sunshades deployed and Western retracted (Image Source: - <http://storage3d.com/>)

Figure 8b (Bottom Far Left): Eastern sunshades retracted and Western deployed (Image Source: - <http://www.greenprophet.com/>)

Figure 8c (Left): Nestled in cavities between floors, the shades can expand or contract within 60 seconds. (Image Source: - B. Kolarevic and V. Parlac)..



Figure 9a (Left above): CH2 Building, Melbourne, Australia (Image Source: - <http://www.construction-innovation.info/>)

Figure 9b (Right above): Louvers in closed position (Image Source: <http://images.adsttc.com/>).

facing façade with a system of timber louvers that rotate on pivots to optimise the penetration of natural light. The movement is facilitated by a hydraulic system controlled by computer (Figs.9a & 9b)[10, 5]. The system is powered by photovoltaic cells and the timber used is recycled. These louvers cut the harsh western sun to protect the façade. The shutters respond to the amount of direct sunlight hitting the western façade; they open fully in the morning and then slowly close up as the sun moves overhead to the west. This adaptive shading system is a rather simple, straightforward way to reduce solar heat gain [10, 5].

4.3 Pneumatic Actuation

Pneumatic actuators are analogous to hydraulic actuators, except that compressed gas, instead of a liquid, is used to generate force. These functioning the same way as the hydraulic actuators where the piston is pushed out from one side of a chamber by air (instead of liquid) that is pumped inside the chamber through the other side. Since the source of input is air, pneumatic actuators are capable of being used in many places of mechanical activity [12]. This concept of bringing motion by use of air or gas under pressure gave rise to the Modular Pneumatic Façade System (MPFS). The MPFS is a kinetic façade system which combines features of biological design (e.g., robustness, modularity, hierarchical design, and kinetic proofreading) and smart technology (e.g., sensor, material, control, and actuation) in order to build a dynamic façade that acts in response to its environment (Figs. 10) [17].

An example of this type of actuation is the Media-TIC building, located in Barcelona, designed by Enric Ruiz-Geli of Cloud 9 and, completed in 2011 (Figs. 11a & 11b). The building is installed with an inflatable skin made out of Ethylene Tetra Fluoro Ethylene (ETFE). This “skin” consists of many air chambers that expand or contract with the changing light. The motion is controlled by a digital sensor which is powered by solar energy. This light sensor tracks the movement of the sun automatically all through the day. While the skin allows light to filter through it, it also protects the inhabitants of the building from direct sunlight reducing the UV rays by 85%. The skin is also “anti-adherent” which means that minimal maintenance is required. The skin consists of three layers of plastic with two air chambers between them that can be inflated or deflated as needed. While the external layer of the skin is transparent, the middle and the inner layers have a design pattern that create shade when inflated and joined together. In other words, it becomes one opaque layer. Not only does this allow diffused light into the building, but also improves thermal insulation [16].

4.4 Material-Based Actuation

In the past two or three decades, there has been a continuous advancement in the field of manufacturing processes and material science. Also, miniaturisation of electronic components have revolutionised the field of computation, communication, actuation and sensing, and has led to the development of “robotic materials” which can combine the mechanisms of sensing and controlling. Robotic materials can use the signals measured from the embedded sensors to activate the properties of the material through embedded actuators by making the relationship between them fully programmable. Such materials

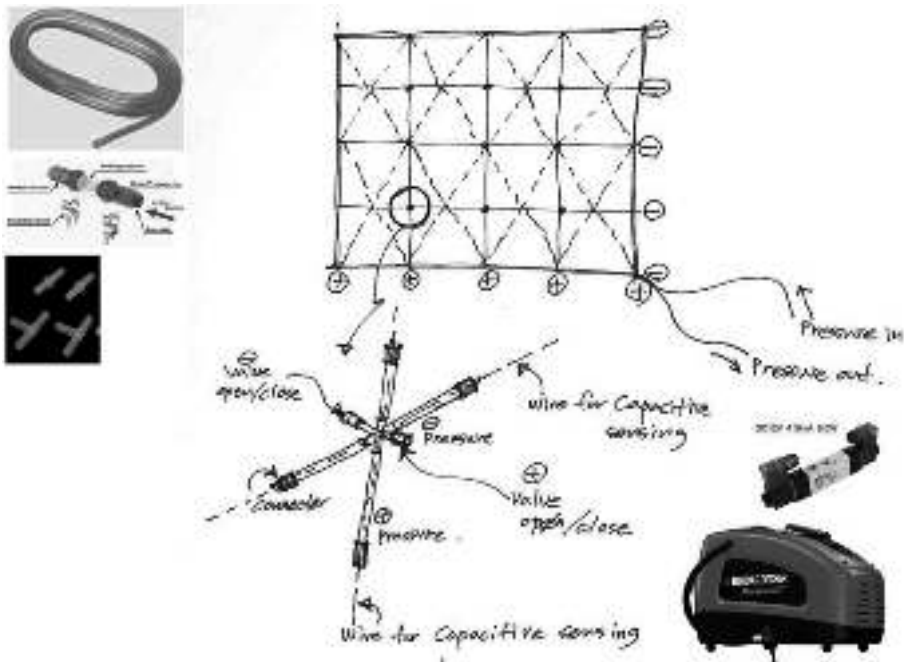


Figure 10: Modular Pneumatic Facade System (Image Source: - <http://courses.media.mit.edu/>).

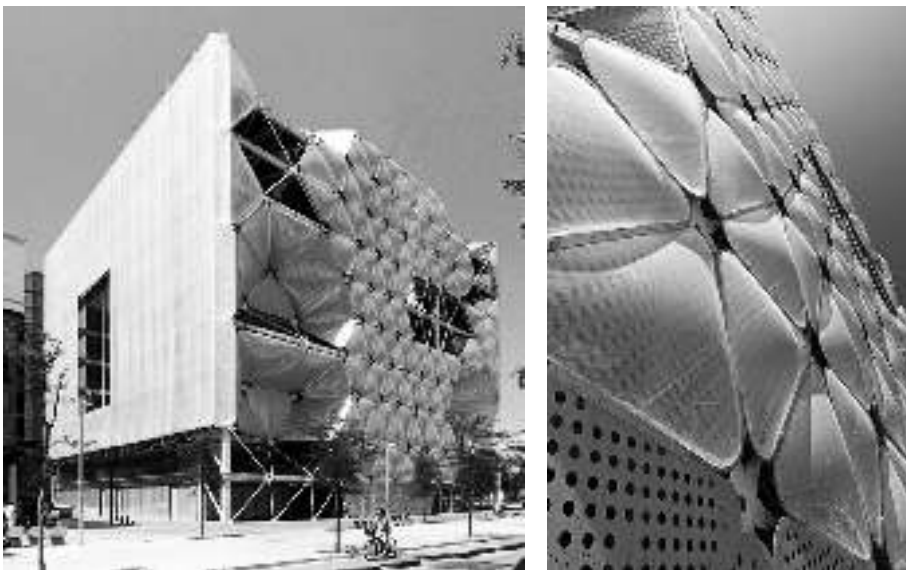


Figure 11a (Right): Media-TIC Building, Barcelona (Source: <http://www.ruiz-geli.com/>)

Figure 11b (Left): Sectional view of Media-TIC Building (Source: <http://www.ruiz-geli.com/>).

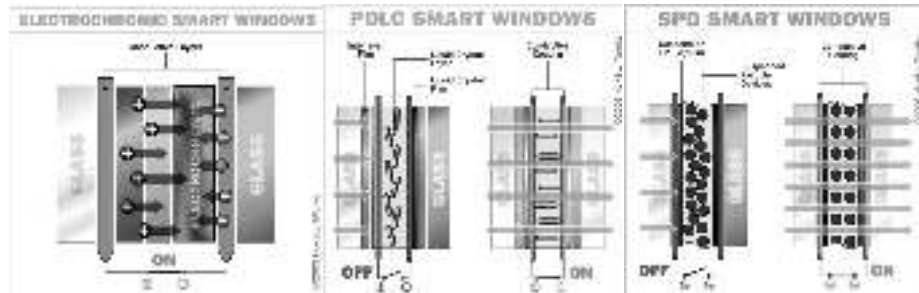


Figure 12: Electrochromic, Suspended Particle Devices and Polymer Dispersed Liquid Crystal Smart Windows (Image Source: - <http://s.hswstatic.com/>).

which have been designed to mimic the adaptability and the multi-functionality of biological systems have multiple applications. This is different from the conventional materials that are responsive to external stimulus by changing just one or two physical properties [14].

One such application is the “smart glass”. Smart glasses, also known as “switchable glasses” (or smart / switchable windows), are those whose light transmission properties are changed when electric current is applied to it (electro-chromic), or under light (photo-chromic), or even heat (thermos-chromic) [10]. This kind of glass blocks some wavelengths of light while letting visible light pass through, and therefore, can change from being transparent to translucent and back. Smart glass technologies include micro-blind, polymer dispersed liquid crystal, and suspended particle devices (Figs. 12). These smart glasses, when installed in the façade of buildings, create dynamic adaptive building envelopes with the capability to cut down lighting, heating, ventilation and air-conditioning costs, thereby eliminating the need for mechanically activated blinds and shades [20].

Biomimetics is a research oriented science which studies how the adaptive nature of living organisms can be mimicked to find a solution to man-made problems. By considering a building facade as a ‘skin’ of a living organism that is adaptive to nature, systems can be developed by which we can make a multi-functional building facade that can adapt itself to nature by using minimum energy, thus, making it sustainable [15].

One such invention is the “actually alive” photo-bio-reactive façade prototype called “SolarLeaf” developed by Arup in collaboration with SSC Ltd. and Colt International. Solar Leaf’s bioreactors need minimal maintenance and are highly efficient for algal growth. The flat photo-bioreactors have four layers of glass. The panel in the front consists of white anti-reflective glass, and the glass panel

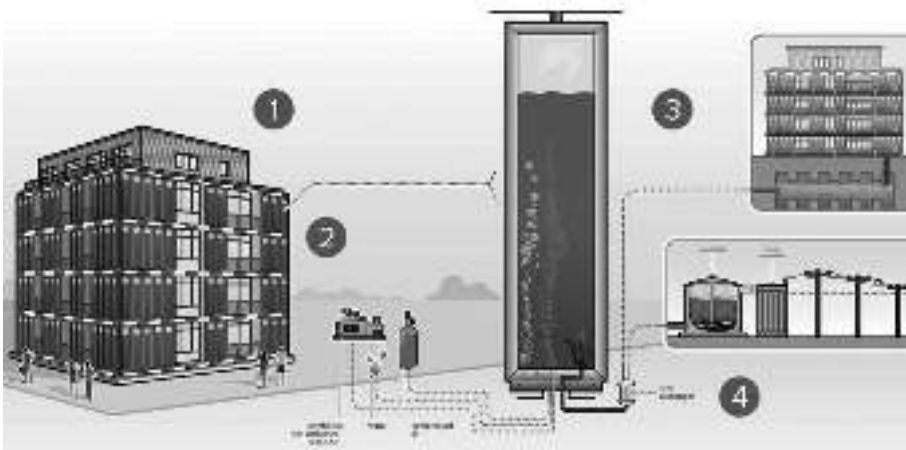


Figure 13a (Top): Bioreactor Panels installed at BIQ House in Hamburg. (Image Source: - <http://www.arup.com/>).



Figure 13b (Middle): Microalgae in the photo-bioreactor panels. (Image Source: - <http://img.weburbanist.com/>).

Figure 13c (Bottom): Complete Process of 'SolarLeaf' (Image Source: - <http://www.sierraclub.org/>)



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in the back have decorative treatments. The two inner panels contain cavity of a capacity of twenty four litres in which the growing medium is circulated. On both sides of the glass panes, cavities are filled with argon for thermal insulation. At the bottom of each bioreactor, compressed air is introduced at intervals. The air creates large bubbles generating an upward flow of water. This upward movement causes the algae to take in light and carbon dioxide. Simultaneously, it washes the inner surfaces of the glass panels by a combination of small plastic scrubbers, water and air. The photo-bioreactor comes with an integration of pipes for servicing the outflow and inflow of the culture medium as well as for supplying air. The idea of photo-bio-reactive façade is to design energy-efficient buildings by utilising the bio-chemical process of photosynthesis. This system can be used in both existing and new buildings [1].

The system was introduced in an experimental project at the International Building Exhibition (IBA) held in 2013 at Hamburg. The four-storey BIQ House has 129 bioreactor panels installed on the south-east as well as south-west façades, measuring 2.5m x 0.7m each (Figs. 13a, 13b & 13c). While the photo-bioreactors act as dynamic shading devices, they can also be used as external cladding element. Hot water is generated by harvesting algae and solar thermal heat in a closed loop system spread over a surface area of 200m² approximately, which is further stored and allowed to ferment. The hot water so generated is used to meet about 1/3rd of the total heat requirement of the fifteen residences in BIQ house[1].

CONCLUSION

There are numerous other examples for the Dynamic Adaptive Building Envelope like the Conservatory buildings in Gardens by the Bay (2012) in Singapore, designed by Wilkinson Eyre; the One Ocean pavilion in Yeosu, South Korea designed by SOMA from Vienna, Austria; Storefront for Art and Architecture in New York (1993), designed by Steven Holl and Vito Acconci; the Communications and Design building for Syddansk Universitet in Kolding, Denmark designed by Henning Larsen Architects; the Kiefer Technic Showroom in Bad Gleichenberg, Austria designed by Ernst Giselsbrecht + Partner, etc.

Loonen, et al. (2013) state that with increasingly stricter energy performance targets to be met, DABE seems promising in becoming a profound contributor to sustainability and energy efficiency without being limited by the need for compromise in terms of comfort. But there is hardly any information about DABE's monitored post-occupancy and operational performance. Also, the study reveals that DABE, at this point, cannot be regarded as a mature concept due to the fact that there are very few cases documented on the topic [13].

According to B. Kolarevic and V. Parlac (2015), automated building skins bring a host of other issues into play that go beyond available state-of-the-art materials and technologies, affordability, durability, low-maintenance requirements, and other various performance targets (such as energy savings, uniform light levels, outside view, etc.). User override is potentially a critical issue in the design of any highly automated adaptive, responsive building envelope system. Social and cultural factors need to be taken into account. There is also a good chance that any mechatronic solution that depends on the current modern technologies could become obsolete relatively quickly. An example that can be cited is that of one of the initial buildings to use an automatic sensor-based system responsive to external environment, i.e., the Arab Institute designed by Jean Nouvel in Paris and completed in 1987. But now the system is no longer working due to mechanical problems, thereby warning architects of the risks of designing kinetic facades [10].

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