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  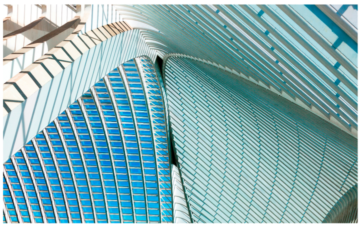 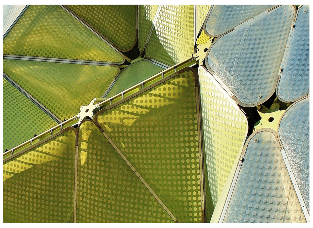 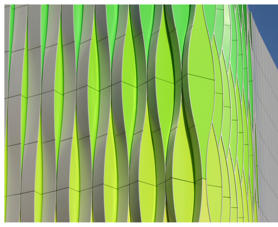

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Adaptive facade systems – review of performance requirements, design approaches, use cases and market needs

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Abstract

The paper reflects the work of COST Action TU1403 Workgroup 3/Task group 1. The aim is to identity research needs from a review of the state of the art of three aspects related to adaptive façade systems: (1) dynamic performance requirements; (2) façade design under stochastic boundary conditions and (3) experiences with adaptive façade systems and market needs.

Keywords: adaptive facades, performance requirements, design approaches, use case, market needs

1. Adaptive Facades Network

Multi-functional and adaptive facades have the potential to significantly improve energy efficiency and economic value of new and refurbished buildings, whilst providing a healthy and comfortable indoor environment to the building occupants.

Due to their function, separating the indoor from the outdoor environment, their performance governs to a large extent the building energy use and is subsequently directly related to achieving the targets formulated by the EU for 2020 [9]. There is an extensive body of knowledge available among R&D centres in Europe. However, the knowledge, expertise, resources, and skills are widely scattered.

The main objective of TU1403 is to exploit the estimated economic potential of EUR 80 million associated with adaptive façade systems. That is achieved by delivering four goals until 2018 [5]:

- Harmonization, sharing and dissemination of technological knowledge between research centres as well as research centres and industries;
- Development of novel concepts, technologies and new combinations of existing technologies for adaptive facades;
- Development of new knowledge with regards to effective evaluation tools and design methods.

1.1 Work group 3 / Task group 1: Integration and interaction of adaptive façades with the building and its systems

This contribution reflects on the activities of task group 1 of the European Concerted Research Action TU1403: Adaptive Facades Network. Task group 1 a subgroup of workgroup 3 is dedicated to evaluate the integration and interaction of adaptive façades with the building architecture and structure; services; indoor environment and occupants as well as external environment. The task groups specific focus lies thereby on three aspects: (a) dynamic performance requirements; (b) façade design under stochastic boundary conditions and (c) experiences with adaptive façade systems and market needs. Task group 1 works complementary to work group 2 and targets the assessment of adaptive facades systems with respect to occupants behavior, commissioning and post occupancy performance.

1.2 Building and system performance

The carbon emissions continuously increase worldwide and pose a threat to the earth's ecosystem. Different actions have been taken to reduce carbon emissions, one being the formulation and implementation of the EPBD, targeting the building sector.

Since the implementation of the "Energy Performance for Buildings Directive" (EPBD) in 2006 [8] the building design approaches have changed due to the advances in renewable technologies. Whilst the traditional design approach focused on minimizing the energy demand, integrating renewables, and using fossil fuels if necessary; the revised design approaches still target (1) minimizing the demand but differ as they aim to (2) producing energy locally from renewable sources and (3) distribute excess energy via local thermal and/or electrical networks [27].

The interdependence of connected agents in thermal or electrical networks poses a great challenge. This is as the direction of energy supply in not simply uni-directional, e.g. from plant to user, but at least bidirectional. The network agents change their role dynamically from plant to user and in reverse dependent on the instantaneous demand. In order to reduce the stress on the network, agents are expected to produce a large proportion of their required load themselves and being able to compensate the remains by either storage, redundancy or lay-off possibilities.

1.3 Future proof buildings

The adoption of futures-thinking related to building design is a consequence from adopting the principles of the sustainability development, which state that one should act today in such a way as to preserve the resources for the generations to come. A future-proof building is a building which is able to respond to changes without becoming prematurely obsolete. Changes result from social, technological, economic environmental or regulatory developments. Following Georgiadou et al. [10] the authors adapted the three major implications arising, from adopting futures-thinking as follows:

1. The need to follow a holistic design process which covers financial, environmental and socio-economic criteria.
2. The requirement to adopt a full lifecycle perspective in order to minimize the environmental impact of building and system design solutions over their lifetime.
3. The need to adapt to an uncertain future due to the occurrence of high impact and unpredictable events which can affect energy use as well as structural integrity.

Other researchers relate the concept of future-proof building to design principles [23] or to the development of cities and districts [24]. In the context of future proof buildings the authors follow the definition of adaptive facades by Loonen et al. [20]:

"A climate adaptive facade has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance."

Based on this definition an adaptive façade ideally comprises the following six functions:

1. Provide shelter from the outdoor environment (weather and human or animal attack)
2. Provide protection from for exceptional load cases such as bomb blast, earthquakes and fire
3. Provide daylight and a view to the outside
4. Thermally insulate, heat and cool the indoor environment according to the occupants preferences
5. Provide the minimum fresh air rate
6. Store and release thermal and/or electrical energy

1.4 Adaptive buildings and systems

The need for adaptive buildings and systems has long been recognized and has been subject to a number of research projects. Terms being used to describe adaptability of buildings are responsive, flexible, robust, resilient among others. Important past and running research project are the IEA Annex 44, the FACET-project and the EU project “Adaptiwall”.

IEA Annex 44 (2004-2011)

The aim of the IEA Annex 44 “Integrating Environmentally Responsive Elements in Buildings” was to integrate the most promising building elements and to define design methods and tools that can be used for selecting responsive elements. The projects concludes that the required design process description for responsive buildings is fundamentally different to traditional buildings as the focus lies not on the design of individual system components but on the integrated design of a great number of components relating to thermal insulation, energy storage and transparency. The project was limited to the consideration of responding to the outdoor environmental conditions. The key principles for a responsive building element were defined based on its ability to perform a responsive action based on: (1) dynamic behavior, (2) adaptability, (3) capability to perform different functions, and (4) intelligent control [11].

FACET (2009-2012)

Different to the IEA Annex 44, the focus of FACET was to investigate the potential of facades with adaptive thermal properties to minimize the energy use for heating, cooling, ventilation and lighting in response to the indoor and outdoor environmental conditions. The research question was: “Which façade properties are required to maintain specific indoor environmental; conditions without interfering with other services [2, 3].

Adaptiwall (2013-2017)

The European Project titled: “Multi-functional light-weight WALL panel based on adaptive insulation and nanomaterials for energy efficient buildings” focuses on existing houses. The project aims to develop a wall panel using adaptive (nano)materials and demonstrate its performance to the European construction industry. The novelty of the panel to be developed are threefold [14]:

1. it consists of lightweight concrete with nano-additives for efficient thermal storage and load bearing capacity;
2. is polymer materials allow the thermal resistance to be adaptive and controllable;
3. it contains a heat exchanger with nanostructured membrane for temperature , moisture and antibacterial control.

2. Methodology

The research methods used to compile this contribution are desk research and literature reviews. The literature review was conducted to gain an overview of the state-of-the-art in the field of Adaptive Facades and to learn about their application to the built environment. Subjects that have been reviewed are: performance requirements, façade components and innovative façade concepts.

3. Design process and performance requirements

The design of integrated building systems is a dynamic and iterative process. A façade design is evaluated based on how it complies with defined requirements. Those requirements can be prescriptive or performance-based. Other terms used for performance-based requirements are functional or objective-based requirements.

The shift away from prescriptive specifications towards functional requirements in building regulations started more than 40 years ago [25]. Prescriptive specifications represent in many cases social needs or lessons learned from fatal situations. In comparison to functional or performance based requirements, prescriptive requirements are recognized to potentially hinder change and innovation as they prescribe solutions, e.g., in form of technologies or material properties [18].

The need for the building industry to change the focus from the process input specifications to the user requirement as process output motivated the PeBBu project [17]. The aim was to increase quality and long-term monetary value for buildings. Lee and Barrett [17] give the following definition for performance based building:

“Performance-based building considers the performance requirements throughout the design life of the building and its components, in terms that both the owner and the user of the building understand, and which can be objectively verified to ascertain that requirements have been met. The requirements are concerned with what a building or building component is required to do and not with prescribing how it is to be constructed.”

Following Almeida [1] the objective for adopting performance-based regulations are threefold: (1) to reduce barriers to trade and increase innovation; (2) to reduce regulation complexity and clarify its intent and (3) to allow more functional buildings at lower costs without scarifying safety.

3.1 Risk based performance requirement

It is noticeable that the focus is changing towards maintaining the energy balance at the designed-to values over predefined periods, which might or might not correspond with the lifecycle of the building or services components. The possibility of performance failure becomes thereby a quantitative fact which can be associated to risk.

Whereas the consideration of risk with respect to building energy use and comfort during operation is not widely recognized, it is an integral part of the design of building structures. The danger of fatalities due to faulty structural designs has ever since guided the design approaches in civil engineering. The potential consequences for the structural designer of a building and it’s components is defined since centuries. Even in the oldest known codes of law, the Hammurabi`s Code of Laws (Mesopotamia, 1800 B.C.), specific clauses are provided, such as:

“§ 228. If a builder builds a house for someone and completes it, he shall give him a fee of two shekels in money for each sar of surface.

§ 229 If a builder builds a house for someone, and does not construct it properly, and the house which he built fall in and kills its owner, then that builder shall be put to death.”

To minimize the risk and the consequences of faulty structural design three main principles are applied around the world:

- minimize the failure risk by exact design guidelines and codes;
- expert reviewing of the structural design;
- build financial savings and insurances for financial compensation when a failure occurs.

For the building services design of buildings and facades the risk assessment is given less priority. There are dedicated design guidelines and codes, but expert reviewing principles are uncommon. Many of today’s erroneous building services designs would have been detected in early stages an expert review would have taken place.

3.2 Architectural perspective on the design of adaptive facades

From a philosophical point of view it is not easy in times of information technologies, electronic media, nanomaterials and start-ups, when within one profession many activities are running together, to define the technical and artistic creativity. In the past, the contours of individual professions were sharper and activities carried out within the professions clearer. From a glance, the past transparency resulted in simpler definitions of the technical and artistic creativity. The need of these sharply defined technical and artistic competences can be felt even now, but always in the context of activity, not related to a profession. For example: an architect can be a good lawyer in the area of building law, and an IT professional can be the designer of a façade’s geometry. Jurovský states in Psychology from 1945 [13] that:

“the good art work is characterized by 1) an unexpected and simple solution from a number of possible solutions and brings something new, 2) the proceeding implementation of solutions by means of expression, which, in case of an architect, are matter and space.”

The design is closely related to construction. Also in this area is undergoing rapid development - and perhaps even towards a closer link than it was before. In Europe we are currently accustomed to tendering especially in the case of public contracts. Its main objective is to save financial resources of the client.

Despite the unquestionable advantages it also has negative aspects arising from the impersonality and strict separation of individual stages of the construction process. Particularly on large projects the designer may not ever come into contact with the supplier. This often results in solutions that are not sufficiently optimized and which could be significantly improved, if the communication between supplier and designer would have been better. A positive example of efforts to overcome this gap represents the so-called design-assist process described by Cruse, 2014 [7].

The design–assist process is an procurement process with the aim to link design to construction and construction to design. That is achieved by creating a contractual relationship between owner and sub-contractor to provide assistance to the design team. In addition to many other advantages such design-assist project delivery method affects the design process itself. By having a breadth of expertise available and invested in the project during the design process, the design team is able to explore material solutions, and their technical opportunities and challenges, very early in the project.

A special field of the application of adaptive façades is building renovation / refurbishment. It requires a very sensitive approach, especially in case of architectural monuments. The existing building substance often limits the use of modern construction techniques - whether in terms of architectural expression and static or heat and moisture transfer. Solutions should be sought that would not significantly impede the existing substance, but suitably supplement it and thereby enhance the quality of its use. An example may be many older office buildings with lightweight curtain walls, which have difficulties to meet the requirements on today’s indoor comfort and energy efficiency. At the same time they are characteristic within the urban environment and many of them became technical monuments (e.g. Baťa buildings in Zlín, Czech Republic, or many administrative buildings from 60 to 90 years of the last century with light aluminum facades).

Their architectural expression principally forms the spirit of many cities. Although it could be possible, the replacement of the original facade with a new-one could easily destroy the architectural appearance of such buildings. The original single or double glazed curtain walls were usually considerably lighter than today's façades with insulating double and triple glazing units in reinforced frames with many air or insulation cavities. In order to preserve the original “easy” look, one of the ways is searching for new materials with positive characteristics of glass, but lower weight, e.g., polymeric materials as proposed by Covre, 2014 [6]. New materials, however, may already contain elements supporting the adaptability of the facade, e.g. by their chemical composition.

4. Adaptive façade and system concepts

The below text blocks introduce exemplary four innovative adaptive system technologies for those in section 1.3 identified functions for adaptive facades.

The Emporium concept

The Emporium concept [26] is characterized as a seasonal heat store installed within a building to minimize the potential exergy gain (low-exergy) and to minimizing energy loss. In this case the term exergy refers to the temperatures which are used in the Emporium system, and which are as close as possible to the demand temperatures (20 ˚C indoor air and 45 ˚C domestic hot water). The water temperature within the thermal heat store are above those two demand temperatures and below 100 ˚C, and 50 to 90 ˚C over the year. These temperatures are delivered by a vacuum tube semi-transparent solar heat collector which is integrated in the southern facade of the building. The seasonal heat storage volume is integrated with the building volume to achieve that all heat losses (more than 50% through 50 cm glass or stone wool insulation) benefit the building and are used for space heating.

Warmbouwen - capillary tubes in external wall of existing buildings

Warmbouwen is an extension to the façade system of monumental buildings. It is described as a concept which potentially increases thermal comfort and decreases energy use for heating of monumental buildings by means of embedding capillary pipework within the plaster on the indoor surface of external walls. The system is moderately heated to 12-20^{o}C dependent on the outdoor ambient conditions to offset temperature gradients and reduce thermal bridging. The system can be powered by heat pumps to the low temperature supply temperature [15].

Solar-driven thermo-acoustic cooler

To increase the use of renewable energy in the building sector, as mandated by the European Performance for Buildings Directive, requires synchronizing energy demand and generation. An alternative approach is converting otherwise unused energy into a form to be used directly. The SOTAC project at Saxion (2015-2017) targets the performance evaluation and market analysis of a solar-driven chiller for the built environment. The deliverables are: (1) the characterization of an solar-driven thermo-acoustic cooler under laboratory conditions, (2) the development of a dynamic simulation model for building integrated performance evolution and (3) stakeholder specific design requirement for a successful market introduction.

Blast enhanced Cable Net Facades by overload fuses

One example of an adaptive façade concept is related to the consideration bomb blast. Unfortunately bomb blast has risen in priority on the list exceptional forces for facades to withstand since 2011. Bomb blast is characterized by shock waves with short time durations but high impulse loads. To withstand such a load facades need to respond dynamically to the instantaneous load change. To design and analyze structural solutions numerical analysis ,e.g., aero elastic damping of flexible façade components is required. The focus of the project to design a solution for the World Trade Center Tower 3 in New York (US) was on the connections between the façade elements itself as well as the connections to the primary building structure. The aim was to dissipate higher shares of energy by plastic deformation. To achieve that the team developed a specific fuse connections to limit the connection forces to the primary structure. With the use of the overload fuses the structural system changes from a system for “classical” loads to a structural system for “blast loads” [28].

5. Adaptive façade components

The review of research on building adaptability by means of thermal storage systems has delved into the components techniques of phase-changing materials (PCM) and trombe wall glass wall technologies and their application to building and facades systems.

Trombe walls

A trombe wall is a passive system consisting of a massive wall, exterior glazing and an air channel in between. the system transfers the accumulated heat by means of transmission and ventilation through vents. It has been identified as an efficient technique in mitigating the high fluctuation of temperatures (Shena Jibao, 2008; Zerrin Yilmaz, 2008), enabling heating energy savings and regulating the thermal comfort of the interior (Stazi, 2012; Hami, 2012). It is also an economically feasible solution with fast payback period, (Arvind Chel, 2008). In a review by Chan et al., 2010, problems occurring in Trombe walls are: low-thermal resistance, inverse thermo-siphon phenomena, uncertainty of heat transfer, influence of the channel width, and low aesthetic value.

Phase change material

PCM materials have thermal properties that enable storing and releasing heat to their surrounding environment by changing their phase from solid to liquid or in reverse. They have been extensively investigated in terms of their applicability and benefits by different researchers and research teams (Farid, 2004, Vineet Veer Tyagi, 2007, Cabeza et al., 2011). Different authors (Pablo Arce et al. 2012) have examined the PCM's adaptive potential under influence of temperature peaks in summer, integration of PCM in windows (Steinar Grynning, 2013), shape-stabilized PCM that brings promising solutions for certain climatic regions, (Zhanga YP, 2006), and research on implementing PCM in radiant floors has been conducted (Roberta Ansuini, 2011; Gonzales Neila, 2008). It has been concluded that PCM's can improve the energy efficiency of the buildings and that it’s a feasible solution (F. J. Neila González et al., 2008, Isabel Ceron, 2011). Research by Castellon, Medrano et al, 2007, has been conducted in integration of PCM in Trombe wall with micro-encapsulation as a more promising method compared to the macro-encapsulation method from the 80's. From the review on the properties and benefits of the phase changing materials and Trombe wall it can be concluded that they are invaluable technique for improving the buildings adaptability and increasing the occupants comfort.

“Glass walls” technologies

Glass wall technologies are continuously improving, new technologies and materials are discovered and are being developed and their implementation in new buildings increases. Glass obtains its adaptive properties by combining it with components which can be separated in five categories:

1. chromogenic
2. mechanical
3. thermal collecting and power producing
4. thermal storage and insulation
5. active coating.

Chromogenic

Chromogenic windows switch between a fully or partially transparent state and a fully or partially reflective or absorptive state. They became popular as they allow to control the solar heat transfer through glazing’s. Consequently they enable to control the indoor temperature and glare to improve the user comfort but additionally reduce the use of heating and cooling systems and the cost associated to it. The change of optical properties can be induced further to a change of light intensity, spectral composition, temperature, electrical field or injected charges. Chromogenic materials can be categorized in two classes according to their particles movement: discrete mass and collective. Physical Discrete mass movement includes ion and localized electron motion while collective physical movement includes dispersed or homogeneously distributed liquid crystal particles.

Discrete mass movement comprises different types of technologic principles such as are photochromic, thermochromic, gasochromic, electrochromic and recently developed photoelectrochromic. While the first two do not require any electrical power, the last three indirectly or directly need to be powered electrically and are typically preferred to the priors as electronic controls enable to predict and suitably tune these windows to the appropriate need and are independent of the outdoor environmental conditions.

Mechanical

Mechanically adaptive glazing include directly or indirectly electrically powered devices such as prismatic glazing, internally ventilated windows, switchable liquid, orientable glass louvres, rotating windows , inflatable glazing and orientable micro-glass pillars. The innovative concept of a non-electrical device using shaped thermos-bimetals embedded in a glazing cavity has been proposed (D.K. Sung, 2012, D.K.Sung 2013). Shaped thermo-bimetals biomimetic breathing skin by opening and closing under thermal change and therefore can be used as a shading device mechanically responding to its ambient temperature.

Using fluids such as air and water has been demonstrated to dynamically control heat transfer through the glazing (R. Lollini, 2010, V. Serra 2010, T. Chow, 2010 and 2011). Another switchable liquid window containing a liquid of low viscosity, a dye presumably with an infrared absorption and with a low freezing temperature which can be introduced or removed from a glass cavity coated with a repellent agent to the liquid showed the additional advantage to dynamically control the solar transmittance, prevent fragment deposition thereby maintaining the window transparency (A. Carbonari et al. 2012).

Mechanically activated louvres are a common feature to control shading and solar heat transfer. An innovative type of louvres made of a screen-printed glass has been demonstrated on the newly built AGC headquarter at Louvain-La-Neuve and is now manufactured by AGC (P. Samyn, J. De Coninck, 2013). The orientable glass lamellas installed in front of a façade is mechanically controllable, enabling to block or not solar radiation according to the outdoor environment and users' requirement. Using specific serigraphic patterns, direct solar heat exposure is prevented while natural diffuse light enters the building thereby ensuring a high comfort level for the occupants.

Thermal collecting and power producing

To achieve near zero-energy or even plus-energy buildings, it is increasingly imperative that the building façade become a source of thermal and electrical energy which can respectively provide heat and power other active elements of the façade or external circuits utilized by building users.

Today, the BIPV and BIST market is growing fast and these systems are progressively directly installed on vertical facades or integrated into glass façades. Providing both power and shading, large non-transparent photovoltaic cells are distributed within the glass surface with space between them to let the light go through the glass. With research of thin film and emerging photovoltaic technologies an increasing number of semi-transparent photovoltaic modules can be found.

Recent PCE world records illustrated on the NREL chart (NREL, 2015) show that non concentrated CIGS reached 21.7% efficiency (ZSW, 2014) and 21.5% efficiency for CdTe technology (FirstSolar, 2014), consequently closing the efficiency gap with silicon heterostructure (HIT) record of 25.6% (Philips, 2014) and 24.2% efficiency for monocrystalline solar cell (SolarPower, 2010) in modules industrially available.

OPV is a very attractive technology as it uses low cost conventional materials which can be coated or printed on a low cost substrate in very large area in a very short time which opens an economy of scale and potentially competitive cost per watt values with additional ecological advantages (C.J. Brabec, 2004). As a reference, in 2012, a multicrystalline silicon module with standard 14.5% PCE, a CdTe module with 12.6% PCE and a CIGS module with 12.5% PCE show the respective manufacturing cost per watt peak values of $0.82/Wp, $0.63/Wp and $0.89/Wp (greentechsolar, 2012).

Thermal insulation

In *vacuum insulating glazing* (VIG) the gas-filled cavity of usual insulating glazing units is replaced by an evacuated cavity separating two glass panes. This technology allows to reach much higher performances. Currently the most insulating glazing available on the market is the triple glazing which can reach a U-value between and 0.5 and 0.8 W/(m².K). A literature survey on the performance of vacuum glazing revealed that it can achieve U-values of 0.3 W/(m².K), whilst preserving a solar factor ranging between 55% and 60%. A high solar factor enables to increase the quantity of "free" energy (heat) brought by the sun. Also, higher light transmission can be achieved, answering a market need for more natural light in the building. An limitation of the current solutions (triple glazing) is their thickness (>40mm), which is not compatible with the traditional frames for double glazed units. The thinner thickness offered by vacuum glazing could also allow in certain cases a "retro-fitting" of the windows already installed (no change of frame) at affordable costs and without the nuisances caused by the complete change of the window. It is therefore very suitable for renovation works. VIG being lighter (15% to 20% compared to triple glazing for most applications), it also leads to lighter building structures and more rational use of materials: the superstructures of building can be designed to support a lower weight. To reach an industrial scale product, current research challenges of VIG consist of maintaining such high performance research results over large glazing areas with special emphasizes on the sealing frame technology. Simultaneously to the continuous improvement on the thermal performance of glass with double, triple and vacuum glazing's.

Active coatings

Active coatings can fulfil functions such as self-cleaning (K. Midtdal, B.P. Jelle, 2013). The idea behind self-cleaning is to protect the surface against or limit the presence and growth of bacteria, fungi and other microorganism. Photocatalytic hydrophilic glazing are self-cleaning while hydrophobic coatings are applied to glazing to act as a water-repellant.

Photocatalytic products proved their self-cleaning action over 25-30 years while hydrophobic-coated products have a short life expectancy of about 3-4 years. Hydrophilic self-cleaning glass have a good self-cleaning effect while hydrophobic glass have a considerably lower self-cleaning effect. Particulate organic matter destroyed by a percentage of 44-48% on self-cleaning surface. Some remaining organic deposit firmly bond to the glass surface and require human intervention. A titanium dioxide layer or a transparent layer of mineral materials on the glass surface decompose organic matter under UV radiation (break down dirt and dust into vapor and carbon dioxide gas). Using the former compound, 5 to 7 days of solar radiation seem enough to operate while the latest normally require about 1-4 weeks. "The hydrophilic properties of the coating causes the water to form large sheets and wash away the broken down organic matter". The hydrophilic properties can be enhanced by using a thin layer of silicon dioxide. The self-cleaning coating is said to last in excess of 15 year or as long as the glazing itself.

5.1 Performance evaluation

To develop complex architectural and structural systems their performance has to be quantified and evaluated during the design process. Paul argues [22], this defines the era of “Digital empirism”. Computational methods are applied, such as the finite element method, allow moving beyond situations for which analytical solutions are available. As a result barriers to complex building design such as verifiability and designability gradually disappear.

Digital Empiricism describes a world that finds stakeholders informed, empowered by decision support systems, and able to describe convincingly to others the logic and rationale behind their decisions. The methodological or technological aspects underpinning this new paradigm are also referred with the terms “Analytics”, “Data Driven Strategy”, “Business Intelligence” or “Big Data”. The empirical paradigm brings with it comforting new levels of certainty, defensibility, and explanatory power to those who are otherwise left to make important decisions substantially on the basis of opinion, corporate precedent, or imagined expectation. This new paradigm can also be used in the design of new technologies for improved adaptive building facades. In this context, building performance simulation plays an important role in supporting the decision-making process, since it allows stakeholders, namely design teams, to have the necessary data to drive the design process of a new technology.

Building performance is the result of many interrelated factors. This is most influenced by building’s shape and orientation, characteristics of building envelope, occupant behavior, weather conditions, building services and control actions [19]. Maver [21] defined the four basic elements of computer-based building performance prediction:

1. representation - the designer generates a design hypothesis which is input into the computer;
2. measurements – the computer software calculates the behavior of the hypothesized design and outputs measures of cost and other performance indicators;
3. evaluation – the designer then examines this prediction and exercises his value judgment; and
4. modification – the designer may decide on appropriate changes to the design. Today, this four-step approach is still the main methodology in building performance simulation in current practice.

Predicting building performance is a very complex, time-consuming and uncertain task since it is difficult to deal with all the above mentioned dynamic, non-linear and multi-physical interactions. In cases of adaptive building facades this is even more complex, since it is necessary to create a model that takes in consideration the changes in the physical proprieties of the envelope, based on the changes of one or more variable (e.g. occupant’s comfort level). According to different studies such as by Kasinalis [16] there are four critical factors that influence the adaptive behavior in Adaptive Façade Systems (AFS): (1) climate; (2) people; (3) timescales; and (4) adaptive mechanisms. The last two are particularly relevant to consider when dealing with adaptive facades. With respect to *timescales*, the traditional application of building performance simulations is based on the use of full-year datasets containing 8760 hourly values per state variable [19]. This timescale provides sufficient accuracy for conventional building simulations and will probably also provide adequate results for AFS’s hourly and diurnal cycles. Regarding the specific context of timescales related to the long-term effects, namely the impacts of future climate changes in the AFS, it is possible to find information about this in the studies developed by e.g. Jentsch [12] and Georgiadou [10] et al..

Regarding the ability of considering the adaptive mechanisms in the building performance simulations applications, reality shows that there are a lot of barriers to overcome in order to allow successful performance prediction of AFS [19]. Opposed to the dynamic climate boundaries, adaptivity in materials proprieties is something that is not considered in the principles of development of most building performance simulation tools. This makes that the adaptive mechanisms for micro-level adaptive façades are limited in common building performance simulation tools. Additionally, the number of dynamic mechanisms for macro-level adaptive façades simulations is also limited. Nevertheless, there are at this level two important exceptions since many tools allow to model and control shading devices and window openings in a dynamic way. Concerning the robustness of the building performance it is necessary to highlight that this is based on several assumptions, e.g. weather data, occupant's behavior and equipment loads. The simulation of innovative materials and technologies in the adaptive façades further increases the level of uncertainty both in the problem definition process and in the definition of the thermos physical proprieties of materials [29]. Additionally there is a general lack of well-accepted strategies for the simulation of AFS. Therefore it is necessary to test the reliability of a model through verification and validation tasks in every AFS model development processes. Nevertheless, at this point, the state-of-the-art shows that there is no general recommended process or standard procedure available for setting the adequate verification and validation process in building simulation [4].

6. Summary

Adaptive façade systems combine ideally a great variety of functions integrating services from many, traditionally individually acting engineering disciplines such as civil, building services, electrical and façade engineering just to name a few. The field to search in order to gain an overview is vast and was limited only by a few keywords such as performance requirements, design approaches, use cases and market needs.

Whilst the authors succeeded to highlight a number of aspects such as performance requirements, design approaches and use cases, little was found with regards to market needs and user acceptance. Although not central to the value of this contribution, the absence of relevant references could be interpreted as knowledge gap. The increasingly stringent performance requirements in combination with the advances in material science and digital empirism present a great opportunity for adaptive facades. However, there are number of great challenges associated with the design, evaluation and operation of adaptive facades such as:

- Risk based related design regulations could support the uptake of adaptive façade technologies as they could stimulate the design of robust performing buildings.
- Integration of structural and energy related aspect with regards to adaptive behavior of facades. The term adaptable is not commonly used related to structural design aspects.
- Design and Performance evaluation of adaptive façade is a complex task. Exceptional load cases such as bomb blast, earthquakes and fire require different materials, technological concepts and design approaches than energy related questions.
- The composition of the design teams of building projects changes with increased performance requirements. Integrated design approaches blur the boundaries of design specialisms and thereby seemingly reduce the transparency related to tasks, responsibilities and accountability.
- There are a great number of interesting system an component concepts readily available to be integrated into adaptive façade concepts. However limited real-life performance experience is available to support the uptake during design.

7. References

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