Adaptive Façades System Assessment: An initial review

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Abstract

The assessment of adaptive facades presents a challenge because there is no established evaluation strategy to systematically reach this goal and many of the available building energy standards and codes have limited applicability for such advanced facades system. This paper reviews current evaluation methods for assessing adaptive facades system through a literature review. It also discusses occupant behaviour, post occupancy evaluation and commissioning issues and presents the procedures. The paper is part of the activities of Working Group 3 in COST Action TU1403 - Adaptive Facades Network. So far we could not find a protocol for assessment of adaptive facades. The reviewed literature is scattered lacking a focus on adaptive facades. There is no agreement on defining what are adaptive facades (sometimes named intelligent, smart, dynamic). We could define specialized technology monitoring techniques to assess the performance of technologies such as fabric-integrated solutions (e.g. electrochromic glazing, phase-change materials, building-Integrated Photovoltaics with heat recovery (BIPV/T, shade shutters) and advanced controls. The review is used to identify gaps in existing assessment methods and helps develop strategies for the holistic evaluation and assessment of adaptive facade systems as part of high performance buildings.

Keywords: façade engineering, advanced fenestration, monitoring, performance, dynamic façade, evaluation

1. Introduction

The assessment of adaptive facades has many challenges and opportunities. The main challenge encountered in Europe is that there are many uncertainties, such as climate change, technology advancement, occupant behaviour, regulation and norms and maintenance issues, all of which directly affect the assessment of adaptive facades and hence the efficient and high performance operation of an adaptive façade. Adaptive façade are made of different subsystems and are rarely designed, commissioned and operated as one integrated interactive system. Different adaptive façade technologies and solutions have different interactions with the HVAC system, occupant comfort expectation and other building subsystems. This results into very complex systems and subsystems with very hard to predict controls and interactions. We are willing in the COST Action TU1403 - Adaptive Facades Network to address those challenges and identify the gaps in the systematic assessment and operation of such solutions, both in terms of commissioning and operation, through literature review and mapping analysis.

For instance, the following questions must be considered:

- What is the appropriate evaluation method (e.g., monitoring or audit) for each major stage of post construction?

- What is the role of simple measurement techniques (e.g., walkthrough audits, simple commissioning, post occupancy evaluation) versus more advanced detailed monitoring (e.g., full monitoring and continuous commissioning) and post occupancy evaluation?
- What other specialized technology monitoring techniques are needed to represent technologies such as fabric-integrated solutions (e.g. electrochromic glazing, phase-change materials, Building-Integrated Photovoltaics with heat recovery (BIPV/T, shade shutters) and advanced controls?

Today there are a great number of façade and envelope technologies that are readily available in the market. However, the decision as to how they are designed, operated, maintained and assessed remains a challenge. Therefore, this paper aims at providing an overview of recent research and development in this field as a well as the assessment of adaptive facades as integrated systems with different subsystems. The following target groups are expected to be involved in the action: researchers, academics, engineers, fabricators, construction firms and standardisation committees.

2. Definition and Life of Adaptive Façades

Adaptive facades are building envelopes that are able to adapt to changing climatic conditions on daily, seasonally or yearly basis. By adaptive we mean the ability to respond or benefit from external climatic conditions to meet efficiently and more important effectively occupant comfort and well-being requirements [1]. Adaptive facades are multi-parameter high performance envelopes that, opposite to fixed facades, react mechanically or chemically to external climate dynamically to meet internal loads and occupant needs [2]. Ogwezi et.al and Favoino discussed the performance of adaptive facades and presented different performance metrics and indicators for this type of facades [3-4]. Figure 1, illustrates four different examples of adaptive facades where climatic control is a key feature of the designed envelope.

Fig. 1a Kiefer technic showroom in Bad Gleichenberg, Austria by Ernst Giselbrecht + Partner, photo by Paul Ott, 1b Al Bahr Towers, Dubai, UAE by Aedasm, photo by Aedasm, 1c South Australian Health and Medical Research Institute (SAHMRI) in Adelaide, Australia photo by Peter Clarke, 1d Thematic Pavilion EXPO 2012 in Yeosu, South-Korea photo by Soma

The overall life of adaptive facades can be divided into eight phases as shown in Figure 2 [5].The first three phases are concerned with the design and performance simulation of the façade. In this phase architects and façade engineers define and identify the façade geometry, structure, materials and aesthetical appearance. This is followed by construction and constructions documents phase before commissioning phases where field inspection and performance testing is done. Commissioning is used in this phase to guarantee that the façade system is erected and installed according to the design requirements and to make sure that all systems are interacting to achieve the expected performance requirements. The final phase, comprise occupancy and operation performance measurement, before finally dismantling the façade. For this study we focused on the commissioning and occupancy operations performance phase.

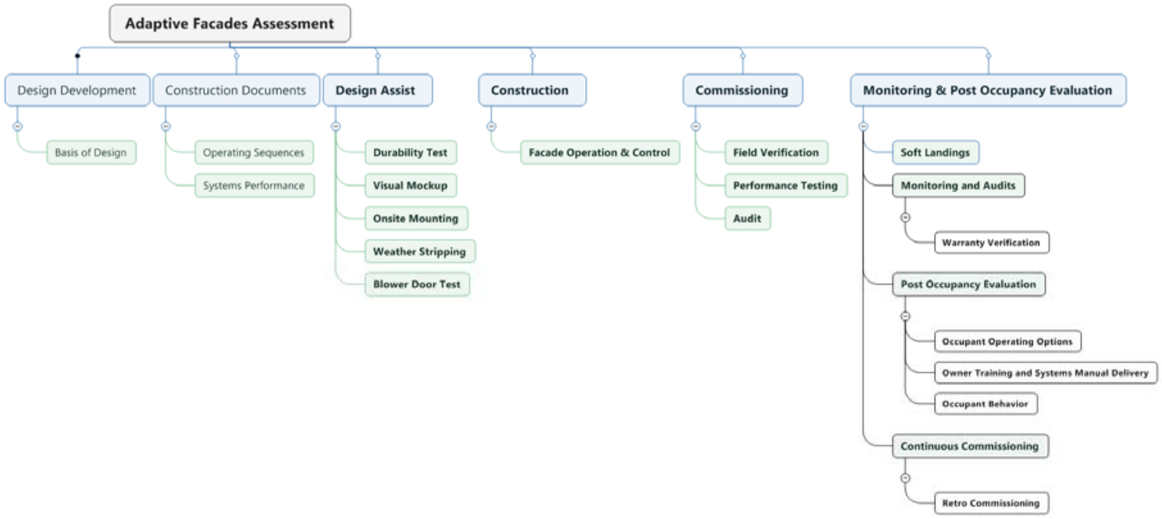

Fig.02, the design process of adaptive facades with a focus on occupancy operations performance, adapted from[5]

3. Literature Review

The following section presents the results of the literature review. We found several existing literature and proposed assessment methodologies for adaptive facades. The headings classify the review literature under three main categories.

3.1 Commissioning

Building commissioning has been gaining momentum and awareness within the building industry as a comprehensive quality assurance process that can be used throughout the buildings life cycle to ensure that the needs and requirements the owner has for the building are met [6]. With the advent of building rating systems such as LEED and BREEAM commissioning became a fundamental procedure for green building certification and credits are awarded for advanced commissioning with focus on air leakage, moisture penetration, thermal images etc. For example LEED is based on the Building Enclosure Commissioning (BECx) process utilized to validate that the performance of materials, components, assemblies, systems and design achieve the objectives and requirements of the owner as outlined in the contract documents [7]. Moreover, the Energy Conservation in Buildings and Community System programme of the International Energy Agency has supported Annex 40 Commissioning of Building HVAC Systems for Improved Energy Performance [8]. The objective of the Annex was to develop, validate and document tools for commissioning of buildings and building services. Worldwide, there are several ISO, EN and national codes, like AS2047 in Australia, AAMA 101 and ASTM 514-09 in the USA, CSA A440-08 in Canada, NBN B25-002-1 in Belgium, BS6375-1 in the UK, FD P20-201 in France, ift FE 05/2 in Germany and CWCT in Bath University. Most of those standards are used for project inception (during the Pre-Design Phase) and continue for the life of the facility (through the Occupancy and Operations Phase). Most of those standards provide calculation and measurement methods for the thermal performance of the envelope and window claddings before construction or production quality control. However, there are hardly any in-situ standards for commissioning of the whole façade system in Europe. Moreover, it is important that none of the commissioning approaches were specifically developed with adaptive facades in mind. Adaptive facades must be properly commissioned and time should be dedicated by the façade engineers to verify that the systems are properly functioning prior to move-in, occupants should be provided educational materials [9], and then followed through in the initial period of occupancy to troubleshoot and fine-tune operations [10].

Measuring Performance Protocols

Performance claims for building envelope and façade cannot be credible without standardized performance measurement protocols that can be applied consistently using performance benchmarks. There are three major protocols used to measure and evaluate building performance. Those protocols provide a conceptual framework in measuring, computing, and reporting performance of projects and facilities. There is a lack of protocols and benchmarks on operational performance of adaptive facades in real buildings, and the number of well-documented case studies is very limited. However, the following protocols are widely used to assess and measure building performance.

3.1.1 Measurement and Verification (M&V)

Measuring and verifying savings from performance contracting projects requires special project planning and engineering activities. Although M&V is an evolving science, industry best practices have been developed. These practices are documented in several guidelines, including the International Performance Measurement and Verification Protocol1 and 2 [11] and ASHRAE Guideline 14: Measurement of Energy and Demand Savings [12]. However, there is not yet a specific M&V protocol for adaptive facades.

3.1.2 Audits

Also called assessments, audits are systematic reviews of the building's energy and water usage and opportunities to reduce it. There is a direct relationship to the cost of the audit, how much data will be collected and analysed, and the number of conservation opportunities identified. The basic audit levels, in order of increasing complexity are: The walk-through audit, standard audit and computer simulation. Although widely used for building performance evaluation, building audit protocols are not accustomed to assess adaptive facades.

3.1.3 Post Occupancy Evaluation

Post-occupancy evaluation (POE) is a protocol for the systematic study of buildings once occupied, so that lessons may be learned that will improve their current conditions and guide the design of future buildings. Various aspects of the occupied buildings' functioning and performance can be assessed in a POE, both chemo-physical (indoor environment quality (IEQ), indoor air quality (IAQ) and thermal performance) as well as more subjective and interactional (space use, user satisfaction, etc.) [13]. POE draws on an extensive quantitative and qualitative toolkit: measurements and monitoring, on the one hand, and methods such as walk-throughs, observations and user satisfaction questionnaires on the other. For example the study of Stevens addressed the influence of occupant control in achieving occupant satisfaction in buildings with intelligent facades [14]. Lee et al 2012 investigated the operational performance and occupant influence in real building using commercially available electrochromic windows [9].

Occupant Behavior Monitoring

Many distributed developments have been reported, but there is not yet a comprehensive state-of-the-art review or universal approach regarding occupant behaviour monitoring. The uncertainty of occupant behaviour remains the dominant problem among reviewed literature.

According to Brager et al. occupants with different degrees of personal control have significant diverse thermal responses, even when they experienced the same thermal environments and clothing and activity levels [15]. Subjects who have more control over thermal conditions of their workplace (in particular, the operable window) had a neutral temperature that was 1.5°C warmer than subjects with minimal control, even though they experienced the same thermal environments with same clothing or metabolism. People in an office with HVAC are less tolerant to suboptimal thermal conditions.

Also occupant control is found to be the dominant issue affecting occupant satisfaction in buildings with intelligent facades. Survey results indicate that facade design has a large impact on the occupants' perceived control over and satisfaction with their environments. There is a close connection between perceived control and actual control (with respect to window use), and that occupants with a high level of perceived control more frequently use their windows than others with a low level of perceived control [16]. Results from a pilot study with a dynamic shading façade show that the ability for users to overrule the automated control operation of the façade is of key importance for ensuring high occupant satisfaction [17]. Monitoring data provide evidence that there is significant relationship between window-opening behaviour patterns and indoor stimulus (i.e., indoor air temperature) it is recommended that further effort is put into finding optimal set points for activation of the solar shading and for controlling the tilt angle of the blinds in order to obtain a robust control strategy with limited overrule actions [18]. In most review studies, only indoor and outdoor temperatures are measured. Or only window opening is only measured in on/off modes, but not the opening angle of windows, this makes results in many cases only applicable to specific buildings with very basic and limited data (no measurement of CO^2, radiant temperature) [19]. There is a need for high resolution with variant comfort indices.

Automatic control systems have been reported as an important component of facade's performance. For example, fault detection and diagnostic (FDD) tools are indispensable for troubleshooting automatic control systems. Data and infrastructure are needed to detect problems with the control system, sensors, and associated hardware [20]. With appropriate selection of occupant-predicting control strategies, impact of occupant behaviours on the building performance can be reduced [21].

Accurate and simple mathematical occupant models are needed to be used by facade designers and engineers and managers. Without accurate occupant models, poor building design choices can be made [22]. Finally, there is a lack of studies on operational performance of adaptive facades in real buildings and protocols to monitor the occupant behaviour.

3.2 Performance Indicators

The performance of adaptive building envelope components cannot be sufficiently characterized by means of static performance indicators (i.e. U-value, g-value, T-vis etc…). This is due to the fact that in many adaptive façades the variability of these indices, due to the changing boundary conditions, cannot be disregarded [23-24]. With respect to double skin facades (DSF), several dynamic performance indices have been proposed. For example the work of Saelens et al. [25] shows the dependency of the U-value and the g-value of a transparent DSF over the air inlet temperature and the air-flow of the ventilated cavity of the DSF as shown in Figure 3.

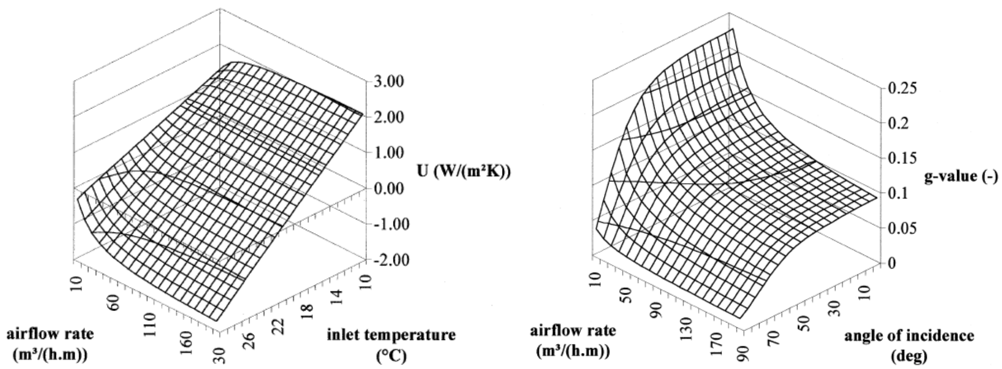

Fig. 03, U-value and g-value as a function of boundary conditions in a DSF [26].

For this reason numerous analytical models were developed and experimentally validated, such as the study by [27]. By means of these models the energy and comfort performance of a DSF can be evaluated directly, by means of either calculating its performance indicator or indirectly by evaluating the energy consumption or the comfort of the space enclosed. When these models are not available the performance is evaluated by means of comparative experimental studies [28], that is the energy consumption (and/or the environmental quality) of a space with an adaptive façade is compared to a space with a state-of-the-art static façade, with the same boundary conditions.

In order to compare the performance of some kind of dynamic building envelopes, some performance indicators have been developed. These performance indicators are suitable for dynamic systems which make use of the heat exchange of a flow into a cavity (included in the façade itself) to regulate the heat flow across the building envelopes. These indicators are: the dynamic insulation efficiency [29], defining the capability of the façade at reducing the entering heat fluxes, by means of the air gap ventilation; the preheating efficiency [30], which is defined as the capability of the façade of preheating the outdoor air in order to supply fresh air to the indoor environment; the btr factor [31], which is defined as the capability of the façade of reducing the temperature difference between the outdoor and the indoor environment, by means of a closed cavity, such as a greenhouse or a double skin façade. These performance indicators can be calculated during the operation of the façade itself and can be used to predict the synergistic operation of the façade with the HVAC systems as well [32]. All these indicators alone are unable to describe the energy performance of a dynamic building envelope in a comprehensive way, because they are either too specific or they influence different end use energy consumptions in different ways (e.g. g-value positively influences heating energy saving and negatively influences cooling energy saving). In order to account for the energy performance of the building envelope in a more comprehensive way, a more holistic approach is needed.

3.3 Comfort and control in the perimeter zone of an adaptive façade

There is no model that describes the relationship between the users and the control of the façade system or a building system in general, although some attempts at defining the nature of this response in the case of the use of some adaptive façade features as shading device or window opening have been developed [33-34].

As far as personal control is concerned, Frontzack et al [35] highlight how there are many other factors influencing the IEQ including personal, climatic and building factors. This was mainly deduced by survey-based studies. Among the building factors one of the most important ones is the perceived level of control over the environmental conditions: "Providing occupants with the possibility to control the indoor environment improves thermal and visual comfort as well as satisfaction with the air quality". These results are partly confirmed by Bluyssen et al [36] who, by means of questionnaires and comfort measurement, found out that beyond the level of environmental variables, there are other important building factors which are affecting the IEQ of the occupants. The main factors, other than environmental parameters, are 'view' and 'control over environmental parameters'. In fact it was found that there was a big improvement in the correlation with the perceived IEQ level and the variables considered, when also control variables were included in the analysis (control on temperature, ventilation, sun shading, lighting and noise) and that this is seasonal dependent. The study shows how there is an improved IEQ when the occupants are able to control noise, sun shading and temperature in summer, and just noise in winter, while negative impacts were registered when one is able to control ventilation and lighting in both seasons. Another step forward to the inclusion of personal control in a unified comfort theory is the work of Haldi et al. [31]. In this research, which makes use of a database of several buildings, the control over environmental parameters is measured by means of adaptive action on building components or building services by the occupants (opening of a window, switching of a light, using a fan or opening and closing a shading device), while the main environmental parameters are measured (temperature, solar irradiance, illumination level, presence of occupants). The aim of the study is to elaborate a behavioural model of occupant's adaptivness to be included in simulation models. This model, different from the adaptive theory, interprets the effect of an occupant as not influencing only its environment but also its perception of comfort (as suggested by [35-36].The inclusion of adaptive action (which are interpreted as physical and physiological action) into the adaptive thermal comfort theory, improves the correlation coefficients between the thermal neutrality and the outdoor temperature for different occupants. The effects of the different actions are then quantified and a probabilistic model, to account for prediction of the effect of this adaptive actions on occupant comfort, is provided.

4. Key challenges of adaptive façade performance assessment

Based on the literature review analysis we could identify four major challenges or characteristics of adaptive facades that make their assessment difficult.

4.1 Novel and Unique

Currently, there exist only a very limited number of documented case studies with information about the operational performance of buildings with adaptive facades. There are many different concepts and technologies are available or under development. Making generalisations generalizations or extrapolations is biased with the small sample of adaptive facades. Also every adaptive facade is unique and there is a lack of benchmarking data. Most systems are one-of-a-kind or tailor made; there is no mature experience available at façade engineers regarding standardised design, construction, operation and assessment of adaptive facades.

4.2 Dynamic and Complex

Traditional or fixed façade component have been assessed using static indicators and metrics such as U-value and g-value. Those static value and metrics have very little meaning in dynamic systems. Adaptive facades also are multi-functional systems, often consisting of multiple sub-systems. They can fulfil multiple roles at the same time. Performance assessments were not developed to address this complexity and dynamism. Monitoring protocols do not exist and many simulation programs lack capabilities to model time-varying building envelope properties [37]. Even the calibration of simulation models remains a serious challenge. For example, how to calibrate an adaptive façade that also includes personal controls? The literature review revealed random monitoring protocols and techniques used for this typology of facades. Moreover, user interaction, overrule options, understanding of the systems and other human factors play a major role in operating adaptive facades. It is known that the level of (perceived) training/education of high-performance building systems has a major influence on the satisfaction [38] of users.

4.3 Intelligent and Sensitive

The effectiveness of the operation strategy (i.e. intelligence of the system) (manual, automated or hybrid) determines performance of dynamic systems such as adaptive facades. This makes it very hard to operate and control adaptive facades because they are highly climate and occupant dependent. Due to climate sensitivity every façade solution is extremely local, reacting to air, radiation and temperature differently. By nature adaptive façades depend on high performance technologies with a high precision and response. This makes them very sensitive and local solutions.

4.4 Unpredictable and Fragile

It is not evident that the design-phase simulation model can also be used by the maintenance party during operation [39]. In many cases performance gaps between design intent and measured performance are encountered. This could be partially attributed to the nature of adaptive façades. Unlike HVAC system performance evaluation, for adaptive facades it is much less obvious to understand how they perform. Also adaptive façade systems are often combined with minimally-sized HVAC systems. There is no back-up system. An illustrative example of the importance of maintenance, are the diaphragm shutters of Jean Nouvel's Arab World Institute in Paris that are not working as designed [40].

5. Conclusion

The assessment of adaptive facades using currently available measuring and evaluation protocols poses a number of challenges and questions, such as benchmark performance and methodology, the complexity and integration of adaptive facades with occupant response, HVAC systems and controls, technology representation and modelling information. This paper reviewed current state of the art of assessment strategies for adaptive facades through literature review. So far we could not find a protocol for assessment of adaptive facades. The reviewed literature is scattered lacking a focus on adaptive facades. There is no agreement on defining what are adaptive facades (sometimes named intelligent, smart, dynamic). We could define specialized technology monitoring techniques to assess the performance of technologies such as fabric-integrated solutions (e.g. electrochromic glazing, phase-change materials, building-Integrated Photovoltaics with heat recovery (BIPV/T, shade shutters) and advanced controls. The next step will focus on selecting case studies of adaptive facades with detailed monitoring performance data in order to better understand their performance and study their optimisation potential. The case studies should seek better understanding of their design process, modelling and real performance. An inventory of the components of adaptive facades systems can be of help in better defining adaptive facade tools. It is important to develop monitoring based benchmarks in order to inform the professional and research community of gaps and needs of adaptive facade assessment.

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