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A Comparative Study of the Energetic Performance of Climate Adaptive Façades Compared to Static Façade Design in a Mediterranean Climate

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Abstract

Energy-efficient design of building façades has so far predominantly been confined to static rigid forms. Recently however, attempts have been made to design environmentally responsive façades, hereby called Climate Adaptive Façades. These have the potential to better address the occupant's requirements, while also reducing energy demand. The present paper focuses on adaptable glazed façades, in a Mediterranean climate. It investigates the simulated energy performance of three types of climate-responsive façades that could be retrofitted to an existing glazed façade, in the process comparing the results to using comparable static façades solutions. Modelling dynamic façades is not an easy task and currently no single building performance simulation package appears to be capable of completely modelling the behaviour of these façades. For this reason a number of simulation packages had to be used to determine the energy demand required to achieve comfortable indoor thermal and lighting conditions. Through the results obtained, it was possible to compare energy demand of a dual-façade design approach, dynamic *vs*. static, thus identifying general trends. The results also highlight the fact that in order to improve over the predicted performance further studies using specialised tools capable of modelling such novel technologies are required.

Keywords: Climate Adaptive Façades; Retrofitting of Buildings; Thermal and Lighting Energy Analysis; Simulation and Modelling

1. Introduction

In developed countries, buildings consume roughly around 40% of the total energy demand [1], with a substantial part of this energy actually used to counter energy losses or gains through the building envelope. In this context, notwithstanding the improvements in high-tech glazing systems, buildings, especially commercial ones, making use of curtain walls are particularly susceptible to high energy fluxes [2, 3].

Whereas the architectural value of a building remains of paramount importance [4], architects and engineers have tried to counter this energy flux by designing façades that deliberately promote passive technologies including for example, specific shading devices for controlling the ingress of solar gains yet exploit daylighting [5, 6]. Such devices are however typically only designed to accommodate specific environmental conditions when in actual fact they are exposed to constant varying conditions (*e.g.* fluctuations in solar radiation, shading from adjacent buildings, *etc.*). Static façades therefore can only be optimized for specific environmental conditions typically those associated with maximising seasonal or annual performance [3]. In the context of a continuously changing environment, static façades therefore may often not be performing at their best design intent.

To improve on the existing situation, recently, attempts have been made to design environmentally responsive building façades, hereby called '*Climate Adaptive Façades*' (CAF). By incorporating established technologies such as smart materials, sensors and building management systems, these type of dynamic façades offer potential opportunities to address the occupant's requirements better and more efficiently than in static building envelopes, thus also reducing a building's energy demand [7-9].

2. Climate Adaptive Façades

2.1 Background

Although the concept of environmentally responsive façades emerged in the early 20th century [10], it was not until the 1970's that the concept was seriously taken into consideration [11].

Climate Adaptive Façades have been defined in various ways, resulting in a multitude of different definitions and terms, e.g. *Climate Adaptive Building Shells* (Loonen *et al.* in [11]) and *Acclimated Kinetic Envelopes* (Wang *et al.* in [12]). The term CAF is hereby being used to describe a façade system which includes both the opaque and transparent wall elements of a building envelope and which dynamically responds to variations in the external environment. In addition, following the terminology developed by Jacob Lam [13], the use of the '*Adaptive*', rather than '*Responsive*', is being used to include the option of user decisions and not only responsiveness to the environment. Thus a more flexible user-sensitive response is initiated here.

2.2 Classification

Over the years various CAF concepts have been proposed. Loonen *et al.* in [14] identified 44 CAF concepts, ranging from '*fully built concepts*' to '*reduced scale prototypes*'. Other researchers [12, 13] use other classification methods to facilitate the identification of different CAF typologies, including according to the type of environmental parameter the façade is sensitive to, or the control methodology.

2.2.1 Type of Responsive Mechanisms

The type of adaptive mechanism a CAF system employs in response to a physical parameter, describes the action performed by the dynamic façade system, to adapt to a particular environmental stimulus. Based on the case studies presented by [14], the type of responsive mechanism employed by CAF system can be categorized according to three types, namely, CAF systems making use of '*property shifting material*' such thermochromic [15] and electrochromic [16] glass which change opacity to control incoming radiation; '*shape shifting materials*', which make use of flexible materials which are able to change their shape, creating openings or closures either through the application of an external force or by reacting to changes in the environment; [17], or '*movable components*' where parts of a façade change their spatial arrangement via moving (*e.g.* sliding, rotating, folding or expanding) components. Most CAF concepts fall under this latter category and most of these CAF concepts have actually been built [14].

2.2.2 Physical Parameter Responsiveness

An important aspect in CAF system development is the type of physical (environmental) parameter the dynamic façade is sensitive to. Various systems have been developed or proposed to respond to different physical parameters including, '*solar radiation responsiveness*' [18], and '*air flow responsiveness*' [19].

2.3 Potential Savings and Extension of CAF as a Retrofit Design Solution

CAF systems have been proven to generate savings in heating, cooling and lighting consumption. When compared to the best performing static design, savings as low as 15% [20] to as high as 50% [21] have been reported, depending on the type of dynamic façade design used.

A particular area which is of interest in the design of CAF systems is the use of such dynamic façades as a retrofit design for improving the environmental performance of an existing building. Considering the general resistance of architects to alter their own design process and given that several buildings with glazed façades have already been designed and built, specific solutions must be considered to address this issue. While the idea of redesigning existing high energy-consuming buildings might seem farfetched, retrofitting an existing façade might not. Accordingly, designing these adaptive façades as retrofit solutions facilitates the future integration of climate adaptive façades in building design. The research presented in this paper therefore aims to preliminary address a specific gap in climate adaptive façades research dealing with dynamic systems as retrofit solutions, through a process based on comparative analysis between using static and dynamic façade design approach.

3. Comparative Studies

As discussed, to investigate the potential of CAF systems, specifically as a retrofit solution for buildings, a comparative study was set up to quantify the effectiveness of different CAF systems compared to traditional static design façade solutions. Based on the classification methodology presented in Section 2.2.1, a set of dynamic façade design criteria were identified to create three Climate Adaptive Façades for a specific

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building exposed to a Mediterranean climate such as that in the Maltese Islands. For an equitable comparison, static alternatives for the dynamic façade designs were also identified. This made it possible to compare a dynamic approach to a conventional static approach to façade design.

3.1 Location and Host Building

The Maltese Islands experience high hours of sunshine, with an average of 300 clear days. Average monthly temperatures lie in the range of 12.4°C to 26.3°C during the winter and summer months respectively [22].

The building selected, the Aragon House Business Centre located in the North-East of the Island of Malta, was selected on the basis of being an office building with a predominantly south-facing glazed façade. It consists of 9 storeys with glazing roughly on all sides and a floor area of approximately 2,398m^2. The wall elements for each storey are divided into two parts: the top half being glazing and the bottom half being an insulated panel with a glazed exterior for aesthetic purposes. The adjacent buildings provide some shading on the building especially during the winter; however the top floors remain exposed throughout the year. The area to be retrofitted with the façade systems was limited to the curved south-west face as shown in Figure 1. The north façades was left unobstructed to let in as much daylight as possible.

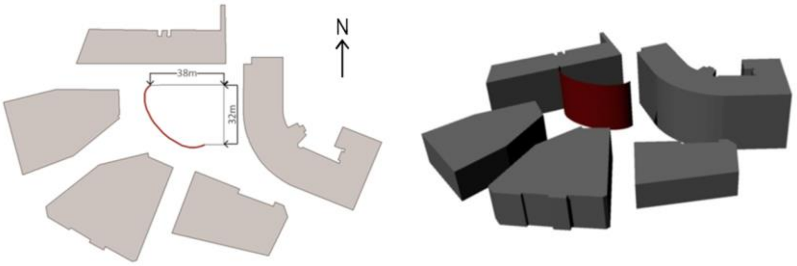

Figure 1: Building site plan showing area to be retrofitted with CAF system

3.2 Façade Design Criteria

The research being presented looks specifically at the classification typology based on CAF systems categorized on the basis of their responsiveness mechanism. Three different solutions representative of each responsiveness mechanism category were therefore modelled. These are shown in Figure 2.

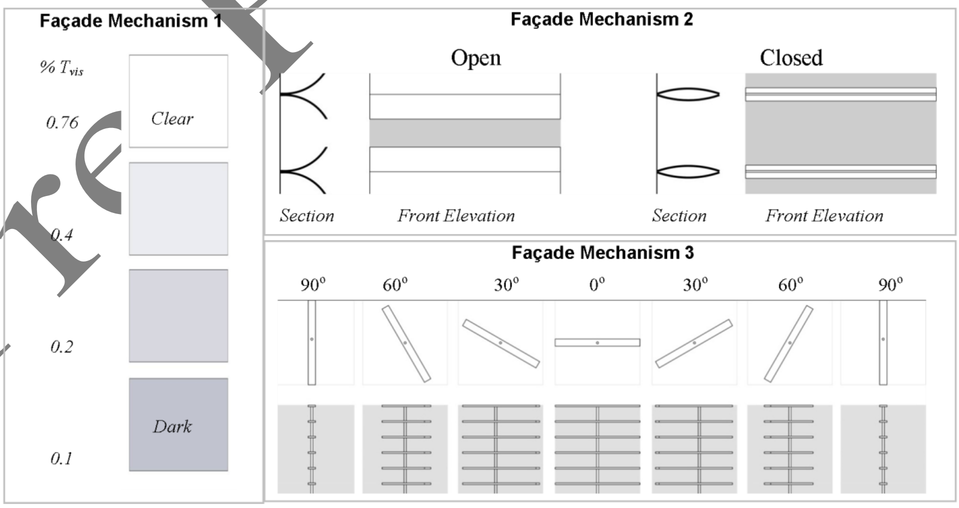

Figure 2: Façade mechanisms modelled

This study focuses on systems which respond to the amount of incident solar radiation as this is the most common type of CAF system. All systems were designed as retrofit solutions, whereby the building layout was left unaltered.

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3.2.1 Façade Mechanism Type 1: Property Shifting Material

Façade Mechanism Type 1 was chosen to be a system comprising electrochromic glazing. Each glazed panel in the south-west curved façade was replaced with commercially available electronically-controlled electrochromic glass, capable of change opacity from a clear transparent state to two intermediate darker states to a final dark state as shown in Table 1. The static alternative, against which a comparison was made, was chosen to be a 20% tinted glazing.

State	Clear	Intermediate (1)	Intermediate (2)	Dark
g-value	0.64	0.32	0.24	0.16
Transmission (%)	0.76	0.40	0.20	0.10

Table 1: Electrochromic Glazing Specifications

3.2.2 Façade Mechanism Type 2: Shape Shifting Materials

Façade Mechanism Type 2 is based on the façade developed by Decker and Yeadon [23], comprising horizontally-positioned bi-metallic strips acting as shading devices, which expand or contract, in response to the incident solar radiation. In this case the static alternative of this dynamic façade consists of wide horizontal louvers all throughout the façade, which would be relatively equal to the contracted state of the dynamic façade.

3.2.3 Façade Mechanism Type 3: Movable Components

The third façade system considered follows the most common form of CAF system; a series of louvered components which rotate about their vertical axis, similar in concept to that present by Abu-Hijleh and Hammad [3]. During periods of high solar radiation, the louvers will rotate to 0° (tangential to the glazed surface and hence offering the highest amount of shading), whereas at low radiation they rotate to 90° (perpendicular to the glazed surface and hence offering the lowest amount of shading). The equivalent static system consisted of fixed louvers placed at an angle of 0°.

4. Research Methodology

Most of the research done on CAF systems has so far mostly been carried out using either experimental or simulation methodologies [3]. Obviously the cost and testing duration associated with real-life testing of multiple CAF systems rendered the use of established and validated building performance simulation tools the most obvious solution.

4.1 Modelling and Simulation

The concept of CAF systems is relatively new and therefore most existing building simulation packages are currently not capable of fully modelling them (especially if the building and façade system are complex geometrical shapes). Switchable technologies have been incorporated into a number of building simulation tools (*e.g.* Energy Plus, ESP-r) [11]. These and the other tools that do cater for a dynamic approach, typically however limit the modelling aspect to a basic minimum, therefore making it very difficult to analyse any building or system that deviates from a basic simple geometrical shape.

On account of the fact that the host building includes a curved surface and that the proposed dynamic façade systems include multiple, complex shaped interdependent dynamic components, a customised solution whereby a number of software tools were used in a sequential manner to produce the required output, had to be developed. The process initially consisted in developing a 3D model for each façade system, for every hour, taking into consideration that the dynamic systems change their state hourly, depending on the position of the sun (hence the incident solar radiation). Following this, the models were imported into a building simulation package to evaluate and analyse the thermal and lighting performance.

4.2 Modelling Phase

Considering the required component level approach, whereby each CAF system component adapts to a

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unique position in response to a given environmental input, Rhinoceros [24] a 3D modelling software specialising in free-form modelling, and Grasshopper [25] a plug-in to Rhinoceros supporting parametric modelling, were used to design the 3D components. As shown in Figure 3a, the surface geometry of the south-west facing curved glazed façade of the building was first modelled and divided into a 55 square grid, with each square representing a 1.65m x 1.65m portion of the whole host surface. Once the grid was created, the squares making up the grid were sub-grouped into a number of sectors based on the amount of incident solar radiation (the input environmental condition) falling on that part of the host surface during one specific time instance. Ecotect [26], a building performance simulation package, was used to perform the solar radiation analysis. Figure 3b shows how the solar radiation varies across the entire area of the host surface, while Figure 3c shows how the 55 square components making up the host surface were sub-divided into four groups or sectors based on the different levels of solar radiation falling on each part of the host surface. Based on the solar radiation incident on that particular segment of the grid a component 3D model, representative of one particular state of the dynamic façade, was then assigned for each of the four groups identified, as shown in Figure 4. The whole process was repeated for each of the hours under investigation.

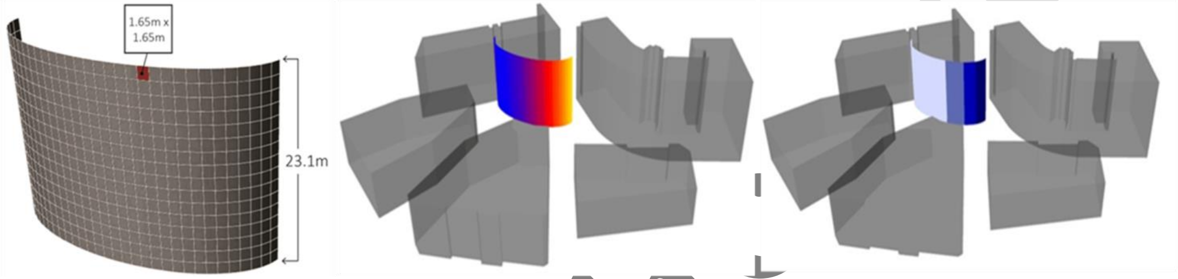

Figure 3: (a) Model surface divided into a grid; (b) Solar radiation pattern input; (c) modelled output response

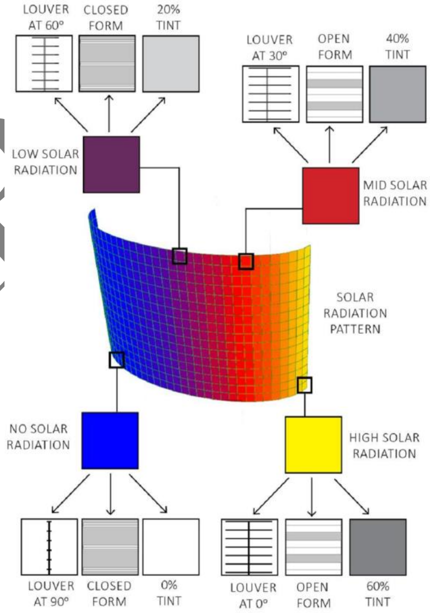

Figure 4: Visual representation of the replacement process

4.3 Simulation Phase

The simulation processes included both thermal and daylight analysis. The building simulation package Integrated Environmental Solutions – Virtual Environment (IES-VE) [27] known for its extensive validation [28] was selected for this process, as it combines good thermal and lighting analysis tools into one package. Two separate days with the least cloud cover were considered for the analysis, one in summer (July) and

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one in winter (December). A single day for each season is generally not considered enough for a representative analysis of the results on a seasonal or annual basis however, being a preliminary study the aim of the study was mainly that of identifying trends in energy savings which could potentially be obtained for different CAF systems in comparison with comparable static systems under the same weather conditions.

For this particular building the analysis focused on the 5th floor (16m above ground level), as this floor is high enough to offer varying degrees of shading (adjacent buildings shade the façade at different intervals) and low enough not to be directly affected by the incident solar radiation absorbed by the roof.

4.3.1 Thermal and Daylight Simulation

The thermal analysis was based on a 1-hour thermal simulation for each of the 84 dynamic modelled façade combinations, with a total obtained for one complete day in summer and winter. The office was considered thermally controlled between 06:00 and 19:00 hours. The lighting analysis used RadianceIES, to assess the illuminance levels in *lux* for the internal floor being examined. The internal area was split into four segments with the average illumination calculated for each segment. Based on the calculated illuminance and assuming that continuous dimming control is available such that any shortfall in the available day lighting is automatically supplemented by artificial lighting, the PSALI principle [29] was used and the number of additional luminaires required for the interior to receive a minimum of 500 lux as per office space requirement [30] was calculated. The number of light fittings required was then multipied by the luminaire rated power and working hours to obtain the energy consumption.

5. Results

Figure 5 and Figure 6 show the total cooling load and the lighting energy required for a summer (July) and winter (December) day respectively.

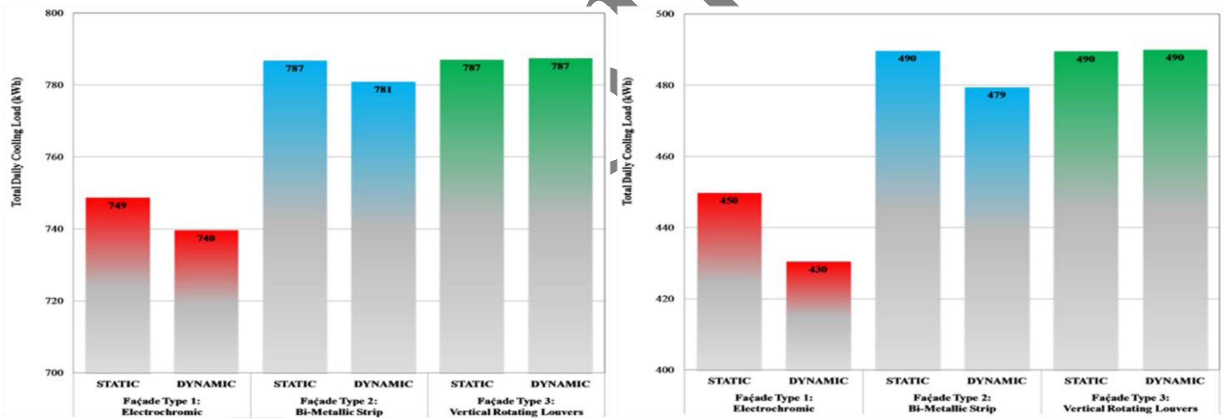

Figure 5: Total Cooling Load (kWh) (a) Day in July; (b) Day in December

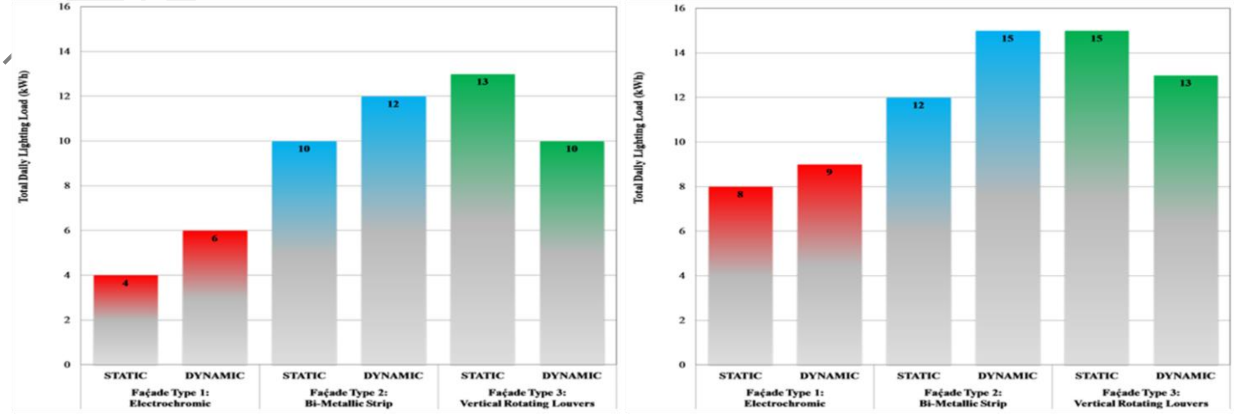

Figure 6: Lighting Energy Consumption *(kWh) (a) Day in July; (b) Day in December*

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The results presented in the following sections are sub-divided into three parts. A first section presents the thermal simulation results obtained for the different façade solutions proposed. In this context a comparative analysis is first carried out between the different façade typologies (*e.g.* use of tinted glazing [Type 1 Façade] *vs.* use of shading devices [Type 2 and Type 3 Façades]) and then between the individual façade solutions (dynamic *vs.* static façades). This permits a broad comparative analysis of the proposed façade solutions, based on the building's thermal performance (building's cooling energy demand). This is then followed by a similar lighting analysis, and a combined (thermal and lighting) total energy analysis for the different façade scenarios proposed. Finally, the assumptions and limitations inherent to the modelling of the façades are discussed.

5.1 Thermal Analysis Results

5.1.1 Comparison between Different Façades Typologies

The calculated daily cooling load is for a single floor of the building, and is based on the selected simulated summer day. Comparing the different façade typologies (Type 1, Type 2 and Type 3) it can be seen that for a typical cloudless summer day, using glass having a low g-value is the most effective method to reduce the cooling demand of the building. Compared to using shading devices (similar to those proposed for the Type 2 and Type 3 Façades), using tinted glass results in a 5% average lower cooling demand for both the static and dynamic façade types. Façades Type 2 and Type 3 show similar cooling load magnitudes, indicating that the shading devices proposed have similar solar heat gain attenuation characteristics.

A similar trend can be observed for a typical winter day. In this case however, the use of electrochromatic glazing results in an average 10% lower cooling demand for both the static and dynamic façade types.

5.1.2 Comparison between Static and Dynamic Façades

5.1.2.1 Façade Mechanism Type 1 – Electrochromic Façade System

Based on the results obtained for the thermal simulations, it can be observed that for the tinted glazing façade system, the percentage difference in total cooling load demand between using the electrochromic dynamic façade and the statically tinted façade is very small, around 1.2%. The difference for a winter day is slightly higher at 4.4%. This small difference between the static and dynamic façade systems tallies with what discussed by Tavares *et al.* in [31], whereby the authors state that for a Mediterranean climate electrochromic glass is mostly effective when placed on the West façade, and that for the South façade no significant improvements are noticed. The slight difference in seasonal performance is mainly attributable to the difference in solar elevation. The higher solar elevation in summer, results in a higher percentage of reflected incident solar radiation, hence the less noticeable difference between the two façade systems.

5.1.2.2 Façade Mechanism Type 2 – Bi-Metallic Façade System

Results show that the use of a bi-metallic dynamic façade system compared to the use of a static wide horizontal louvered façade system results in a 0.8% cooling energy demand reduction for the selected summer day and 2% for the selected sunny winter day. In this case it is noticeable that whereas the shaded area difference between static and dynamic façade is significant, the difference in the respective total cooling load is small - the difference in cooling load does not reflect the amount of glazed area shaded.

5.1.2.3 Façade Mechanism Type 3 – Vertically Rotating Louvered Façade System

Thermal results show that the difference in the total daily cooling load between using the static and dynamic vertically louvered façade systems is practically negligible for both the summer and winter days. An explanation for such a result could be the fact that when the louvers are positioned perpendicular to the glazed surface, therefore fully open, they still provide shade from any radiation approaching from the sides.

5.2 Lighting Analysis Results

5.2.1 Comparison between different Façades Typologies

Similarly to the cooling energy demand the most energy efficient façade typology is the one making use of electrochromic glazing. In this case, the glazing is the least intrusive of the three façade systems in terms of obscuring the ingress of natural daylight, hence its low artificial lighting energy demand requirement.

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5.2.2.1 Façade Mechanism Type 1 – Electrochromic Façade System

Contrary to the thermal simulation results, the lighting energy demand for the tinted glazing façade was found to be higher for the dynamic electrochromic façade system than when using the statically tinted façade system. This increase in energy consumption is due to the fact that while darker states of the electrochromic glazing material block solar radiation resulting in lower solar gains, they also block more daylight, therefore requiring more lighting power to keep the space lit at the required level. The difference in lighting power demand is as high as 50% at certain times of the day. In terms of visual comfort, although more lighting power is required in the dynamic façade approach, glare from the south facing façade is less likely to occur.

5.2.2.2 Façade Mechanism Type 2 – Bi-Metallic Façade System

Following the same trend observed for the tinted glazing façade system, the lighting energy demand for the dynamic bi-metallic façade system scenario was found to be larger than in the static wide horizontal louvered system. The increase in shaded area in the dynamic façade models blocks more daylight from entering the space therefore requiring more lighting power to keep the space lit at the required level of 500 lux. The difference in daily energy consumption between the static and dynamic façade systems was of around 20%.

4.2.2.3 Façade Mechanism Type 3 – Vertically Rotating Louvered Façade System

Contrary to both previous systems, with regards to lighting consumption, the vertically-rotating louvered dynamic façade system exhibited energy savings in comparison to the statically fixed vertical louvers system. The daily energy savings amount to around 23% in summer and 13% in winter. This amount of energy savings is due to the fact that compared to the static system, the vertically-rotating louvered dynamic façade system with its open louver configuration is still able to let in indirect daylight.

5.3 Overall Combined Analysis of the Proposed CAF Systems

When combining the results obtained for the lighting and thermal simulations, it becomes apparent that in terms of the energy demand magnitude, the thermal results heavily outweigh the lighting results.

Comparing the seasonal results it is significant that higher savings are obtained for winter rather than summer. A reason for such a difference could be the fact that with regards to heat transfer in buildings, direct ingress of solar radiation plays an primary role in winter, whereas in summer the heat transfer into the building is predominantly due to the temperature difference between the indoors and outdoors. Electrochromic glazing seems to offer the most promising results in terms of energy savings, and its low up-keep and maintenance required makes the dynamic approach for this façade system the most suitable, not only compared to its static equivalent but also in comparison with the other two systems.

5.4 Assumptions and Limitations of the Research

Given the novelty of the subject it is to be expected that a number of assumptions had to be taken in consideration. Similarly, the methodology used still needs to be refined, not least because of the problematics related with modelling and simulating complex shaped façades and their components.

5.4.1 Applicability to Different CAF Systems

Given the considerable number of CAF concepts which have been proposed or developed recently, and the huge difference in their mode of operation it is practically impossible for any individual research to be representative of all of these. In this context, the study presented was limited to the three most common systems and therefore the results can only be considered valid for the designs described.

5.4.2 Thermal Simulations Limitations

The analysis required a 1-hour thermal simulation for each of the dynamic models. However, IES-VE, only allows a minimum of a continuous sequential 24-hour simulation. Because of this, a customised procedure was adopted to determine the heating or cooling loads using IES-VE for an hourly timeframe, whereby.a 24-hour thermal simulation for all the 1-hour models was first performed and then, the specific heating and cooling value for the specific hour in question was extracted.

It is acknowledged that such a method does not fully replicate the changes in energy stored due to the thermal mass of the building, however, the complex geometry of both the dynamic façades and the building

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dictated the building performance package used. Whereas tools such as ESP-r and DesignBuilder/EnergyPlus have been identified by other researchers as appropriate for certain CAF system applications [11], the direct applicability of such tools to model complex geometry is still problematic.

5.4.3 Façade Operation Energy Consumption

The power consumption to activate the façades is not being included in the analysis as the actual power requirement is very susceptible to the type of façade mechanism utilised.

6. Conclusions

This aim of this work was to investigate the energy performance of CAF systems, which has received growing interest in the recent years. Specifically, the case of three CAF systems (an electrochromic tinted glazed façade, a shaded façade based on a contracting and expanding bi-metallic strip and a shaded façade based on a vertically-rotating louvered system) as possible retrofit solutions to improve the energy performance of an existing office building was investigated. In this context this research specifically looked into whether using a dynamic approach to façade design is more energetically advantageous over using conventional static systems. Given the complex geometries involved, a sequential modelling process had to be developed, whereby a number of parametric modelling tools and building performance simulation packages were used. Owing to the limitations this study was faced with, not least with modelling complex geometry shaped façades, conclusive answers on the extent of energy savings which CAF systems can offer cannot be presented. Nonetheless, general trends observed through this research indicate that out of the three proposed solutions electrochromic glazing appears to be the most advantageous CAF system with seasonal energy savings of up to around 5% compared to a static façade system.

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