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The route to an ideal adaptive glazing facade

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Abstract

The development of adaptive building envelope technologies is considered a crucial step towards the achievement of the nZEB target. This paper presents a method to devise an ideal adaptive façade and evaluate its energy saving potential. This is based on the minimisation of the total primary energy consumption, by means of single-objective optimization, and applied to a case study of an office reference room in the climate of London. The main aim of this work is to find a method to establish which is the ideal/optimal range of adaptive thermo-optical performance of a glazed façade, according to the time scale of the adaptive mechanisms. This method can be used to devise targets for future product development. The results show that the time scale of the adaptive façade mechanism is proportional to the energy saving potential. Modelling limitations have been identified for façades with daily and sub-daily adaptiveness, but directions to overcome these limitations are given.

1 Introduction

The 20-20-20 European policy established new and more stringent CO_2 emissions targets. This imposes new challenges for the development of new concepts and technologies that are capable of reducing the energy consumption of buildings, while maintaining acceptable levels of indoor environmental comfort. The new 2010 EPBD Recast ([1] Energy Performance of Buildings Directive 2010/31/EU) requires that by the end of 2020 (2018 for public buildings) all new constructions should be “nearly Zero Energy Building” (n-ZEB). In order to achieve this objective, two main strategies need to be adopted in the design and operation of buildings: (a) reduce the energy consumption to the lowest extent, and (b) supply the remaining energy demand with on-site renewable energy generation.

In this context the building envelope can play a significant role in reducing buildings energy consumption and increasing on-site energy production. The improvement of the building envelope energy efficiency can be achieved by means of two different design strategies: an *"exclusive"* and a *"selective"* approach. In IEA Annex 44 - Responsive Building Concepts and Responsive Building Elements ([2], Perino et al., 2007) - the limitations of the *"exclusive"* approach at reducing energy consumptions are pointed out, i.e., there is a limit for the energy saving achievable by means of energy efficient building concepts, designed excluding the outdoor from the indoor environment with a very well-insulated and air tight building envelope. On the other hand the potential of a *"selective"* approach is highlighted: energy efficient building concepts can be designed by adopting a building shape and envelope, which is a '*selective filter*' between the outdoor and the indoor environment. This can be achieved by incorporating in the building envelope functions such as of managing and modulating energy and mass flow, with the aims of maximizing the energy saving and the indoor environmental comfort. Such an improvement can be achieved by means of *adaptive* or *Responsive Building Elements* (RBEs) and systems. These show an active and dynamic behaviour, by passively or actively adjusting their thermo-optical properties in a reversible way, Loonen et al.(2013) [3], in order to adapt to changing boundary conditions (depending on the climate and use of building. In the framework of the IEA–ECBCS Annex 44 activity ([2], Perino et al., 2007), adaptive building envelope systems, such as Double Skin Facades (DSF) or Advanced Integrated Façades (AIFs), are identified among the most promising RBEs in terms of building energy saving potential. This is due to the key role that the building envelope plays in controlling the energy and mass flows between outdoor and indoor environment (and vice-versa), as well as by enhancing solar energy exploitation. Many other adaptive building envelope technologies can be identified, either in the market or in the R&D stage: smart glazing ([4], Baetens et al., 2010), movable solar shading ([5], Nielsen et al., 2011), phase change materials ([6], Kuznik et al., 2011) and multifunctional facades ([7], Favoino et al., 2013).

2 The route to the next-generation adaptive facades

Many research efforts are currently underway in the area of adaptive facades, but several important factors have yet to be established. In particular: (a) the extent to which the adaptiveness of the façade can reduce the energy demand of a building compared to a static façade; (b) the building properties and time-scale of the adaptive façade mechanism that have the largest influence on the building energy consumption; and (c) the selection of the most appropriate design and control strategy of an adaptive façade according to the building typology and the climatic location. Addressing these issues could provide a significant step towards the definition of an ideal adaptive façade. An ideal adaptive façade can be defined as a façade able to minimize the total energy consumption of the indoor space by means of adapting its thermo-optical properties to varying outdoor/indoor environmental conditions (i.e. solar radiation, air temperature, wind velocity, internal loads, etc…). This could be achieved by either tempering, storing, shifting, admitting, redirecting or transforming the energy and mass flow through the envelope *(selective approach)*, or rejecting it *(exclusive approach)*.

There have been different research efforts to evaluate the potential of adaptive building envelope technologies at reducing building energy consumptions while maintaining indoor environmental comfort. Some of them, such as Zanghirella et al (2010) [8] and Goia et al. (2013) [9], are technology specific, that is they numerically and/or experimentally compare the performance of a specific adaptive system against state-of-the-art static façade technologies. This approach is ill-suited to the research issues presented above, because it evaluates a specific case of adaptive mechanisms and technology (in terms of adaptiveness time scale and dynamic façade properties). In contrast an inverse approach could be more suitable: knowing the climatic and building context, the optimal adaptive façade properties and reactivity of the façade could be derived.

To date only a few researches have adopted an inverse approach. Two examples of these works are Ye et al. (2013) [10] and Loonen et al. (2011) [11], in which two different methods to devise an ideal adaptive building envelope system are presented. The work of Ye et al. (2013) [10] concerns the evaluation of the ideal performance of a single glazing façade in two different seasons. In this study the adaptive façade parameters are the optimal optical properties of the single glazing, whose optimal values are theoretically derived, and its performance calculated by numerically evaluating the energy saving of a reference room adopting such an ideal technology. This study is limited to a seasonal adaptiveness of the glazing facade (two sets of ideal properties are found, one for winter and one for summer). Loonen et al. (2011) [11] pursues a similar aim but with a different approach. The authors attempt to identify the ideal properties of an opaque façade and its optimal window-to-wall ratio *WWR*, by means of multi-objective optimisation. In contrast with Ye et al. (2013) [10], optimisation is used to solve the inverse problem. The peculiarity of this optimisation method is that the time horizon of the optimization is set according to the time scale of the adaptive mechanisms, which is in this case monthly. In fact the optimisation are done on a monthly basis, so that the façade is supposed to have a monthly adaptiveness, meaning that it has the capability to change its properties once a month. In both studies, the sum of net energy demand for heating and cooling is considered as a cost function for optimization, while lighting energy demand is disregarded. Moreover, net building energy consumption is considered rather than primary energy. Important considerations can be taken from Loonen et al. (2011) [11]: the definition of the constraints of the building envelope adaptive properties (control variable in the optimisation) is of primary importance, as the building envelope properties corresponding to the energy demand minima are likely to lie on these boundaries in most cases. Moreover, it is concluded that optimisation of dynamic façade properties for time horizons shorter than one month is not possible with this method, unless the results of one optimisations are set as the initial conditions of optimisation on following time horizons. However neither a method to define the limits of the search space is given, nor the effect of using a smaller time horizon is assessed. The first aim of the present work is to identify a method to devise the ideal/optimal range of adaptive thermo-optical performance of a glazed façade, according to the time scale of the adaptive mechanisms. The second is to assess the energy saving potential of an ideal/optimal adaptive building envelope technology, by means of evaluating the energy consumption of a reference room enclosed by the ideal adaptive façade.

3 Methodology

The evaluation of the ideal combination of adaptive façade properties is performed by means of minimization of the primary total energy consumption of a reference office room, according to the time scale of the adaptive mechanism. The yearly specific primary energy consumption, E_p, is adopted as the cost function to be minimized. This is the sum of the yearly specific primary energy consumption for heating $E_{p,heat}$, cooling $E_{p,cool}$ and lighting $E_{p,light}$:

$$f(X) = E_p = E_{p,heat} + E_{p,cool} + E_{p,light} \quad \left[\frac{kWh}{m^2y}\right] \tag{1}$$

The time-scale of the adaptive mechanism, or in other words the reactivity of the adaptive façade, can span from seconds to seasonal adaptation ([3], Loonen et al., 2013). In order to account for different time scales of the adaptive mechanisms two main methods can be devised for the optimisation. The choice between the two methods relies on the ratio between the time horizon of the optimisation (reactivity of the façade) and time constant of the building. Where the time constant of the building system can defined as the total thermal capacity of the building, *C*, divided by the total heat transfer coefficient between the outdoor and the indoor, (i.e. *U-value* in the case of an opaque wall with no mass exchange between the indoor and outdoor environment):

$$\tau = \frac{C}{U_{value}} \quad [s] \tag{2}$$

The first method, known as optimization of non-dominant delay systems, is adopted when the time horizon of the optimization is higher than the time constant of the building. The optimization problem can be considered as a summation of subsequent equilibrium states with a shorter duration (i.e. monthly), which can be simulated separately, as shown in equation (3):

$$min \sum f(t_i, \mathrm{X}) = \min f(t_1, X) + \min f(t_2, X) + \ldots + \min f(t_i, X) \tag{3}$$

where $X=[x_1,x_2,..,x_n]$ is the vector identifying the ideal façade properties at each time horizon t_i, and *f* is the cost function (i.e. the energy consumption of the room enclosed by the façade with property *X*). This is based on the assumption that the effect of the thermal mass of the building is negligible ([12], ISO EN 13790 Standards, 2008). This method can quantify in sufficient detail the potential of adaptive facades only for long term adaptiveness of the façade, while it could be used to highlight the trend in the energy consumption if a faster reactive façade is employed.

The second method, known as optimisation of dominant delay systems, is chosen if the time horizon of the optimisation is comparable with, or less then, the time constant of the building. In such a case the optimisation problem cannot be considered as a summation of equilibrium states, because the internal energy of the system at the initial time step of one optimisation is influenced by the final conditions of the preceding one, which is a function of the optimal state in the precedent time horizon. Therefore the value of the objective function, and consequently the ideal states of the façade, are influenced by the thermal history of the system, and thus by the ideal state of the facades at preceding time steps. In fact, the shorter the time horizon the larger the impact of the starting boundary conditions and the larger the error in performing disconnected simulations ([11], Loonen et al., 2011).

Current state-of-the-art energy simulation tools do not support optimisation via the second method (i.e. dominant delay systems), so that for the purpose of this paper the evaluation will be carried out with the first method (non-dominant delay systems). This is achieved by changing the time horizon at which the cost function, E_p (1), is evaluated. In this work the time horizon is changed from one year (ideal static façade), to one month (ideal monthly adaptive façade), to one day (ideal daily adaptive façade). In order to evaluate the performance of the ideal adaptive facades, the 12 monthly and 365 daily primary energy consumptions will be summed to calculate the yearly primary energy consumption, E_p, for the specific ideal adaptive facade. The yearly primary energy consumption is then compared with the primary energy consumption of an office room with both a reference static façade and a yearly optimized ideal static façade. Due to the fact that the time constant of the enclosed office room (nearly 20 hours) is comparable with the time horizon of the optimization for the daily adaptive façade, the results do not assure that the global minimum (yearly energy consumption) is found, but they provide a preliminary insight into the energy saving potential of a daily adaptive façade. The time constant of the enclosed office room was calculated numerically by evaluating the response of the room air temperature to a stepped outdoor temperature disturbance (no solar radiation, no internal loads and no control on the indoor environment is considered).

The method presented above is applied to the case study of a South oriented reference office room (3 m wide x 5 m deep x 3.5 m high) located in London (Heating Degree Days 1828 °C, 15.5 °C baseline). The façade which is exposed to the outdoor climate is the one with adaptive features (3 m x 3.5 m), while the other surfaces are adiabatic. The *WWR* of the façade is 40 %. Table 1 shows the reference facade characteristics. Both HVAC and lighting systems are ideal, thus a perfect regulation system is adopted. Indoor environmental comfort is considered as a constraint in the optimization: indoor temperature set-points for heating and cooling are set to 20 °C (heating) and 26 °C (cooling), with a nocturnal set-back of 12 °C and 40 °C, respectively; 500 lux is the illumination level threshold value (on the office desk, 0.8 m high, with two reference point positioned at 1.67 m and 3.33 m from the façade) for the on/off dimming of the artificial lighting system; the primary air ventilation rate is set to 1.4 l/sm^2 when the office is occupied. Schedules for the building services, lighting, equipment and occupation are defined according to the NCM database ([13], BRE, 2010). The lighting power density is set to 18.75 W/m^2, the equipment power density is 13.46 W/m^2 and the occupation density is 0.111 $pers/m^2$. An average seasonal efficiency of the heating plant of 0.80 is considered, a Seasonal Energy Efficiency Ratio of 3.5 is set for the cooling plant, while the UK fuel factors for natural gas (1.026) and for electricity (2.58) are used ([14], SAP, 2011).

Table 1. Office reference room characteristics.

Façade property	Unit	Value
U_{wall}	$[W/m^2K]$	0.27
$U_{glazing}$	$[W/m^2K]$	2.0
g-value	[-]	0.72
τ_{vis}	[-]	0.76
U_{roof}	$[W/m^2K]$	0.25
$U_{basement}$	$[W/m^2K]$	0.25
C_{wall}	$[kJ/ m^2K]$	414
$C_{partition}$	$[kJ/ m^2K]$	25
C_{slab}	$[kJ/ m^2K]$	424
IR n50	[ACH]	2 (10 m^3/sm^2)

4 Optimisation parameters and tools

In order to devise an ideal adaptive façade for the case study considered, the façade properties that can dynamically change and their ranges of variation must be identified first. The façade properties are the control variables for the optimisation. For glazings these properties are the *U-value*, *g-value* and visible transmission τ_{vis}. According to Jin et al. (2013) [15], these properties, together with the *WWR*, are the façade parameters that have the largest influence on the total net energy consumption and the indoor environmental comfort of a reference office building in London, when compared to opaque façade properties.

The ranges of ideal adaptive properties of the façade are defined such that each single property (i.e. *U-value*, *g-value*, τ_{vis}) can vary in a domain that is physically feasible. Table 2 shows the ranges of variation of the three glazing façade properties for different glazing technologies, namely single glazing, double glazing and triple glazing unit (SGU, DGU and TGU respectively). The variation range of optical properties is obtained by imagining that an ideal adaptive façade could vary its optical properties continuously among all possible commercially available static glazing optical properties. A broad list of commercially available glazing is found in the Window Database ([16], Window, 2011). The variation of the *U-value* and *g-value* is obtained either by changing the surface characteristics (such as the emissivity), or by changing the cavity characteristics such as the gas pressure. The lowest *U-value* achievable with a DGU by means of reducing the cavity air pressure is 0.2 W/m^{2}K, obtained with a Vacuum Insulation Glazing VIG ([17], Manz, 2008). To obtain the ranges of U-value, g-value and τ_{vis} of different multiple panes technologies the relationship for the calculation of g-value and τ_{vis} found in Jelle (2013) [18] are adopted. The entire calculation procedure to obtain the ranges of variability is omitted for brevity. The technology with the biggest variation of thermo-optical property is the DGU, so that its variation ranges are adopted for the analysis. The final control variables and variation range used in the optimization are summarized in Table 3.

Table 2. Comparison of ranges of glazing properties for different technologies and measures.

Tech	Method	τ_{vis}		g-value		U-value	
		Min [-]	Max [-]	Min [-]	Max [-]	Min [W/m^{2}K]	Max [W/m^{2}K]
SGU	Surface (a)	0.000	0.993	0.104	0.913	2.307	6.037
DGU	Surface (a)	0.000	0.985	0.043	0.841	1.512	3.324
	Pressure (b)	0.525	0.525	0.246	0.248	0.210	4.742
	Surface and pressure (a)+(b)	0.000	0.985	0.023	0.839	0.204	5.140
TGU	Surface (a)	0.000	0.978	0.033	0.779	0.887	2.262
	Pressure (b)	0.261	0.261	0.146	0.140	0.111	2.503
	Surface and pressure (a)+(b)	0.000	0.978	0.016	0.777	0.109	4.366

Table 3. Façade control variables, thermo-optical characteristic physical boundaries.

Variable	Units	Range [Min : Step : Max]
U-value	[W/m^{2}K]	0.2 : 0.1 : 5.14
g-value	[-]	0.02 : 0.02 : 0.84
τ_{vis}	[-]	0.01 : 0.02 : 0.98

In the course of the optimisation it is important to account for the physical limit in the relationship between the *g-value* and τ_{vis}, which arises from the ratio of the energy contained in the solar visible spectrum compared to the whole solar spectrum at the sea level ([19], NREL, 2013), which can be written using the following equation:

$$T_{vis} - \frac{g\text{−}value}{0.428} < 0 \tag{4}$$

The physical limit described in Eq (3) is implemented in the cost function for the optimisation by means of a logarithmic barrier function, so that the optimisation problem can be finally written as:

$$\min of\, f(X) = E_p + z = E_{p,heat} + E_{p,cool} + E_{p,ligh} + z \tag{5}$$

$$z(X) = -\,\mu \log\left(\frac{g\text{−}value}{0.428} - T_{vis} + \epsilon\right) \tag{6}$$

where $\mu = 0.0001$ and $\varepsilon = 0.00001$, by changing $X=[U\text{-}value,\ g\text{-}value,\ \tau_{vis}]$.

For the optimization GenOpt software ([20], Wetter, 2011) is coupled with a building energy simulation software EnergyPlus ([21], EnergyPlus, 2013). The workflow is described as follows: (a) Matlab RA2013 is used to generate a variable time horizon of the optimisation and to post-process the results of the optimisations; (b) GenOpt is used to define the cost function, set the variables and their constraints, set the parameters of the optimisation algorithms and run the optimisation; (c) the objective function is evaluated in EnergyPlus, based on the model managed by GenOpt.

Different optimisation algorithms were tested in order to obtain a good performance of the optimisation process in terms of CPU time and results. Table 4 compares the performance of the different algorithm tested: Genetic Algorithm (GA), Generalized Pattern Search GPS with Hookes and Jeeves (HJ) implementation (GPSHJ), GPSHJ with multiple starting points (GPSHJMS), Particle Swarm Optimization (PSO) and PSO with HJ implementation (PSOGPSHJ).

The settings for the optimisations done with GenOpt are given in ([20], Wetter, 2011), while for the GA a population size of 60 and a generation number of 20 is adopted. The GA implementation is done in Matlab by means of the model developed by Jin et al. (2013) [15], which makes use of NSGA-II, while all the others are implemented in GenOpt. The efficiency of the algorithms is measured in terms of duration of the optimization and the optimum found on a base case, which is the yearly optimization of the south oriented static façade of the reference office room in London, with four control variables *(WWR, U-value, g-value* and T_{vis}).

Table 4. Comparison between optimisation algorithms.

Algorithm (Tool)	CPU time [s]	Results
GA (Matlab)	15120	Non optimal
GPSHJ (GenOpt)	1251	Non optimal
GPSHJMS (GenOpt)	6238	Optimal
PSO (GenOpt)	1075	Non optimal
PSOGPSHJ (GenOpt)	1260	Optimal

The best trade off between computational time and optimality of the results is achieved by means of a hybrid optimisation algorithm (PSOGPSHJ). This does not have the shortest computing time, but it converges to a yearly optimal solution, which was previously evaluated by GPSHJMS with increasing number of starting points until convergence on same results was reached several times. Therefore, PSOGPSHJ algorithm is adopted for the subsequent optimisation. The evaluation is carried out for the enclosed office reference room presented above, for different time scales of the adaptive mechanism, namely, monthly (M) and daily (D). As a means of comparison, the primary energy consumption of the office room with the reference façade (R), and of the office room with the yearly optimised façade (Y) is considered.

5 Results and discussion

The results of the optimisations carried out for the case study of a south oriented enclosed office located in London are summarized in Table 5 and Figure 1. In particular Table 5 shows how much primary energy can be saved (energy saving percentage, ES), compared to the office with the reference facade, R. The performance of the reference case, R, is compared with the yearly optimized solution where also the WWR is optimized (Y_{WWR}), with the yearly optimized solution (Y), with the monthly adaptive façade (M), the daily adaptive facade (D), and finally with an optimised daily adaptive façade represented by the subscript Min, that will be discussed later in the paper. The adoption of a monthly ideal adaptive glazing façade (M), i.e. a glazing façade which is able to change its thermo-optical properties on a monthly basis, can reduce the total primary energy consumption of an office room by 22%, compared with the same room with a reference façade. The largest energy savings are achievable on the cooling primary energy, while a slight increase in the primary energy for lighting is found. A fairer comparison can be done with an office reference room with a glazed façade which has been optimized on a yearly basis (Y), or where also the *WWR* is optimized together with the glazing thermo-optical properties (Y_{WWR}), with an optimal *WWR* of 64%. In this way the adaptive solution can be compared to the best-case of a static façade solution. In this case the energy saving is reduce by 10 % and 8 %, respectively.

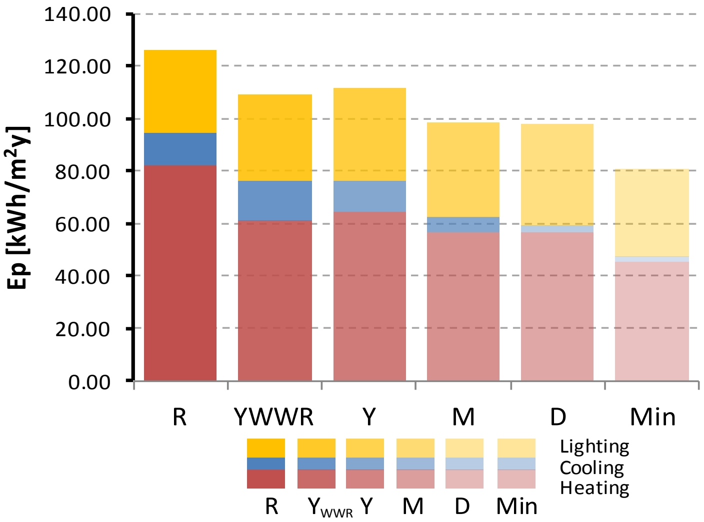

Figure 1. Specific primary energy consumption: R = Reference facade; Y_{WWR} = Yearly optimization (U-value, g-value, $\tau_{vis,}$ WWR); Y = Yearly optimization; M = Monthly optimization; D = Daily optimization; Min = Minimum between M and D.

Table 5. Total Specific primary energy consumption for different optimizations (Ep) and Energy Saving compared with R (ES) for: R = Reference room; Y_{WWR} = Yearly optimization (U-value, g-value, $\tau_{vis,}$ WWR); Y = Yearly optimization; M = Monthly optimization; D = Daily optimization; Min = Minimum energy consumption.

	Ep tot [kWh/m^{2}y]	Ep heat [kWh/m^{2}y]	Ep cool [kWh/m^{2}y]	Ep light [kWh/m^{2}y]	ES tot [%]	ES heat [%]	ES cool [%]	ES light [%]
R	126.26	81.89	12.93	31.44				
$Y_{WWR64\%}$	109.08	61.41	14.66	33.01	14	25	-13	-5
Y	111.67	64.18	12.10	35.39	12	22	6	-13
M	98.37	56.58	6.07	35.72	22	31	53	-14
D	97.77	56.83	2.10	38.84	23	31	84	-24
Min	80.76	45.07	2.31	33.38	36	45	82	-6

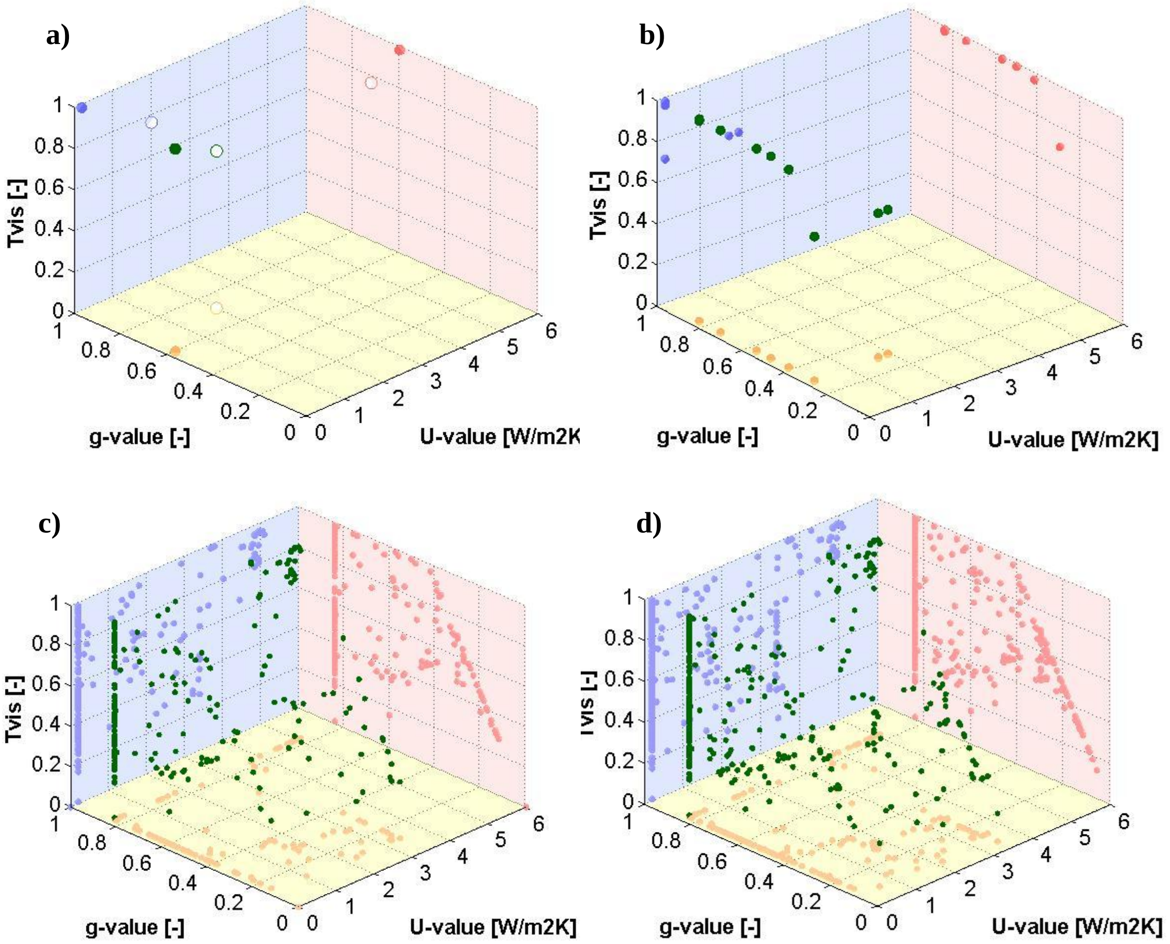

Figure 2. 3D scatter plot and projections of the adaptive glazing façade thermo-optical characteristics (U-value, g-value, τ_{vis}) for the South-oriented office reference room in London: a) R = Reference room (white dots) and Y = Yearly optimization (coloured dots); b) M = Monthly optimization; c) D = Daily optimization; d) Min = Minimum energy consumption points between monthly and daily optimization.

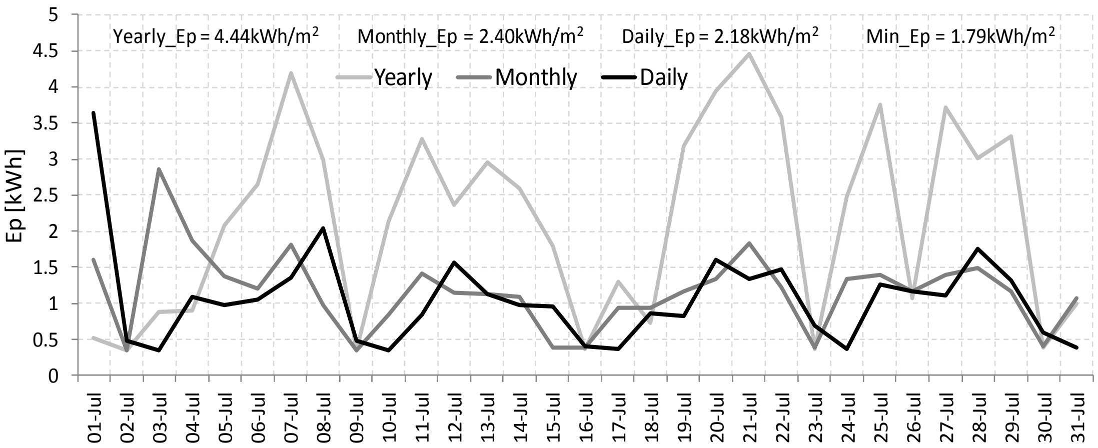

Figure 3. Daily total primary energy consumption, E_p, for the daily, monthly and yearly optimizations, for the south oriented office reference room in London, in the month of July.

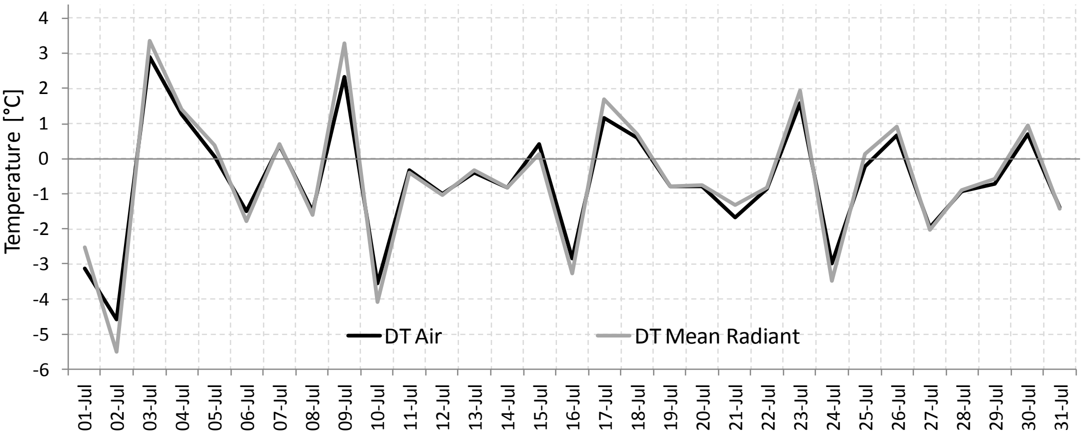

Figure 4. Difference between ending boundary conditions (temperatures) of a daily optimisation and the starting boundary condition (temperatures) of the subsequent optimisations. Results shown for July.

The thermo-optical properties of the reference façade R, the yearly optimized façade Y and the monthly optimized façade M are shown in Figure 2.a and 2.b. The figure represents in a 3D space (coordinates *U-value*, *g-value* and τ_{vis}), the optimal thermo-optical properties of the façade (green dots), and the projections on the different planes (*U-value* - *g-value*, *U-value* - τ_{vis}, and *g-value* - τ_{vis}). In particular the physical limit of the ratio between the *g-value* and τ_{vis} in equation (4) is evident in Figure 2.c, which represents the ideal states of the adaptive daily glazing façade in each day of the year. The physical limit is the sloped boundary on the red surface, with a slope of 1/0.428.

From Table 5 and Figure 3 it is evident that there is no significant difference in terms of primary energy consumption between the monthly and the daily adaptive façades, devised with the method proposed. A closer look at Table 5 reveals a significant improvement on the cooling energy consumption when a daily optimization is performed compared to the monthly one, and an opposite trend on the lighting energy consumption. In Figure 3 the daily total energy consumption of the office room is plotted for the month of July, which is the month with the highest cooling consumption and where the biggest differences in cooling energy are found between the monthly and daily optimisations. The energy consumption of the yearly optimised façade is always higher than the monthly adaptive one, except for the first day. While the façade with a daily adaptiveness does not always have a lower daily energy consumption than the façade with a monthly adaptiveness. This means that although the façade is optimised daily, since the optimization are not linked, i.e. the ending boundary conditions of one optimisation are not the starting boundary conditions of the following one, the optimum of one day do not assures the optimum to be reached on a larger time scale. This represents the limitation of adopting an inverse approach with disjointed simulations for dominant delay systems. This is clearly shown in Figure 4: the difference between the starting boundary conditions (air and mean radiant temperature) of one optimisation and ending boundary conditions of the precedent one are plotted for the month of July. It is clear that there are significant differences between ending and starting temperatures (air and mean radiant) of two subsequent optimisations. So that the sum of the daily energy consumptions of a daily optimized façade is far from the achievable optimum. Moreover a higher lighting energy consumption can be explained by the fact that the physical limit in the ratio between the *g-value* and the τ_{vis} in (4) and the cooling loads from the day before are limiting the τ_{vis}, so that even optimal daily values of the three control variables are not able to provide a global minimum of the total primary energy consumption.

In order to give a more accurate measure of the realistic performance of a daily adaptive façade, the results from the monthly and daily adaptive façade can be combined: the minimum between the monthly and the daily optimised primary energy consumption is selected for each day. In this way the façade will adopts daily thermo-optical properties corresponding to the minimum daily energy consumption between the daily and monthly adaptive facade (Figure 3). By doing so for the whole year it is possible to obtain the Min values shown in Table 5 and Figure 2.d. This result in a total primary energy saving of 36% compared to the reference façade. This is however an approximate measure, which can nevertheless give a result closer to the global minimum, showing a trend towards the energy saving achievable by means of a façade with a shorter response time. Looking at the range of thermo-optical properties of a daily adaptive glazing façade, devised with the above method (Figure 2.d), it is noticeable that for the majority of the days the ideal adaptive façade properties lie on at least one of the control variable constraints (i.e. minimum *U-value*, maximuum *g-value* and τ_{vis}, maximum *g-value*-τ_{vis} ratio). In fact for nearly 70% of the days the optimal *U-value* is close to the lower bound of 0.2 W/m^2K, 50 % of the days the optimal τ_{vis} value is close to the upper bound of 0.88, 40% of the days the optimal *g-value* is close to the upper bound of 0.98, while 20% of the time the ratio τ_{vis}/*g-value* is close to the physical limit of 0.423. The relationship between daily climate boundary conditions and optimal daily thermo-optical properties still have to be assessed, but it can give useful insights into the parameters influencing the design and control of the ideal adaptive façade.

Comparing all the results in Figure 1, it is clear that an ideal static glazing façade (Y) could decrease the primary energy consumption of an office enclosed reference room located in London with 40% WWR by 12%, the thermo-optical properties of such a façade need to minimize the total heat transfer coefficient, while maximizing the visible transmission. While a monthly ideal adaptive glazing façade (M) is able to provide an additional 10% energy saving compared to the yearly one. Finally a daily ideal adaptive glazing façade (Min) is potentially able to save an additional 14% energy compared to the monthly case study, 24% compared to the ideal static glazing (Y) and 36% compared to the reference static façade (R).

6 Conclusions

Adaptive building façades are considered as a significant step to improve the energy efficiency of buildings. This study proposed a method to identify the thermo-optical properties of an ideal adaptive glazing façade by means of an inverse approach, which makes use of optimization. The method is based on a total (thermal and lighting) energy approach. It accounts for different time-scales of the adaptive response and implements physical constraints of glazing façade thermo-optical performance. The above method is used to quantify the potential primary energy saving of a South oriented office room located in London. It is shown that a glazing façade with monthly adaptiveness can significantly reduce the energy consumption in the case study presented. Moreover a less accurate quantification of the potential energy saving achievable with a daily adaptive glazing façade is provided, demonstrating that a faster reactivity of the glazing façade could enable the achievement of higher energy savings.

The limitations of the proposed method are highlighted in the case of devising the properties of a daily adaptive facade, in particular it is highlighted how conventional optimisation process is unable to capture the air and mean radiant temperatures at the end of one optimisation and transfer them as the starting boundary conditions of the subsequent optimisation. This leads to sub-optimal results, even thought a method is proposed to significantly reduce this effect.

Future work will expand the case studies analyzed to different climatic conditions, *WWR*s and orientations. Moreover different time frames of the adaptive mechanisms could be analyzed, i.e. seasonal, that may be achievable with more low-tech solutions, or with different starting/ending days (for the monthly adaptiveness). In order to provide more accurate results for the daily and sub-daily adaptiveness a method is needed to take into account the effect of the difference of starting boundary conditions and the effect of sub-daily adaptive façade control choices.

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