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## Towards an ideal adaptive glazed façade for office buildings

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### Abstract

The development of dynamic building envelope technologies, which are capable of adapting to changing outdoor and indoor environments, is considered a crucial step towards the achievement of the nearly Zero Energy Building target. The main aim of this work is to present a method for defining the ideal/optimal range of adaptive thermo-optical performance of a glazed façades with different reaction time, in order to assess the potential of future adaptive glazed façades. This is achieved by means of a performance-oriented method, making use of single-objective optimisation, based on the minimisation of the total primary energy consumption. The method is applied to the case study of a reference office room with a fixed window-to-wall ratio in three different temperate climates. The results show that, as expected, the energy savings are inversely related to the façade reaction time. The amount of energy savings is a function of the variability of outdoor conditions and their closeness to the comfort range. The results from this study should be particularly useful for guiding future development of adaptive façade technologies.

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### 1. Introduction

New and more stringent CO<sub>2</sub> emissions targets are established in the 20-20-20 European policy, imposing new challenges for the development of new design methods, concepts and technologies aimed at reducing the energy demand of buildings, while maintaining acceptable levels of indoor environmental comfort. The 2010 EPBD Recast [1] (Energy Performance of Buildings Directive 2010/31/EU) requires that by the end of 2020 (2018 for public buildings) all the new constructions should be “nearly Zero

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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 demand within the building, and (b) supply the remaining energy demand by means of on-site renewable energy sources [2].

The building envelope and, specifically, the transparent part of the building envelope can play a significant role in reducing buildings energy consumption and achieving higher level of indoor environmental quality [3]. Such an improvement can be achieved by means of two different design strategies: an “*exclusive*” and a “*selective*” approach. In the “*exclusive*” approach the building envelope is conceived as a “*static*” barrier that excludes the outdoor environment from the indoor environment by means of through a very well-insulated and air tight building envelope. There is however, a limit to the energy savings achievable by the “*exclusive*” approach [4]. Much greater energy savings may be achieved by designing the building form and the envelope as a “*selective*” filter between the outdoor and the indoor environment [4]. The ability to manage and modulate the heat and mass flow in “*selective*” building envelopes may be achieved by making use of *adaptive* or *Responsive Building Elements* (RBE) and systems, that show an active and dynamic behaviour, by passively or actively adjusting their thermo-optical properties in a reversible way in order to adapt to changing outdoor environmental conditions with different reaction times (from seconds to seasonal adaptiveness depending on the technology) [5]. Indeed, of the various energy efficient technologies considered by IEA–ECBCS Annex 44 activity [4], adaptive technologies embedded in the building envelope systems are considered to have the largest potential to minimize the energy consumption of buildings. In particular Double Skin Facades or Advanced Integrated Façades [6], smart glazing [7], movable solar shading [8], phase change materials [9] and multifunctional facades [10] are identified among the most promising adaptive façade systems and components in terms of energy reduction potential.

## **2. The ideal adaptive façade and the route to next generation adaptive façades**

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 building design parameters and time-scale of the adaptive façade mechanism that have the largest influence on the building energy consumption; and (b) the selection of the most appropriate design and control strategy of an adaptive façade according to the building typology and the climatic location. In order to address these factors systematically it is essential to first define a method to devise the thermo-optical time-dependent properties of an ideal adaptive façade. In particular, the definition of an ideal adaptive façade, according to the climatic location and type of building, can help in defining the most effective time-scale of the adaptive mechanisms, the most effective ranges of variability of thermo-optical properties and the maximum amount of energy saving achievable, thereby making it possible to identify the need and the path to the development of new façade materials, technologies and product.

There have been different research efforts to evaluate the energy saving potential of adaptive building envelope technologies. Some of them, such as Zanghirella et al [11], numerically and/or experimentally compare the performance of a specific adaptive system with a state-of-the-art static façade technology. This approach, namely direct or traditional approach [12], appears to be ill-suited to the research issues presented above, because it evaluates a specific case of adaptive mechanisms (in terms of time scale of adaptive mechanisms and adaptive façade properties) and technology. In the direct approach the performance of a new system/technology is characterized first; a model (or comparative experiment) is developed and the performance of such a system applied to specific cases is evaluated; finally properties of the system/technology or its control strategy are optimized to improve its performance. The shortcomings of this approach are highlighted by Zeng et al. [12], who, in contrast, presents the potential of an inverse approach: the ideal value of one of the thermo-optical properties of the building envelope

can be evaluated by minimizing or maximizing a cost function, which is different in the case of passive (no HVAC) or conditioned buildings, consisting in either indoor environmental comfort or energy consumption, or both of them. The main limitation of the approach of Zeng et al. [12] is that it cannot be used when multiple ideal adaptive properties need to be identified. To date only a few researches have adopted an inverse approach, in order to evaluate multiple ideal adaptive properties of a building façade.

Two examples of these works are Ye et al. [13] and Loonen et al. [14], in which two different methods to devise an ideal adaptive building envelope system are presented. The work of Ye et al. [13] concerns the evaluation of the ideal performance of a single glazing façade in two different seasons. So that it is limited to seasonal adaptiveness of the glazing facade (two sets of ideal properties are found, one for winter and one for summer) and to the optical properties only (i.e. transmission and absorption coefficient of a single glazing unit). Loonen et al. [14] pursue a similar aim but with a different approach. The authors attempt to identify the ideal properties of an opaque façade and the optimal window-to-wall ratio *WWR*, by means of multi-objective optimisation through genetic algorithm. In this case the time horizon of the optimisation is set according to the time scale of the adaptive mechanisms, or reaction time of the façade. The optimizations are performed on a monthly basis, so that the façade is assumed to have a monthly adaptiveness, meaning that the façade is capable of changing its properties once a month. In both studies, the sum of the ideal energy demand for heating and cooling is considered as the cost function in the optimisation, but the lighting energy demand is disregarded. Moreover, ideal ambient energy, that is the energy needed at the ambient node, is considered as a cost function, rather than primary energy, that is the energy needed when it is produced. Important considerations can be taken from Loonen et al. [14], namely: a) in order to evaluate the impact of a long reaction time (i.e. monthly adaptiveness) on the energy consumption the time horizon of the optimisation can be set equal to the reaction time of the façade; b) the definition of the constraints of the building envelope adaptive properties (control variable constraints of the optimisation) is of primary importance, as the façade properties corresponding to the energy demand minima are likely to be very close to these boundaries. The method devised by Loonen et al. [14] can define multiple ideal properties of an adaptive façade. Even though the authors concluded that the optimisation of the façade properties for smaller time horizons by means of this method is not reliable, unless the results of the previous optimisations are set as the initial conditions of the optimisation on the following time horizon.

The aim of the present work is to present an inverse method to devise the ideal/optimal range of adaptive thermo-optical performance of a glazed façade. At this purpose the total primary energy (heating, cooling and lighting primary energy) will be used as a cost function. The method is then deployed to assess the energy saving potential of an ideal/optimal adaptive building envelope technology, for increasing reaction time of the facades in different climate conditions. Not only monthly adaptiveness is assessed, but a realistic figure of the performance of an ideal daily adaptive glazing façade is given.

### 3. Method and tools

In order to devise an ideal adaptive façade, the façade properties that can dynamically change and their ranges of variation must first be identified first. Jin et al. [3] performed a sensitivity analysis on building performance in terms of energy consumption, indoor environmental quality and whole life cost, of early-stage design parameters, including façade, architectural and building services design parameters. Figure 1 summarizes the results from Jin et al. [3] as far as the façade design parameters are concerned. The façade design parameters considered are: a) the Window-to-Wall-Ratio (*WWR*); b) the U-value (*U<sub>g</sub>*), g-value and visible transmission  $\tau_{vis}$  of the transparent façade; c) the U-value of the opaque façade (*U<sub>p</sub>*); d) the Infiltration Rate (*IR*) of the façade.

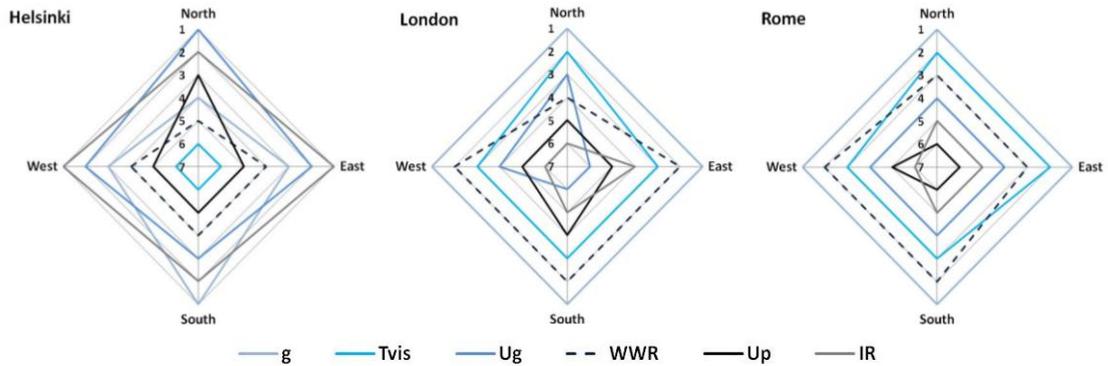


Fig 1. Influence of façade design parameters on total energy consumption of office building for different locations and orientations .

Table 1. Façade control variables, thermo-optical characteristic physical boundaries.

Variable	Units	Range [Min : Step : Max]
U-value	[W/m <sup>2</sup> K]	0.2 : 0.1 : 5.14
g-value	[-]	0.02 : 0.02 : 0.84
$\tau_{vis}$	[-]	0.01 : 0.02 : 0.98

Figure 1 shows the ranked influence of façade design parameters on the total energy consumption (heating, cooling and lighting) of an enclosed office building located in Helsinki, London and Rome. The ranking is done according to the absolute value of the Standardized Regression Coefficients (SRC) of the global sensitivity analysis. The façade parameters pertinent to glazed facades, i.e. the *U-value* of the glazing (*Ug*), *g-value* and visible transmission  $\tau_{vis}$ , together with the *WWR*, are the ones with the largest influence on the total ideal energy consumption and the indoor environmental comfort, for a reference enclosed office building located in Helsinki, London and Rome. Therefore the ideal properties of the adaptive glazed façade, which will vary according to the boundary conditions, are the *U-value*, *g-value* and visible transmission  $\tau_{vis}$ . In the following analysis the *WWR* is equal to the reference office building in London, Helsinki and Rome, i.e. 40%. Future work will extend the analysis to different *WWR*s. The ranges of variation of each single property (i.e. *U-value*, *g-value*,  $\tau_{vis}$ ) are summarized in Table 1. These ranges are obtained by assuming that an ideal adaptive system can change its thermo-optical properties within the full physical performance range confined by static state-of-the-art glazing. More details about how these ideal ranges of thermo-optical properties are found are given in Favoino et al. [15].

The evaluation of the ideal combination of adaptive façade properties is performed by means of minimisation of the primary total energy consumption of the reference office room, in which the time horizon of the optimisation is set according to the time scale of the adaptive mechanism. The façade properties are the control variables for the optimisation. The yearly specific primary energy consumption,  $E_p$ , adopted as the cost function to be minimised, is the sum of the yearly specific primary energy consumption for heating  $E_{p,heat}$ , cooling  $E_{p,cool}$  and lighting  $E_{p,light}$ . Therefore the optimisation problem can be written as:

$$f(X) = E_p + z = E_{p,heat} + E_{p,cool} + E_{p,light} + z \tag{1}$$

$$z(X) = -\mu \log\left(\frac{g-value}{0.428} - T_{vis} + \epsilon\right) \tag{2}$$

where  $z(X)$  is a hard constraint on the control variables, representing the physical limit in the ratio between the  $g$ -value and  $\tau_{vis}$  [16], ( $X$ ) is the vector of control variables ( $U$ -value,  $g$ -value,  $\tau_{vis}$ ),  $\mu = 0.0001$  and  $\varepsilon = 0.00001$ .

The optimisation is performed by coupling an optimisation software, GenOpt [17], with a building energy simulation software, EnergyPlus [18]. The process involves the following key steps: (a) Matlab RA2013 is used to generate a parametric model with variable orientation and time horizon of the optimisation; (b) the parametric model is fed to GenOpt, where the objective function and the façade control variables are defined (Table 1), which runs the optimisation; (c) the objective function is evaluated by EnergyPlus and the results returned to GenOpt; (d) the results from each optimisation are returned from GenOpt to Matlab for the analysis of the results. In GenOpt, a hybrid optimisation algorithm, namely Particle Swarm Optimization with Generalized Pattern Search with Hookes and Jeeves implementation [17], is used for the optimisation. This was selected between different algorithms in order to assure global optimality. Some details of the comparison between different algorithms are given in Favoino et. al [15].

In order to account for different reaction time of the façade the method explained in Loonen [14] is used: the optimisation problem can be considered as a summation of subsequent equilibrium ideal states with a shorter duration (i.e. the sum of monthly optimisations can give a measure of an adaptive façade with monthly reactivity). This is based on the assumption that the effect of the thermal mass of the building is negligible [19]. This method can accurately quantify the energy saving potential of adaptive facades with long reaction times (i.e. seasonal, monthly), and it could be used to provide the approximate energy saving potential if a façade with a short reaction time is employed (weekly, daily). In this paper the numerical analysis is performed on the basis of façades with long reaction times (i.e. monthly, M), while a method is presented in order to evaluate the trend towards the potential reduction in energy saving of daily adaptive façade (D/Min). These two cases (M and D/Min) are compared with a yearly optimised facade (Y, ideal static façade) and with a reference façade (R), which are "static" façade (not able to change their thermo-optical properties over time), whose properties are described in Table 2. Details will be given in this paper about the difference between D and Min results.

Table 2. Office reference room characteristics.

		Rome	London	Helsinki
HDD [base]	[°C]	1415 [20]	1828 [15.5]	3902 [18.5]
$U_{wall}$	[W/m <sup>2</sup> K]	0.29	0.27	0.17
$U_{glazing}$	[W/m <sup>2</sup> K]	2.00	2.00	1.00
$g$ -value	[-]		0.72 (N, S) -0.58 (E, W)	
$\tau_{vis}$	[-]		0.76 (N, S) -0.61 (E, W)	
$f_{Elec}$	[-]	1.7	2.58	2.18
$f_{Nat Gas}$	[-]	1	1.026	1

The method presented above is applied to the case study of a reference office room (3 m wide x 5 m deep x 3.5 m high) located in three different temperate climates (Helsinki, London and Rome). The façade is surface with adaptive features (3 m x 3.5 m), while the other surfaces are adiabatic. Indoor thermal comfort is considered as a hard constraint in the optimisation: indoor temperature set-points for heating and cooling are set to 20 °C and 26 °C, respectively, 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) for the on/off dimming of the artificial lighting; the primary air ventilation rate is set to 1.4 l/sm<sup>2</sup> when the office is occupied. Schedules for the building services, lighting, equipment and occupation are defined according to the NCM database [20]. The lighting power density is set to 18.75 W/m<sup>2</sup>, the equipment power density is 13.46 W/m<sup>2</sup> and the occupation density is 0.111 person/m<sup>2</sup>. 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. Different reference facades and fuel factors are used in order to take into account for different national climatic and legislation contexts [2].

#### 4. Results and discussion.

The results of the optimisations undertaken on a reference office building are presented in two ways: the first one shows the energy saving potential of an increasing responsive façade, while the second shows the range and variability in the adaptive properties required to achieve the largest possible energy saving. The first results, summarized in Figure 2, show the four façade orientations for: a) Helsinki, b) London and c) Rome. In particular it is showed the total specific primary energy consumption for the enclosed office room in the different "static" optimized ( $Y$ ) and adaptive design with different reaction time, i.e.  $M$ ,  $D$  and  $Min$  (filtered daily results), compared to the reference office building,  $R$ . The second results, i.e. the ideal state of the adaptive façade and in particular the thermo-optical properties of the monthly optimised façade  $M$  and  $Min$  (daily filtered) optimized façade, are shown in Figure 3 and 4. The figures represent in a 3D space of coordinates  $U$ -value,  $g$ -value and  $\tau_{vis}$ , the optimal state of the façade (green dots), and the projections on the different planes ( $U$ -value -  $g$ -value,  $U$ -value -  $\tau_{vis}$ , and  $g$ -value -  $\tau_{vis}$ ). In particular Figure 3 shows the ideal adaptive states of the façade for the London office in the four orientations, while Figure 4 represents the ones for the South oriented façade of Helsinki and Rome, for comparison purposes with the London one. Results for all the façade types, orientations and locations are available, but have been omitted for brevity.

The "Min" results were obtained by filtering the daily results  $D$ . This merits a more detailed explanation: from Figure 2 it is evident that there is no significant difference in terms of primary energy consumption between the monthly and the daily adaptive façades. A closer look at the share in the energy consumption 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. This is due to the fact that although the façade is optimised daily, since the optimisations are not linked, i.e. the ending boundary conditions of one optimisation are not the starting boundary conditions of the following one, so that the states of the systems (i.e. radiant and air temperatures) are not updated in subsequent optimisations [15]. In order to give a more accurate measure of the realistic performance of a daily adaptive façade, the results from the daily-adaptive façade were filtered. The filtering process consists in comparing the daily primary energy consumptions of the monthly-adaptive façade with the daily primary energy consumption of the daily-adaptive façade, and for each day the minimum between the two is selected. In this way the façade will adopt daily thermo-optical properties corresponding to the best energy performance on that day between the daily and monthly adaptive facade. By doing so for the whole year it is possible to obtain the filtered daily results ( $Min$ ) for the energy saving potential shown in Figure 3, and for the ideal states shown in Figure 4 and 5. This filtering process is however an approximate approach and the accuracy of the "Min" results is as yet uncertain, but this I thought to be a considerably better approximation than the more conventional  $D$  values for façades with a shorter response time. A more rigorous and accurate approach would involve updating the system states, as internal air, material and radiant temperatures, during the simulation process.

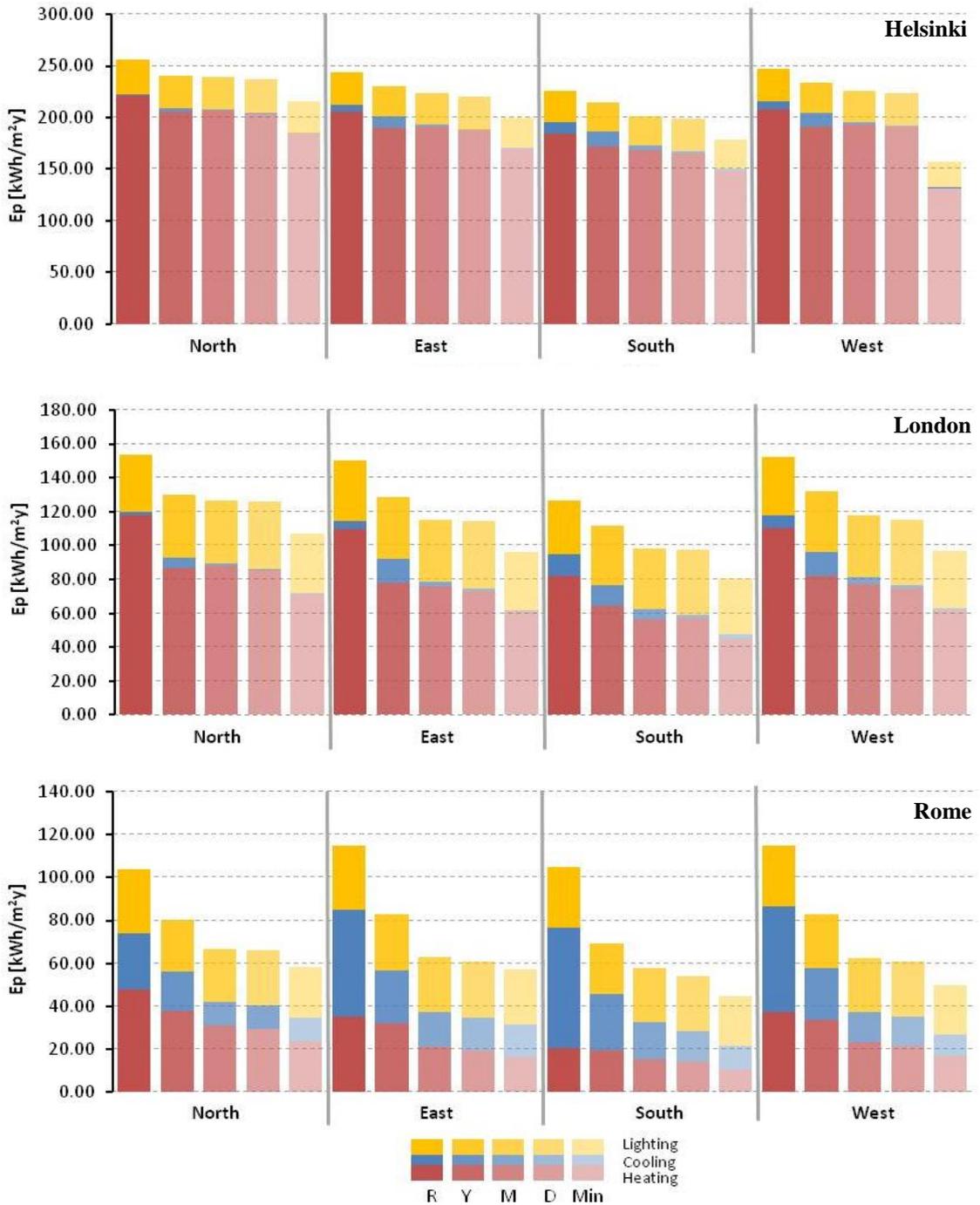


Figure 2. Specific total primary energy consumption for different orientation and reaction time of the ideal adaptive glazing façade for the climate of Helsinki, London and Rome (R=Reference, Y=Yearly optimised, M=Monthly adaptiveness, D=Daily adaptiveness, Min= filtered daily adaptiveness).

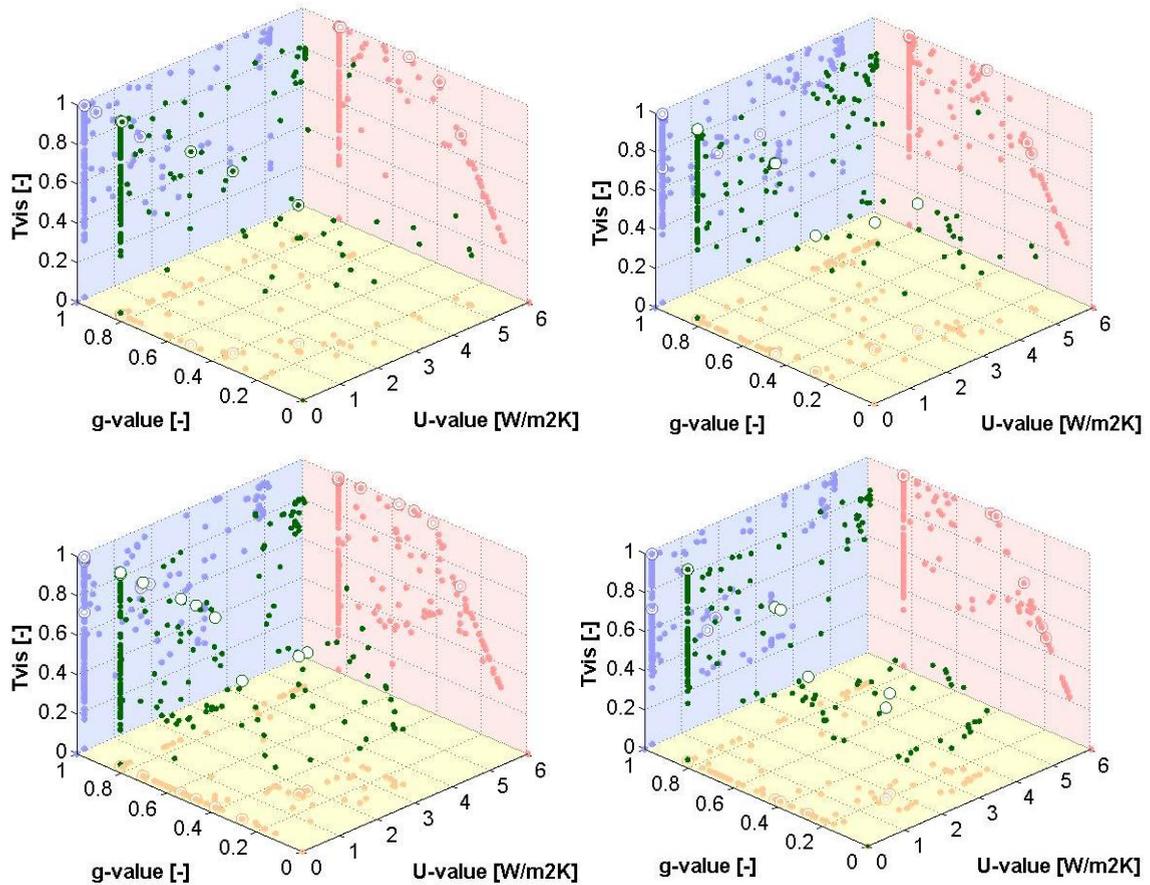


Figure 3. Ideal adaptive façade thermo-optical properties (Monthly: white dots; Min: green dots) and their projections for London façade: a) North, b) East, c) South, d) West.

Both reference  $R$  and yearly optimised  $Y$  façade represents state-of-the-art "static" optimised solution, and the difference between the two indicates that the reference façade is a sub-optimal solution for the specific building design and climate. Thus  $Y$  façade is a fairer reference case against which the performance of an adaptive façade may be evaluated, as it provides the highest energy saving achievable with static glazing technology. It is interesting to note that in the climate of Helsinki, in which the "exclusive" approach alone [4] should provide consistent energy saving potentials, the  $Y$  façade decreases the primary energy consumption by only 5-6%, while in other hotter climates optimising the transparent envelope to the most appropriate static technology gives better results (12-13% reduction in energy consumption in the case of London, and 25-35% for Rome, depending on the orientation). This is partly due to the dependency of the importance of glazing design parameters over energy consumption on climatic context, i.e. IR and WWR are more important than glazing design parameters in Helsinki climate (Figure 1), and to the fact that the starting reference case  $R$  was not really well suited for the climate of Rome. The difference between  $R$  and  $Y$  façade is anyway representative of the limitations of the "exclusive" approach at designing the building envelope, even for extreme climates. In fact in the case of Helsinki the average façade U-value was decreased from 0.50 to 0.18  $W/m^2K$ , but low energy savings are achieved. An adaptive façade with a monthly responsiveness ( $M$ ) shows really few improvements, in fact

no difference in terms of energy efficiency is noticed for the North façade, while 2-5% energy savings are achievable respectively for East/West and South oriented façade. An ideal daily adaptive façade (*Min*), due to its ability to change daily its thermo-physical properties, could potentially reduce the primary energy consumption by 10%, irrespective of the orientation. As far as the ideal states of the *M* and *Min* façade are concerned, in the North façade there is a higher variability of the *U-value* compared to other variables, while in the South and East/West façade both range and variability of other variables (*g-value* and  $\tau_{vis}$ ) are much higher than the North one.

In the London case study, for a North façade, the improvements in energy consumption due to a monthly adaptive façade compared to the *Y* facade are negligible (2%), while higher energy saving (10-12%) can be achieved for other orientations. When a façade with a shorter responsive time is employed, 15-24% energy saving can be achieved compared to a state-of-the-art ideal static façade. This constitutes a 13-14% energy saving when compared to a façade with monthly adaptiveness. The ideal states of London daily adaptive façade (Figure 3) for all the orientations, show the importance of selecting the correct constraints of the transparent façade variables. 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*, maximum *g-value* and  $\tau_{vis}$ , maximum *g-value*- $\tau_{vis}$  ratio [16], i.e. sloping line in the red projections). In fact the optimal *U-value* is close to its lower bound (0.2 W/m<sup>2</sup>K) for nearly 70% of the days; the optimal  $\tau_{vis}$  is close to its upper bound (0.98) for 50 % of the days; the optimal *g-value* is near its upper bound (0.88) for 40% of the days; while 20% of the time the ratio  $\tau_{vis}/g-value$  is equal to the physical limit of 0.423. A frequency analysis of the ideal states of the ideal monthly and daily adaptive façade could be useful to understand whether the continuous range of variability could be effectively replaced by a small number of discrete states within that range, or by smaller more effective ranges.

The Rome case study shows the highest potential energy savings of the three climates considered in this study. This is most pronounced in the West-oriented façade. In particular the energy saving due to the adoption of a monthly adaptive façade are nearly the double than the other climates, including the north façade, moreover the *Min* results show the higher decrease in energy consumption (up to 25-30%) compared to the *Y* façade. The main reason is that an adaptive façade is more effective in decreasing cooling energy demand, which is more significant in hotter climates. Although the benefits of adaptive facades can still be significant in colder climates such as Helsinki.

It is important to note that these results represent the upper limit of the performance achievable by means of a monthly adaptive glazed façade and a projection of the performance achievable by means of an ideal daily adaptive glazing façade. The term ideal, in fact, stands for an ideal range of variability, whose limits were derived theoretically, so that although physically achievable the appropriate glazing products have yet to be developed.

## 5. Conclusions.

Adaptive building façades are considered a significant step towards the improvement of the energy efficiency of buildings. This study proposed a method to identify the performance of a monthly and daily ideal adaptive glazing façade by means of an inverse approach, which makes use of optimization of the total energy demand. It accounts for different time-scales of the adaptive mechanism and implements physical constraints of glazing façade thermo-optical performance. This method is used to quantify the potential primary energy saving of an ideal adaptive glazing façade, with 40% WWR, applied to an office room located in three different climatic locations with different orientations.

It is shown that a glazing façade with monthly adaptiveness can significantly reduce the energy consumption in the case studies presented. Moreover a first quantification of the potential energy saving achievable with a daily adaptive glazing façade is provided, demonstrating that a shorter reaction time of

the glazing façade could result in higher energy savings. Both the magnitude of the energy saving achievable and the most effective range of variability of ideal states of the façade strongly depends on the climate context and orientation of the room/building. In general North exposed facades present lower energy saving potential by the employment of adaptive glazing, especially for façade with long response times, while saving up to 20% for monthly and 30% for daily-adaptive façade may be achievable. In general the highest decrease in energy consumption is achieved in the cooling primary energy demand of the building for all the orientation (80-90% reduction). This results represent an ideal limit of the performance achievable by means of an adaptive glazing façade.

The limitation of the proposed method is that this optimisation process is unable to update the states of the system during the simulation process. This leads to sub-optimal results for the daily adaptive glazing, even though a method is proposed to reduce this effect.

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