The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies

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A B S T R A C T

The development of dynamic building envelope technologies, which adapt to changing outdoor and indoor environments, is considered a crucial step towards the achievement of the nearly Zero Energy Building target. It is currently not possible to evaluate the energy saving potential of innovative adaptive transparent building envelopes in an accurate manner. This creates difficulties in selecting between competing technologies and is a barrier to systematic development of these innovative technologies.

The main aim of this work is to develop a method for devising optimal adaptive glazing properties and to evaluate the energy saving potential resulting from the adoption of such a technology. The method makes use of an inverse performance-oriented approach, to minimize the total primary energy use of a building. It is applied to multiple case studies (office reference room with 4 different cardinal orientations and in three different temperate climates) in order to evaluate and optimise the performance of adaptive glazing as it responds to changing boundary conditions on a monthly and daily basis. A frequency analysis on the set of optimised adaptive properties is subsequently performed to identify salient features of ideal adaptive glazing.

The results show that high energy savings are achievable by adapting the transparent part of the building envelope alone, the largest component being the cooling energy demand. As expected, the energy savings are highly sensitive to: the time scale of the adaptive mechanisms; the capability of the façade to adapt to the outdoor climatic condition; the difference between outdoor climatic condition and the comfort range. Moreover important features of the optimal thermo-optical properties are identified. Of these, one of the most important findings is that a unique optimised technology, varying its thermo-optical properties between a limited number of states could be effective in different climates and orientations.
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1. Introduction

The 2010 Energy Performance of Buildings Directive Recast [1] requires that by the end of 2020 (2018 for public buildings) all the new buildings should be "nearly Zero Energy Building" (n-ZEB). Compared to the sole objective of energy conservation in building this imposes more demanding requirements for new design methods, concepts and technologies, as it imposes a net zero yearly balance between the energy demand and the energy harvested by means of renewable energy sources. In order to achieve this objective, two main strategies need to be adopted in the design and operation of buildings [2]: (a) minimize the energy demand within the building to the highest extent, and (b) supply the remaining energy demand by means of on-site renewable

energy sources. The former can be achieved by means of two alternative design strategies: one is "exclusive" and the other is "selective". The "exclusive" approach considers the building envelope as a "static" barrier that excludes the outdoor environment from the indoor environment by means of a very well-insulated and air tight building envelope. There is, however, a limit to the energy savings achievable by the "exclusive" approach [3]. Larger energy savings may be achieved by designing the building and its envelope as a "selective" filter between the outdoor and the indoor environment [3]. "Selective" building envelopes modulate the heat and mass flow by making use of adaptive or Responsive Building Elements and systems, which passively or actively adjust their thermo-optical properties or operation in a reversible way in order to adapt to changing outdoor/indoor environmental conditions (i.e. solar radiation, air temperature, wind speed and direction, internal loads, etc.), with different time scales of the adaptive mechanisms (from seconds to seasonal adaptiveness depending on the

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technology) [4]. Indeed, of the various energy efficient technologies considered by IEA–ECBCS Annex 44 activity [3], adaptive technologies embedded in the building envelopes are considered to have the largest potential to minimize the energy use in buildings. In particular, Double Skin Facades or Advanced Integrated Façades [5], switchable glazing [6], movable solar shading [7], wall integrated phase change materials [8], dynamic insulation [9] and multifunctional facades [10] are identified as the most promising adaptive façade systems and components in terms of energy reduction potential.

In conventional static (non-adaptive) building envelopes, the transparent element typically provides the largest potential for energy saving. This was quantified by Jin and Overend [11], who performed a sensitivity analysis on building performance in terms of energy use, indoor environmental quality and whole-life cost of early-stage design parameters (including façade, architectural and building services design parameters). These findings are summarized in Fig. 1, which shows the ranked influences on the total energy use (heating, cooling and lighting) of an enclosed office building located in Helsinki, London and Rome, of: (a) the Window-to-Wall-Ratio (*WWR*); (b) the *U-value* (U_g), *g-value* and visible transmission T_{vis} of the transparent façade; (c) the *U-value* of the opaque façade (U_p); (d) the Infiltration Rate (*IR*). The ranking is obtained from the absolute value of the Standardized Regression Coefficients (*SRC*) of the global sensitivity analysis. From Fig. 1 it is evident that the glazing thermo-optical properties, i.e. the U_g, *g-value* and T_{vis}, together with the *WWR*, have the largest influence on the total ideal energy demand. From this it is pertinent to assume that adaptive transparent building envelopes would have a significant impact on the energy use in buildings, but the energy saving potentials of a generic adaptive transparent building envelope has yet to be evaluated and the optimal range of adaptive thermo-optical characteristics that maximizes the energy saving achievable has yet to be established.

The aim of this study is therefore to develop a method to evaluate the maximum potential of the transparent building envelope at reducing the energy use in buildings by modulating its thermo-optical properties in response to real-world (transient) boundary conditions. To achieve this: a new design tool is developed that adopts an inverse method in order to devise an ideal, or optimal, adaptive transparent façade; the optimal thermo-optical characteristics of this adaptive glazing are characterized; the energy saving achievable by the adoption of this technology in a typical building is evaluated; a frequency analysis on the set of optimised adaptive properties is performed in order to identify important features of ideal adaptive glazings.

The paper is subdivided into the following sections: in the second section the state-of-the-art adaptive glazing technologies are reviewed, followed by a discussion about the definition of the characteristics of optimal adaptive glazed façades; in the third section an overview of the methods to devise optimal adaptive façades is provided, highlighting their main limitations; in the forth section the new method and tool are presented; this is followed by the results section in which the energy saved with the optimal adaptive glazed facade, the modulation ranges of its optimal thermo-optical properties and important features of optimal adaptive glazings are presented.

2. Switchable glazing: a performance based state of the art analysis

The so called switchable/smart/dynamic/adaptive glazing technologies are capable of dynamically modulating their thermo-optical properties in response to changing external climate and/or internal loads (occupancy, light or equipment usage). This adaptiveness can be described by the two extreme states of the glazing: a transparent (bleached) state and a coloured (darkened) one. These are characterized by a particular *g-value* (proportion of total solar radiation transmitted through the glazing) and visible transmission T_{vis} (proportion of solar visible radiation transmitted through the glazing). The modulation of thermo-optical properties can be either a self-triggered adaptive mechanisms, in which case the technology is said to have a passive or smart adaptive behaviour, or by an external stimulus, whereby the technology is said to be active or intelligent [4].

Passive technologies include thermo-chromic TC [12], thermo-tropic TT [13,14] and photo-chromic PC glazing. In these technologies the change in *g-value* and T_{vis} is triggered by a change in the internal energy, inducing a phase transition or phase separation in the TT or TC layer, which is revealed by a temperature variation. a While in PC the modulation in optical properties is triggered by the amount of energy in the incident radiation.

Active technologies such as electro-chromic EC, light particle devices LPD, and liquid crystal devices LCD, require a change in the electrical potential to trigger a change of *g-value* and T_{vis}. The adaptation in EC is achieved by changing the amount of free electron density in a metal based oxide, such as W, Mo, Ir, Ti, V, Ni and Nb oxides, or polymer, such as PANI and PEDOT [12,15]. Various technologies exploit the EC feature of these materials in order to achieve an optically controllable window. These technologies are classified into *gasochromic*, *all-solid state electrochromic* and *photo-electrochromic PEC*. In the first case, the molecules are in gaseous state, while in all the others they are in solid state. An electrical field is applied in order to inject/remove electrons into/from the metal oxide molecules, which results in the colouring/bleaching of the material. In PEC the layer of EC material is coupled with a photovoltaic material layer for electron injection, so that the EC system can be self-powered. An evolution of PEC is represented by photo-volta-chromic (PVC), which differs from PEC in that the photovoltaic and electrochromic functions can be separated, thereby facilitating its integration with building management systems [16]. The modulation of optical properties in LPD and LCD is triggered by an electrical current inducing a magnetic field, to align the suspended particles or the liquid crystal, which are otherwise randomly ordered, thus allowing light to pass through. Therefore these devices need continuous potential difference to maintain a certain state, thus requiring a higher electrical energy demand than EC materials [12].

Regardless of the switching mechanism, all these switchable glazing technologies can be described by their ability to modulate T_{vis} and *g-value*. Their performance in this regard can be characterized by:

1. Minimum and maximum values of the modulating ranges ($T_{vis,min}$ and $T_{vis,max}$, *g-value*$_{min}$, *g-value*$_{max}$) and implicitly the modulation ranges (ΔT_{vis}, Δ*g-value*), which measures their capability of modulating the amount of total solar and light energy entering the indoor environment.
2. The luminous efficacy K_e, which is the ratio between T_{vis} and *g-value* of each state of the adaptive glazing [17]. It gives the amount of light radiation compared to the total amount of solar energy transmitted through a glazing.[1] K_e can be also referred to as spectral selectivity of the glazing. This ratio indicates the capability of the glazing to transmit a selected range of solar spectrum

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[1] This definition, although it is dependent on indoor and outdoor boundary conditions due to the definition of the *g-value* [20], takes into account not only the energy that is directly transmitted through the glazing, but it also include the solar energy that is absorbed and re-emitted towards the indoor environment by the glazing ($T_{vis}/$*g-value*). Therefore it can be considered as an analogous concepts to the luminous efficacy of a lighting source.
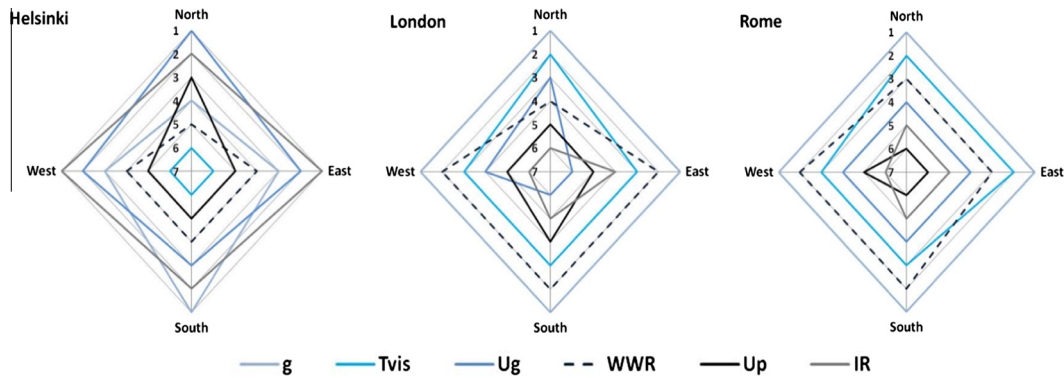
Fig. 1. Influence of façade design parameters on total energy consumption of office building for different locations and orientations, after Jin and Overend [11].

to the indoor environment and implicitly the component that is reflected and re-irradiated to the outdoor environment. Values between 0.10 and 0.58 indicate that the solar energy admitted (directly transmitted and re-irradiated) in the indoor environment is mainly in the infra-red range of the solar spectrum; values of 1.00 indicate that the proportion of energy in the infrared and visible part of the solar spectrum is maintained when transmitted through the window; values of 1.365 indicate that equal amounts of infra-red and visible components are transmitted into the building; higher values of this ratio indicate an increase in the visible radiation transmitted, up to a value of 2.41, when only visible radiation is transmitted into the building. This constitutes the theoretical maximum K_e which is limited by the ratio of the energy contained in the solar visible spectrum compared to the whole solar spectrum at the sea level, which is approximately 41.5% [18]. This theoretical limit is slightly higher than the physical limit of K_e, as in order to achieve it the amount of solar radiation which is absorbed by the glazing and re-emitted towards the indoor environment should be zero.

Fig. 2 compares the optical and thermal properties of the switchable glazings reported in literature [7,12–16] with commercially available 'static' DGU windows (grey data points). The DGU[2] properties shown in the graph are derived from the International Glazing Database [19] of single glass layers. Each switchable glazing is represented by a straight line connecting the minimum and maximum value of its thermo-optical properties. In particular, while a static technology can be represented by a single data point (single state in terms of g-value and T_{vis}), an adaptive glazing could potentially assume any of the states along the line representing its thermo-optical properties. Note that the path between the minimum and the maximum states may be a straight line segment or a curve depending on the technology. Where the T_{vis} and g-value for a particular glazing were not directly available, the optical properties (absorptivity α (−), transmissivity τ (−), reflectivity ρ (−)) available in literature were used to calculate the g-value and T_{vis} according to the ISO 9050: Glass in Buildings [20]. The maximum theoretical K_e is plotted in Fig. 2 by a black dashed line.

3. The ideal adaptive glazed façade

An ideal adaptive façade can be defined as a façade which is able to minimize the total energy use in the indoor space (energy for heating, cooling, lighting and ventilation) while simultaneously improving the level of the indoor environmental quality, by adapting its thermo-optical properties to transient outdoor/indoor
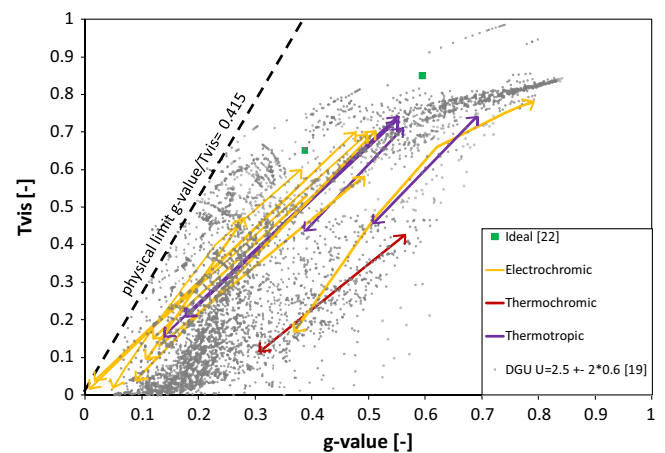

Fig. 2. T_{vis} and g-value of smart glazing technologies compared to commercially available static DGUs.

environmental conditions. This could be achieved by modulating the thermo-optical properties in order to either temper, store, shift, admit or redirect the energy and mass flow through the envelope (selective approach).

It therefore follows that the ideal adaptive glazing is one that minimizes the total energy use in the indoor space by means of modulating all its thermo-optical properties, these properties being the T_{vis}, g-value and U-value of the glazing. The following properties and characteristics need to be established in order to identify an optimal adaptive glazing:

- the most effective modulation range of each thermo-optical property of the glazing, i.e. T_{vis}, g-value and U-value;
- the interdependencies between the modulation of one property and the modulation of the other properties;
- the most effective time scale of the modulation range, i.e. seasonal, daily, hourly, etc.;
- most effective control strategy for the switching of thermo-optical properties.

The thermo-optical properties of an ideal adaptive glazing are not expected to be "universal", as they will be a function of the climatic location, type of building etc. The method of establishing the ideal adaptive glazing for specific boundary conditions and identifying the salient characteristics is however useful as it evaluates the maximum amount of energy savings achievable by adaptive glazing for reference boundary conditions and it helps to steer the development of the future generation of adaptive glazings.

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[2] Each DGU consists of two equal layers of glass with a 10 mm air cavity interposed, where low-e coating or solar control coating is always facing the glazing cavity.

3.1. Direct and inverse methods for ideal adaptive façades

There have been different approaches to determine the ideal/optimal time-dependent building envelope properties for a certain scenario. These approaches have been applied to evaluate one or multiple optimal building envelope adaptive properties as follows: one optical property of the transparent part [15,21,22] or one thermal property of the opaque part [23–25] of the building envelope at the time; the Window to Wall Ratio (WWR) [26]; multiple properties of the building envelope simultaneously [27–30]. These studies can be classified into theoretical [15,21], direct [22] and inverse approaches [23–30].

In the theoretical approach the ideal properties (in these cases optical properties of a single glass layers) are defined based on deduction, but there is no validation from either simulation or experiments. This is a limitation as these properties are likely to depend on the climatic location and the building typology, so that properties derived in this way are likely to be sub-optimal in other contexts of application.

In the direct approach the performance of a proposed 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 optimised to improve its performance [22,23] by means of comparative experiments/simulations and trail and error. As highlighted by Zeng et al. [23], the direct method appears to be ill-suited to the research problem in the present study, because it evaluates a specific case of adaptive mechanisms (in terms of time scale of adaptive mechanisms and modulation of single façade characteristics) and technology.

The potential of employing an inverse approach are presented in [23]: the optimal time series of values of one thermo-optical property of the building envelope (i.e. the specific heat capacity for a building envelope component in this case) can be calculated by means of minimization or maximization of a cost function. This cost function can consist in either the indoor environmental comfort or the energy consumption, or both. With the approach of Zeng et al. [23], optimisation is adopted to devise the sequence of optimal properties of the adaptive building envelope component. The main limitation of this approach is that, since the numerical problem is solved explicitly, it cannot be used when multiple ideal adaptive properties need to be identified.

A further development of the inverse approach is presented by Kasinalis et al. [27]. In this work the authors' main objective is to identify the optimal properties of an opaque façade and the optimal *WWR* by means of a multi-objective optimisation approach. One cost function of the optimisation is the total yearly energy demand of the building enclosed by the adaptive façade, this is calculated as the summation of the energy use in shorter periods (months in this case). Therefore one optimisation is performed for each sub-yearly period, resulting in a specific set of optimal façade properties for each period. Finally the global optimum is considered as the sum of the single optimal results. Therefore the properties and the performance (energy use) of the optimal adaptive façade are calculated as the sum of the independent static facades, simulated separately. A similar approach is adopted by Favoino et al. [28,30] to optimise long-term adaptive glazing properties; while the same inverse approach is extending to shorter adaptiveness of the façade (from months to hours) by Goia and Cascone [26], to optimise the *WWR*, and by Martinez [29], to optimise different hourly adaptive façade properties simultaneously. In these studies [26–30] the adaptive façade behaviour is approximated as the sum of the performance of different static façades for the relevant sub-annual time horizons. Though this cannot be considered always correct, in fact the effect of varying material properties at a certain time can affect the energy transfer through the building envelope and the energy balance of the indoor environment with a certain delay (hours or days), depending on the thermal inertia of the building.

In order to evaluate the performance of an active adaptive building envelope component in an accurate manner, it is essential to account for the transient material properties, and in particular how the variation of the material properties at a given instant affects future (in respect to the instant the material property is varied) energy use. This is commonly referred to as receding horizon control [31] (RHC). This is a feedback non-linear control technique, that involves solving an optimisation problem at each time step to determine the control sequence over a certain future time horizon. Using RHC, a system can be controlled near its physical limits (performance bound), achieving higher performance than linear control [31]. Consequently if the time horizon for the optimisation (time scale of the adaptiveness of the façade) is of the same order of magnitude of the time constant of the building and no receding horizon control is adopted, the solution found (in terms of both façade properties and performance) can be far from the optimum. As a result, in Favoino et al. [30] there seems to be no improvements between the monthly adaptive glazed façade and the daily adaptive one calculated with the inverse method [30], not adopting RHC control.

The inverse methodology therefore appears suitable for devising multiple optimal thermo-optical properties of a glazed façade, and of an adaptive façade in general. However its implementation, which is described by means of different case studies in [26–30], is constrained by the following limitations of current whole building energy performance simulation tools: (a) capability of simulating varying building envelope properties; (b) capability of implementing receding horizon control; (c) capability of explicitly setting the initial boundary conditions of the system, i.e. the initial conditions of subsequent optimisation. The first limitation can be bypassed by adopting the approximation of dividing one simulation/optimisation into the sum of different independent simulations/optimisation with different static material properties, as in [26–30], but this can result in the shortcomings previously highlighted. While the other limitations (b and c) are overcome in this paper by means of two measures: setting the initial boundary conditions of one optimisation as the ending boundary condition of previous one, as suggested in [27,30]; by introducing receding horizon control for adaptive thermo-optical properties, when a modulation faster than the inertia of the system is adopted in the adaptive façade.

4. Methods and tools

In this study the inverse methodology is adopted in order to devise optimal adaptive glazing properties and to evaluate the resulting reduction in the energy demand of a building. The inverse approach is extended by addressing the limitations identified in the previous section. The methodology is subsequently implemented to evaluate and optimise the performance of ideal adaptive glazed façade with a time scale of the adaptive mechanisms of the order of months and days, on the case study of a typical office room in the four cardinal orientations in Helsinki, London and Rome. The energy use of the office enclosed by the ideal adaptive glazed façade is compared to a reference façade (a static façade complying with national standards) and a yearly optimised one. The optimisation variables consist of the thermo-optical properties of the glazed portion of the façade, while the opaque parts, that meets the minimum requirements imposed by national regulations, remain unchanged. The performance of the ideal adaptive façade constitutes the upper limit of the performance achievable by a monthly and daily adaptive glazed façade for commercial buildings.

4.1. Software framework

A simulation tool was specifically developed to overcome the afore-mentioned limitations of whole building energy performance simulation software. This tool (Fig. 3) integrates an evaluation module (building energy simulation software EnergyPlus [32]), an optimisation module (GenOpt [33]), and a control module (Matlab [34]).

The evaluation module computes the cost functions for the optimisations involved in the RHC. These can be computed from a variety of outputs of EnergyPlus (i.g. total primary energy demand of the building, thermal comfort, luminous comfort etc...). Specifically in this study the total primary energy use is adopted as the cost function (i.e. the sum of the primary energy use for heating, cooling and lighting). The Energy Management System (EMS) of EnergyPlus [35] is employed to vary the thermo-optical properties of a material or a construction during simulation runtime according to a pre-determined control strategy. In particular a construction object was created with unknown material properties, corresponding to the ideal adaptive glazing to be controlled. The controlled variables are the thermo-optical properties of the glazing, namely *U-value*, *g-value* and T_{vis}. Moreover the EMS is used to compute the cost functions used by the optimisation module.

The optimisation module, GenOpt, performs the optimisation to determine the optimal thermo-optical properties of the glazed façade that minimize the energy demand over a certain cost horizon.

The control module (Matlab) replaces the user in setting the inputs of the optimisation module and the evaluation module. These inputs include: (a) the orientation and the climate of the building; (b) the period of time to be simulated; (c) the time scale of the adaptive mechanisms; (d) the adaptive properties (variable of the optimisations), their modulation ranges and the constraints of the variable space for the optimisation; (e) the length of the planning horizon and cost horizon; (f) the initial state of the system (i.e. temperature of the thermal zone and of all the surfaces in the thermal zone arising from the previous optimisations).

Similarly to Corbin et al. [36], in the present tool, the time horizon for each optimisation is made up of: a planning horizon, the time frame in which the façade properties can be varied; a cost horizon, the time taken into account for the evaluation of the cost function. The latter extends beyond the planning horizon and it is required as the effects of modulating the glazing properties on the total energy balance can extend beyond the period (time frame) in which they are modulated. An excessively short cost horizon can yield a solution that is optimised for that time frame, but may increase the energy use of the following period. The Thermal History Management method [36] is adopted to set the initial boundary conditions of the building according to the ending boundary conditions of the previous optimisation. Although explicit state update in EnergyPlus is not possible, this method consists of a preconditioning period, with the function of setting the initial conditions of the system in one simulation equal to the ending conditions of the previous optimisation. This is achieved by re-simulating the system with the previously optimised control logic for a certain time frame before the beginning of the planning horizon. The length of the pre-conditioning period (c.f. Section 4.3) depends on the thermal inertia of the system [36].

By using this bespoke tool the optimisation process involves the following key steps (Fig. 3):

(A) a parametric EnergyPlus model with variable orientation, climate, control strategy, optimisation horizons and material properties is created;
(B) Matlab is used to set the different parameters of the model and the inputs for the optimisation;

(C) the parametric model is automatically fed to GenOpt, which generates alternative control sequences for the adaptive properties to be evaluated;
(D) the specific control sequence is implemented into the EMS system of EnergyPlus;
(E) the cost function is evaluated by EnergyPlus and the results are returned to GenOpt;
(F) the results from the evaluations are used by GenOpt to define the optimal control strategy (time sequence of optimal façade properties);
(G) the results from each optimisation are returned from GenOpt to Matlab for THM and for the analysis of the results;
(H) Matlab shifts the cost horizon for a period equal to the planning horizon and the sequence is repeated from (B) to (G) until the end of the simulation period is reached.

The optimisation process described requires the construction of the parametric EnergyPlus model (in A) and the set-up of the initial parameters and optimisation inputs (in B), while the rest of the process is fully automated. The shortest time scale of the adaptive glazing properties that is adopted in the present work is one day (24 h), even though a shorter modulation time could be achieved (i.e. hourly or sub-hourly). In this case it is limited by the inability of EnergyPlus to integrate the control of the artificial lighting system with the intermediate states of an adaptive glazing. Sub-daily adaptiveness of the opaque building envelope can therefore be simulated, but it is not considered in this study. The integration with the lighting system for sub-daily optimisation of adaptive glazing is the object of future development.

4.2. Case study

The specific thermo-optical properties of the ideal glazing depend on the boundary conditions of the system, which consist of the external boundary conditions (the climate) and of the internal conditions, i.e. the type of building, its internal loads and the integration of the building services with the façade [37]. For this reason a unique case study, as in [22], cannot be considered representative, hence a series of case studies is investigated in this paper. The case studies are represented by a typical office reference room (3 m wide × 5 m deep × 3.5 m high) located in three different temperate climates (Helsinki, London and Rome), in the four cardinal orientations, with a WWR of 40% on a single façade. The typical office room is flanked by identical offices on its other three sides at the same level and on the level immediately above and below it. The glazing of the façade (40% of 3 m × 3.5 m) has adaptive thermo-optical properties, the opaque part of the façade meets the minimum requirements set in the national standards for each specific climatic zone (Table 1).

Indoor comfort is considered as a hard constraint in the optimisation, which means that indoor temperature has fixed set-points for heating and cooling (20 °C and 26 °C respectively) with a nocturnal set-back (12 °C and 40 °C respectively); 500 lux is the threshold illumination level (at desk level, 0.8 m high, 1.5 m far from the façade) for the 5-step-dimmable artificial lighting system; the primary air ventilation rate is set to 1.4 l/sm² when the office is occupied. Schedules and peak loads for the building services, lighting, equipment and occupation are defined according to the UK NCM database [38]. The lighting power density is set to 12.75 W/m², the equipment power density is 13.45 W/m² and the occupation density is 0.111 person/m². An average seasonal efficiency of the heating plant of 0.85 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
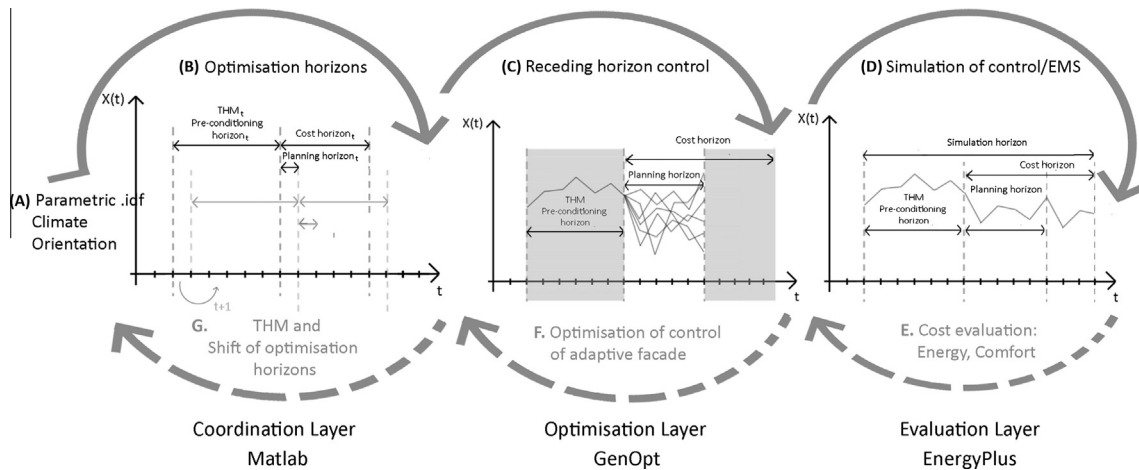
Fig. 3. Software architecture and optimisation horizons (control and cost horizon). The arrows in this figure represents the flow of the inputs/models (continuous line) and of the outputs/results (dashed line).

Table 1
Office reference room and reference façade (R) characteristics.

Climate	Heating degree days [base] (°C)	U_{wall} (W/m² K)	$U_{glazing}$ (W/m² K)	g-value (–)	T_{vis} (–)	f_{Elec} (–)	$f_{Nat\ Gas}$ (–)
Rome	1415 [20]	0.29	2.00	0.72 (N, S) -0.58 (E, W)	0.76 (N, S) −0.61 (E, W)	2.180	1.000
London	1828 [15.5]	0.27	2.00			1.026	2.580
Helsinki	3902 [18.5]	0.17	1.00			1.700	1.000

Table 2
Thermal capacity of the constructions adopted in the office reference room..

Construction	Unit	Insulated cavity brick wall	Curtain wall (LI)	Concrete slab	Composite concrete – steel deck slab (LI)
Internal thermal capacityt[4]	(kJ/m² K)	36.2	21.7	67.8	67.2
External thermal capacity[4]	(kJ/m² K)	106.3	23.2	29.3	29.9
Superficial mass	(kg/m²)	412	54	675	315
Time lag	(h)	11.61	1.63	10.61	6.26

[4] In the case of a horizontal partition, if it is considered as a ceiling, the internal and external thermal capacity need to be inverted.

account for different national climatic and legislation contexts in Rome, London and Helsinki [39].

The thermal inertia of the office reference room is represented by the time constant. This is calculated numerically, by means of measuring the response of the reference room (in terms of indoor air temperature) to a step solicitation in outdoor temperature.[3] The time constant is measured as the time required by the indoor air temperature to decrease its value by 63.2% of the step temperature solicitation. The resulting time constant of the reference office is between 42 and 63 h, depending on the U-value of the glazing, which is one of the variable thermo-optical properties for the ideal adaptive glazing (cfr. Section 4.3). This is a relatively high inertial effect and it is due to the high thermal capacity of the constructions adopted in the office reference room (concrete slabs and insulated cavity brick external wall). In order to assess the sensitivity of the results to the thermal inertia of the building, an office room with lower thermal inertia is also analysed for the South orientation in the three climates, this is referred to LI (Low Inertia) in the results section. This lower thermal inertia office reference room adopts an opaque curtain wall and a composite concrete–steel deck slab construction, resulting in a time constant between 15 and 24 h. The thermal

capacity (internal and external), the superficial mass and the time lag of the constructions used in the high and low thermal inertia office are summarized in Table 2, these are calculated according to EN ISO 13786:2008 [40]. Moreover it has to be noted that the effect of the thermal capacity of the window itself is neglected by the Energyplus software in the energy balance of the simulated system.

The numerical analysis is performed on the basis of façades with a Monthly (M) and Daily (D) modulation time. These two cases are compared with a yearly optimised facade (Y, ideal static glazing) and with a reference glazing (R). The properties of R façade are representative of the minimum performance required by the national regulations. While the Y façade is representative of the best performance achievable by means of a static glazing, whose properties are derived (by minimizing the yearly total energy use in the office reference room) with the same inverse methodology described in the previous sections.

4.3. Optimisation parameters

The optimisation parameters to be defined in the coordination layer are: ranges of adaptive thermo-optical properties (defining the variable space for the optimisation) and their interdependencies (constraints); cost function; length of the cost horizon; optimisation algorithm and optimisation algorithm parameters.

[3] For this evaluation no internal loads (occupant, lights and equipment) and no solar loads are considered in the room model.

The ideal glazed façade properties that can be modulated dynamically (optimisation variables) are the *U-value* (W/m² K), the *g-value* (–) and the *T_vis* (–). For each property a modulation range is calculated assuming that an ideal adaptive glazing can modulate its thermo-optical properties in a continuous way within the full physically feasible thermo-optical range. These physically feasible ranges are confined by the properties of existing static state-of-the-art glazing systems, i.e. single (SGUs), double (DGUs) and Triple Glazing Units (TGUs). The variation of ideal adaptive properties is achieved either by changing the surface characteristics (coatings), or by changing the cavity properties, e.g., the gas pressure. The lowest *U-value* achievable in a 1 mm thick cavity by means of reducing the cavity air pressure (i.e. achieving a vacuum insulated cavity) is 0.20 W/m² K for a DGU [41] and 0.11 W/m² K for a TGU. The list of commercially available glazing in the IG Database [19] was used to define the range of variability for the T_{vis} and *g-value*. The ranges of *U-value*, *g-value* and T_{vis} of different multiple panes technologies were calculated from the relationships of *g-value* and T_{vis} found in [20]. The calculation procedure for obtaining the modulation ranges is omitted for brevity. Table 3 shows the variable ranges of the three properties for these glazing technologies.

The glazing with the largest variation of thermo-optical properties is the DGU, therefore its modulation ranges are adopted for the analysis. The optimisation variables and modulation ranges used in the optimisation are summarized in Table 4.

The ideal time series of adaptive glazing thermo-optical properties during a whole year is evaluated by minimizing the primary total energy use of the typical office room, E_p (kW h/m² y), as the sum of the yearly primary energy use for heating $E_{p,heat}$, cooling $E_{p,cool}$ and lighting $E_{p,light}$. The optimisation problem can therefore be written as:

$$\min \begin{cases} \text{if } Z\,(X(t)) \leq 0.41 \; f(X) = E_p = E_{p,heat} + E_{p,cool} \\ + E_{p,ligh}\left(\frac{\text{kW h}}{\text{m}^2\text{y}}\right) & (1) \\[4pt] \text{if } Z\,(X(t)) \geq 0.41 \; f(X) = E_p + Z = E_{p,heat} + E_{p,cool} \\ + E_{p,ligh} + kZ(X(t))^2 \left(\frac{\text{kW h}}{\text{m}^2\text{y}}\right) & (2) \\[4pt] \text{where } Z(X(t)) = \frac{g\text{-}value - 0.423 \cdot T_{vis}}{\sqrt{1+0.423^2}}\,(-) & (3) \\[4pt] \text{and } X(t) = \left(U\text{-}value(t)\left(\frac{\text{W}}{\text{m}^2\text{ K}}\right), g\text{-}value(t)(-), T_{vis}(t)(-)\right) & (4) \end{cases}$$

where $X(t)$ is the vector of adaptive glazing properties as defined in Table 4, $Z(X)$ is a penalty function introduced to constrain the variable space $X(t)$, representing the distance of the solution from the theoretical limit k_e, $f(X)$ is the cost function, $k = 10$ for daily adaptive façade and $k = 10^2$ for the monthly one, t is the modulation time of the façade thermo-optical properties (monthly, M, and daily, D). The value k is chosen such that the penalty function is one order of magnitude larger than the total primary energy use in the building.

A hybrid algorithm, named Particle Swarm Optimisation (with constriction coefficients) with Generalized Pattern Search

Table 4
Modulating ranges of glazing thermo-optical properties.

	U-value (W/m² K)	g-value (–)	T_vis (–)
Range [Min: Step: Max]	0.2: 0.05: 5.14	0.01: 0.01: 0.84	0.01: 0.01: 0.98

Hookes–Jeeves implementation (GPSPSOCCHJ) was used for the optimisation [33]. This algorithm was chosen as it offered the best trade-off between computational time and optimality of the results when compared with alternative algorithms. The hybrid optimisation algorithm (GPSPSOCCHJ) achieves this as it couples a global stochastic population-based optimisation algorithm (PSOCC) with a local one (GPSHJ), ensuring that a result close to the global minimum is found with the first algorithm, which is then improved by the local search [42].

For the monthly adaptive façade the cost horizon coincides with the planning horizon. While for the daily adaptive façade the planning horizon is set to one day, while the cost horizon is set to 3 days, in order to take into account the variation of thermo-optical properties on the following two days and to capture weekend dynamics, as suggested by [36]. Moreover for the daily adaptive façade, the optimal length of the pre-conditioning period for THM (Section 4.1) for the reference room with high thermal inertia was found to be 21 days, according to the experiment explained in [36], therefore this is used for both cases (high and low thermal inertia).

5. Results

The results of the optimisations undertaken on a typical office room in four cardinal orientations and in three different climates are presented in this section in three ways: (1) the energy saving potential of the optimal glazed façade with progressively shorter modulation time of adaptive thermo-optical properties (from month to day); (2) the modulation ranges (i.e. the variability of the adaptive properties) required to minimize the total primary energy use; (3) frequency distribution of each thermo-optical property in its modulation range and the effectiveness along the modulation range in terms of energy saving. Moreover the relationships between different properties and the common features of the ideal glazing technology that could guide the development of next-generation switchable glazing are discussed.

5.1. Energy saving potential of ideal adaptive glazing

The specific total primary energy use in the typical office room and the share in the primary energy for heating, cooling and lighting is shown in Fig. 4 and Table 5. The analysis is performed for three climates, i.e. Helsinki, London and Rome, and four orientations (North, East, South and West). Four different case studies

Table 3
Comparison of ranges of glazing properties for different technologies and measures.

| Tech	Method	T_vis Min (–)	T_vis Max (–)	g-value Min (–)	g-value Max (–)	U-value Min (W/m² K)	U-value Max (W/m² K)
SGU	Surface (a)	0.000	0.993	0.104	0.913	2.307	6.037
DGU	Surface (a)	0.000	0.985	0.042	0.841	1.512	3.324
	Pressure (b)	0.525	0.525	0.245	0.247	0.210	4.742
	Surface and pressure (a) and (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	0.145	0.140	0.111	2.503
	Surface and pressure (a) and (b)	0.000	0.978	0.016	0.777	0.109	4.366
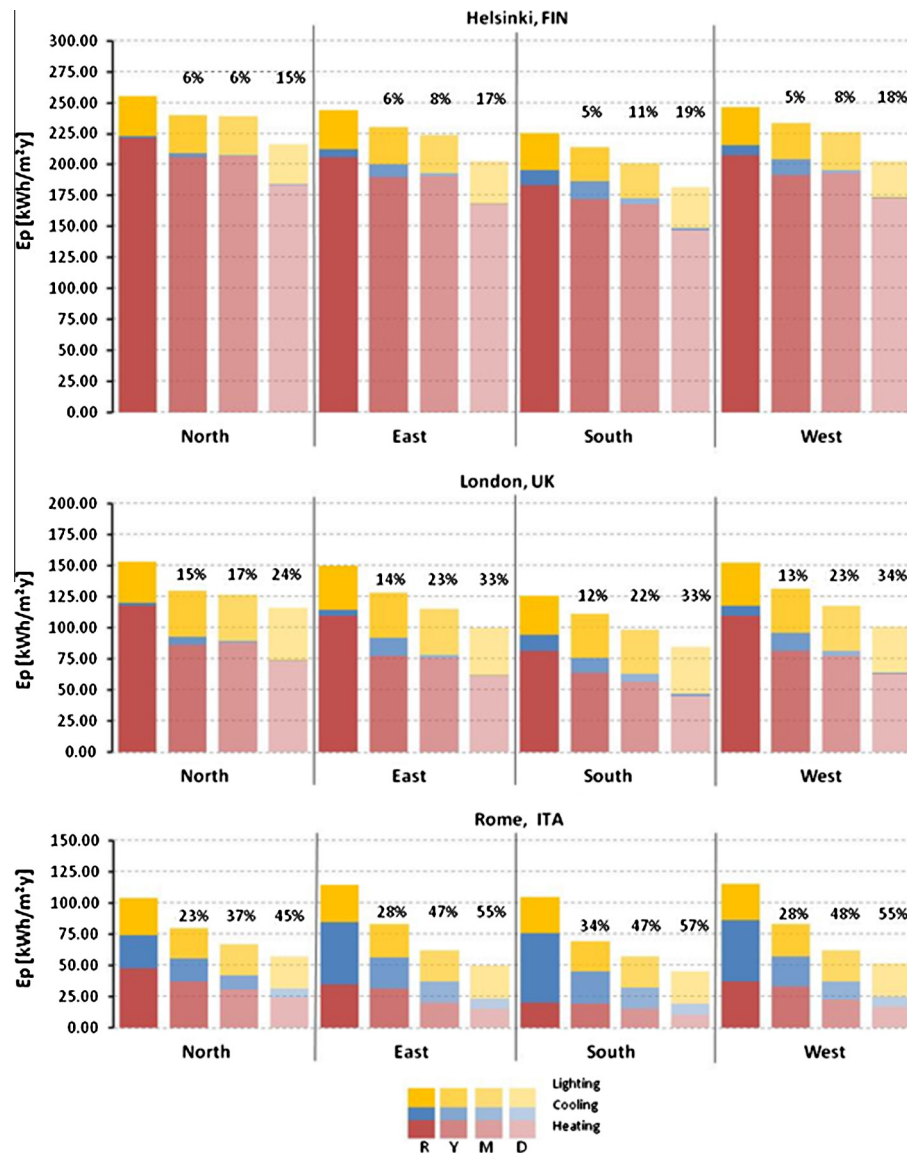
Fig. 4. Specific total primary energy use for different orientation and reaction time of the ideal adaptive glazing façade for the climate of Helsinki, London and Rome (R = reference, Y = yearly optimised, M = monthly adaptiveness, D = daily adaptiveness,). Percentages indicates the energy savings compared to the R façade.

are considered for each location and orientation: (a) the Reference façade (R), which satisfies the minimum requirements in each national context; (b) the Yearly optimised glazed façade (Y), which minimizes the total yearly primary energy demand and corresponds to the best possible "static" glazed façade in the domain defined by commercially available products (Fig. 2); (c) the ideal Monthly adaptive glazed façade (M), which is able to adapt its thermo-optical properties on monthly basis; (d) the ideal Daily adaptive glazed façade (D), that is able to adapt its thermo-optical properties on a daily basis (24 h). In order to assess the sensitivity of the results on the thermal inertia of the building the performance of a lower inertia (LI) reference office room is evaluated for the three different climates, with the different façade case (R, Y, M and D), for the South orientation only. The LI office results are shown in Table 4.

Both reference R and yearly optimised Y façades represent a state-of-the-art "static" solution, a difference between R and Y case indicates that, in terms of total energy use for the specific building typology and climate, a better performing "static" glazed façade

than the one required by national standards is available. Consequently the Y façade is a more appropriate benchmark, as it provides the highest energy saving achievable with the best static glazing technology. However Energy Saving (ES) potential in Fig. 4 is expressed with respect to the reference façade R.

It can be seen that in Helsinki, in which the "exclusive" approach alone should provide substantial energy saving potentials [3], the Y façade reduces the primary energy use by only 5–6% compared to the R case study, while in other warmer climates selecting the most appropriate static technology has a larger effect on the building energy use (12–13% reduction in London, and 25–35% in Rome, depending on the orientation). This is because static glazing parameters have a smaller effect on energy balance in Helsinki, where other factors such as WWR and infiltration rate are more significant than in London or Rome (Fig. 1). In addition the starting reference case R is ill-suited for office buildings in the climate of Rome, in terms of thermo-optical properties of the reference glazing. In any case the differences between R and Y cases represent the energy saving limit of the "exclusive" approach at designing the

Table 5
Energy use and energy saving potential of ideal adaptive glazed façade.

Case	Orientation	Ep tot (kW h/m² y)	Ep heat (kW h/m² y)	Ep cool (kW h/m² y)	Ep light (kW h/m² y)	ES tot (%)	ES heat (%)	ES cool (%)	ES light (%)
Helsinki									
	North	255.71	221.08	1.68	32.96				
	East	243.93	206.06	6.31	31.55				
R	South	225.67	183.68	12.19	29.80				
	South – LI	230.33	185.47	15.07	29.80				
	West	246.66	207.67	7.78	31.21				
	North	239.96	206.01	3.21	30.74	6	7	−91	7
	East	230.23	189.66	11.02	29.55	6	8	−75	6
Y	South	214.47	172.32	13.99	28.16	5	6	−15	5
	South – LI	208.45	162.49	17.81	28.16	9	12	−18	5
	West	233.32	191.40	12.66	29.27	5	8	−63	6
	North	239.34	206.56	1.20	31.59	6	7	28	4
	East	223.88	190.83	2.37	30.68	8	7	62	3
M	South	201.52	168.17	4.72	28.63	11	8	61	4
	South – LI	205.39	171.33	5.26	28.80	11	8	65	3
	West	226.14	192.74	2.99	30.41	8	7	62	3
	North	216.74	183.73	0.09	32.91	15	17	94	0
	East	202.40	167.99	0.21	34.20	17	18	97	−8
D	South	181.84	147.19	1.40	33.25	19	20	89	−12
	South – LI	182.58	151.22	1.76	29.60	21	18	88	1
	West	203.04	172.51	0.34	30.19	18	17	96	3
London									
	North	153.61	117.55	2.40	33.66				
	East	150.22	109.61	5.13	35.48				
R	South	126.26	81.89	12.93	31.44				
	South – LI	133.63	81.61	20.58	31.44				
	West	152.19	110.16	7.53	34.51				
	North	130.19	86.62	6.52	37.05	15	26	−172	−10
	East	128.62	77.79	14.20	36.63	14	29	−177	−3
Y	South	111.67	64.18	12.10	35.39	12	22	6	−13
	South – LI	113.07	64.38	13.30	35.39	15	21	35	−13
	West	131.69	81.83	14.07	35.79	13	26	−87	−4
	North	126.80	87.95	1.78	37.07	17	25	26	−10
	East	115.34	75.76	2.65	36.94	23	31	48	−4
M	South	98.37	56.58	6.07	35.72	22	31	53	−14
	South – LI	103.78	60.53	7.08	36.17	22	26	66	−15
	West	117.78	77.15	4.36	36.26	23	30	42	−5
	North	116.17	73.46	0.24	42.47	24	38	90	−26
	East	100.49	61.05	0.43	39.02	33	44	92	−10
D	South	85.17	44.93	1.62	38.62	33	45	87	−23
	South – LI	87.45	46.46	1.97	39.02	35	43	90	−24
	West	100.74	63.00	0.78	36.96	34	43	90	−7
Rome									
	North	103.89	47.80	26.38	29.71				
	East	114.71	35.16	49.88	29.67				
R	South	104.93	20.62	55.72	28.59				
	South – LI	118.98	22.15	68.25	28.59				
	West	115.18	37.08	49.45	28.65				
	North	80.15	37.67	18.33	24.15	23	21	31	19
	East	82.98	32.05	24.84	26.09	28	9	50	12
Y	South	69.25	19.33	26.21	23.71	34	6	53	17
	South – LI	84.20	20.26	40.23	23.72	29	9	41	17
	West	83.01	33.28	24.59	25.14	28	10	50	12
	North	65.06	30.84	11.08	24.89	37	35	58	16
	East	60.79	20.74	16.60	25.37	47	41	67	14
M	South	55.14	15.28	17.28	25.08	47	26	69	12
	South – LI	69.87	19.07	25.42	25.38	41	14	63	11
	West	60.20	22.79	14.61	24.81	48	39	70	13
	North	57.16	24.37	7.13	25.66	45	49	73	14
	East	50.54	15.47	8.20	26.87	56	56	84	9
D	South	45.32	10.80	8.53	25.99	57	48	85	9
	South – LI	49.70	13.84	9.87	25.99	58	38	86	9
	West	51.64	17.10	8.09	26.46	55	54	84	8

transparent building envelope. While the additional energy savings achievable in the *M* and *D* cases indicate the advantage of the "selective" one.

Generally in the Helsinki climate an optimal monthly adaptive glazing (*M*) makes relatively small improvements. In fact, a negligible energy saving is obtained for the North façade, while 2–6% energy savings are achievable for other orientations. An ideal daily adaptive façade (*D*), could potentially reduce the primary energy use by an additional 10% in a climate like Helsinki, irrespective of

orientation. The break-down in heating, cooling and lighting energy demand shows that in the *Y* case the energy demand for cooling is increased, whilst the energy for heating and lighting is reduced. In fact, in *Y* optimised cases a lower *U-value* and an higher T_{vis} and *g-value* are adopted compared with *R* cases. This is an expected result as Helsinki is in a heating dominated climate, where consuming electricity for cooling is more efficient than using natural gas for heating, compared to other climates in this specific case study (c.f. fuel factors in Table 1 and HVAC

efficiencies). On the other hand a dynamic glazed façade (M and D cases) could reduce the cooling energy demand up to 97%, but increasing the energy needed for lighting proportionally to the dynamicity of the façade. In the M case the heating energy demand is not significantly reduced compared to the Y case, but there is significant drop between the M and the D case. This is only partially due to the relative increase in the lighting energy demand, but mainly related to the capability of the adaptive glazing to maximize the amount of solar radiation admitted in the indoor environment. As a result, a responsive glazing in this climate could eliminate the cooling loads, to the detriment of saving in lighting energy demand, whilst maximizing at the same time the amount of solar energy admitted through the glazing to balance heating loads.

London shows similar trends to those observed in Helsinki, in terms of differences between the four orientations, and the trends of energy saving for heating, cooling and lighting. In this case however, the relative energy saving achieved with an adaptive glazing is higher due to the fact that the outdoor climatic conditions are closer to the indoor comfort conditions. For the North façade, the improvements in energy demand of a monthly adaptive glazing compared to the Y façade are negligible (2%), while higher energy saving (10–12%) can be achieved for other orientations. When a façade with a shorter modulation time is employed (D), 15–24% energy saving can be achieved compared to the best ideal static façade Y. This constitutes an additional 13–14% energy saving when compared to a façade with monthly adaptiveness. By changing the thermo-optical properties of the glazing the reduction of the cooling loads are significant, in fact they are decreased by more than 90%, while the increased energy use for lighting is inversely proportional to the modulation time.

The Rome case study shows the highest potential energy savings of the three climates, both in relative and absolute terms. In particular the relative energy saving due to the adoption of a monthly adaptive façade is nearly twice that of other climates. Moreover case D shows the highest decrease in energy use (up to 25–30%) compared to case Y. The main reasons are that an adaptive façade is more effective in decreasing cooling energy demand, which is more prevalent in hotter climates and that the outdoor climate conditions are closer to the indoor comfort range throughout the year. It is also evident that seasonal/monthly adaptiveness is more effective in hotter climates than in colder ones, while more modest improvements are achieved by reducing modulation time from monthly to daily, compared to colder climates.

Apart from the performance in individual climates and orientations, some general considerations can be drawn from these results:

(1) The energy saving potential is inversely proportional to the modulation time: on the average a 10% reduction could be achieved by an ideal monthly adaptive glazed façade, while a further 10–15% could be saved by a daily adaptive one. Both heating and cooling energy demands could be reduced by reducing the modulation time, even though the energy for lighting is always increased compared to case Y. The latter trend may be reversed if the adaptive glazing is integrated with a faster reactive lighting system (continuous dimming) with higher luminous efficacy (thus lower power density), such as a LED system.

(2) The difference in the energy saving potential of adaptive façade with a lower modulation time for the North oriented office compared to the other orientations is indicative of the sensitivity of the total energy use of the office room to the solar radiation, and the ability of an adaptive glazing to moderate this effect. Moreover it is noticed that the decrease in the cooling energy demand is more pronounced when going from a yearly optimised glazing to a monthly adaptive one, rather than from a monthly to a daily adaptive glazing. Opposite trends can be observed for the heating energy demand.

(3) Both the daily (D) and monthly (M) optimal adaptive glazed facades can simultaneously reduce the annual heating and cooling energy demand. In contrast, the optimal static glazed façade (Y) can only reduce either the heating or cooling energy demand. This is due to the fact that a static optimised façade is not able to respond to contrasting requirements throughout the year, i.e. admitting solar gains in winter and rejecting them in summer.

(4) The energy saving potential of adaptive glazing is sensitive to the climate. The highest energy saving is observed in temperate climates (Rome) where the difference between the outdoor climate conditions and the human comfort range is smaller and in which there is a larger winter/summer climate variation. In fact the largest effect of adopting an ideal adaptive glazing is that the energy demand for cooling is almost eliminated in all the climates and consistently reduced in the cooling dominated climate of Rome. This result could be even more important in possible future climate scenarios, in which average temperatures as well as extreme climatic episodes (heat waves, climate variability) are expected to increase [43].

(5) The sensitivity of energy performance of the office buildings in respect to thermal inertia decreases with the modulation time of the thermo-optical properties of the adaptive facades. Comparing in Table 4 the South and South LI (low inertia) cases it is evident that the total energy use for R and Y case is more sensitive to thermal inertia than cases M and D. This is due to the fact that the heating and cooling energy use are a function of thermal inertia. As the energy use for cooling is the most sensitive to both thermal inertia and modulation time of thermo-optical properties, the difference between the two cases (higher and lower thermal inertia) could be reduced by a faster modulating façade.

5.2. Ideal adaptive glazing thermo-optical properties

The optimal properties (U-value, g-value and T_{vis}) of the ideal adaptive glazing in a south-orientated façade in Rome are represented in Fig. 5. Different cases are represented in a 3D space including: (a) Case D (small green data points), and their projections on the different planes (U-value – g-value small yellow data points, U-value – T_{vis} small blue data points, and g-value – T_{vis} small red data points); (b) Case M (white data points with white projections); (c) Case Y (large green data points with large coloured projections) and (d) Case R (black dot with grey projections). Results for all locations and orientations are not shown here for brevity, but they are available in the supplementary data. Fig. 5 is representative of the patterns noticeable for the adaptive glazing in other locations and orientations, even though the data points for the other colder climates are slightly shifted to higher g-values and T_{vis}, and there is a large frequency of low U-values. These differences are discussed in Section 5.3.

A common feature in all graph is the frequency of data points on the limits of the variable space X(t) = [U-value, g-value, T_{vis},], which reveals the importance of the boundaries of the optimisation search space. In fact a consistent grouping of data points can be noticed along the lower and upper boundaries of the U-value (0.2 W/m^2 K and 5.14 W/m^2 K), lower boundary of the g-value (0.01), lower and upper boundary of T_{vis} (0.01 and 0.98), upper boundary of the ratio T_{vis}/g-value (2.41). For example, T_{vis}/g-value limit can be seen in the red projection plan as a dashed line with a slope of 2.41. Fig. 5 therefore suggests that: (1) it is important
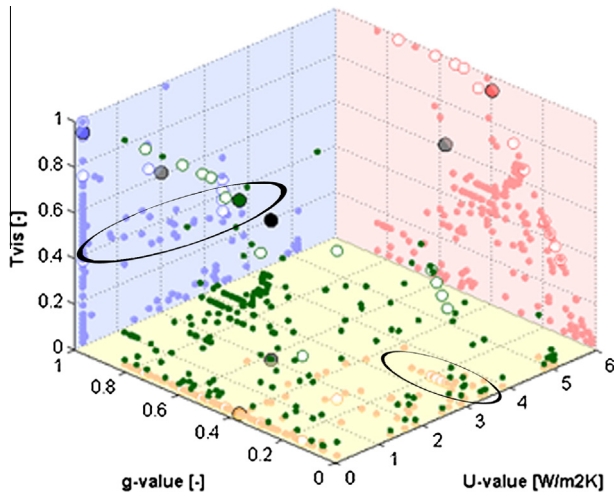
Fig. 5. Ideal adaptive façade thermo-optical properties (reference: grey big dot; Yearly: green big dot; monthly: white dots; Min: green small dots) and their projections for Rome ideal glazed façade South oriented. Dashed circles represent concentrations of optimal solutions in certain areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to determine the correct boundaries of the search space as the solutions are likely to lie very close to them; (2) a larger modulation range of adaptive properties (ΔT_{vis}, Δg-value and ΔU-value) would result in more significant energy savings.

The solution space is not randomly populated and certain patterns in the solution space can be identified (Fig. 5, black circles). In particular: higher *U-values* correspond to lower *g-values* and higher T_{vis}/g-value ratios, higher T_{vis} and *g-values* correspond to lower *U-values*. This behaviour indicates that the three properties are varying synergistically to minimize the energy demand. These patterns are generally grouped in response to seasonal climatic variations and the orientation of the façade, even if some outliers are present.

Fig. 6 shows that each monthly adaptive ideal glazing property (larger data points) correspond to the most frequent daily solutions (smaller data points) in the corresponding month. Some examples can be seen in Fig. 6: in the heating season (Fig. 6, January) the optimal *U-value* is always constant and equal to 0.2 W/m² K, while the T_{vis} and *g-value* are highly variable, but their ratio is always lower than 1.00; in the cooling season (Fig. 6, July) the ratio T_{vis}/g-value is constant and equal to 2.41, while the *U-value* varies between higher values (0.2 –4.00 W/m² K for London, and

2.00 –5.14 W/m² K for Rome), moreover its variability is very sensitive to the variation of *g-value* and T_{vis}; in the mid-season (Fig. 6, April) the highest variation of T_{vis} and *g-value* is registered, with K_e spanning from 0.1 to 2.41.

Even with such a high variability of the solution along the year, some clusters of solutions along certain intervals emerge. This indicates that although it may be difficult to accomplish all the data points with a single technology, it may be possible to devise simpler technological solutions (or simpler controls) that can switch thermo-optical properties between discrete states.

Fig. 2 indicates that existing smart glazing technologies have a limited modulation range of K_e, but Fig. 5 suggests that the optimal solutions require a large range of K_e. During the heating season values between 0.1 and 1 are more frequent, in the cooling season a state close to the physical limit of 2.41 is generally preferable, while in the mid season the highest variability (1–2.41) is required. The requirements for modulation of the spectral selectivity according to the season indicates that the ideal adaptive glazing technology is required to switch its spectral selectivity from one part of the solar spectrum to the other. In particular the optimal technological solution should be able to independently modulate the visible and the infrared part of the solar spectrum. Recent research by Llordes et al. [44] has shown that it is possible to achieve such a spectral selectivity modulation in a unique EC technology, that is able to independently modulate the infra-red and visible part of the solar spectrum, when an external electrical current is applied. This modulation could also be achieved by means of a combination of different EC technologies, such as coupling EC [15] with infrared EC [45–47].

5.3. Frequency analysis of ideal thermo-optical characteristics

The afore-mentioned clustering of points could reduce the complexity of optimal adaptive glazing technologies and their control strategy. It is therefore pertinent to perform a frequency analysis of the solution space for the daily ideal adaptive glazing *D*. This is carried out to understand: (1) the most frequent intervals/values for each adaptive property and (2) the intervals/values for each thermo-optical property in the *D* case, which makes the largest contribution to reducing energy demand with respect to the yearly optimised static solution, *Y*. This analysis could be useful to establish the frequency distribution of each single adaptive property in its domain of variability, thereby establishing whether technologies with the same ability to modulate a specific thermo-optical property could be effective in different orientations and in different climates, and whether discrete values of thermo-optical properties could effectively replace a continuous modulation range.
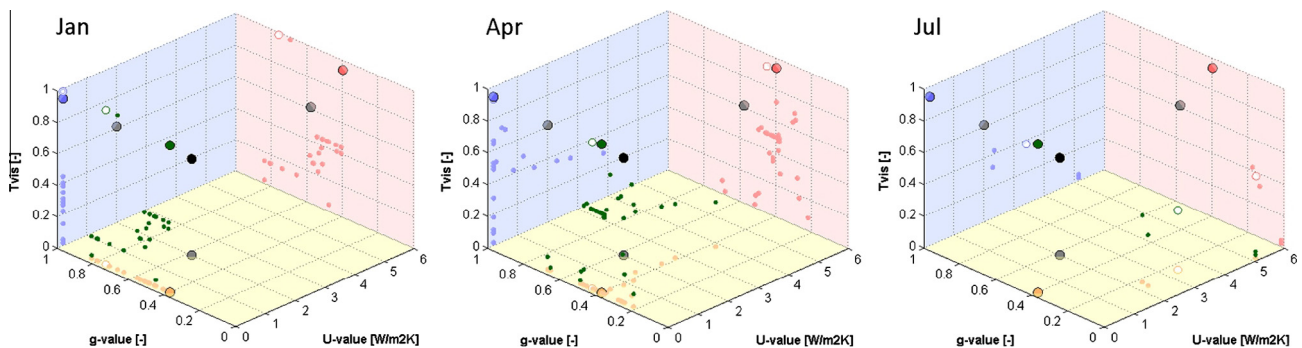

Fig. 6. Ideal adaptive façade thermo-optical properties (reference: grey big dot; yearly: green big dot; monthly: white dots; Min: green small dots) and their projections for Rome South oriented façade for: (a) January, (b) April and (c) July monthly period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In order to perform the frequency analysis two measures are defined:

- the cumulated time frequency *ctf* of each adaptive property X_i over the yearly period:

$$ctf_{X_i} = \frac{\int_{X_{i0}}^{X_{i0}+\Delta X_i} \frac{1}{t}\big|_{X_i-\delta<X_i<X_i+\delta}}{\int dt} \ (\%) \qquad (5)$$

that can range from 0% to 100% and indicates the proportion of time during the year (*t*) during which a certain property (X_i) lies within a certain interval of values;

- the performance frequency η_Y of each adaptive property X_i compared to the best static solution (*Y*):

$$f_{\eta_{X_i}} = \frac{Ep_{optY} - Ep_{idealadaptive}}{Ep_{optY}}\bigg|_{X_i-\delta\le X_i\le X_i+\delta}\bigg|_t \ (\%) \qquad (6)$$

that ranges from 0% to 100% and defines the energy saved by varying each adaptive property X_i in a certain range compared to the static yearly optimised solution over the same period (*t*).

The integral (yearly) values of η_Y for each property corresponds to the difference between the total energy saving potential (ES) of the daily ideal adaptive glazing (*D*) and the yearly optimised solution (*Y*) in Table 5.

The values of the *ctf* and of the η_Y of each adaptive property X_i are shown in Figs. 7 and 8. Fig. 7 shows the results for different climates (Helsinki, London and Rome) for the south oriented façade (darker lines), for the office room with high and low inertia (LI, with lighter colour lines). Fig. 8 shows results for different orientations (North, East, South, West) in Rome, and the results for the low inertia South oriented office (black lines). The four graphs for each figure present the results for (a) *U-value*, (b) K_e, (c) T_{vis}, and (d) *g-value*, respectively. The slope of the *ctf* profiles indicates that the relevant property under analysis has a higher frequency in that corresponding interval, while peaks of η_Y indicate the percentage of energy saved when the corresponding property lies within a certain interval of values. The dashed vertical lines represent the values of the corresponding property in case *Y*.

From this analysis the following observation can be made:

(1) *U-value* (Figs. 7a and 8a): in colder climates (Helsinki and London) the *U-value* is equal to its lower boundary (0.2 W/m² K) for at least 80% of the time. While for a hotter climate like Rome the *U-value* is at its lower limit for 50% of the time, but for more than 30% of the remaining time it lies on the upper limit of 5.14 W/m² K (Fig. 7a). Therefore for heating dominated climates modulating the *U-value* of the glazing is less effective than modulating other thermo-optical properties, whereas it could be much more effective to do so in hotter climates, where the modulation range needs to be maximized. The performance frequency η_Y for colder climates shows that the highest amount of energy saving, compared to the case *Y*, is saved when the *U-value* is equal to 0.2 W/m² K, and it is due to a change in optical properties (T_{vis} and *g-value*). For the Rome case instead two peaks are present in the η_Y, one at 0.2 with nearly 10% of energy saved and other at 5.14 with more than 25% energy saving. The η_Y for colder climates shows similar peaks to those in Rome, meaning that most of the energy can be saved when the *U-value* assumes few discrete values. Considering the same climate but different orientations the same pattern can be observed (Fig. 8a): two peaks for η_Y around the lower and upper boundary are present together with two to three peaks, depending on the orientation, along the modulation range. The values at which these frequency peaks occur seem to be independent of the orientation or climate.

(2) K_e (Figs. 7b and 8b): different climates present different peaks in terms of how much energy can be saved in each interval, but the most effective intervals are not sensitive to the climate (Fig. 7b). In particular for colder climates a lower peak at 0.25 is present. This represents a technology that is able to transfer part of the solar energy from the visible to the infrared part. For hotter climates the effectiveness of the spectral selectivity is decreased for lower values of K_e and increased for values closer to the physical limit, therefore when these values (2.41) occur, only visible radiation is transmitted through the glazing. These two peaks occur in different climates. Another effective interval is in the region of 1.00. These peaks are also present at different orientations (Fig. 8b), although the effectiveness depends on the orientation. Another important common feature for different climates and orientations is the requirement to modulate the visible and infra-red part of the solar spectrum independently in order to minimize the energy demand, as previously noted.

(3) T_{vis} (Figs. 7c and 8c): for all climates and orientations the most effective values are between 0.1 and 0.2 with 5%, 20% and 30% of energy saved in Helsinki, London and Rome respectively (Fig. 7c). The interval extends to values of 0.5–0.6 with up to 10% additional energy saved if a hotter climate is considered. All the yearly optimised values tend to maximize the solar energy transmitted in the visible spectrum in order to reduce the lighting energy demand, an ideal daily adaptive glazing tends to minimize the energy use for cooling. Therefore the effective modulation range of T_{vis} for a daily adaptive glazing can be reduced to an interval between 0.01 and 0.5, regardless of the climate and orientation (Fig. 8c). There is a relatively small amount of energy that could be saved by extending the modulation beyond this range.

(4) *g-value* (Figs. 7d and 8d): in contrast to the modulation of the visible transmission, the most frequent (and most effective) *g-values* are close to both the lower and higher boundary (i.e. close 0.1–0.2 for all the climates and with a further value higher than 0.7 for colder climates only). In Rome (Fig. 8d) the *ctf* and the η_Y are independent from the orientation and the modulation range can be effectively reduced in a similar way to that suggested fot T_{vis} above. This could be achieved with a glazing that is able to modulate the solar radiation in the infrared spectrum only [45–47].

(5) The ideal thermo-optical properties of the adaptive glazing are not affected by the thermal inertia of the office building. Comparing the frequency analysis in terms of *ctf* the difference between the high and low inertia reference office room is negligible and the same solutions are found in the optimisation for the same days of the year. Small differences are found in the magnitude of the peaks of η_Y indicating that although the energy saving potential of the *D* case compared to the *Y* varies for lower thermal inertia building, the optimal solution in terms of ideal thermo-optical properties does not change. Therefore these results could potentially be extended to buildings with different thermal inertia.

6. Discussion

The results presented in this paper constitute the upper limit of the performance achievable by a monthly and daily adaptive glazed façade for commercial buildings. The term ideal or optimal, in fact, stands for an ideal range of variability, whose limits
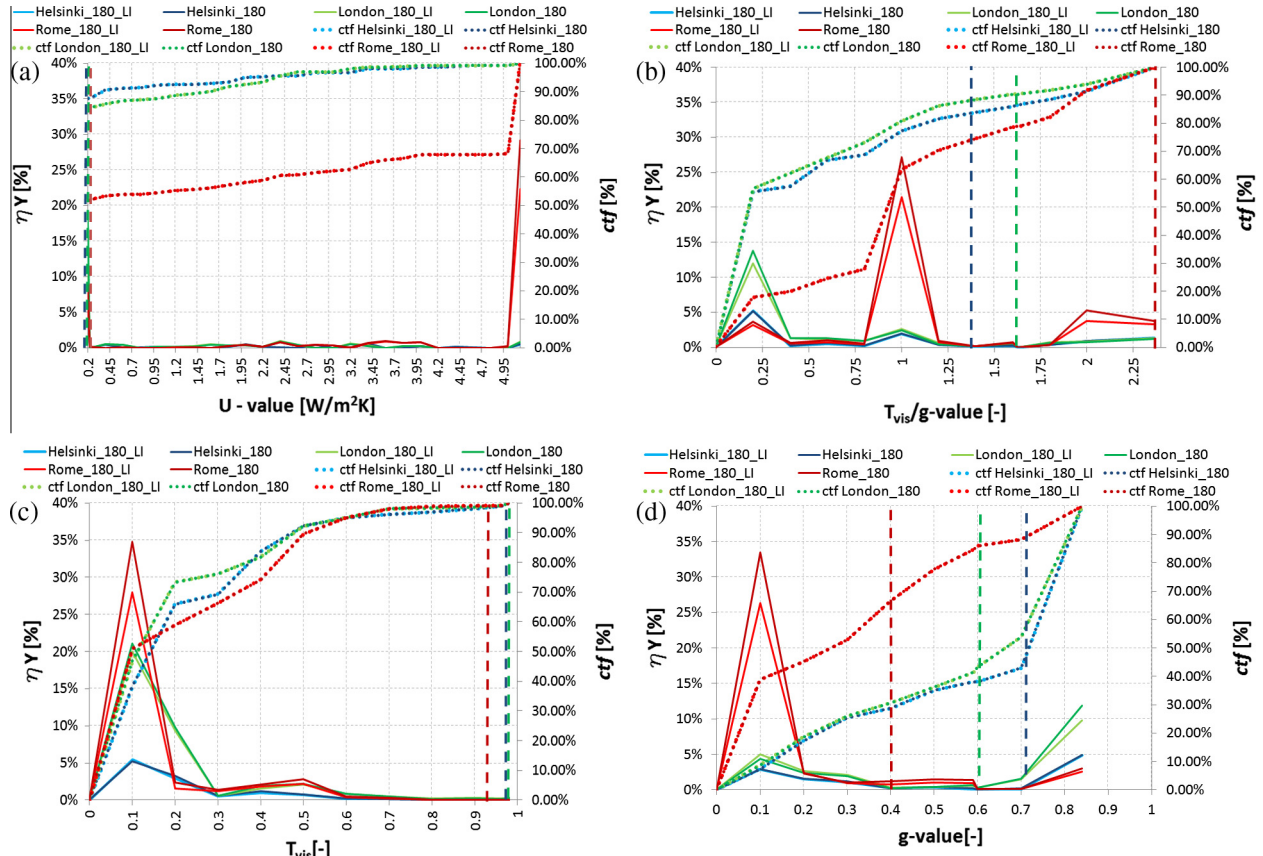
Fig. 7. Frequency analysis for South oriented ideal adaptive glazing properties: (a) *U-value*, (b) *T_vis/g-value*, (c) *T_vis* and (d) *g-value*.
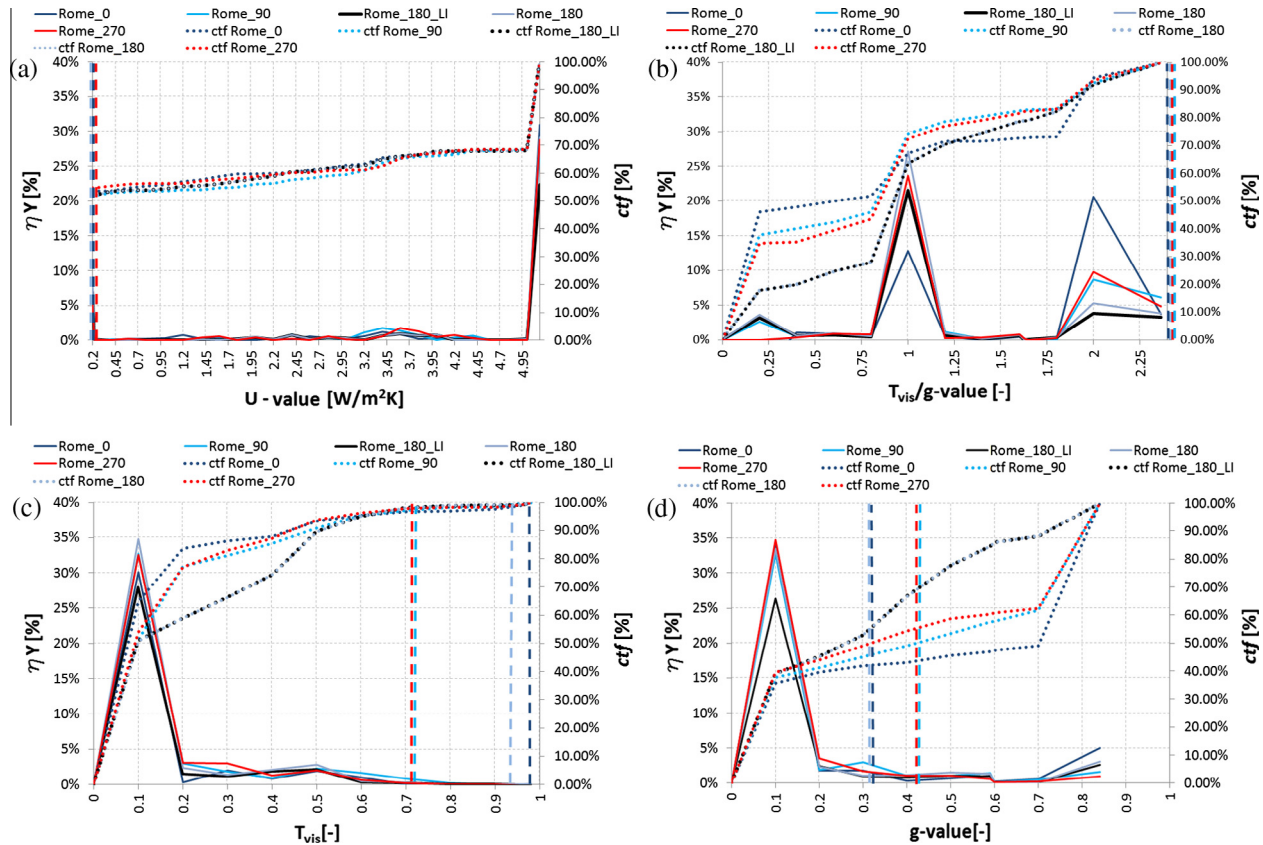

Fig. 8. Frequency analysis for Rome ideal adaptive glazing properties: (a) *U-value*, (b) *T_vis/g-value*, (c) *T_vis* and (d) *g-value*.

were derived theoretically. The limits are physically achievable, although the appropriate glazing products have yet to be developed.

Important considerations can be drown from these results concerning the operational energy saving potential of adaptive glazing, the features required to achieve this saving and the most effective modulation ranges of the thermo-optical properties.

In particular it was found that in colder climates, like London and Helsinki, a significant reduction in operational energy can be achieved by modulating the optical properties on a daily basis when compared to a monthly modulation. Furthermore modulating the *U-value* of the glazing in these climates yields limited energy savings. While in hotter climates, such as Rome, larger energy savings are achievable, due to the capability of reducing the cooling energy demand by means of a seasonal and daily adaptive glazing. In particular, a step-change in energy saving is achieved when adopting a monthly adaptive glazing in lieu of a static glazing. Moreover adaptive glazing appears to have a high potential in mitigating the effects of future climate scenarios, as they are able to reduce cooling demands, more effectively than heating energy use.

From a technological point of view, the desirable features for future generations adaptive glazing in terms of energy saving are: (a) providing the largest possible modulation range in *U-values* particularly for hotter climates; (b) independently modulating the transmission of the glazing in the visible and the infrared portion of the solar spectrum; (c) providing a higher luminous efficacy K_e closer to its theoretical limit; (d) the modulation range of the visible transmission and the total solar transmission do not need to be extended to the entire physically feasible range, but can be limited to an upper bound of 0.5–0.6; (e) the ideal thermo-optical states of the adaptive glazing could be reduced to a few discrete states in order to reduce the technological complexity of the solution and of the control strategy, but the effectiveness of this possibility needs further investigation. Moreover the optimal thermo-optical properties of the adaptive façade calculated with the present method are not affected by the thermal inertia of the building. Even tough the effectiveness of an adaptive façade is sensitive to the thermal inertia of the building, but this sensitivity reduces with the modulation time of the adaptive façade.

On this basis by analysing the data from different climates and orientations, it is possible to develop a single glazing technology or system that can accommodate the performance characteristics and the level of adaptiveness of different climates, orientations and buildings.

7. Conclusions

Adaptive building façades are considered a significant step towards the improvement of the energy efficiency of buildings and the achievement of nZEB objectives. This study proposed a method to identify the performance of a monthly and daily ideal adaptive glazing by means of an inverse approach, which makes use of the minimization of the total energy demand of the building. The method/tool accommodates different time-scales of the adaptive mechanism and can implement physical constraints, as for the thermo-optical properties of the glazing. This method is subsequently used to quantify the potential reduction in energy use of an office room that could be achieved by means of an ideal adaptive glazing and to identify the performance characteristics of the best performing adaptive glazing. This is done by applying the inverse approach to a typical office, with 40% WWR, located in three different climatic locations and with four different cardinal orientations.

It was shown that the energy saving potential is proportional to the modulation speed of the glazed façade. The magnitude of the achievable energy savings is sensitive to the climate and orientation of the room/building, but the most effective modulation ranges and values of thermo-optical properties of the optimal adaptive glazing appear to be independent of the climate and the orientation. In general, the highest decrease in energy use is achieved in the cooling primary energy use of the building. From the analysis of the ideal range of thermo-optical properties it is found that common features can be identified at a technological level for an optimal adaptive glazing, showing that the same technology could be used in different climates, orientations and buildings with different thermal mass.

From a methodological point of view this work represents an investigation into the ideal properties of physically feasible adaptive glazing technologies in terms of energy saving potential. In doing so it provides a tool to assess the full energy saving potential of next generation smart glazing and to guide the product development of more innovative adaptive transparent façade technologies.

A limitation of this study is that indications of the ideal states of adaptive glazing technologies is determined by minimizing the total primary energy use in the building, regardless of any local discomfort that may arise (e.g. glare or asymmetry in radiant temperature). To this end the tool is being updated in order to take into account comfort constraints in the cost function, as well as multi-objective optimisation, in order to optimise the solution not only in terms of energy use, but also in terms of indoor environmental quality. Moreover the tool and these results are being extended to evaluate the effect of a faster modulation of thermo-optical properties (hourly and sub-hourly).

Acknowledgements

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.05.065.

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