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

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ABSTRACT

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.

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.