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New Possibilities of Sun and Glare Protection with a Structured Switchable Glazing

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Glazing units used for architectural applications have an enormous potential for optimization. Currently, daylight management as well as solar and shading control can be provided only through a combination of various individual elements, such as glass panes, venetian blinds and additional glare protection elements. This combination of several separate elements not only leads to a higher consumption of resources, as well as higher production costs. It also entails additional maintenance costs. In order to overcome these shortcomings, the authors have developed a switchable glazing unit with adjustable light and energy transmission properties. This unit uses an anisotropic liquid. The functional component consists of a liquid crystal layer enclosed between two coated glass substrates, thus it is an integral part of the glazing unit. Due to the structure of the conductive layer, it is possible to subdivide the glazing unit into small areas (so-called pixels) that can be switched individually. The transparency of each pixel can be controlled independently. The glazing unit itself can be used as an effective daylight and shading control. This integral approach opens the door for new architectural applications. The authors currently focus their research on the development and tests for control strategies of the switching process itself. These control strategies are numerically validated and then tested at the ILEK façade test facility. The paper presents the first results of a performance analysis based on numerical simulations.

Keywords: Switchable glazing, adaptive glazing, liquid crystals, control strategies, building simulation

1. Motivation

Efficient sun and glare protection is crucial for the thermal and visual comfort of building users. Adequate daylight availability is equally important for user comfort. The fulfillment of these three requirements has always been a challenge for façade designers, but with the wide spread of high-rise and highly glazed buildings the challenge has become even more demanding. With the rise of the ecological awareness among architects and stakeholders, another function of the building façade has become crucial: the façade now also has to contribute towards minimizing the energy demand of a building. Conventional building envelopes fulfill these functions by the use of various separate elements, including sun protection systems, glazing units and glare protection elements.

A static or convertible mechanic sun protection is usually placed outside, in order to prevent the solar energy flux through the glazing. However, this solution is not appropriate for high-rises and for façades in regions of high wind velocities. Compromises like second-skin façades or energetically adverse internal sun protection are less effective or resource-consuming. Moreover, most sun and glare protection systems limit the view to the outside. These limitations often lead to a lack of acceptance by building users. The accumulation of multiple elements also leads to a rise of manufacturing and maintenance costs. Furthermore, it is hardly possible to optimize all the elements. Triggering of the sun protection system for its maximal efficiency can only occur at the expense of transparency. Not only does lack of transparency lead to a decrease in indoor comfort, but also to higher energy consumption due to artificial lighting. Higher transparency on the contrary may cause glare effects and lead to a rise in the energy demand for cooling.

As apparent from the description above, the design of many common building envelopes represents numerous compromises. They could be eliminated by using a multifunctional, structured adaptive glazing system with integrated sun and glare protection functions. Such a glazing system has been developed by the authors and will be presented in the following pages.

2. Structured switchable glazing: properties and implementation

The main component of the switchable glazing developed by the authors is a thin substructured switchable cell which is embedded in an insulating glazing unit. The unit can be either provided with its own control system or integrated into the building automation system.

The switchable element consists of a nematic liquid crystal layer which is held between two thin glass substrates and complemented with additional conductive and polarizing layers. It is based on a technology used for liquid crystal displays (LCD) (Collings 2002, Haase 2004, Chen 2011). Due to the characteristics of the liquid crystal used it is named twisted nematic cell (TN-cell). Through the application of a low voltage (~3-15 V) the rod-shaped liquid crystal molecules align according to the applied voltage and thereby control the transmission of light and energy. With the voltage application, the normally transparent cell can be switched dark. The transmission state of the cell is continuously variable within the switching range. Because of its high efficiency, the system consumes less than 1.5 W/m². Like liquid crystal displays, the TN-system exhibits very high switching speed. The change from the transparent to the dark state requires only a few milliseconds.

The polarization directions of the two applied polarisers are perpendicular to one another in order to allow for a maximum of transparency in the inactive state of the switchable cell. The authors tested both polarising coatings within the cell and polarising foils on the outer faces of the glass substrates (Haase et al. 2011, Haase et al. 2014, Haase and Husser 2014, Husser et al. 2014, Haase and Gültekin 2015). The present paper focuses on the system with external polarising foils. As in usual liquid crystal displays, conductive layers of the TN-cell can be structured in a laser or photolithographic process. In this process the cell is subdivided into pixels that can be switched individually. Every pixel is connected to the control unit via a transparent conductive path (transparent wiring) which generates a thin unswitchable gap between adjacent pixels. The cell layout presented in this paper features a gap width of approximately 1.6 mm and a pixel pitch of approximately 16.3 mm.

Due to the application of polarisers and the reflection and absorption effects of the glazing itself, TN-cells reach a maximal light transmittance of about 37 %, making it comparable to other sun protection glazing systems. Though, the pixel transmittance of the TN-cell can be varied down to approximately 1 %. This variability unfolds an additional potential in comparison with conventional glazing systems – it may allow the abandonment of external shading devices. The spectral transmittance of a single pixel of the TN-cell is shown in Fig. 1.

The influence of the pixel gap leads to an increased light transmission in the dark state of the entire TN-module. As mentioned, transparent wiring is needed between the pixels, therefore the equivalent minimum transmittance of the system increases slightly in dependence on the amount and the dimensions of the pixel gaps. The cell presented within this paper has an equivalent minimum light transmittance of approximately 5 %. The equivalent switching range of this substructured cell amounts to 32 %.

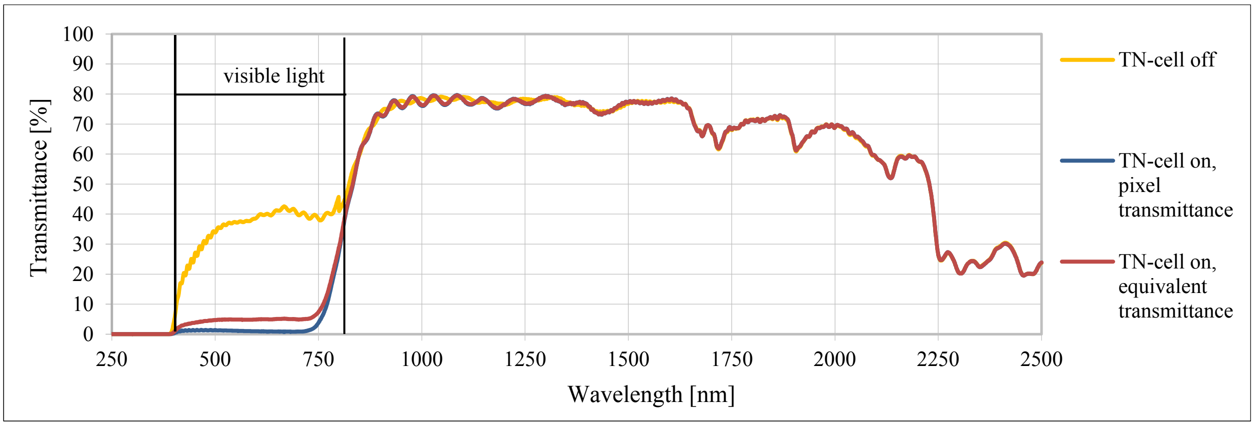


Fig. 1 Spectral transmittance of an unstructured TN-cell with external polarisers

The TN-cells are integrated into an insulating glazing unit (IGU), either in a lamination process with the outer pane of the IGU or with mechanical fixings between the inner and the outer pane. The glass panes can be additionally coated with low-e coatings as common in conventional IGUs, in order to improve the energy performance of the system. Four possible integration methods for the described TN-cell are shown in Fig. 2.

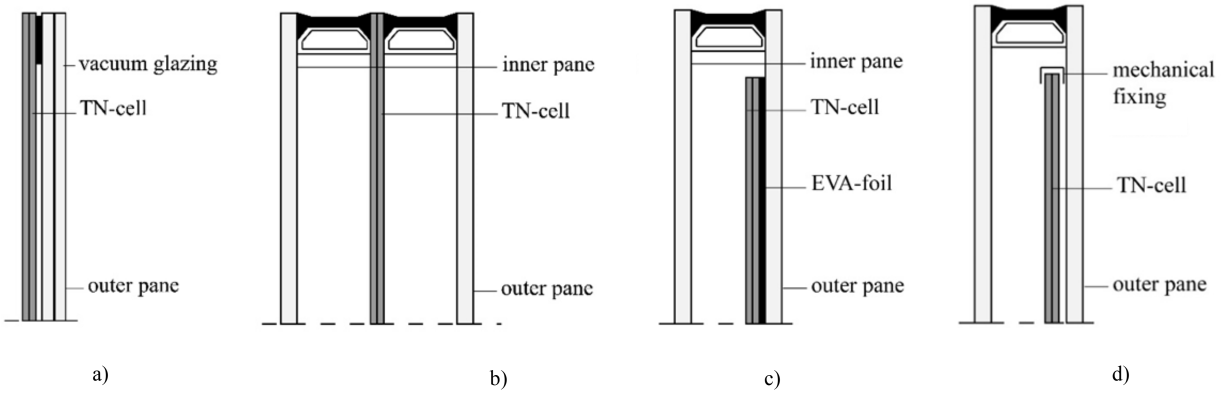


Fig. 2 Possible integration methods of TN-cells into insulating glazing units. Drawings: M. Husser, ILEK

The use of vacuum glazing (method a) can contribute to a significant reduction of the total thickness of the system, though it gives no protection to the switchable cell on the indoor side. Another option is to embed TN-cells into insulating glazing units (Fig. 2 b). As the second layer of a triple-IGU, the TN-cell is protected from outside influences, and manufacturing is less complex. A third method shown in Fig. 2 c allows an effective heat exchange between the absorbing TN-cell and the outside surface, therefore it is recommended by the authors (Haase et al. 2014, Haase and Husser 2014). For in situ tests, the authors modified this method and used flexible fixing elements in order to mount TN-cells onto the outer pane of the insulating glazing unit (method d) (Haase and Gültekin 2015). Method d was chosen for the analysed glazing.

The authors succeeded in manufacturing a prototype of the substructured switchable glazing and implementing it in a façade test facility, as shown in Fig. 3 (Haase and Gültekin 2015). The functional components were produced by the company BMG MIS GmbH Luminator Technology Group. The IGU-panes were delivered by Okalux GmbH. Due to the production constraints, the cell dimensions were limited to approximately 320 mm x 275 mm. Therefore the prototypic cells had to be arranged in multiple rows in order to cover a floor-to-ceiling glazing. Nevertheless, bigger cell dimensions are technologically possible as soon as the production equipment will be available.

The façade test facility, a two-storey timber building at the University of Stuttgart, includes four test rooms. Each of these rooms can be considered an independent office space (Haase and Husser 2013). The authors chose the following IGU for the tests: outer pane with a selective coating on position 2, 5 mm air gap with fixing elements for the switchable cells, 2.6 mm TN-cells, 40 mm air gap and the inner pane with a low-e-coating on position 5. In order to provide further comparability of test results, this glazing was the basis for numerical simulations that are presented in chapter 3.

Fig. 3 Prototype of the structured switchable glazing in a façade test facility.TN-cells partially darkened. Phot.: J. Rettig, ILEK

3. Performance simulations

3.1. Boundary conditions

An individual office consisting out of a light timber construction and a fully glazed south façade was simulated. The room dimensions were 2.00 m x 4.20 m x 2.70 m and the interior surfaces had similar properties to the wooden surfaces of the façade test facility (see Fig. 3). In the first step, the location in Stuttgart was considered in the simulation. Next, application proposals for other regions were made.

The city of Stuttgart is representative in South-West Germany for the transition climate. In this climate, an adaptive glazing system shows its most interesting potential. The extreme variability of the climatic conditions causes the need for adaptation of the glazing properties. During cooling dominated periods a relatively low transmittance of the glazing is expected in order to prevent solar gains. During heating dominated periods on the contrary, high solar gains and high light transmittance are desirable. On the other hand, especially due to the low solar altitude in winter, an effective shading is necessary to avoid glare effects. Due to the structuring of the presented TN-system it is possible to provide extremely low light and energy transmittance only in selected glazing areas, while providing high transmittance in the other areas.

The effectiveness of the switchable glazing system depends on its control strategy. Therefore the authors are currently developing strategies for different fields of application for the TN-glazing. The first strategy for office buildings will be presented hereby, as highly glazed office buildings and high-rises are considered to be the first vast application area for the presented adaptive glazing system.

3.2. Control strategy

Within the presented strategy the total glazing area was subdivided into a glare protection zone and a temperature control zone. The two zones can be controlled separately in order to fulfill different comfort requirements. Because of the substructuring of the glazing unit into individually controllable pixels, the desired zoning is easily possible (Haase et al. 2011, Husser et al. 2014).

The glare protection zone is as small as possible and its location and size depend on the number of people occupying the room. In an individual office with worker's view point at a distance of about 1 m from the façade, a façade area of up to approximately 0.25 m² is needed to prevent direct glare for this single person. According to the sun path calculation, the glare reduction zone is automatically placed at the intersection between direct sunbeams and the viewing direction of the office worker, as shown in Fig. 4.

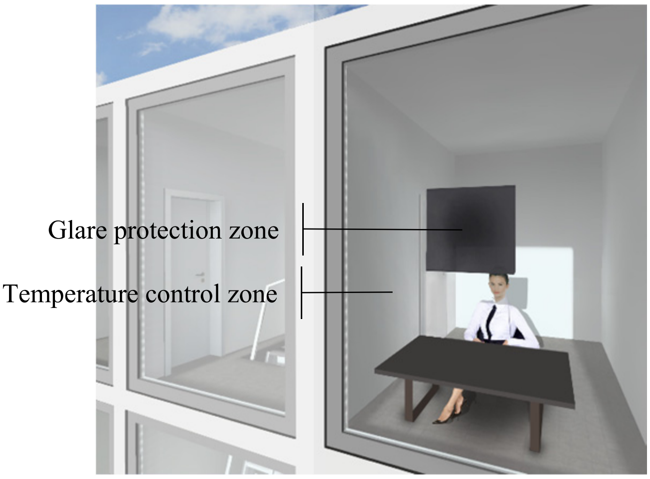


Fig. 4 Substructuring of the glazing area in separately controlled zones. Rendering: V. Kalaydzhieva, ILEK (Kalaydzhieva 2015)

The transmittance of the glare protection zone is controlled in order to prevent direct glare. Within numerical simulations the Daylight Glare Probability factor (DGP) according to Wienold and Christoffersen (Wienold and Christoffersen 2006) was used to detect the glare effect. The developers of the DGP formula defined a DGP value higher than 0.42 as a high probability for presence of a disturbing glare effect and DGP higher than 0.53 – for an intolerable glare effect, according to user assessments (Wienold 2009). Hence, if a glare effect is detected within the simulation, the transmittance of the glare protection zone is stepwise reduced till the DGP value is below 0.4. The authors used ten switching steps between the maximally dark and maximally transparent state of the glazing, what is considered a good compromise between simulation efforts and the continuous switching ability of the TN-system.

The remaining zone is controlled according to the indoor temperature within the human comfort range in order to reduce the cooling and heating energy demand. Between 20 °C and 26 °C the glazing is darkened stepwise, linked to the increasing room temperature. As soon as the indoor temperature reaches 26 °C, the cooling system has to be turned on. As soon as the temperature falls under 20 °C, the heating system provides the comfort temperature.

In this strategy, the used time schedule was kept very simple. The heating and cooling were not turned off during the user's absence, therefore additional energy savings can be expected in more advanced control strategies. Within the next development steps the control of the façade glazing will depend on the user's presence in the room. In situ, the presence can be determined with presence sensors and schedule assumptions have to be made within numerical simulations.

The presented strategy is relatively uncomplicated and was tested to enable the first evaluation of the system's potentials. The simulation method and its results will be presented below.

3.3. Simulation method

For the simulation of the TN-glazing system and its control process, an appropriate simulation tool had to be found. It became apparent, that the simulation tool had to be able to cope with several requirements that are untypical for common simulation profiles. First of all, the adaptive behavior of the system had to be interpreted. Moreover, the visual and thermal impacts of the system's variability had to be simultaneously analysed.

In order to interpret the adaptation process, the software tool TRNSYS (Transient System Simulation Program) 5.3.0.0 (What 2015) was chosen. According to Loonen (Loonen 2010), TRNSYS is the only tool among the three analysed tools which enables simulating adaptive behaviours of building systems. Also, according to the authors, it is one of the very few suitable simulation tools on the market. TRNSYS was originally developed in 1970's by Klein, Duffie and Beckmann for simulations of active solar systems (Gassel 1997). Thus, due to its modular structure, it is very extendable. Different building elements can be found in the library and are called as types. One of them, the TYPE 56 was used for modelling the single office room with a fully glazed south façade, as described in the chapter 3.1. The glazing system for the south façade was modelled with a software by Lawrence Berkeley National Laboratory, Optics 5.0 and Window 6.3 (Mitchell et al. 2013). These programs enable simulating glazing systems on the basis of spectral analysis of the glazing components. Subsequently, the glazing data can be exported into building models, e.g. TRNSYS-models.

Unfortunately, TRNSYS offers no possibility to simulate daylight conditions. Therefore additional software had to be used for the simulation of lighting aspects. A software combination of Radiance for Windows (Fuller 2015) and Daysim (Daysim 2015) was chosen. Radiance, developed by the Lawrence Berkeley National Laboratory, is a backward ray-tracing software which enables simulations of daylight performance metrics in consideration of the local climate and sun position. In order to accomplish annual lighting analyses, a Radiance-based software Daysim by Christoph Reinhart was used. This software aims at calculating dynamic, climate-based daylighting metrics over the year. Since 2010 Daysim is able to predict discomfort glare from daylight through the year by means of the daylight glare probability metric DGP (Daysim 2015). Moreover, it calculates the lighting energy needed for artificial lighting in the scene during the year. In the described simulation, the artificial lighting is switched on with the desired intensity as soon as the horizontal illumination on the workplane undercuts 500 lx within the working time between 8:00 a.m. and 5:00 p.m..

The needed building model for Radiance and Daysim can be imported either from Autodesk Ecotect Analysis (Autodesk 2015) or Google SketchUp (SketchUp 2015) that are both 3D-modelling programs. The climate data for simulation scenes was imported from EnergyPlus weather database (Weather 2013).

Provided with daylighting results from Daysim, the energy performance simulation of the adaptive system was undertaken in TRNSYS. The variability of glazing properties due to the switching process was achieved by means of varying the glass ID during the simulation. This method enables stepwise changes of the system properties.

The simulation method is illustrated in the following Fig. 5.

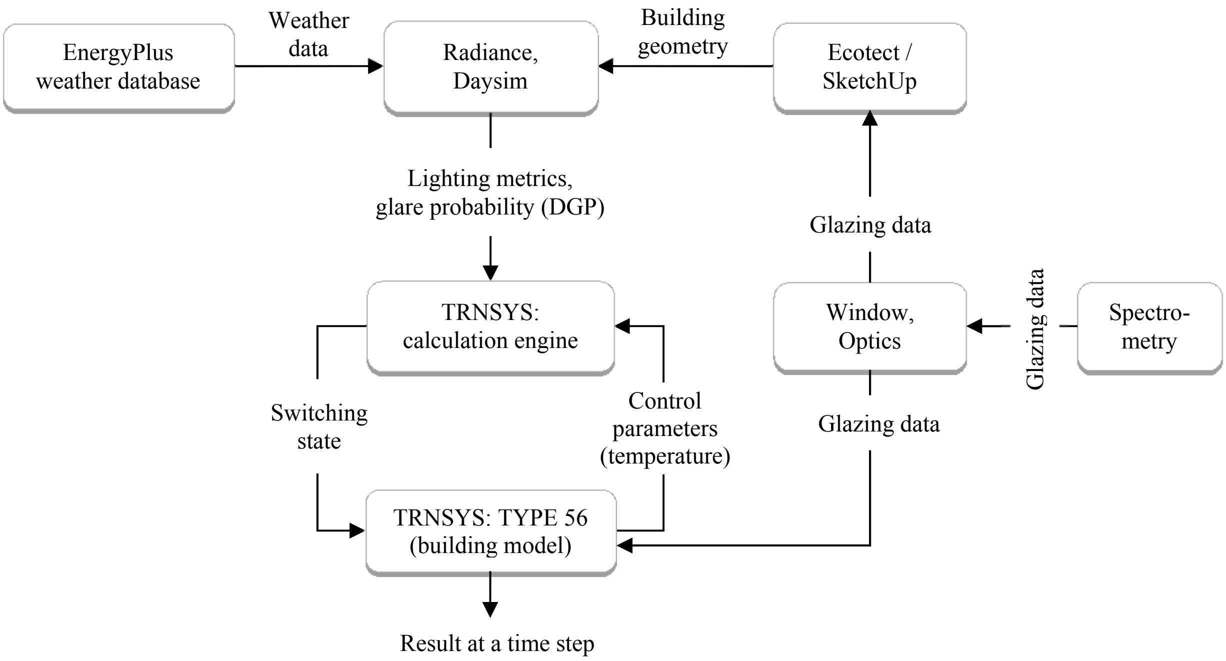


Fig. 5 Simulation method

3.4. *First results*

The authors simulated in the test office room the performance of the adaptive TN-glazing with the described control strategy. The energy performance of the chosen adaptive glazing was compared with two other glazing systems, as presented below:

A – reference glazing with a low-e coating:
6 mm white glass | 16 mm air gap | 4 mm white glass | 16 mm air gap | 6 mm white glass with a low-e coating on position 5

B – reference glazing with a low-e coating and venetian blinds:
venetian blinds | 6 mm white glass | 16 mm air gap | 4 mm white glass | 16 mm air gap | 6 mm white glass with a low-e coating on position 5

C – structured TN-glazing:
6 mm white glass with a selective coating on position 2 | 2.6 mm TN-cell, fixed on the outer pane with approx. 5 mm air gap | 41 mm air gap | 6 mm white glass with a low-e coating on position 5

The described glazing systems are schematically depicted in the following Fig. 6.

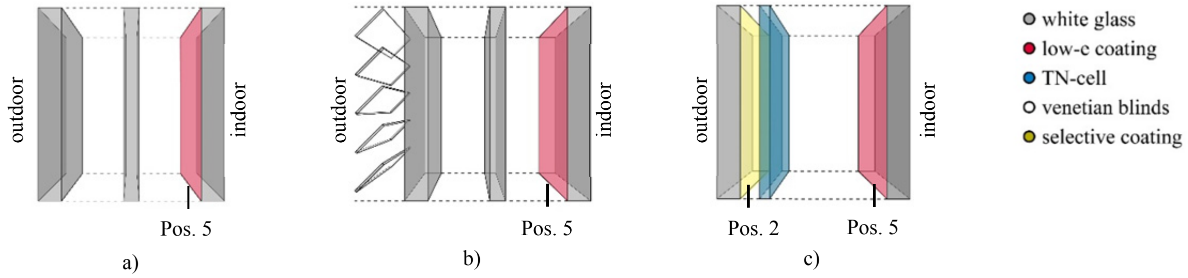
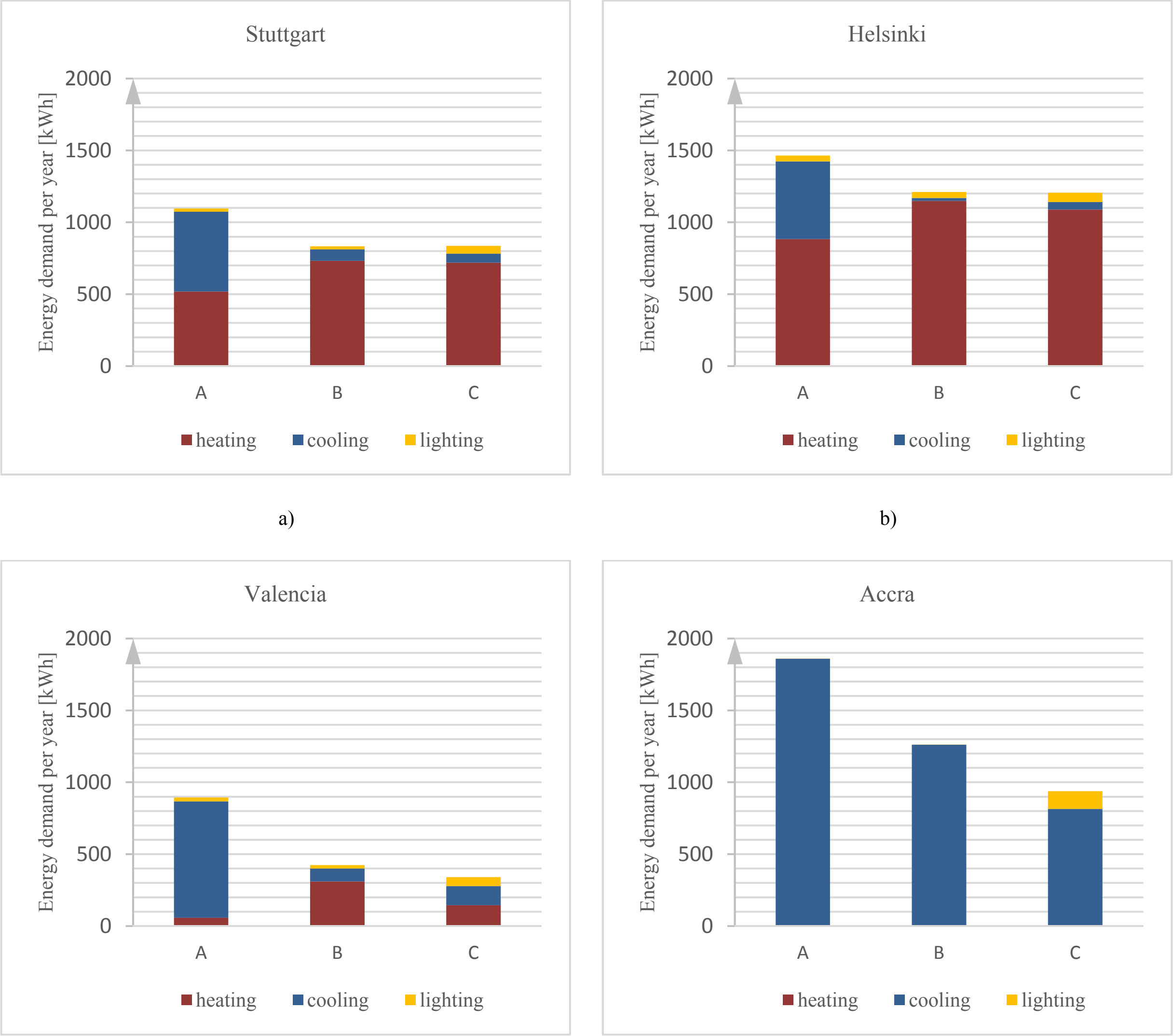


Fig. 6 Simulated glazing systems: a) glazing A, b) glazing B, c) glazing C. Drawings: D. Meurer, M. Husser, ILEK

The performances of those glazing systems were simulated over a period of one year. Additionally to Stuttgart (48° 46' N, 9° 10' O) in Germany, the performance in three other locations was analysed: Helsinki (60° 10′ N, 24° 56′ O) in Finland, Valencia (39° 29′ N, 0° 2′ W) in Spain, Accra (5° 03′ N, 0° 13′ W) in Ghana. The energy performance analysis is depicted in Fig. 7.



a)

b)

c)

d)

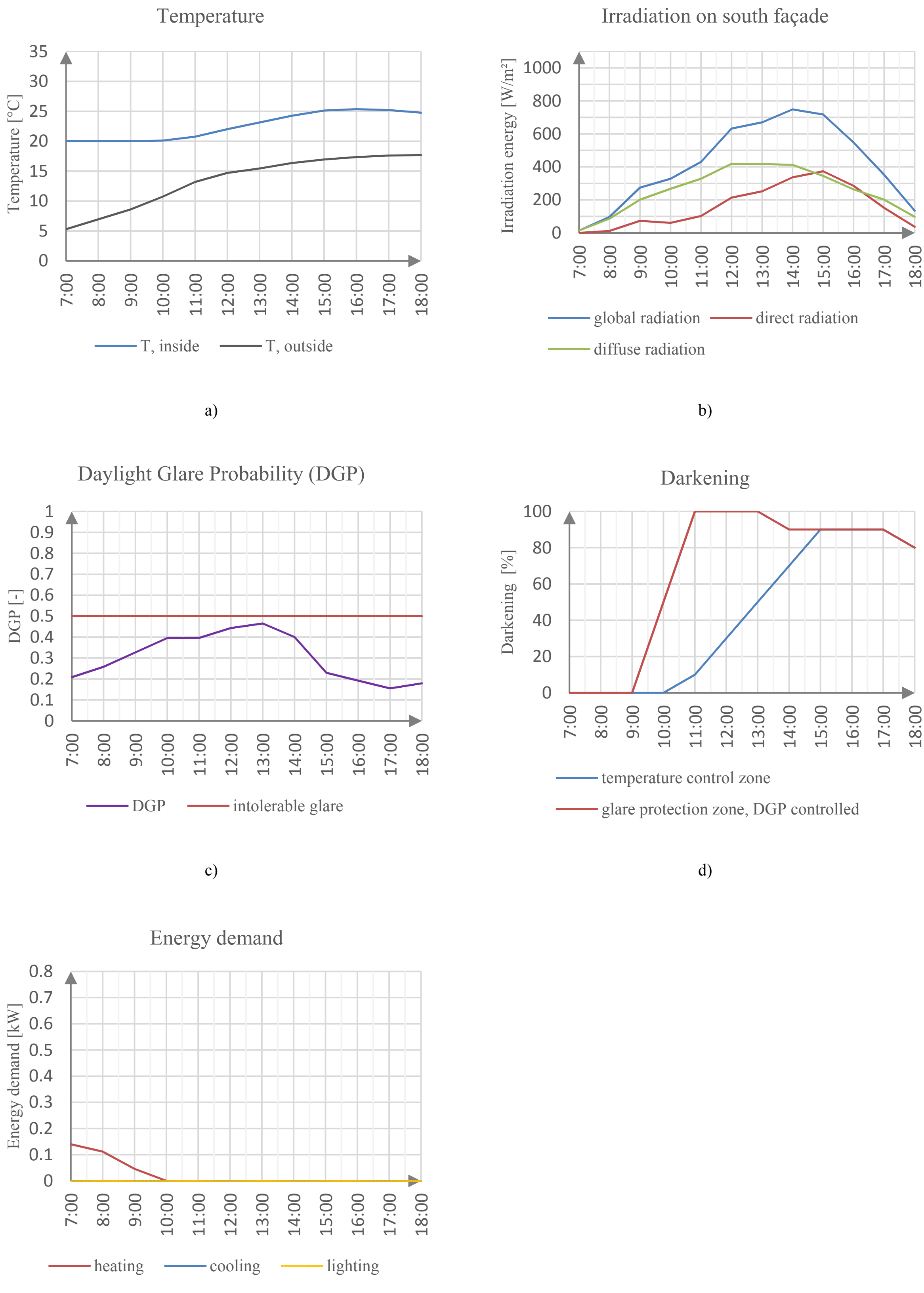
Fig. 7 Energy performance of a structured TN-glazing in comparison with reference glazing systems

The first simulation results already show reasonable potential of the substructured TN-glazing and the simplified control strategy. As far as the energy demand is concerned, the performance of the TN-glazing (IGU C) is comparable to the performance of a triple insulating glazing with an external sun shading device (IGU B). The energy demand for the shading device control was not included in the simulation.

In heating dominated regions, the heating demand of the room with a TN-glazing is slightly higher than in rooms with reference façades due to the used control strategy, but the cooling demand decreases. The cooling energy saving potential of the TN-glazing is even more apparent in hot climes, for example in Accra (see Fig. 7).

On the other hand, in warm regions, the artificial lighting demand increases slightly in the room with the TN-glazing because of the temperature based darkening of the predominant glazing area. Therefore, while the proposed control strategy shows high potentials for temperate and continental climes, less intensive darkening schemes should be taken into account in tropical and megathermal climes, in order to provide better daylighting conditions. Nevertheless, the TN-glazing has an important advantage over the conventional sun protection systems even in hot climes. Activated conventional systems usually lead to a view disruption, while applying the TN-glazing enables an unobstructed view to the outside even at high darkening states of the glazing.

As an example for the functionality of the presented structured glazing with the temperature and glare based controlling, a factor analysis for a changeable spring day in Stuttgart will be presented below (see Fig. 8). On that day the cloudiness and therefore the direct solar radiation varies, so that high flexibility of a shading system is demanded.



a)

b)

c)

d)

e)

Fig. 8 Factor analysis for a structured TN-glazing in the south façade of the test room in Stuttgart on 03 April (changeable spring day)

As apparent, because of low air temperatures in the early morning, a small amount of heating energy is needed to provide the minimal indoor temperature of 20 °C. During the day the switching process of the TN-glazing takes control of the thermal comfort in the room. The main window part is darkened stepwise with the increasing temperature. In order to prevent glare from high solar irradiation about noon the glare protection zone (DGP controlled window part) is activated. Thus, the efficiency of the TN-glazing and the presented control strategy is revealed in an effective glare reduction and a comfortable indoor temperature profile.

As shown in Fig. 7, the induced energy performance is highly promising as well. It is comparable to high performance glazing systems with mechanical sun protection, even if these are calculated without taking into account the additional energy demand for operating of these mechanical systems.

4. Architectural potentials

In comparison to conventional façade solutions, the switchable, substructured TN-glazing developed by the authors shows significant advantages. It is characterized by a large switching range and a very short switching time. The possibility of implementing the switchable glazing units in standard framing systems, combined with their minimal connection requirements makes the system perfect for being applied into new building façades as well as for retrofitting existing buildings.

As shown within the first simulations, the TN-glazing has the potential to replace conventional insulating glazing units with external shading. The integration of sun and glare protection functions, complemented with an effective controlling, leads to a remarkable comfort improvement. The glare is the main comfort factor which can be influenced by the implementation of the TN-glazing. Moreover, a slight reduction of the building's energy demand is expected. Additionally to the reduction of cooling energy demand, the reduction of embodied energy and of the resources consumption, compared with common façade solutions, are remarkable advantages of TN-glazing.

The rising social consciousness about contracting resources depots goes hand in hand with puristic esthetics in the architecture and in the product design. At this time a multifunctional façade becomes the answer to ecological and esthetical questions. Waiving of additive solutions leads to an architecture of simplified expression and complex functionality. Rethinking such architectural elements as the sun protection, the wall and the opening can possibly take place in the near future. The sun protection is no longer a secondary device which has to fill out strictly defined boundaries. The wall and the opening do not have to have defined boundaries either. The possibility of darkening any required areas of the glazing makes the façade flexible and changeable. The areas of light and energy transmission, glare protection and visual contact can be flexibly redefined in dependence on actual needs, as shown in Fig. 9.

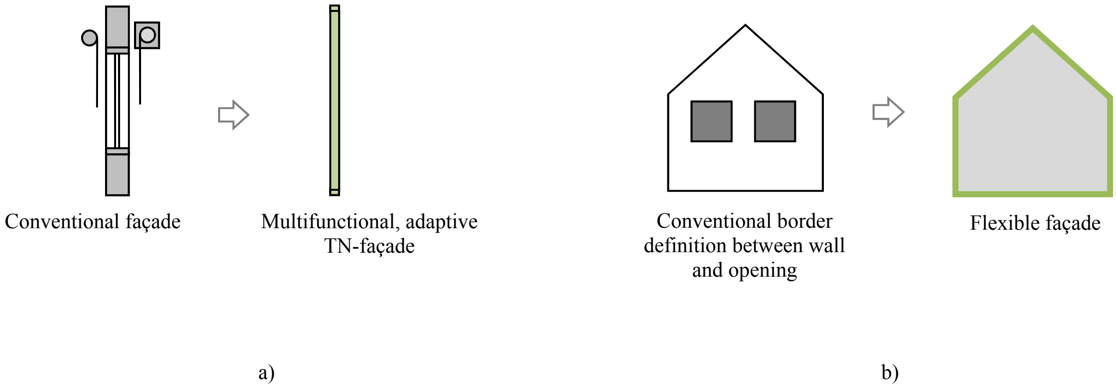


Fig. 9 Evolution aspects of the building façade. Drawings: M. Husser, ILEK

At night, in conjunction with interior lighting, the substructured façade can be used as a large-scale display to present images or messages. The following Fig. 10 illustrates several application possibilities of the structured adaptive glazing in a fully glazed façade. The depicted flexibility is only one example for the expected wide application field of this system.

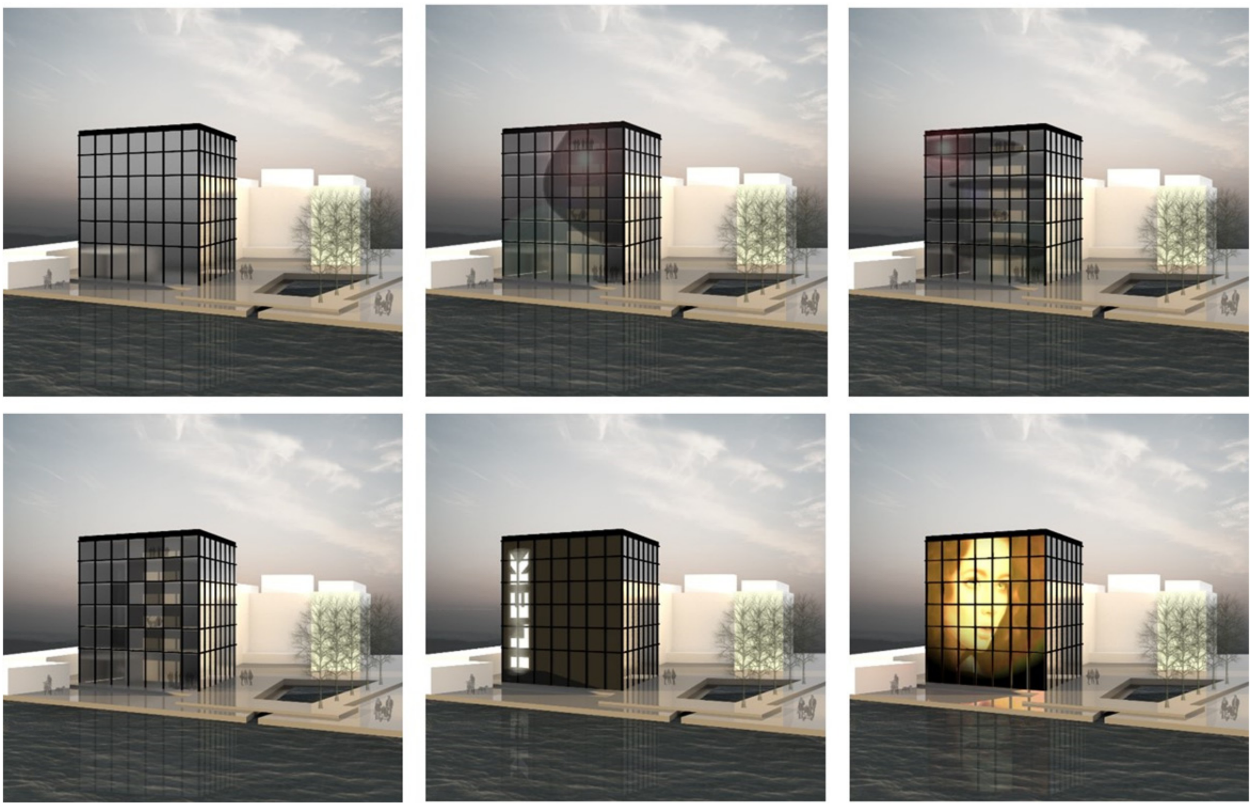


Fig. 10 Application possibilities of the structured adaptive glazing in a fully glazed façade. Renderings: S. Leistner, ILEK

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