Performance simulation of climate adaptive building shells - Smart Energy Glass as a case study

R.C.G.M. Loonen*, M. Trčka, D. Cóstola, J.L.M. Hensen

Unit Building Physics and Systems, Department of Architecture Building and Planning,
Eindhoven University of Technology, The Netherlands
Contact: r.c.g.m.loonen@tue.nl

ABSTRACT
As opposed to traditional building shells, climate adaptive building shells (CABS) do have the ability to change their properties and behavior over time. Provided they are designed and operated effectively, CABS offer the potential for energy savings without the need for compromising comfort levels. This paper explores the role that building performance simulation (BPS) can play in designing CABS. After analyzing the distinguishing characteristics of CABS, the need for BPS is introduced. The potential role of BPS is then illustrated via the case study of Smart Energy Glass. Based on a description of underlying physics, the model abstraction process is discussed first. This results in an integrated model for performance simulations that couples TRNSYS and DAYSIM. This model is empirically validated and subsequently used to evaluate the potential of Smart Energy Glass in a renovation case under various operational scenario’s. The paper concludes with some suggestions for future research and development of Smart Energy Glass.

Keywords: climate adaptive building shells, building performance simulation, smart energy glass

1. INTRODUCTION
Most people spend up to 90% of their time indoors (Bougdah and Sharples, 2010), which justifies our strive for buildings that are as safe, healthy and comfortable as possible. Historically, it has always been the building shell that provided shelter and protection against the negative influences caused by erratic external conditions. With the advent of artificial lighting and heating, ventilation and air conditioning (HVAC) systems in the twentieth century however, part of this important task has gradually been delegated to the building services. As a consequence, the building shell lost its role as moderator for energy and comfort, and it is nowadays more or less accepted that buildings pose a major load on our environment.

Motivated by the growing demand for ways to promote levels of sustainability in the building sector, it is worthwhile to reconsider the role of the building shell. Unlike only being a wrapper, the building shell can be entrusted with multiple functions that dictate the building’s energy consumption and perception of indoor environmental quality. Traditionally, most building shells are ‘static’, whereas the climatological boundary conditions and user’s preferences are constantly changing. As a result, traditional façades cannot adapt itself to the changes it is exposed to, and this results in a loss opportunity for both energy saving and increasing thermal and visual occupant comfort. Climate adaptive building shells (CABS) on the other hand consider the building shell in a fundamentally different way. CABS can
actively adapt their behavior over time in response to changing environmental conditions and performance requirements. As a result, application of CABS seizes the opportunity to again transform indoor spaces in ‘mediated’ rather than ‘manufactured’ environments.

CABS is only one designation for a concept that is described by a multitude of different terms, including: active, dynamic, kinetic, intelligent, responsive, smart, etc. Although all these expressions have a somewhat different meaning, they are often used interchangeably and in an ad hoc manner. In this study, the term CABS is adopted, and is defined as follows:

* A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell improves overall building performance in terms of primary energy consumption while maintaining acceptable indoor environmental quality.

The relevance of adaptivity in construction elements was also recognized by the recently completed international project, “Annex 44 - Integrating Environmentally Responsive Elements in Buildings” (Aschehoug and Andresen, 2008), carried out in the framework of the Energy Conservation in Buildings and Community Systems (ECBCS) Programme, of the International Energy Agency (IEA). IEA Annex 44 concluded that the development, application and implementation of responsive building elements is considered to be a necessary step towards further energy efficiency improvements in the built environment.

2. CHALLENGES IN DESIGN OF CLIMATE ADAPATIVE BUILDING SHELLS

The design of CABS is not always a straightforward task. CABS are typically complex systems, consisting of several interrelated components that are active across various physical domains. In this article, we focus on the four physical domains in Figure 1, hence, CABS can be classified in one of fifteen surfaces. Introduction of CABS moreover changes the traditional way in which buildings are designed; CABS are intrinsically dynamic, and therefore it requires the design of a ‘process’ rather than an ‘artifact’ (Moloney, 2007). By exploiting advances in material sciences, and due to the widespread availability of sensors and actuators, there are a large range of technological options for making the building shell adaptive (Ritter, 2007; Klooster, 2009; Schumacher et al., 2010). Thus far however, application of CABS in practice remains limited (Loonen, 2010a).

![Figure 1: The relevant physics of CABS can be classified according to one of the 15 surfaces in this graph.](image-url)
Before becoming mainstream, first some barriers that are rooted in the complex nature of CABS need to be bypassed. More than traditional building envelopes, design of CABS has to address (i) maintenance issues, (ii) the human aspects associated with dynamic behavior of the envelope, and (iii) how the new technology merges with the existing practices of the “conservative” building industry. Adding adaptive features to the building envelope does not directly guarantee successful operation. In order to achieve the desired goals, CABS have to respond to changing conditions in real-time and in an effective way. In addition, some kind of concerted activities have to take place; the various subsystems in the façade have to cooperate, together and with other building services, to resolve conflicts, handle trade-offs and satisfy performance requirements synergistically and in the best possible way.

In principle, most of these barriers and challenges can be traced back to a lack of awareness and fundamental understanding about CABS' performance. Consequently, there is a demand for effective tools and instruments that can provide increased insights in the design process of CABS. These tools should be able to quantify the performance of CABS, which in turn increases transparency about how performance benefits during operation might outweigh first cost arguments. In addition, these tools should be able to rationalize the uncertainty and associated risks that are introduced with the implementation of CABS.

In accomplishing the challenging task of designing CABS, it is no longer adequate to completely rely on past experience, rules of thumb or other traditional design tools (e.g. analytic calculations, empirical relationships, selection charts and nomograms). Using BPS on the other hand, makes it possible to predict why, how, and when a building will consume energy. BPS tools are able to map the dynamics between the building and its systems, the ambient environment and occupants; and consequently can predict building performance. Most state-of-the-art BPS tools have a history of gradual development and extension of capabilities. At the time these tools were created, software-developers had no incentive to implement adaptive behavior into building shell models. This inheritance is now the reason that the state-of-the-art in BPS lacks abundant capabilities for performance prediction of CABS. As opposed to the dynamics of boundary conditions, properties of the envelope are coded as constants that are fixed throughout the simulation in the majority of BPS applications. Nevertheless, a number of capabilities to simulate adaptive behavior is available (Loonen, 2010b), and fortunately, the tools are still amenable to continuous developments. Enhanced domain integration and incessant extension of capabilities will certainly improve the utility of model outcomes for CABS. Software developments also promote more flexibility which enables modelers to analyze systems that are ahead of technology rather than only having the opportunity to use predefined functionalities. In addition, the ever increasing computational power in addition favors shorter simulation periods which opens the door for consideration of more design and control alternatives.

3. SMART ENERGY GLASS

This paper explores the potential role that BPS can play in designing CABS by taking the innovative window technology Smart Energy Glass (SEG) as an illustrative case study. The working mechanism of SEG is based on a polymer coating that is placed between two layers of glass. These layers together form the external pane of an insulated glazing unit. By applying an external voltage to the coating, it is possible to control the optical properties of the window within less than a second. SEG can be switched into three different states: a bright state, a dark state and a translucent state. The polymer coating in SEG also acts as planar waveguide in the same way as a luminescent solar concentrator (LSC) (Goetzberger...
and Greube, 1977). The dye molecules absorb part of the incoming sunlight and re-emit photons in random direction at a longer wavelength. Via this mechanism, part of the incoming light is captured and redirected to the edges of the window where photovoltaic cells are situated to convert the collected radiation into electricity. The generated electricity is stored in a battery and used for switching the state of the window. SEG is thus an autonomous device, with no need for external wires, and is therefore especially attractive in renovation projects (Benson and Branz, 1995).

SEG is currently not a market-ready commercial product, but is still under development. Research and development activities currently focus on optimizing absorption and emission spectra, thermal performance of the window, optical losses, electrical circuits, stability and longevity of the dye, etc. The work presented in this paper complements and interacts with these activities by providing computational support for assisting the innovation processes.

3.1 Modeling Smart Energy Glass

3.1.1 Electrical model

In its most elementary form, SEG can be described and modeled as a LSC with tunable optical properties. The working mechanism of LSC’s basically consists of two parts: (a) collection and concentration of photons and (b) conversion of these photons into electricity. Figure 2 gives a schematic overview of the working mechanisms in SEG.

![Figure 2: Schematic overview of the physical phenomena taking place in SEG, with: (i) reflection, (ii) transmission, (iii) absorption, (iv) re-emission, and (v) internal reflection.](image)

Literature on LSC’s reports several computational methods for evaluation of electrical output (e.g. Chatten et al., 2003; Schüler et al., 2007; van Sark et al., 2008). These models are typically used for predicting photon trajectories and investigating loss mechanisms, and consequently, they are too detailed for the purpose of predicting building performance. In this study electrical output is modeled at a higher abstraction level, which better suits the research objective. The model is based on empirical knowledge obtained after conducting experiments. The experiments were set-up with the emphasis on elucidating SEG’s behavior under different light incident angles (Figure 3).
Tests were carried out on a SEG sample with an area of 5x5 cm$^2$, without PV cells. The sample was illuminated with a 300 W solar simulator equipped with filters to approximate the spectral make-up of the sun (AM 1.5 spectrum). The emission output coming from the edge was determined by placing one end of the sample adjacent to the entry port of an integrating sphere that was equipped with a spectral light measurement array to determine the spectral radiant power. Variation of angle of incidence was accomplished by rotating the sample’s supporting mechanism in the direction of the white arrow in Figure 3(b).

Based on the results of these experiments, electrical output can be predicted according to Equation (1),

$$P_{el} = P_{opt} \cdot \eta_{pv} = 4 \cdot I_{tot} \cdot A_f \cdot \cos(\theta) \cdot K_\theta \cdot \eta_{opt, \perp} \cdot \eta_{pv}$$

(1)

where $P_{el}$ is electrical output [W], $P_{opt}$ is optical output at one edge [W], $\eta_{pv}$ is photovoltaic conversion efficiency [-], $I_{tot}$ is incident solar radiation [W/m$^2$], $A_f$ is face area of the window [m$^2$] and $\theta$ is solar angle of incidence [$^\circ$]. Equation (1) further introduces $K_\theta$ and $\eta_{opt, \perp}$. The incidence angle modifier ($K_\theta$) is an empirical relationship, and characteristic property of SEG, that takes into account how electrical output decays as a function solar angle. The normal optical collection efficiency ($\eta_{opt, \perp}$) is different for each window state, but is independent of incident radiation intensity, and angle of incidence.

### 3.1.2 Optical and thermal model

The optical properties of SEG are altered by changing the global alignment of molecules in the dye. Characterization of these properties in bright and dark state was done for SEG samples in an experimental set-up with integrating sphere and spectrophotometer. Values for reflectance and transmittance were measured according to the protocols in ISO 9050 (2003). This data was then transformed into spectrally averaged properties with the aid of the software tool OPTICS, developed by Lawrence Berkeley National Laboratory (LBNL, 2010).

![Figure 4: Schematic representation of interlayer process in OPTICS.](image)
The software reads in measured data as ‘laminate interlayer construction’, where the SEG-layer is placed between two layers of glass with known properties (Figure 4). The algorithms in the tool (Rubin et al., 1998) then calculate the optical properties of this interlayer to yield the properties of the SEG coating only. Subsequently, OPTICS serves as ‘virtual glass laboratory’ because it allows this coating to be applied to an extensive number of glazing materials available in the international glazing database (IGDB). After constructing an appropriate fenestration system, the optical properties of the entire SEG window in terms of visible transmittance result as output. Thermal window properties were established in a subsequent step by using the complementary software tool WINDOW5 (LBNL, 2010).

4. PERFORMANCE PREDICTIONS OF SEG

4.1 Tool selection

In practice, a number of different BPS tools is being used for performance prediction in building design, with each tool having its own characteristics and possibilities (Crawley et al, 2008). Users of BPS ought to select the tool that best suits their needs and manage the job with the capabilities that tool offers. Selection of appropriate candidate tools for performance prediction of CABS has to consider at least the following four requirements:

- the adaptive features of the building shell;
- the way adaptive behavior is controlled (control stimuli);
- the applicable physical interactions introduced by this adaptivity;
- the desired (mix of) performance indicators at the appropriate level-of-detail.

The relevant physics of SEG fits in surface $O$ in Figure 1. This simulation requirement necessitates that thermal, optical and electrical models are interpreted simultaneously, and therefore confirms that a combination of stand-alone tools for each of the domains is inappropriate for the purpose. An analysis of candidate tools reveals that two programs can cope with integrated simulations of the thermal, optical and electrical domains: ESP-r and EnergyPlus. The possibility to change the window properties in three states during runtime is identified as prerequisite for successful simulation of SEG. TRNSYS (TRNSYS, 2010) appears to be the single tool that is able to aptly handle this adaptive behavior. Unfortunately, TRNSYS does not offer the possibility to predict the building’s daylighting performance (Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Adaptation</th>
<th>Thermal</th>
<th>Optical</th>
<th>Electrical</th>
</tr>
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<tbody>
<tr>
<td>ESP-r</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EnergyPlus</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
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</table>

The decision was made to use TRNSYS for performance prediction in the thermal and electrical domain, and to couple this model with the results of dynamic daylight simulations in DAYSIM (DAYSIM, 2010).

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4.2 Simulation strategy

Figure 5 shows a schematic representation of the simulation strategy that is used for performance predictions of SEG. Daylight simulations are first conducted in a preprocessing stage for all window states independently. DAYSIM calculates annual time-series of five-minute luminance and illuminance values at specific sensor-points. This data is then supplied to TRNSYS that ‘selects’ the right data during run-time corresponding to the controlled window state. Data is flowing across the three domains at every time-step and therefore data exchange is dynamic. The simulators in DAYSIM and TRNSYS are however invoked consecutively and therefore the workflow is sequential. This approach is justified by the short-term dynamics of daylight performance that does not suffer from ‘history effects’.

![Simulation strategy for the SEG model.](image)

The control component plays a central role in SEG’s simulation model as indicated in Figure 5. The crude output files from DAYSIM are first rearranged in a spreadsheet tool and then imported in TRNSYS via free format data readers in expert mode (TYPE 9e). Every time-step, this data is accessed by the control component which decides upon the right adaptive actions on the basis of an imposed control strategy. This control logic is implemented via equation-types containing conditional statements that compare model output (e.g. temperature, window luminance, workplane illuminance) to target values and return window ID for the next time-step as output. This window ID is passed on to the thermal and electrical model and used in the respective calculations for the next time-step. The window state, together with incident
radiation results in amount of collected radiation via the use of ‘equation-types’. This energy flux is then converted into electricity via a photovoltaic array model (TYPE 180).

The influence that SEG exerts on thermal performance of a zone or building is evaluated by using the TRNSYS multizone building model (TYPE 56). In the simulations, window properties are changed during run-time with a function called variable window ID. Environmental conditions are ensured to be identical to those subject to the daylight model by selecting the same weather file. Internal heat gains of the building depend on the state of the window since the amount of artificial lighting changes with daylight availability. Together with occupants’ presence, this data is imported from the data files pre-calculated by DAYSIM.

5. VALIDATION
Thus far, the performance of SEG has only been tested as small samples under the controlled conditions of a laboratory environment. Doing experiments in windows exposed to atmospheric conditions, is however indispensable for gaining more confidence in model assumptions. By comparing simulated results with the outcomes of an experiment, the SEG simulation model is empirically validated.

![Figure 6: Impression of the experimental set-up for the empirical validation study](image)

All measurements took place at the test façade facility on the campus of Eindhoven University of Technology (Figure 6). The orientation of this façade is west, no significant obstructions that block direct solar radiation are present. A SEG prototype, dimensions 35x40 cm², was used for the purpose of validation, and a test-box was installed to mimic the effects of an office zone behind the façade. This paper only presents the validation results for the electrical model.
Electrical performance of SEG was evaluated by monitoring the output voltage of the PV cells. To achieve this, the electrical circuit of PV cells was subdivided in four segments; one at each side of the window, and connected to fixed loads with a resistance of 1 kΩ. At the same time, environmental boundary conditions were recorded as well.

![Graph showing measured electrical output voltage and solar irradiance on a sunny day](image)

**Figure 7:** Measured electrical output voltage on a sunny day in [V] for the four edges of the window, together with measured solar irradiance on the façade in [W/m²].

The results of measurements for a sunny day are given in Figure 7. Results demonstrated that the electrical output is different at each side of the window. The model as described in Section 3.1 is based on the waveguiding effect only, and therefore assumes equal electrical output at all four sides. This assumption introduces significant underprediction of electrical output that is not negligible and therefore deems the initial model unacceptable. To overcome this deficiency, the electrical model was extended with a component that accounts for the radiation that directly falls onto the PV cells. The modified expression for electrical output is given in Equation (2),

\[
P_{el} = P_{el} + P_{direct}
\]

\[
P_{el} = 4 \cdot I_{tot} \cdot A_i \cdot \cos(\theta) \cdot K_{phi} \cdot \eta_{opt,i} \cdot \eta_{pv} + \sum_{j=1}^{4} (I_{dir,j} - I_{refl,j}) \cdot A_{pv,i} \cdot \eta_{pv}
\]

where, the first part of the equation is equal to Equation (1), \(I_{dir}\) is direct beam irradiance hitting the PV cell [W/m²], \(I_{refl}\) is reflected radiation at the interface [W/m²], \(A_{pv}\) is area of the PV cell [m²] and \(i\) represents the position of the PV cell in the frame. The expression includes a summation over the four edges, because the position that the PV cell occupies in the window frame - and thus its orientation and shading - determines the amount of received radiation. This effect is modeled in TRNSYS by obstructing the respective views to the sky via TYPE 34 shading components. Finally, the reflection component is introduced in the
model because a part of the radiation that would have hit the bare PV cells is lost in advance due to specular reflection at the external SEG window pane.

![Figure 8: Comparison between measured (solid) and simulated (dashed) output voltage on a sunny day.](image)

Figure 8 again shows the results for the same sunny day, but now in comparison with the simulation results of the modified electrical model. The PV cells facing downwards (top) and facing the north (left) do not receive any direct beam radiation and therefore the simulation results for these PV arrays, as displayed in Figure 8, are identical and similar to results of the initial model. It can be observed that the shapes of the simulated curves compare reasonably well to those measured. In addition, the relative magnitude of increments in output between the segments is also represented in the model. Given the relatively large amount of sources of uncertainty (e.g. temperature dependency, reflected radiation from the environment, losses in electrical circuits), the model predicts the actual electrical output with fairly good similarity. Therefore, the conclusion is made that the model is valid within the boundaries and purposes of this study.

6. CASE STUDY

6.1 Model set-up

SEG is a coating that can be applied to any glazing system. The technology is still under development and the performance of the dye continues to be improved. The SEG properties in this study were selected on the basis of a research prototype that takes into account issues of aesthetics, efficiency, UV-stability and homogeneity, but is only able to switch in the visible wavelength area.

The analysis in this study is restricted to a two-person south-facing perimeter office zone, situated at an intermediate floor, and is assumed to be surrounded by identical office spaces. These adiabatic boundary conditions were selected to ascertain that observed performance differences are effectively attributable to SEG. Storage of thermal energy in internal partitions is taken into account, and typical office equipment amounts to a heat load of 10 W/m². The
dimensions and geometry of the zone are given in Figure 9. The window-to-wall ratio of the south façade equals 35%.

![Figure 9: Schematic representation of the office room that is used in the simulations.](image)

Occupancy in the office room follows DAYSIM’s probability-based five day workweek-schedule with intermediate and lunch breaks. Artificial lighting (15 W/m² installed power) switches according to this same schedule and is continuously dimmable up to an indoor illuminance of 500 lx on the basis of the LIGHTSWITCH-2002 algorithms (Reinhart, 2004). Lighting control is triggered by a work plane photosensor at a distance of 1.8 m from the envelope. Thermal conditions in the zone are controlled on the basis of indoor air temperature, with setpoints for heating (20°C) and cooling (24°C) between 8 a.m. and 17 p.m., and a heating setpoint of 16°C outside working hours.

Identical weather files in EPW-format are supplied to both DAYSIM and TRNSYS. Stochastically generated short time-step (five minute) solar irradiance data files (Walkenhorst et al., 2000) are created once for every case, and are used for predicting daylighting performance.

Earlier simulation studies with electrochromic windows indicated that selection of the reference case can make or break feasibility of the entire concept (Lee and Tavil, 2007). Comparing to improper reference values can disguise the true potential of the technology and is on the other hand misused to manipulate stakeholders’ opinions. This study evaluates the potential to use SEG as window replacement in a renovation case. In these applications, the prospects of SEG’s adaptive behavior are especially promising because it is a self-sufficient ‘device’ that can be installed according to the plug-and-play principle.

The reference case assumes conventional double glazing and opaque construction elements with typical insulation standard for office buildings constructed around 1975 (Petersdorff et al., 2006). Solar shading and brightness control in the reference case is achieved via manually controlled internal venetian blinds. Operation of blinds in the simulations is controlled in DAYSIM on the basis of the Active users profile. This stochastic algorithm assumes that blind settings are rearranged on a regular basis with the aim of maximizing daylight availability while excluding glare (Reinhart, 2004).
6.2 Control strategies

The number of possible strategies for controlling SEG’s adaptive behavior is virtually infinite. The aim of this paper is to explore their potential and provide some first insights in the cause-and-effect relationships of various options. It was not intended to seek for the best possible strategy nor to account for the practical implementation aspects of these algorithms. Table 2 provides an overview of control strategies that were being studied.

Table 2: Overview of the six investigated control strategies

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Reference case</td>
</tr>
<tr>
<td>B</td>
<td>SEG always switched in the bright state</td>
</tr>
<tr>
<td>C</td>
<td>SEG always switched in the dark state</td>
</tr>
<tr>
<td>D</td>
<td>SEG switched to the dark state when indoor air temperature $\geq 21^\circ C$</td>
</tr>
<tr>
<td>E</td>
<td>SEG switched to the dark state when daylight illuminance on work plane ($E_h$) $\geq 700\text{lx}$</td>
</tr>
<tr>
<td>F</td>
<td>SEG switched to the dark state when window luminance ($L_v$) $\geq 1500\text{cd/m}^2$</td>
</tr>
</tbody>
</table>

6.3 Performance indicators

The energy saving potential of SEG is assessed by considering overall annual energy demand, subdivided in terms of energy required for heating, cooling and artificial lighting. A second performance indicator (PI) is peak heating and cooling demand. Saving energy is however only acceptable when this occurs in absence of discomfort. Consequently SEG’s impacts on comfort are at least equally important.

In this paper, thermal comfort is assessed on the basis of overheating risk. This is accomplished by counting the number of hours that indoor air temperature exceeds $25^\circ C$. Allowing discomfort during maximum 5% of working hours is usually seen as realistic and economic target value in the trade-off between energy and comfort. As a result, this amounts to an allowed number of 100 overheating hours.

Visual comfort is evaluated by considering the risk of glare, which is defined as “the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility” (IESNA, 2000). Multiple assessment methods and performance indices are in use to evaluate the occurrence of glare (Bellia et al., 2008). The current DAYSIM distribution does not come with a module for direct assessment of the risk of glare. The tool is however capable of calculating surface luminance values, and these can be transformed into the desired performance indicator. Occurrence of glare is found to be affected by many interrelated factors, including: absolute luminance of the glare source and surrounding surfaces, transient adaptation of the eye, surface reflectances, type of work (screen, paper), position in the room, etc. In this study, the risk of discomfort caused by glare is assessed by counting the number of times when the ratio between window luminance ($\frac{L_v}{L_v}$) is

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1 An extension with dynamic daylight glare probability (DGP) functions based on glare rating classification and frequency distributions (Wienold, 2009) is planned for the next version of DAYSIM.

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and paper task luminance \(L_h\) is higher than 10:1 (IESNA, 2000). Occurrence of glare is further extended with the additional clause that \(L_i \geq 2000\ \text{cd/m}^2\), in order to exclude from analysis cases with high contrast but low brightness. Levels of maximum allowed visual discomfort typically exist in terms of design recommendations rather than fixed standards. All these guidelines agree that occurrence of glare should be ‘as low as possible’; the trade-offs in relation to other PIs should rationalize for each situation whether this strive is justifiable.

7. RESULTS

7.1 Energy and comfort

Figure 10 shows annual energy demand and comfort performance for each of the six cases as given in Table 2. The results suggest that cooling energy demand after window replacement with SEG is cut by more than a factor two. In addition, installed cooling power capacity was found to be safely reduced with more than 30\% (from 1.0kW to 0.67kW) when SEG is installed, while still achieving sufficient thermal comfort levels.

Figure 10: Comparison between energy and comfort performance of the reference (A) and SEG (case B to F) in a renovation case. With on the left axis: heating, cooling and lighting energy consumption [kWh], and on the right axis: risk for overheating [h] and glare [times].

Figure 10 further shows that heating energy demand for the basecase (case A) compares well to that for SEG, even though the window U-value of SEG is lower as a result of the presence of a low-E coating. Closer inspection at the energy balance reveals that the transmission losses after renovation are indeed lower, but this difference is almost compensated by the decrease in valuable passive solar gains. The lower visible transmission values of SEG also
give rise to a relatively large electricity demand for lighting. The results further show that occurrence of glare in the reference case is comparatively high. This is caused by the fact that (i) the window has a high visible transmittance, and (ii) blinds are operated manually.

Considering SEG as an alternative can provide an adequate solution for fulfilling both thermal and visual comfort requirements. If continuously in the bright state (case B), total energy consumption gets reduced, but glare is still a problem. When always switched to the dark state (case C), the occurrence of glare drops drastically, but at the same time this also introduces an undesirable higher energy demand for artificial lighting. Implementation of an appropriate control strategy (e.g. case D to F) is the key that allows for profiting from the benefits of both the dark and the bright state. Apparently, best results are obtained when window state is controlled based on stimuli from the luminous environment (case E or F). In these cases, daylight is only allowed when desired and blocked when unwanted.

It can be observed that electricity generation potential of SEG is not included in the results. This is because the produced amount of electricity is two orders of magnitude lower compared to the scale of hundreds of kWh in Figure 10. Currently, the focus is on making adaptivity of the window self-sufficient, which appears to be a realistic ambition.

The combined effects of high heating and lighting energy demand together make that savings in overall energy demand in this particular case are only marginal. More dominant are the impacts of SEG on indoor environmental quality. The actual renovation potential of SEG however is likely to be more differentiated, because of the following reasons:

- Any attempt to model occupant control of shading devices adds to the uncertainty in outcomes of the simulation. The reference situation in this case assumes the optimistic setting of active blind control. Blinds are opened and closed as to maximize daylight utilization and thus represent the best case scenario for manual blind control in terms of energy. In practice, a much more passive operation of blinds, and thus degradation in performance is likely to be expected. SEG on the other hand is easily integrated in the building automation system (BAS), which makes that difference are likely to become more clear.

- The case-study assumes continuous dimming control, where daylight levels are almost perfectly supplemented by artificial lighting. In both new and old buildings, this might be a too idealistic representation of reality. When internal heat gains are considered to be more independent of ingress of daylight, the energy saving potential of SEG’s adaptivity is supposed to be higher.

- More aspects than only operational energy demand and comfort levels play a role in the decision for renovation or preservation. A distinct advantage of SEG is the fact that shading devices are no longer required which (i) ensures access to outdoor views, (ii) reduces maintenance costs, and (iii) allows for better utilization of the beneficial psychological and physiological aspects of daylight. In addition, renovation with SEG may prevent early demolition, and thus increases economized exploitation of the building while extending resource efficiency of the building’s life cycle. A third aspect is the translucent window state which enables both privacy and diffuse daylight utilization. With current BPS tools, these effects are hardly quantifiable.

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2 Luminous efficacy of the light sources is assumed identical in both cases. A more conservative reference situation would result in higher energy saving potential.

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7.2 Risk of radiant asymmetry

Especially in the dark state, SEG absorbs a relatively large amount of incident solar radiation and for that reason creates an increase in window temperature. As a result, application of SEG is suspected to constitute a potential source of local discomfort. The risk of radiant asymmetry due to SEG as warm wall was assessed on the basis of results from the simulation model. Figure 11 shows the simulated surface temperature of the internal SEG window pane in the dark state, in comparison with ambient air temperature and the mean surface temperature of the other zone surfaces. The temperature difference between wall and window reaches a maximum of 9°C on the hottest day.

![Figure 11: Surface temperature of wall and window, and ambient air temperature during six days in summer.](image)

Radiant asymmetry was calculated according to ASHRAE (2001). ISO 7730 specifies an allowable threshold value of 23°C for radiant temperature asymmetry, which corresponds to a PPD of 5%. Assuming that the view factor from the occupant to the window in spaces with moderate window-to-wall ratio’s go up to approximately 0.5, this results in a maximum allowable window temperature of 65°C. On the basis of the simulations it can be safely concluded that for the investigated configuration there is no cause for concerns regarding discomfort due to the high window pane temperature. On the contrary, cold window surfaces likely offer a much higher risk of discomfort because the allowable temperature difference is much lower.
8. DISCUSSION

This study is the first that attempts to bridge the gap between the fundamental research in LSC’s and its practical application in architecture. A consequence of this novelty was the fact that outcomes of an empirical validation study were necessary input to ensure reliability of the simulation model. It

should however be noted that such test facilities are often not available, and efforts often not justifiable in routine design processes.

On the basis of the presented simulations it is not yet possible to give conclusive answers about SEG’s energy saving potential. Indications of performance benefits are better substantiated once a more elaborate parametric study is conducted\(^3\). The concept however seems promising because energy savings can be achieved while at the same time comfort levels improve. On the other hand, the results do also suggest that there is still room for improvement compared to recent studies with other switchable glazings (e.g. Jonsson and Roos, 2010; Mardaljevic and Nabil, 2008; Piccolo, 2010). The deviations in performance may be explained by the following reasons:

- Most comparative studies are based on thermal or daylight performance only, whereas this study considers the integral performance aspects simultaneously. Consequently, performance trade-offs are effectively included in the analysis and this removes the unconscious bias towards solutions that are out of balance (i.e. too much in favor of either thermal or visual performance).

- Switching the optical properties of SEG primarily takes place in the visible wavelength area. Blocking solar gains is therefore followed by a proportional increase in lighting energy use. The net result is that solar gains are exchanged for internal gains, and consequently part of the energy saving potential is counterbalanced. The luminescent dye technology however makes extension of the switching range to other parts of the spectrum viable. The ultimate solution would be a window that is capable of switching visible and infrared transmittance independently. Research efforts pursuing this aim are underway, but currently the luminescent materials active in the infrared wavelength area still suffer from low stability, low quantum efficiency, and a relatively small absorption spectrum (Goldschmidt, 2009).

- The bandwidth for switching SEG is relatively narrow compared to other switchable windows. In addition, SEG only switches in either one of three states, without the possibility for gradual transitions in between.

SEG is still in the prototype phase, and more work is required towards optimization of the final product design. BPS can help to identify the focus of attention for future product development in the laboratory as well as in the actual integration in the building shell. An appealing opportunity that SEG offers is the possibility of selecting switchable window properties for the dark, bright and translucent state. This makes it possible to develop, tune and optimize multiple SEG-coatings, each for a different application area. These properties are however subject to some fundamental restrictions as illustrated in Figure 12.

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\(^3\) Including variations in window-to-wall ratio, orientation, type of building, renovation vs. new building, occupant’s behavior, climate, etc.
A high visible transmittance in the bright state (1) is attainable, but this also involves a relatively high level of transparency in the dark state, and accompanying losses in electricity generation potential. On the other hand, a larger switching range (2) is also possible, but this then puts a constraint on the maximum level of transparency in the bright state. The simulation model as presented in this paper provides a good point of departure to investigate which optical properties and control strategy yield the optimum balance for heating, cooling and lighting energy demand. At the moment, this is still an open question.

9. CONCLUSION

Despite of the anticipated performance benefits, application of CABS in current architectural practice is still limited. Because design of CABS is a challenging task, decision makers are wary of taking the risk. Consequently, the potential of CABS currently remains largely unexplored.

BPS is able to facilitate increased insights in the system’s dynamics, ranging from short-term impacts to seasonal cycles, and also makes it possible to explore the integrated effects and trade-offs of various operational control strategies. This allows for supporting informed design decisions, which enables BPS to perform as a catalyst for taking the advantages of adaptive building shells.

The assertion that BPS can be a valuable instrument in designing buildings with CABS was confirmed in the case study of SEG. BPS not only displayed its traditional capabilities as a design aid, but also proved to be useful as active tool in product design and development.
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