Simulating Switchable Glazing with EnergyPlus: An Empirical Validation and Calibration of a Thermotropic Glazing Model

SIMULATING SWITCHABLE GLAZING WITH ENERGY PLUS: AN EMPIRICAL VALIDATION AND CALIBRATION OF A THERMOTROPIC GLAZING MODEL

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ABSTRACT

Adaptive transparent building envelope technologies could play a significant role in decreasing energy use in buildings and providing a more comfortable indoor environment. In order to evaluate these potentials in an economic and accurate manner, it is essential to have numerical models and simulation tools which correctly reproduce the behaviour of such components at the building level.

This paper presents and discusses the empirical validation of models for thermo-tropic glazing, a specific adaptive transparent glazing, by means of a whole building performance simulation tool, *EnergyPlus*. Moreover, this study highlights the differences between two modelling approaches (EnergyPlus built-in and EMS models) and experimental data.

Negligible differences are noted between the two modelling approaches, even though the models do not completely agree with experimental data unless a model calibration is performed. The EMS modelling approach could be successfully extended to other dynamic glazing technologies that do not have a built-in model available in EnergyPlus, provided that an accurate thermo-optical characterisation of the dynamic glazing is available.

INTRODUCTION

Adaptive glazing technologies (Beatens et al., 2010) are very promising building envelope technologies in terms of reducing the energy use in buildings while improving indoor environmental quality. These systems can modulate the optical and thermal properties of the transparent portion of the façade in response to changing boundary conditions, thereby improving energy and indoor environmental performance.

In order to evaluate the performance of state-of-the-art and more innovative adaptive glazing technologies (Garcia et al. ,2013 and Hoffmann et al. 2014), and to optimize their design for building integration, it is important to rely on whole building performance simulation (BPS) tools that are able to accurately reproduce their dynamic behaviour when integrated at the building level.

The two-fold aim of this work is to present an empirical validation of two alternative adaptive glazing modelling approaches and to compare the performance of the two models, using the well-established *EnergyPlus* BPS tool (US Dept of Energy, 2014). This paper focuses on a thermo-tropic glazing, which is able to change reversibly its thermo-optical properties according to the temperature of the glazing itself, and whose specific model is already available built-in in Energyplus.

In the paper, the alternative approaches for modelling adaptive glazing technologies in EnergyPlus are presented. The characteristics of the thermo-tropic glazing are summarized, together with its laboratory optical characterisation and with results from an experimental programme. Finally, the results from the experiments and the models are compared and the differences are discussed.

METHODOLOGY

At the present, the capability of BPS tools to evaluate the performance of switchable glazing is limited. This is due to the following reasons: (1) the tool includes built-in models for relatively few established adaptive glazing technologies (i.e. thermo-chromic or electro-chromic glazing), while others (i.e. photo-cromic, near-infrared electrochromic, independently visible-near infrared tunable electrochromics, photo-volta chromics, etc…) are not usually available; (2) the level of modelling the control of either building services or active adaptive technologies is not sufficient to correctly integrate active adaptive technologies with building services (Favoino et al., 2015). Different modelling approximations were adopted (Goia et al, 2013, De Forest et al, 2013, Favoino et al., 2014) in order to overcome these two limitations such as: 1) the properties and the performance (i.e. energy use) of the adaptive glazing (or adaptive building envelope components) are calculated as the sum of independent static technologies, simulated separately; 2) the optimal control of thermo-optical properties providing the lowest energy use is found as the one having the minimum energy use between the independent simulations. These assumptions can invalidate the results of the simulations (Favoino et al. 2015, Loonen et al., 2014). In this work an alternative modelling method, that can be used to overcome the limitations described above, is presented. This approach can be employed for any kind of adaptive glazing and adaptive building envelope technology and offers high control possibilities – the optimal control of adaptive envelope components is investigated in (Favoino et al., 2015).

This alternative modelling method makes use of the built-in Energy Management System (EMS) tool of *EnergyPlus*, and will be referred to as EMS method or model. In order to verify the reliability of the EMS model, it is compared to a built-in model of *EnergyPlus* (hereafter termed E+ method/model) for a specific adaptive glazing technology, namely thermo-tropic (TT) glazing. Together with the EMS method, the *EnergyPlus* built-in model for TT glazing is also tested, the specific object used in *EnergyPlus* for the built-in model is:

"WindowMaterial:GlazingGroup:Thermochromic".

Results from numerical simulations carried out with both models (EMS and built-in) are compared against experimental data obtained through a characterisation of the TT technology under real outdoor boundary conditions, by means of a full scale test cell facility.

The glazing configurations tested in the experimental programme and compared to the two alternative models are:

- *TGU*: a triple glazing unit as a reference (thermo-optical characteristic of each layer were taken from datasheet);
- *TT+TGU*: a triple glazing unit with the TT glass layer on the external side (TT layer properties from optical characterisation);

The reference TGU glazing is a 8/15/8/15/4 unit with both cavities filled at 90% with Argon and characterised by the following glass layers (from outside to inside):

- 8 mm clear glazing;
- 8 mm extra clear glazing;
- 4 mm clear glazing with low-E coating.

The TT glazing is a laminated glass of 9.5 mm total thickness with the TT layer placed between the glass panes.

MODELLING ADAPTIVE GLAZING

EMS usually refers to the automated control system that handles all the building energy related systems (e.g. HVAC plants and components, but also building envelope components, such as windows or shading systems). The EMS is based on a structure consisting of sensors, control logics and algorithms, and actuators that operate on the components to be controlled.

Recently, EnergyPlus Runtime Language (ERL) was added to *EnergyPlus* (Ellis et al. 2007) in order to allow the simulation tools to replicate an EMS. The system is based, as in the real word, on same elements of a real EMS – that is, sensors, control logics and algorithm, and actuators. In the latest release of the EMS system (US DOE, 2013) new actuators were introduced in order to control thermo-optical properties at building envelope level. The available actuators control different building envelope adaptive components and properties, such as window shading devices, slat angle of the shading device, surface heat transfer coefficients, material surface properties, surface construction state (material construction properties), and surface boundary conditions. Moreover, any scheduled action in *EnergyPlus* can be controlled by means of an actuator. A control algorithm can be designed in the EMS, adopting the ERL programming language, in order to control any actuator, based on data from the sensors (wherein any output from *EnergyPlus* can be treated as a potential sensor).

The surface construction state actuator can be used to simulate variable thermo-optical properties, and therefore an adaptive glazing (Actuated Component Control Type: Construction State; Actuated Component Type: Surface). This specific actuator allows different constructions, characterised by different properties, to be defined, using different materials. The constructions can thus be managed according to the designed control algorithm, so that each component of the construction can be substituted by another one during the simulation runtime, following the defined control algorithm. The different constructions are required to have similar thermal capacity. Considering that a thermo-tropic glazing is able to reversibly change its optical properties (solar and visible) according to the temperature of the thermo-tropic layer (as presented in the next section), the control algorithm can be designed so that a different construction is adopted at each different temperature of the glazing, with conditional (*if else*) statements:

IF T_{glass_AVG} *<=*T_{x1}*degC,*
SET TT_glazing=TT_properties@T_{x1}*degC,*
ELSEIF T_{glass_AVG}*<=*T_{x2}*degC,*
SET TT_glazing= TT_properties@T_{x2}*degC,*
ELSEIF….
….END;

Where *TT_glazing* is the construction identifying the adaptive glazing and *TT_properties@*T_{xn}*degC* is the construction with thermo-optical properties corresponding to a certain temperature (T_{xn}*degC*). The inequalities above are specific to this case study, but can be designed according to the specific control required by the adaptive glazing, therefore the statement can be changed and the variables can be either ascending or descending. The same logic can be used to control the glazing thermo-optical properties according to different sensors/status of the building envelope system and/or boundary conditions. In fact, in order to simulate other passive or active adaptive glazing technologies, the control can be based on the signal from sensors such as: temperature of the construction element (thermo-chromic/tropic glazing); amount of solar radiation on the external side of the glazing (photo-chromic glazing); heating or cooling demand, amount of daylight in the indoor environment (for electro-chromic and liquid crystal glazing, or shading devices) and so on**.**

No evidence was found in literature about the reliability of the EMS modelling approach when applied to dynamic building envelope components. In this work, the use of EMS for modelling an adaptive glazing technology is compared against the built-in *EnergyPlus* model for thermo-chromic glass panes, which can be used to simulate thermotropic technologies too. In fact, a thermo-tropic glazing can be considered, from an energy balance perspective, equivalent to a thermo-chromic one, the only difference between the two being the direction of the transmitted solar radiation (thermo-tropic is light diffusing when not transparent).

CHARACTERISATION OF THERMO-TROPIC GLAZING PROPERTIES

Thermotropic materials are a particular group of chromogenic layers that exhibit a reversible change in optical properties depending on the temperature of the two components constituting the thermotropic layer itself, by means of phase separation or of phase transition (Muehling et al., 2009). The technology tested and modelled in this paper is based on a core-shell particle suspension. When the temperature of the thermotropic layer is below phase change temperature (range) of the core material (*off-state*), shell and core have similar refractive index, resulting in high visual and solar transmittance. When the temperature of the thermotropic layer exceeds the phase change temperature of the core material, its refractive index changes (due to the phase change from solid to liquid). This leads to scattering phenomena in the bulk of the material, decreasing the transparency of the thermotropic layer (*on-state*), while increasing at the same time the reflectance and/or absorptance.

Laboratory optical characterisation

Spectro-photometric measurements were carried out in laboratory in order to characterise the optical properties of the thermo-tropic laminated glass pane (sample TT). A large integrating sphere (diameter 75 cm) was used to accurately measure the transmission and reflection coefficients in case of scattering phenomena. The optical bench is equipped with a light source (300 W xenon arc lamp) and a detection system, resulting in a measurement error of ± 0.02. Detailed description of the optical bench can be found in (Goia et al, 2015).

The characterisation was carried out at different temperatures, recorded through the thermal camera Testo 875-2i. The camera was previously calibrated by comparison with temperature measurements carried out with a thermocouple. Spectra of (beam-hemispherical) transmitted/reflected radiation were recorded versus a Spectralon white reference. Solar (ρ_e) and visual (ρ_l) transmittance and reflectance (at near-normal incidence angle), were then obtained following the methodology presented in (EN ISO, 2003).

In table 1, the integral values of solar and visible transmittance are reported for surface temperatures of the sample ranging from 11 °C to 46 °C. The switching phase occurred in the range between 28 °C and 34 °C (measured at the surface of the glass pane), but the highest change **of τ_l and τ_e** was recorded between 32 °C and 34 °C. The material presented a translucent aspect also when it is in *off* state with a τ_l of 0.66 and a τ_e of 0.45. Transmission in *on-state* is τ_l of 0.52 and a τ_e of 0.36. Visual and solar properties were lowered, when switching from transparent to translucent state, by 21% and 20% respectively. During *off-state* (11 °C-13 °C sample temperature) a ρ_l of 0.07 and a ρ_e of 0.10 were registered, whereas a ρ_l of 0.16 and a ρ_e of 0.10 were measured during *on-state* (sample temperature: 45 °C). The spectral transmittances of the *on-* and *off-state* are plotted in Figure 1, which shows that there is no significant change in the selective behaviour between the two states.

Table 1 Transmittance against sample temperature.

T_{glass} [°C]	τ_S (ISO 9050) [-]	τ_L (ISO 9050) [-]
46	0.36	0.52
40	0.36	0.53
38	0.37	0.53
36	0.37	0.54
34	0.38	0.55
32	0.43	0.62
30	0.43	0.63
28	0.45	0.65
26	0.44	0.65
22	0.45	0.65
11	0.45	0.66

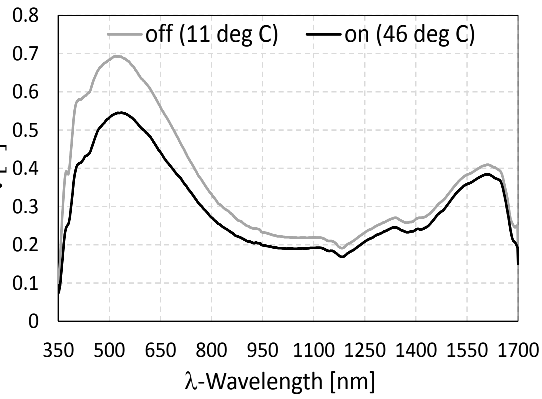

Figure 1 Spectral transmittance for on *and* off *states.*

Experimental characterisation in outdoor test cell

The tested samples were mounted on the TWINS outdoor test cell (Serra et al., 2010) exposed to external boundary condition; the measurement programme lasted over two years. TT and TT+TGU technologies were alternatively tested together with a TGU reference technology. The test cell measures 1.6

m (width), 3.6 m (depth) and 2.5 m (height). The indoor air temperature in the test cell was continuously maintained at the desired set point (26 ± 1 °C), by means of a full air conditioning system. The tested technologies were mounted on the south façade of the test cell and each glazing measured 140x80 cm. Thirty sensors, connected to a data logger, previously verified and calibrated, were used to measure temperatures, heat fluxes exchanged at the indoor surface, and solar radiation with a sample rate ranging from few seconds to 1 minute. Data were post-processed in order to obtain values every 5 minutes. Temperature and heat flux sensors (both external and internal) were accurately shielded from the solar radiation where necessary in order to avoid inaccuracy due to overheating phenomena. For this purpose, a reflective foil and a plastic semi-cylindrical shading element were used to protect the sensors. Sensor accuracies are: ±0.5 °C for the thermocouples, ±5% for the heat flux meters, ±2% for the pyranometers.

Both the TGU and TT+TGU were tested under the same boundary conditions. The experimental data from the period between the 12th and 15th April 2013 were selected to be compared to the two models. This was selected because both medium to high vertical solar radiation on the South façade were present, and the temperature of the TT layer spanned over the entire switch range, with values between 9.6 °C and 46.1 °C.

TEST CELL MODEL IN *ENERGYPLUS*

The test cell was modelled and simulated with EnergyPlus 8.1. The measured internal air and surface (walls, floor and ceiling) temperatures of the test cell were used as boundary conditions in the *EnegyPlus* model of the test cell, in order to reduce the inaccuracies related to other test cell parameters that were not characterised (e.g. infiltration rate, emissivities of surfaces). As far as the internal surface temperatures are concerned, a guarded ring was modelled, that is a thermal zone around the test cell and its zone air temperature controlled equal to the average measured temperature of the internal surfaces (walls, floor and ceiling). To ensure that the test cell surface temperatures were equal to the guarded ring air temperature, the surfaces dividing the test cell and the guarded ring were modelled as fictitious walls having a very high thermal conductivity and a very small thickness and specific heat capacity.

External air temperature and solar radiation data were fed to the simulation tool by modifying the weather file according to the data registered in the selected periods. However, it is important to underline that only global solar radiation data perpendicular to the the South façade were available from the measurement programme. *EnergyPlus* requires global horizontal, direct beam and diffuse horizontal solar radiation among the input data to calculate the global solar radiation impinging on a surface. These values were numerically estimated for each timestep. The global solar radiation impinging on the façade simulated by *EnergyPlus* was subsequently compared against the measured values and agreement was found, according to Figure 2. Selecting measured days with clear sky (low cloud cover) reduced the difference between measured and simulated vertical solar radiation on the South façade (Figure 2).

RESULTS

The comparison between the models and the experimental results was carried out both qualitatively and quantitatively. The profiles of the measured and simulated a) surface temperature of the glazing ($T_{glass,in}$ [°C]), b) transmitted solar radiation through the glazing (G_{in} [W/m^2]) and c) heat flux (radiative long-wave and convective) on the internal surface of the glazing (HF_{lw} [W/m^2]) are compared. Quantitatively, three indicators of fitness of the models with the experimental data are calculated:

- Mean Bias Error (MBE):

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(X_{mod} - X_{exp}) \quad (1)$$

- Root Mean Square Error (RSME):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{mod} - X_{exp})^2} \quad (2)$$

- Percentage Root Mean Square Error (PRMSE):

$$PRSME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\frac{X_{mod} - X_{exp}}{X_{exp}})^2} \quad (3)$$

where n is the number of measurements (1152 data points, 1 every 5 minutes for 4 days). The indicators were calculated for all the three measurements mentioned above (a, b and c).

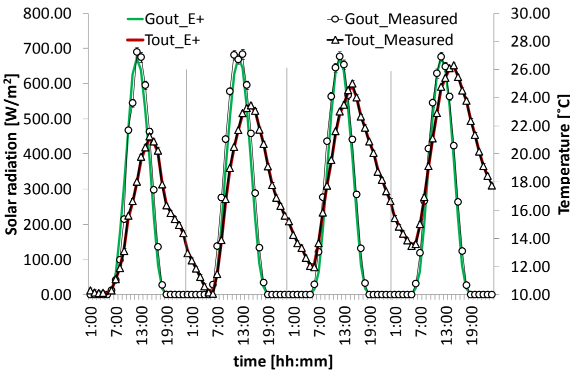

Figure 2 Vertical solar radiation (South) and external temperature of the period 12th-15th April.

Models validation

In order to define a baseline for comparison between simulations and experimental data, the results of the simulation of the TGU reference glazing were first validated against the empirical data. The comparison between measured and simulated glass internal temperature ($T_{glass,in}$), transmitted solar radiation (G_{in}) and surface heat fluxes (HF_{lw}) for the TGU technology are given in Figure 3 (G_{in} and $T_{glass,in}$) and Figure 4 (HF_{lw}).

Generally, a good agreement is found between the simulation and the experimental data for the TGU. Two discrepancies between experiments and simulation are also found and can be explained as follows: measured internal temperature and heat fluxes present 2 hours delay compared to the simulation results, due to the fact that *EnergyPlus* does not take the thermal mass of the glazing into account (US DOE, 2014); a peak difference in the HF_{lw} is noticed in afternoon hours, and this is probably due to overheating (by direct solar radiation) of the heat flow meter sensor during the measurement programme of the TGU (although this was shielded with a reflective aluminium foil). MBE, RSME and PRSME for the TGU are showed in Table 2, giving a reference to be compared with indicators for the models for the TT-TGU glazing.

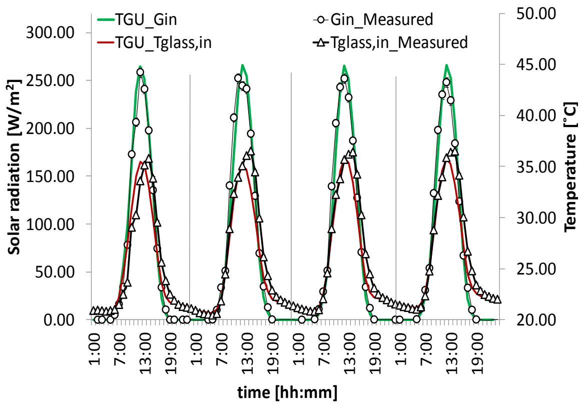

Figure 3 Comparison between experimental data and simulation for the TGU (period 12th-15th April).

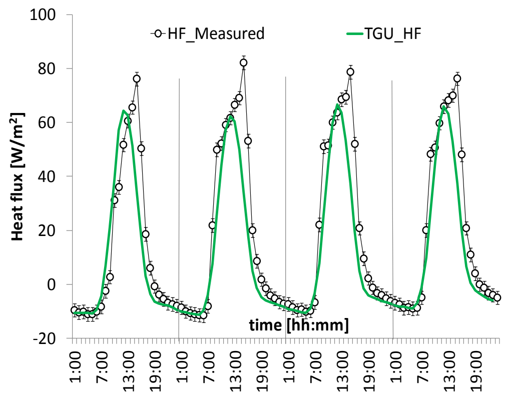

Figure 4 Comparison between experimental data and simulation for the TGU (period 12th-15th April).

Table 2 Model fitness indicators for TGU model.

T glass, in [°C]			G_{in} [W/m2]		HF_{LW} [W/m2]	
MBE	RMSE	PRMSE	MBE	RMSE	MBE	RMSE
-0.5	1.5	5.1%	-0.6	11.5	-6.3	13.7

Although a complete optical characterisation of the TT glazing was performed, a discrepancy between experimental and numerical data was found, regardless of the modelling approach adopted to replicate the features of the TT layer.

In Figure 5, 6 and 7 the comparison between the simulation and the experimental data is shown for the *TT+TGU* glazing, for the $T_{glass,in}$, G_{in}, and HF_{lw}, respectively. In each graph, the E+ built-in model is compared against the experimental data, while the differences between the E+ model and the EMS model are shown on the secondary axis (with a magnified scale). Model fitness indicators for all the models (E+ and EMS) are shown in Table 3.

While there is good agreement between the measured and simulated G_{in} , according to Figure 7 and Table 3, there is a difference between measured and simulated data for the *TT+TGU* with optical properties according to the material characterisation, as far as the $T_{glass,in}$ and HF_{lw} are concerned. The discrepancies founds are in terms of delay and peak value differences between simulated and measured surface temperatures and heat fluxes. Analogously with the TGU, the 2-hour delay between simulated and measured temperatures and heat fluxes on the inner surface of the glazing is due to to the fact that *EnergyPlus* does not take the thermal mass of the glazing into account in the energy balance.

The differences between simulated and experimental data are magnified during peak solar radiation hours, resulting in 3-4 °C difference for the $T_{glass,in}$, and up to 10-15 W/m^2 for the HF_{lw}. These differences are reported in a quantitative way also in Table 3 (TT+TGU E+ and EMS), with 7% PRSME and nearly 0.5 °C average deviation (MBE), and more than 12 W/m^2 RSME for the $HF_{lw.}$ Although the TT+TGU fitness indicators do not differ much from the TGU ones, when looking at the profiles (Figure 6, 7 and 8) these differences result evident. These gaps can be explained by a difference in the optical properties of the TT glazing during the experimental campaign in the test cell, compared to the optical characterisation. This results effectively in an increased TT glazing reflectance, as the solar energy absorbed by the glazing and re-emitted towards the internal environment is lower in reality than what is calculated with the model (according to internal surface and heat flux measurements).

Models calibration and performance simulation

A calibrated model, which is able to better reproduce the experimental measurements, is required in order to assess how much the difference between the two alternative modelling approaches could influence the calculation of the energy consumption of a building, and what is the energy saving achievable by means of the TT-TGU.

In particular, in the previous section is noted how the solar reflectance of the TT glazing in the test cell appears to be higher than the optical characterisation. Therefore, a calibration of the model was carried out by changing parametrically the solar reflectance of the TT glazing in order to match the experimental data. It was assumed that the reflectance of the TT glazing at each temperature is increased by the same factor. The solar and luminous reflectance are increased of the same value, from the values available from the experimental characterisation in steps of 0.025, from + 0.025 to +0.30. The best fit with the experimental data is obtained for an additional reflectance of + 0.25. The best fit is obtained qualitatively and quantitatively, in terms of MBE and RSME for both $T_{glass,in}$ and HF_{in}. For the sake of brevity, only the results for the best model matching the experimental data are given (TT+TGU_mod, green line in Figure 5, 6 and 7). This results in an additional reflectance (solar and luminous) of 0.25, regardless of the state (temperature) of the TT glazing.

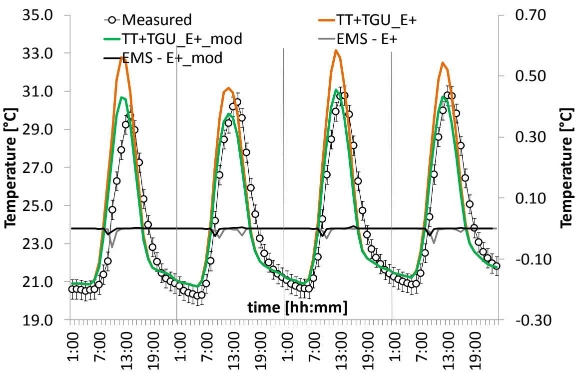

Figure 5 Comparison of glass internal surface temperature for the TT+TGU (12^{th}-15^{th} April).

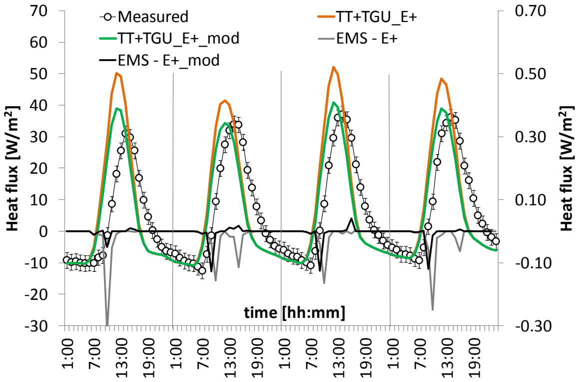

Figure 6 Comparison of heat fluxes across the TT+TGU glazing (12^{th}-15^{th} April).

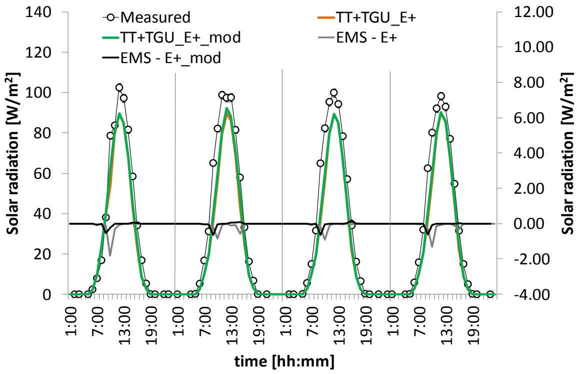

Figure 7 Comparison of transmitted solar radiation for the TT+TGU glazing (12^{th}-15^{th} April).

It can be noticed that the calibrated model is able to reproduce the trend and the peaks of the measured temperature and heat flux data better than the model based on the optical characterisation of the TT glazing (Figure 5 and 6) both qualitatively and quantitatively. This is confirmed by the MBE, RSME and PRSME which are considerably reduced: 5% average error and negligible mean average error on the $T_{glass,in}$ and 10 W/m^2 RSME for the HF_{lw}. A negligible difference between the EMS and the *EnergyPlus* model for the calibrated *TT+TGU* is measured as well. This difference (black line in Figure 5, 6 and 7) is reduced compared with the non-calibrated model, and slightly anticipates the switching process of the TT layer.

To compare the effectiveness of the TT technology in reducing the energy use and peak loads, and to compare the differences between the EMS and *EnergyPlus* models in terms of energy demand, the calibrated models of the TT-TGU and of the TGU glazing are used to assess the energy use of a reference office building room in the climate of Torino (Italy), using the IWEC Torino climate data. The office reference room model is built to reproduce the geometrical characteristic of the outdoor test facility. An ideal HVAC system is used to maintain 20°C in winter (0.85 efficiency, 1.00 natural gas fuel factor), and 26°C in summer (3.5 SEER, 2.18 electricity fuel factor). Constant illuminance level of 500 lux is maintained in the room by means of artificial lighting (continuous dimming, 12.75 W/m^2 power density). Equipment power density and schedules, and occupation schedule (0.11 person/m^2) for office buildings are considered (ASHRAE, 2010).

The specific primary energy consumption of different alternatives are compared: TGU; TT+TGU (EnergyPlus and EMS model) with optical properties according to optical characterisation and calibrated to fit experimental data (mod); TGU with TT layer as mid layer of the TGU (TT(mid)+TGU); TGU with internal or external venetian blind (0.7 slat solar and luminous reflectivity) with cooling demand control (lower blinds when cooling load is present).

In Table 4 the primary energy use (total and in heating, cooling and lighting) and the peak loads (lighting peak LP, heating peak HP and cooling peak CP loads) of the different cases are compared. It can be noticed that the TT technology slightly decreases the total primary energy use of the office reference room (slightly more than 5% compared to TGU); this is mainly due to a big decrease in cooling energy use (almost 40%), while heating and lighting energy demand are increased. These trends are reflected also in terms of peak load reduction. The TT-TGU solution is outperformed in terms of energy performance by the TGU solution with the external blind, this is due not only to the active control (cooling demand control) of the external blind, but also to the increased difference in optical properties between shaded and un-shaded state of the solution with venetian blind compared to the TT+TGU. Nevertheless, there is always a negligible difference between the EMS and the *EnergyPlus* model, if compared difference in energy use between alternative glazing solutions (Table 4). Although a small discrepancy exists between the calibrated model (mod) and the model adopting the optical characterisation of the TT glazing in terms of total energy use, this difference is increased when considering the heating/cooling energy use only, and heating/cooling loads.

DISCUSSION

The differences measured between the *E+* built-in model and the EMS one are negligible in terms of calculated energy use of a reference room. These differences are reported in all the figures on the secondary axis, which is magnified by one order of magnitude. The differences are mainly measured during daytime when the TT glazing switches from the *off-state* to the *on-state*. This is due to the fact that, when the EMS is used, the state of the TT glazing can be controlled by means of the surface temperature of the glazing component only (in this case, external surface temperature). On the contrary, the *E+* built-in model controls the state of the TT glazing through the internal temperature of the glass layer itself. Therefore when the TT layer is on the internal or external layer of a building envelope construction (the TGU in this case), the difference between the two modelling approaches can be negligible, and the two models can be used alternatively. This may not be the case for a TT layer (or other adaptive building envelope technology) inserted as intermediate layer of a multi-layered construction element (i.e. a TT layer as the middle layer of a TGU unit), as in the case of TT(mid)-TGU in Table 4. In this case, there is a higher difference between surface temperatures and temperature of the layer with switchable thermo-optical properties, resulting in higher difference between EMS and E+ model in terms of energy use and peak loads. Moreover, in this case the temperature dependent variability range of optical properties was quite limited (Table 1), thus the small differences between the two alternative modelling approaches.

Therefore, the EMS model could be adopted to simulate adaptive glazing technologies, regardless of the switching mechanisms, unless: the variation of the properties of the glazing is strongly temperature dependent; the adaptive component is not in one of the two surfaces of the construction element (indoor or outdoor). In these cases, higher differences between EMS and EnergyPlus built-in models may arise and they could require to be evaluated for the specific case.

CONCLUSIONS

This paper presents an alternative modelling approach for adaptive glazing using the building performance simulation tool *EnergyPlus*, by means of the embedded EMS tool, for the specific case study of a thermo-tropic glazing technology. The EMS model is compared to the built-in available model. The study compares and calibrates the two models against experimental data collected during an experimental programme carried out with an outdoor test facility in the climate of Torino, Italy.

Table 3 Model fitness indicators.

	T glass, in [°C]			G_{in} [W/m²]		HF_{LW} [W/m²]	
	MBE	RMSE	PRMSE	MBE	RMSE	MBE	RMSE
TT-TGU E+	0.48	1.75	6.8%	*-5.16*	*8.59*	1.72	12.61
TT-TGU EMS	*0.48*	*1.75*	*7%*	*-5.25*	*8.75*	*1.72*	*12.60*
TT-TGU mod E+	*-0.01*	*1.38*	*5%*	*-5.16*	*8.59*	*-0.84*	*10.31*
TT-TGU mod EMS	*-0.02*	*1.38*	*5%*	*-5.25*	*8.75*	*-0.86*	*10.29*

Table 4 Total primary specific energy consumption and maximum loads of the office reference room

Name	PE kWh/m²y	PE light kWh/m²y	PE heating kWh/m²y	PE cooling kWh/m²y	LP kW	HP kW	CP kW
TGU	135.1	17.7	65.7	51.7	0.15	1.60	1.76
TT-TGU E+	129.4	18.5	80.6	30.3	0.15	1.67	1.28
TT- TGU EMS	129.4	18.5	80.7	30.3	0.15	1.67	1.28
TT(mid) - TGU E+	121.1	15.8	76.1	29.2	0.15	1.66	1.37
TT(mid) -TGU EMS	120.2	15.8	75.0	29.4	0.15	1.65	1.38
TT-TGU mod E+	128.2	18.5	81.4	28.3	0.15	1.66	1.22
TT-TGU mod EMS	128.2	18.5	81.5	28.2	0.15	1.66	1.21
TGU_ext blind E+	108.2	18.6	66.9	22.7	0.15	1.60	1.06
TGU_int blind E+	134.9	18.5	67.2	49.1	0.15	1.60	1.71

It is concluded that negligible differences arise between the two alternative modelling approaches, according to the different metrics analysed: profile of surface temperature, transmitted solar radiation, long wave heat exchange; quantitative model fitness indicators; total energy use of an office reference room. Therefore, the EMS modelling approach can be considered a suitable alternative to the *EnergyPlus* built-in model, and it could also be successfully extended to other dynamic glazing technologies that do not have a built-in model available in *EnergyPlus*, provided that an accurate thermo-optical characterisation of the dynamic glazing is available.

NOMENCLATURE

ρ_e = solar reflectance [-]
ρ_l = luminous reflectance [-]
τ_l = luminous transmittance [-]
τ_e = solar transmittance [-]
G_{in} = transmitted solar radiation [W/m^2]
G_{out} = incident solar radiation [W/m^2]
HF_{in} = heat flux on the inner surface [W/m^2]
MBE = mean bias error
PRMSE = percentage root mean squared error
RMSE = root mean squared error
$T_{glass,in}$ = inside surface temperature of glass [°C]
T_{glass_AVG} = average temperature of glass layer [°C]
TGU = *triple glazing unit*
T_{out} = outdoor air temperature [°C]
TT = *thermo-tropic*
TT+TGU = *thermo-tropic + triple glazing unit*
T_{xi} *degC* = temperature step x_i

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