Dynamic commercial façades versus traditional construction: energy performance and comparative analysis

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Abstract

Key parameters in studying the balance between the need for daylighting and view versus the need for controlling of solar gains, reducing energy use and maintaining human comfort are: (i) smart glazing products (ii) dynamic envelope components and (iii) lighting and HVAC controls. A typical office building with large perimeter zones is used as an example. The basic model has brick exterior walls with 20 % punched windows. A comparative analysis is performed for a more transparent envelope with dynamic systems including shading and lighting controls, for the climates of Chicago and Rome. An integrated, validated thermal-lighting model with flexible system controls is used to simulate complex façade operations for reducing glare problems while maximizing useful daylight. The results show that more transparent facades result in lower operational costs and source energy use, although total site energy use can be higher for heating-dominated climates.

1 Introduction

Compared to traditional masonry wall construction, lower thermal resistance values of large glass facades can result in increased heat losses and solar gains. Nevertheless, a major consideration is to maximize utilization of natural light and reduce lighting energy consumption by employing lighting controls. Active or dynamic façade systems refer to the design of control algorithms and the control operations that directly impact the function, position, performance and the physical properties of façades that affect building energy consumption. Such active (dynamic) systems include motorized shading, glazing products with controllable properties, variable set points, controlled lighting and similar technologies that have the potential of saving energy or improving comfort for the occupants. The concept of dynamic façades, with appropriate adjustment to changing outside conditions, allows flexibility in the integration of design considerations, and may lead to a balance between positive and negative impacts of solar energy in perimeter zones. The balance between daylight provision and reduction in energy consumption or demand through appropriate control of solar gains is the main question that has been addressed in previous studies (Shen and Tzempelikos, 2012, Hviid et al., 2008, Franzetti et al., 2004, Tzempelikos et al., 2010).

Recent advancements in lighting and shading control and properties have shown a potential for energy use reduction or improvements in thermal or visual comfort (Tzempelikos and Athienitis, 2007, Nielsen et al., 2011). Shading systems controlled based on different criteria

have been investigated. Palmero-Marrero and Oliveira (2010) and da Silva et al. (2013) showed that different shading control strategies may achieve diverse performance. Moeseke et al. (2007) found that the complex control rule combining internal temperature and solar irradiation surpassed the control rule based on solar irradiation or internal temperature alone in balancing comfort and energy savings. More recently, Tzempelikos and Shen (2013) presented new comparative control strategies for roller shades, aiming to reduce energy use while maximizing daylight utilization and outdoor view. The latest independent studies (Tzempelikos and Shen 2013, Goia et al., 2013) on the impact of window-to-wall ratio (WWR) and dynamic façade elements on energy use for air-conditioning and lighting generally concluded that WWR between 30%-50% achieves optimal results; Ochoa et al. (2012) suggested that up to 70% WWR is suitable for the climate of Amsterdam.

Advanced whole building simulation programs like EnergyPlus have already integrated deterministic shading control patterns based on a single variable or different variables– but even then, shading positions are limited to fully on and fully off conditions (Atzeri et al., 2013). Blind controllers based on multiple variables were developed by Daum and Morel (2010). Simplified tools assisting at the early design stage (Petersen and Svedsen, 2010) are useful in evaluating the potential impact of façade design decisions. Some of these tools emphasize on intelligent façades including energy and comfort criteria (Ochoa et al, 2009, Hellstrom et al., 2007) sometimes including occupant behavior (Reinhart, 2011). In some cases (Hitchcock et al., 2008), important simplifications have to be made and the users have no access to specific inputs (i.e., shading control modes and set points).

In this paper, a developed integrated thermal-lighting model is used to compare a “traditional” building with punched windows with a “modern” curtain wall construction having large window façades, for two different climates (Chicago and Rome) and for different orientations. The model is validated with EnergyPlus for the cases with and without shading and lighting controls. An expanded model is then used to simulate energy use and daylighting metrics with more advanced shading controls. The results show the advantages and disadvantages of transparent dynamic façades and the potential benefits of retrofitting existing buildings with respect to shading operation.

2 Model parameters, description and comparison with EnergyPlus

Two types of new office buildings are compared in this study. The “traditional” building has typical masonry (brick) walls and punched windows with 20 % WWR for all orientations. The “modern” building has curtain wall construction and 70 % WWR for all orientations. Punched window frames have a thermal resistance of 0.176 m^2 K/W; the curtain wall framing resistance is equal to 0.251 m^2 K/W. The total thermal resistance of the opaque sections is equal to 3.5 m^2 K/W, for both buildings –note that this is a high value resulting in more conservative results as discussed later. The same type of glazing is also used in both buildings. It has a spectrally selective low-emissivity coating on surface 2 and the U-value is equal to 1.62 W/(m^2 K). The angular properties are obtained from WINDOW 7 (2013) and direct transmittance curves are shown in Fig. 1.

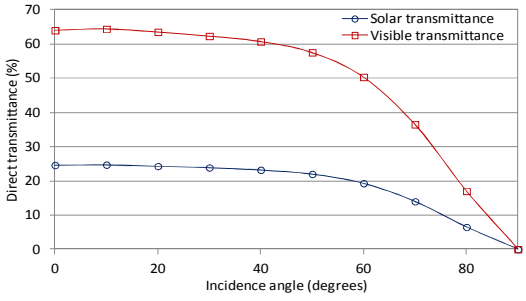

Figure 1: Glazing solar and visible transmittance as a function of incidence angle

A perimeter office (5 m × 5 m × 3 m high) for each building type (intermediate floor) is selected for detailed analysis. The office has only one exterior façade; the other surfaces (walls, floor and ceiling) are in contact with conditioned interior spaces that have the same indoor air temperature as the studied space (but not adiabatic, to account for convection heat transfer). The floor and ceiling thermal resistances are equal to 0.9 m^2 K/W for both buildings. Interior walls separating rooms have a resistance of 0.53 m^2 K/W.

A coupled thermal-daylighting model (Shen and Tzempelikos, 2012) is used for the annual performance analysis. The thermal module uses the implicit finite difference thermal network approach to predict the transient thermal response of the studied space. Non-linear heat transfer coefficients are simulated for interior and exterior convection and radiation at each calculation time step based on EnergyPlus correlations. Solar radiation absorbed by each node and heat gains to the air node by convection (due to window-shade gap airflow, equipment, occupants and electric lighting) are represented by appropriately modified input sources; heat storage in thermal mass is represented by capacitances. Heat balance nodal equations are solved simultaneously to determine the node temperatures and energy flows between all connected nodes at each time step. The energy balance equation for a node (*i*) with thermal storage is:

$$C_i \frac{T_{i,p} - T_{i,p-1}}{\Delta t} = \sum \left(\frac{T_{j,p} - T_{i,p}}{R_{ij,p}} \right) + S_{i,p} \quad (1)$$

where: T is temperature, p is the time step, j represents all nodes connected to node i, R_{ij} is total thermal resistance between nodes i and j, C_i is capacitance of node i, and S_i is total heat input to node (i). For the convective heat transfer and airflow inside the glazing-shading cavity, a model similar to ISO 15099 (2003) and EnergyPlus was used, based on a pressure-balance equation.

The daylighting module uses TMY3 illuminance data and the Perez et al. model (1990) to predict exterior illuminance on the façade. Interior light fluxes and illuminance values after inter-reflections are calculated using a radiosity-based method with one-bounce ray-tracing when direct illumination is present (sunlit areas). This entire calculation is completed for each time step for a pre-selected grid on the work plane surface. Based on these values, continuous dimming of electric lights is activated, to maintain the target (set point) illuminance (usually 500 lux) on the work plane (0.8 m from floor). The required electric lighting power E_L at each time step is calculated from Eq. (2) if the daylight levels, E_i , are lower than the illuminance set point E_s.

$$E_L = \frac{P_L \cdot A}{E_s} \cdot \frac{\sum (E_s - E_i)}{n} \quad (2)$$

where P_L is the lighting power density, A is the work plane area, and n is the number of calculation points on the work plane. The required electric lighting power for all the grid points at each time step is averaged to obtain the overall electric lighting load as opposed to using a fixed reduced lighting usage at the extremes of a workday. The electric lighting load is then used to calculate the heat gains (convective and radiative) from electric lighting in the thermal module, at the same time step. This is part of the S_i heat input in Eq. (1). The model (developed in Matlab) finally predicts all parameters (surface temperatures, heat transfer coefficients, heating and cooling load, daylighting metrics, and electric lighting use) as a function of time for the entire year.

2.1. Base case comparison

The first step for model verification was to compare the heating and cooling demand with EnergyPlus, for a base case scenario for the two climates, where no internal gains or lighting/shading are used for both office spaces. A constant set point of 23 °C was used for this base case. Heating and cooling are always available. Fig. 2 presents monthly heating and cooling energy demand results for both spaces (south-facing), for Chicago and Rome respectively. The results show that (i) the base case model is in good agreement with EnergyPlus and (ii) that the transparent façade results in higher heating and cooling demand when lighting and shading are not taken into account. Due to increased solar gains through larger windows (no shading), the cooling demand differences are higher, as expected. The demand results can be used to extract site and source energy consumption results: assuming a natural gas heating system (seasonal efficiency of 80 %) and electric cooling (COP = 3.5), the annual source energy consumption for Chicago is 66.5 kWh/m^2 for the traditional building and 106.8 kWh/m^2 for the modern building. Respective values for Rome are 36.1 kWh/m^2 and 68.5 kWh/m^2. The source-site ratio for electricity is 3.167 for Chicago and 2.137 for Rome. These values are indicative of the "bare" impact of envelope construction on energy use without considering any lighting and shading controls, and are useful for comparison with the next results that demonstrate the impact of façade and lighting system options.

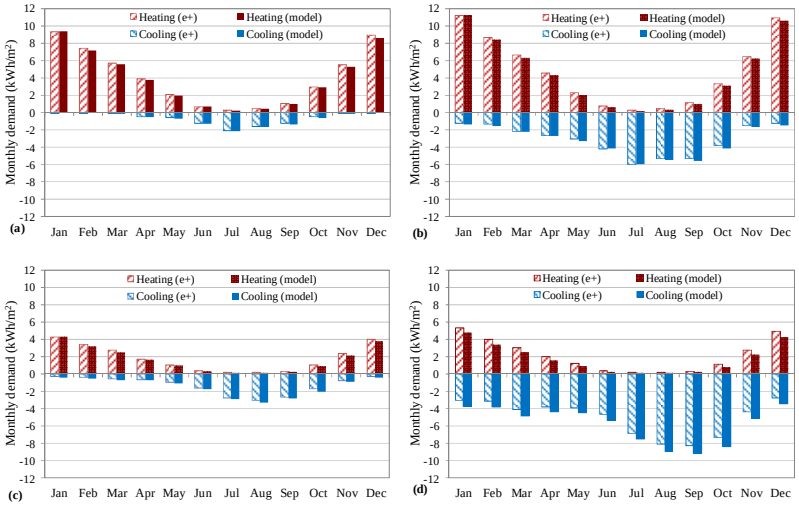

Figure 2: Base case monthly heating and cooling energy demand comparison between EnergyPlus and current model for (a) traditional building in Chicago (b) modern building in Chicago (c) traditional building in Rome and (d) modern building in Rome

2.2. Comparison including lighting and (simple) shading control

The two offices are compared next with each other -and with EnergyPlus- considering internal gains, daylighting metrics, lighting controls and basic shading operation. The spaces are occupied from 8:00 am to 6:00 pm. Internal heat gains from equipment are based on a load factor of 5.4 W/m^2 (ASHRAE, 2013). Two occupants are assumed in each office (resulting occupant density: 12.5 m^2/person), with 75 W sensible heat gains for each occupant. The installed lighting power density is 12 W/m^2 for the traditional building and 9 W/m^2 for the modern building (T-5 HO lamps). Electric lights are controlled based on available daylight on the work plane. One or several virtual points on the work plane can be used for that purpose. Here, the results are based on a sensor point at the center of the room, to directly compare with EnergyPlus results. Continuous dimming is used for the lights, with a minimum dimming level of 10 %.

Interior roller shades are employed for all windows, but different fabric properties are used for the two spaces. The shade visible transmittance is 7 % and the solar transmittance is 6 % for both cases. However, the curtain wall building uses a reflective shade (77 % reflectance),

while a standard fabric (37 % reflectance) is used for the punched windows. The shades are simply controlled in this case, closing when incident total solar radiation on the façade exceeds 300 W/m^2 to mimic manual operation (Foster et al., 2001) or simple automated shade operation. Heating, cooling and lighting energy demand (loads), as well as daylighting metrics and shading operation (at every time step and annually) were calculated for all cases and compared to EnergyPlus results, as shown in Table 1 for the case of a south-facing office. A constant set point of 23 °C is again used in this comparison.

Table 1. Annual energy demand (loads) comparison with EnergyPlus for both building types and climates (south-facing office).

Location	Office type	Annual heating demand (kWh/m^2)		Annual cooling demand (kWh/m^2)		Annual lighting demand (kWh/m^2)	
		EPlus	Model	EPlus	Model	EPlus	Model
Chicago	Traditional office	31.5	32.2	40.6	41.8	19.1	20.9
	Modern office	49.9	48.7	56.4	50.7	7.0	7.1
Rome	Traditional office	14.0	14.1	59.7	61.8	21.8	23.6
	Modern office	23.7	21.0	83.8	79.8	7.6	7.5

The results of Table 1 show that higher WWR for the modern building results in higher heating and cooling demand but lower lighting demand (due to daylight provision and lighting control employed), that also affects cooling energy use. Cooling demand is higher than heating (even for Chicago) since internal gains are now considered –heating and cooling demand for the modern building in Chicago are close as expected. The model results are in good agreement with EnergyPlus for all cases (also for hourly and monthly results) and therefore the model can be used to simulate more advanced cases (presented in the next section).

Except for energy results, several daylight metrics were also calculated (e.g. spatial and continuous daylight autonomy, useful daylight illuminances, percentage of outside view and daylight glare probability). An interesting observation is made when the daylighting results are analyzed in detail and compared with EnergyPlus. Although the lighting energy demand results (Table 1) are quite close and shading operation (shading position at every time step) is almost identical between the two models, the daylighting metrics have differences. An example is shown in Fig. 3. Daylight autonomy, a measure of the amount of time when daylight levels on the work plane are sufficient during working hours, is plotted for the two building types and climates –in terms of monthly-averaged values due to the large amount of data. EnergyPlus uses the split-flux method for lighting calculations and always overestimates daylight autonomy compared to the detailed current model, which traces sunlit areas when the shades are open (or partially open) and was validated against full-scale experimental data (Tzempelikos and Shen, 2013). The differences are higher for smaller punched windows (traditional office) but also significant for the modern office; nevertheless, these differences are not reflected in the lighting energy use results of Table 1 –the error is less than 10 %- which means that there is a disparity in the way EnergyPlus calculates electric lighting use considering daylight controls. Similar issues in daylighting calculations with EnergyPlus were also identified by Loutzenhiser et al. (2007).

The results can be used to calculate site and source energy use for the two building types using the conversion factors mentioned in the previous section. The benefits of daylighting in the modern building are evident in total source energy consumption results (Fig. 4). The reduction in lighting energy use exceeds the penalty for increased heating and cooling energy use (compared to the traditional office) for both climates. The total source energy consumption of the modern office is 12 % lower than the traditional office in Chicago and 15 % lower

in Rome. A more detailed analysis with advanced controls and cost calculations is presented next.

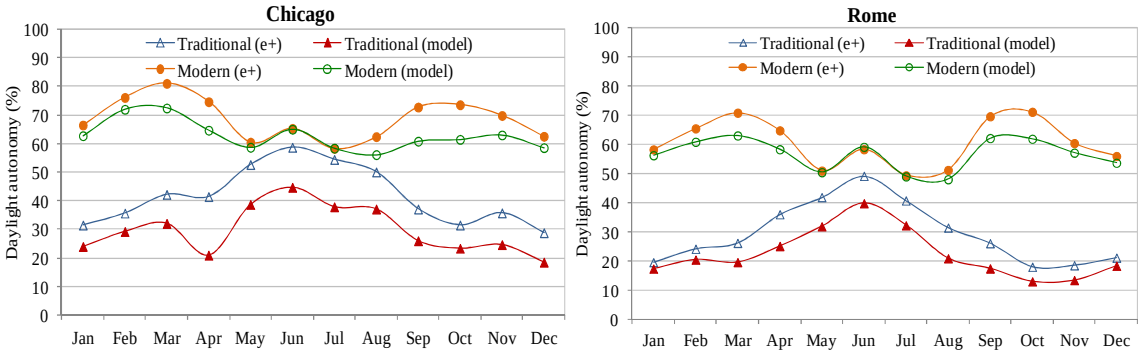

Figure 3: Comparison of daylight autonomy results (monthly-averaged values) between current model and EnergyPlus for the traditional and modern south-facing office in Chicago and Rome

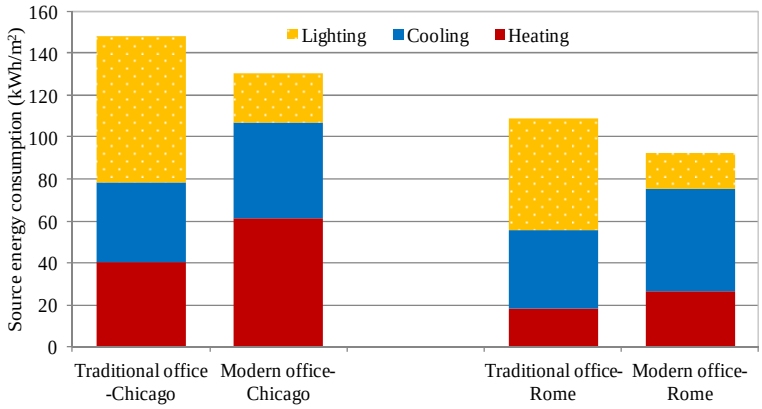

Figure 4: Source energy consumption comparison for the two spaces in Chicago and Rome

3 Overall comparison of building types and performance evaluation including variable set points and advanced shading control

The previous sections presented results for "simplified" cases, in order to verify the model with EnergyPlus and provide a basic comparison between the two office types. A constant temperature set point was used (23 °C), while shading control was based on an open/closed scenario (300 W/m^2 incident solar radiation) during all times (day and night). In this section, the flexible integrated model is used to investigate cases with more advanced shading controls and realistic thermostat set points.

Variable temperature set points are used for the heating and cooling. In heating mode, the set point is set to 20 °C during office hours (8:00 am-6:00 pm) and 18 °C during non-office hours. In cooling mode, the set point is 24 °C during office hour and 26.6 °C during non-office hours.

3.1. Shading control strategies considered and analysis

Shades are controlled differently for the traditional office (punched windows) and for the modern office (curtain wall). For the punched windows, an open/closed control during working hours (same as above) is used and shades remain closed at night. For the curtain wall façade, a variety of shading control options is used as follows:

- Open/closed control 1 (set point: 300 W/m^2 incident radiation) and closed during the night (same as for the punched windows for direct comparison)
- Open/closed control 2 (set point: 150 W/m^2 incident radiation) and closed during the night
- Advanced shading control with intermediate shading positions

The first two options were considered to emphasize the impact of set point when open/closed controls are considered. Table 2 compares the annual source energy consumption and daylight autonomy between the two control set points for major orientations in Chicago and Rome. The "conservative" control of 150 W/m^2 (assuming shades will be closed when there is direct sunlight or considerable diffuse light components) results in significant increase in energy use (up to 16 % for Chicago and 40 % for Rome). This is due to increased lighting energy use due to less available natural light (heating and cooling energy are not much different). The high differences in daylight autonomy between the two control modes (for both locations and all orientations) show exactly that effect. Zhang and Lam (2010) suggested a set point of 15000 lux to close shades which is quite close to this control. Note that this case is not unrealistic since recent studies (Galasiu and Veitch, 2006, O'Brien et al., 2013, van Den Wylmelenberg, 2012) have shown that occupants do not tend to move shading devices frequently –they could remain closed for long periods of time.

Table 2: Annual source energy consumption and daylight autonomy for major orientations in Chicago and Rome with the two open/closed shading control set points.

Location	Orientation	South		East		North		West	
	Control set point (open/closed)	300 W/m^2	150 W/m^2	300 W/m^2	150 W/m^2	300 W/m^2	150 W/m^2	300 W/m^2	150 W/m^2
Chicago	Total source energy consumption (kWh/m^2)	83.1	95.0	85.9	99.0	79.9	92.8	88.8	101.1
	Average annual daylight autonomy (%)	62.8	39.5	75.4	53.2	86.4	65.7	72.7	51.0
Rome	Total source energy consumption (kWh/m^2)	57.8	94.8	49.9	81.0	39.1	62.6	51.8	82.4
	Average annual daylight autonomy (%)	56.7	37.0	73.7	57.5	85.5	74.0	70.4	55.4

3.1.1 Advanced shading control strategy description

The advanced shading control was developed to improve daylight availability without causing glare for the occupants. Shades do not need to operate in an open/closed mode in order to achieve this objective; on the contrary, they can move to intermediate positions that depend on solar position, sky conditions and solar penetration depth relative to the occupant position. The control can be automated (with manual override); a detailed comparison of such shading control strategies was presented by Tzempelikos and Shen (2013).

In this paper, the advanced shading control refers to an improved control method to protect the occupant area from direct sunlight, while adjusting the roller shade height in order to prevent high illuminances at all times and maximize daylight provision under cloudy sky conditions (Shen and Tzempelikos, 2013). The process involves two steps: the first consideration is to prevent direct sunlight from falling on the work plane area close to the occupant at all

times. This can be easily achieved with continuous movement (proportional control) of shades to intermediate positions depending on solar geometry, orientation, and position of the occupant relative to the façade. If the occupant is at a distance D from the façade, then the shade opening height at any given time can be calculated from:

$$h_{sh} = D \cdot \tan(\Omega) \quad (3)$$

where: h_{sh} is the height of the open shade (bottom side) with respect to the work plane area and Ω is the solar profile angle (function of solar altitude and surface solar azimuth).

The limitation of this approach has to do with high illuminance values on the work plane due to: (i) sunlight entering through the unshaded (bottom) part of the window –even though it is not directly incident on the work plane (ii) completely open shades during cloudy but relatively bright conditions or (iii) open shades during summer, when the sun is high in the sky and sunlight is not falling on the work plane but significant amounts of light enter the space. Any of these situations is bound to cause glare, when the amount of transmitted daylight is high. A second consideration is therefore included, to reduce the risk of high illuminances when necessary. Nabil and Mardaljevic (2006) suggested that work plane illuminance values are usually preferred to be below 2000 lux to avoid visual discomfort. Thus, an extra criterion is to maintain work plane illuminance below 2000 lux. Considering that, employing illuminance sensors on the task area is not practical, the approach followed here is to use a sensor on the window (measuring transmitted light) and develop appropriate correlations between transmitted illuminance and work plane illuminance.

This was achieved with the "effective illuminance" control concept, where the overall transmitted illuminance (through shaded and unshaded portions of the window) using the control of Eq. (3) is plotted against work plane illuminance at target (occupant) points on the work plane throughout the year. Simulation can be used for that process, using TMY3 data with the Perez et al. model (1990) and an interior luminous flux processing engine such as the radiosity method or a mix of ray-tracing and radiosity solutions (Chan and Tzempelikos, 2012). Using these correlations, we can establish a threshold (upper limit), above which work plane illuminances would be unacceptable (shades will not move to open further) and set a constraint in shading control to avoid high illuminances and risk of glare.

The effective illuminance through the window(s) is defined as:

$$E_{eff} = \frac{E_g \cdot A_g + E_{sh} \cdot A_{sh}}{A_g + A_{sh}} \quad (4)$$

where E_g and E_{sh} are the illuminance transmitted through the unshaded and shaded window parts respectively; A_g and A_{sh} are the areas of the unshaded and shaded window parts. The effective illuminance for the modern office studied in this paper is plotted against work plane illuminance at the center of the room (all working hours in the year), as shown in Fig. 5. This plot is almost identical for both locations. A threshold (E_{esp}) of about 14000 lux is determined, in order to avoid exceeding 2000 lux on the reference point on the work plane at any given time in the year. E_{esp} and shade position h_{sh} (portion of unshaded window) are then related by:

$$E_{sh} \cdot (H - h_{sh}) + E_g \cdot h_{sh} = E_{esp} \cdot H \quad (5)$$

where H is the entire window height. The final shade position is finally decided as the minimum of the two considerations from Eq. (3) and Eq. (5), to ensure protection from high illuminances while allowing the maximum possible amount of daylight without direct sunlight on the work plane area:

$$h_{sh} = \min\left\{D \cdot tan\Omega \, , \frac{(E_{esp} - E_{sh}) \cdot H}{E_g - E_{sh}}\right\} \quad (6)$$

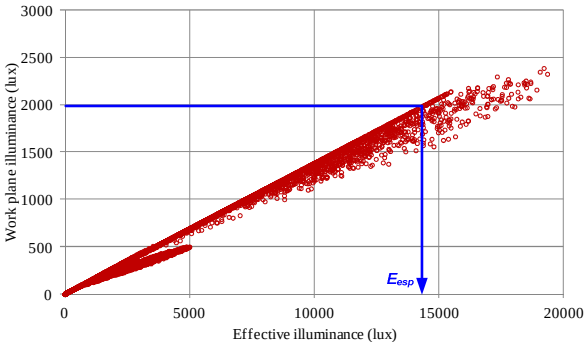

Figure 5: Correlation between "effective" transmitted illuminance and work plane illuminance to determine threshold E_{esp} for controlling shade intermediate positions.

3.1.2. Comparison between advanced shading control and open/closed operation for the modern office

The advanced shading control results in similar energy consumption as the open/closed control with 300 W/m^2 (incident solar radiation) set point. However, the shading operation and daylight performance are completely different, as shown in Fig. 6 for the case of the modern building in Chicago. The advanced shading control results in increased daylight autonomy with less unshaded window time-area fractions (% of working hours when shades are open or partially open) for all orientations. This can also translate to lighting energy use benefits, depending on how the daylight autonomy -or continuous daylight autonomy- is calculated.

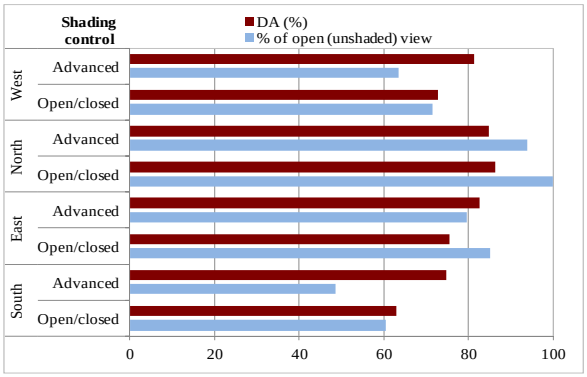

Figure 6: Modern building in Chicago: comparison between daylight autonomy and percentage of working time when shades are partially open (average percent area of unshaded window) with open closed control (300 W/m^2 set point) vs. advanced control.

To further study the advantages of the advanced shading control with intermediate shading positions, a glare analysis is performed. The simplified daylight glare probability (DGPs), as proposed by Wienold and Christoffersen (2006), is a suitable index since it considers the vertical illuminance at the eye level. The simplified glare probability is defined as:

$$DGPs = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \quad (7)$$

where E_v is the vertical illuminance at the eye level. This equation neglects the influence of individual glare sources, but has shown to provide reliable results in the absence of direct sunlight on occupants' eyes (such as in the case considered here with solar protection), compared to the Wienold's detailed daylight glare probability that includes the luminance of potential glare sources within the field of view (Wienold and Christoffersen, 2006, Wienold,

2009). The DGP scale suggests that the risk of glare becomes significant when DGP exceeds 35 % for more than 5 % of the working hours.

DGPs values were calculated for the open/closed control and the advanced shading control, for the same reference point at the center of the modern office, for a seated person (1.1 m from the floor) facing the window. Fig. 7 compares DGPs results as a function of working hours throughout the year, for a south-facing office in Chicago and for a west-facing office in Rome. The simple open/closed control results in several hours with glare probability exceeding 35 % for both cases; these are eliminated with the advanced control, also showing that 2000 lx is a good set point for work plane illuminance. When advanced shading control is combined with optimized shading properties, the benefits in energy consumption can be also realized (Tzempelikos and Shen, 2013).

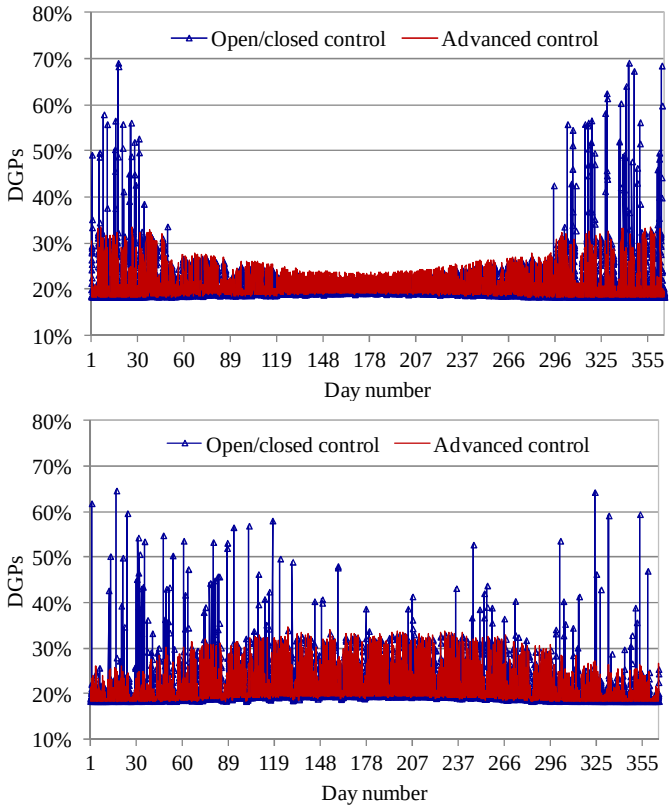

Figure 7: Simplified daylight glare probability as a function of time with open/closed shading control (300 W/m^2 as set point) and with the advanced control for a south-facing modern office in Chicago (top) and a west-facing office in Rome (bottom).

3.2. Overall comparison between traditional and modern building

The modern office with advanced shading control and the traditional office with open/closed control were then compared in terms of site and source energy consumption as well as in terms of operational costs. Heating and cooling system efficiency and site-to-source conversion factors are listed in section 2.1 above. Variable thermostat set points are used as described above to simulate realistic operating conditions. Note that the advanced shading control method requires consideration of extra (sunlit) sub-surfaces in the room which need to be taken into account separately in the thermal and lighting calculations (extra thermal nodes and luminous exitances respectively).

Fig. 8 compares the two offices (for all four orientations) in terms of site energy use for Chicago and Rome. The modern building consumes slightly more energy in Chicago, due to the increased heating requirements with larger windows. The effects of orientation are evident:

south-facing offices with more solar gains reduce the difference in heating requirements between the two office types while lighting energy use is significantly different; therefore, in this case, the total site energy use is almost the same. In contrast, north offices have limited daylight provision and differences in heating dominate. Overall, for Chicago the heating penalty due to increased window area (for the modern building) is higher than the benefits of decreased lighting energy use. However, the breakdown of energy use is important since the cost of energy is different for electricity and natural gas; the total cost for the modern building is lower as discussed next.

The situation is different for Rome: the heating requirements are minimal for this climate, and cooling and lighting have equally important shares. For all orientations except north, the benefits of reduced lighting energy use outperform the penalty for increased cooling requirements (which are also reduced from effective light dimming and advanced shading operation with reflective shades), and therefore the total site energy use is lower for the modern building.

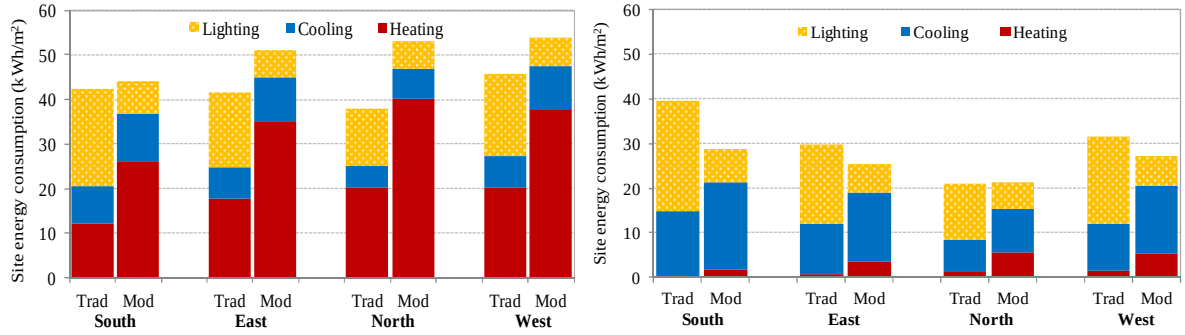

Figure 8: Site energy consumption comparison between traditional and modern office for Chicago (left) and Rome (right).

The source energy consumption results show similar trends (Fig. 9). The modern building has a lower overall source energy use for both climates and all orientations (with the exception of north-facing offices in Chicago). The site-to-source conversion factors are higher for lighting and therefore the total source energy consumption for the traditional building is clearly higher. The differences are larger for the south and west-facing offices in both locations. The results also show the impact of climate (source energy use in Rome is 30 kWh/m^2 lower than Chicago on average).

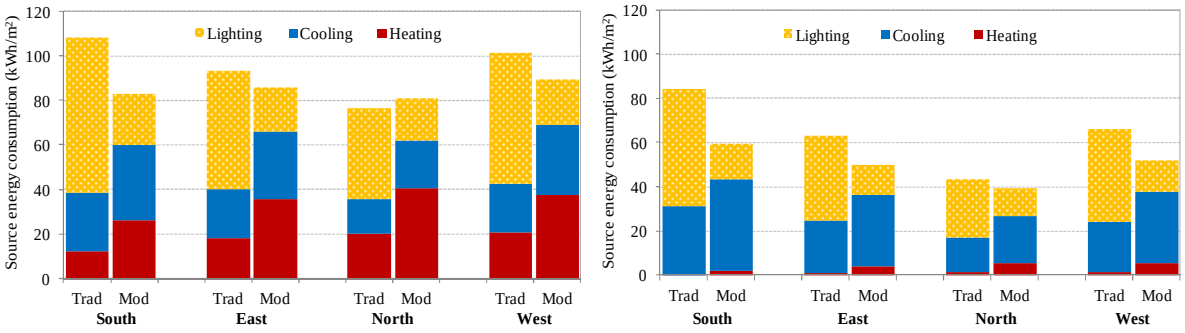

Figure 9: Source energy consumption comparison between traditional and modern office for Chicago (left) and Rome (right).

The final comparison between the two building types is made in terms of annual operational costs. According to the US annual energy review (2012), the most recent average price of electricity for the commercial sector is $0.096/kWh and the commercial cost of natural gas is

typically \$7.82/1000 ft^3. Assuming that 1000 ft^3 of natural gas can produce 1021 kBtu (300 kWh) of heat, the equivalent unit cost of natural gas is \$0.029/kWh. In Italy, the average price of electricity for the commercial sector is 0.237 €/kWh (\$0.32/kWh) and the commercial cost of natural gas is typically 0.70 €/m^3, equivalent to 0.066 €/kWh (or \$0.089/kWh).

Based on these numbers and the site energy use results of Fig. 8, the annual site (operational) energy cost for all the studied cases can be estimated. The results are listed in Table 3. The total annual energy cost for the traditional building is higher than the modern building for all orientations, due to the higher price of electricity (used for lighting and cooling) compared to natural gas (used for heating). This is also true for the climate of Chicago (except north-facing offices) despite the fact that the modern building consumes more total site energy (the breakdown is more important). These results show that the breakdown of energy use and the interactions between lighting and thermal parameters need to examined carefully. Note that the performance of the traditional building would be even lower if opaque walls with a lower R-value had been used, since 3.5 m^2 K/W is considered quite high for most existing buildings with brick cavity walls. In specific locations, time-of-use charges differ and this will need to be considered, along with variable system COP.

Table 3. Comparison of annual operational cost (for heating, cooling and lighting) per unit floor area for the two office types in Chicago and in Rome.

Annual operational cost (\$/m^2 of floor area)								
Location	**South**		**East**		**North**		**West**	
	Traditional office	**Modern office**	**Traditional office**	**Modern office**	**Traditional office**	**Modern office**	**Traditional office**	**Modern office**
Chicago	3.2	2.3	2.7	2.4	2.2	2.3	3.0	2.5
Rome	12.6	8.8	9.4	7.3	6.4	5.5	9.8	7.4

4 Conclusion

This study compares the energy performance of perimeter zones in two commercial building types: a "traditional building", with brick cavity walls and 20 % WWR, and a "modern" building, with curtain wall construction and 70 % WWR. The two buildings use the same high performance glazing, but a more reflective shade is used for the modern building. Façade design is considered a part of perimeter zone design, and the objective is to balance the need for daylighting and view versus the need of controlling of solar gains and maintaining human comfort, while reducing energy demand for air-conditioning and lighting. An integrated thermal-lighting model, previously validated with experimental measurements, was compared with EnergyPlus for simplified thermostat, shading and lighting controls, for the climates of Chicago and Rome. The limitations of EnergyPlus in daylighting modeling were identified and it was shown that the modern building results in higher source energy consumption for both climates if simplified controls are used. The effect of open/closed shading control set points was also investigated, to emphasize its importance and effect on energy use and daylight autonomy.

The model for the modern building was then expanded to include advanced shading controls with intermediate positions that were developed to maximize daylighting while reducing the risk of glare. To avoid using virtual work plane sensors, correlations between work plane il-

luminance and transmitted light can be determined to establish a threshold for selecting intermediate shade positions in order to avoid glare. The advantages of the advanced control compared to an open/closed control were clear in terms of daylighting efficiency and glare protection. Note that this new type of control, also applicable in shading retrofit applications, needs careful practical implementation (e.g. freezing times) to avoid frequent operation of shading devices, which could disturb occupants.

The two building types are then compared with variable thermostat set points to simulate realistic conditions. Simple open/closed shading controls (300 W/m^2 incident solar radiation) are used for the punched windows, while the advanced control is used for the curtain wall façade. A perimeter office for each building type was analyzed in detail, in four orientations and for the two different climates, in terms of site and source energy consumption, and annual operational cost.

Although the modern building has a higher total site energy use in Chicago (due to increased heating requirements with larger windows), the breakdown of energy use results in lower operational costs for most cases, compared to the standard building with punched windows. The effect of orientation is important, since north-facing offices have limited daylight provision and reduced solar gains therefore differences in heating dominate, resulting in higher energy use for the modern office for that case. Overall, the modern office annual operational costs are \$0.9/m^2 (of floor area) lower compared to the building with punched windows, for south-facing offices in Chicago; this difference reduces for other orientations.

In Rome, where cooling and lighting dominate, both total site energy use and operational cost is lower for the curtain wall office for all studied cases. The benefits of reduced lighting energy use outperform the penalty for increased cooling requirements (which are also partially reduced from effective light dimming and advanced shading operation with reflective shades). The annual operational costs for the modern office in Rome are \$2-4/m^2 lower compared to the traditional building, for all orientations except north. For both climates and all orientations, the source energy use is lower for the curtain wall office since the lighting part carries the weight of the site-to-source conversion factor. North-facing offices in heating-dominated climates are the only exception. Finally, the energy use in Rome is lower than the energy use in Chicago, due to a milder climate and efficient solar protection.

This study shows that transparent façades not only provide more natural light and outdoor view, but, if appropriately controlled and integrated with perimeter zones systems and controls, they may result in lower energy use and operational cost compared to traditional brick façades with smaller punched windows. In specific locations, time-of-use charges differ and this needs to be considered in the future, along with variable COP for the cooling system for different climates. A further analysis of initial costs would be useful for overall economic evaluation. The interactions between daylighting and thermal requirements and comfort need to be further studied in terms of advanced materials (glazing, framing, shading, and thermal storage) and integrated, optimized HVAC, envelope and lighting controls.

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