# Coupling dynamic energy and daylighting simulations for complex fenestration systems

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## Abstract

A new tool for energy and daylighting analysis of complex fenestration systems (CFS) is presented. The tool couples the daylighting simulation engine Radiance with the dynamic building simulation engine TRNSYS and performs integrated simulations using the bidirectional scattering distribution function (BSDF) that characterizes the CFS. The use of the tool allows us to implement flexible shading controls based on thermal and daylighting comfort parameters. In order to demonstrate the tool functionality two different control strategies for a shading device, composed of movable venetian blinds, are compared and analyzed.

## 1. Introduction

The use of natural resources through innovative technologies is an excellent way to reach high energy savings and indoor comfort in a building. Daylight in particular influences the thermal and visual comfort, the well-being and health of the building's users, and the energy demand for artificial lighting, heating and cooling. In this work, we focus on the CFS technology (Complex Fenestration Systems). CFS are those systems that contain non-specular layers and whose optical properties present complex dependence on angle and wavelength. That dependence is described by the Bidirectional Scattering Distribution Function (BSDF) (F. E. Nicodemus, 1970; F. Nicodemus et al., 1977). The CFS include fritted and translucent glass and shading devices, such as venetian blinds, woven shades and perforated screens.

These systems provide a good management of solar gains both in terms of energy saving and indoor comfort and are being increasingly used in sustainable design. Therefore, it is important to have a tool that is able to simulate these technologies reliably. In order to obtain accurate results about the thermal and optical response of the fenestration system, the tool has to include the BSDF data in the calculation method. Klems (J. H. Klems, 1994a; J H Klems, 1994b) developed a calculation method to evaluate the BSDF data, which can be generated using window modelling software (e.g. Window7 from LBNL) or simulation programs (e.g. TracePro or Radiance's "genBSDF"). The BSDF can be measured with a goniophotometer (Andersen et al., 2006).

Several tools on the market able to perform integrated energy and daylighting simulations already exist (e.g., DIVA, ESP-r, DesignBuilder, IES-VE), but all have certain limits: either they cannot be combined with TRNSYS or they do not offer the flexibility to decide at each time step during the simulation how to control the CFS.

*OpenStudio* integrates EnergyPlus for energy simulations and Radiance for daylighting simulations. The thermal model used to describe the CFS is based on BSDF data according to ISO 15099. On the other hand, the three-phase method (Saxena et al., 2010; Ward et al., 2011) algorithm provides climate-based daylighting simulation using the BSDF file. One limit is in the usage of BSDF data that are only contained in the *OpenStudio*'s database. In addition, dynamic shading control is not supported, and lighting schedules for each window and shading state combination are pre-calculated and then passed to EnergyPlus for the thermal simulations.

"Mkschedule" (Molina et al., 2014) is a program

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that provides integrated simulations for CFS using the Radiance's three-phase method (3PM) and EnergyPlus. The control algorithm is kept out of the main program and it can be defined through a "Lua" script. The control is flexible and can be based on weather file information or on the output of daylighting simulations. However, the tool does not allow us to apply a control based on thermal parameters.

*Fener* is a recent tool, developed at the Fraunhofer institute, that performs energy and daylighting simulations for advanced analysis of CFS in a single thermal zone (Bueno et al., 2014). The model uses the 3PM and the BSDF data to evaluate indoor illuminance measured by virtual sensors arranged on a sensors grid and solar irradiance absorbed by indoor surfaces. The solar gains are used to evaluate the heat balance of the building. Fener cannot perform multi-zone energy simulations.

"Artlight" is a tool that enables daylighting simulation for CFS in Trnsys. It was developed in the project "Light from Façade" promoted by "Haus der Zukunft" (Link01). The daylighting simulation was performed with the 3PM. The thermal simulations could be performed with Trnsys by choosing among three approaches (called "g-value", "fc model", and "abs") to evaluate the thermal behavior of the daylighting system (Geisler-Moroder et al., 2012). The control strategy could be done on thermal and daylighting parameters. The simulation tool has not been made available.

The present study, developed within the European EU/FP7 project CommONEenergy (Link02), presents a novel tool for the energy and daylighting simulation of CFS (De Michele, 2014). The tool is embedded in a TRNSYS "Type" (a functional block that can be used within the software environment) that calls Radiance's 3PM during the dynamic building simulation.

The tool allows us to share information among TRNSYS and Radiance at each time step. The control is done in TRNSYS in order to be able to choose at each time step the optimal configuration of the shading system. It also allows us to calculate the light dimming schedule within the TRNSYS environment. The control can be set on daylighting and thermal parameters, such as illuminance on the work plane, total radiation on the façade, and internal air temperature, according to the designer's strategy.

To demonstrate the capabilities of the tool, we have compared two strategies for controlling venetian blinds with variable slat angle, with different objectives. The first control strategy aims to increase the energy saving (*Th-Control*), whereas the second one aims to improve the visual comfort (*DLT-Control*). In both cases, artificial lighting can be dimmed. The control strategies shown aim to demonstrate the capabilities and functionalities of the tool. Providing new optimal strategies is not an objective of this work

## 2. Method

### 2.1 Coupling thermal with daylighting simulation

Considering the state-of-the-art tools and their limitations, we have aimed at developing a simulation tool that can provide:

- Integrated dynamic energy and daylighting simulations for CFS using the BSDF data and the 3PM
- Dynamic shading optimization in terms of solar thermal gains and visual comfort at each time step
- Flexible user-defined control strategies

### 2.2 Trnsys

TRNSYS is an environment used to simulate the dynamic performance of building energy models. A main feature is its modular architecture. The several functional blocks provided by the software are called "Types", which can be compiled into DLLs (Dynamically Linked Libraries) for easy sharing and high computational speed. The Types can be linked together to model the interactions between the building components and systems. The linking of the Types is relatively user-friendly thanks to the graphical user interface. The Type dedicated to the thermal building simulations is the "Type56". Trnsys can embed also custom components developed with standard programming languages (C++ and Fortran).

At the state of art, TRNSYS cannot evaluate CFS in depth because it is not yet able to manage the BSDF data. Nevertheless, a new Type is under development that will take into account the BSDF according to ISO 15099 for detailed short wave radiation calculations (Hauer et al., 2014).

## 2.3 Radiance and the three-phase method

Radiance is a validated software already able to manage BSDF data in order to perform daylighting simulations of CFS. In particular, using the 3PM it is possible to perform dynamic daylighting simulations with a climate-based approach. The algorithm is based on the matrix equation i=VTDs, where i is the computed illuminance (or alternatively, irradiance), V is a view matrix that relates the sensors to the CFS, T is the transmission matrix that describes how radiation passes through the CFS and is defined through the BSDF file, D is the daylighting matrix that relates the outer surface of the window to the sky dome, and s is the sky vector that describes the sky condition using the Perez model (Perez et al., 1993; Perez et al., 1990).

## 2.4 Description of the novel TRNSYS Type_DLT

Taking advantage of the development framework offered by TRNSYS, we have developed a new TRNSYS functional block dedicated to daylighting simulations. The novel Type called "Type_DLT" (DayLighTing), written in the C++ programming language, performs the 3PM for dynamic, climate-based daylighting simulations of CFS.

The Type_DLT receives the following input from the weather file:

- Latitude and longitude
- Month, day of the month, hour of the day
- Direct normal illuminance
- Diffuse horizontal illuminance

In this way, it can identify the building location (and thus calculate the sun path) and the information for the climate-based analysis.

The following parameters are set in the Type's control panel:

- Thermal zone for which the shading system is controlled
- Shading state, determining which BSDF is used
- Number of windows associated with the same shading state

These parameters are necessary to identify the thermal zone where CFS are controlled, which CFS assigned to that zone are controlled, and which are the initial conditions for the simulation. A BSDF data file has to be provided for each shading state.

In order to control a series of thermal zones independently, the Type can be added as functional block to the simulation model multiple times, with different parameters, inputs, and outputs.

The outputs of the Type are:

- Maximum (or average, minimum, etc.) illuminance value over the sensor grid
- Current shading state

The control algorithm, defined through a series of equations which can involve inputs and outputs of other Types, the Type56, and the Type DLT are interlinked. Loops between Types can be formed. By default, TRNSYS performs iterations within each time step until all parameters, inputs and outputs of every Type have converged.

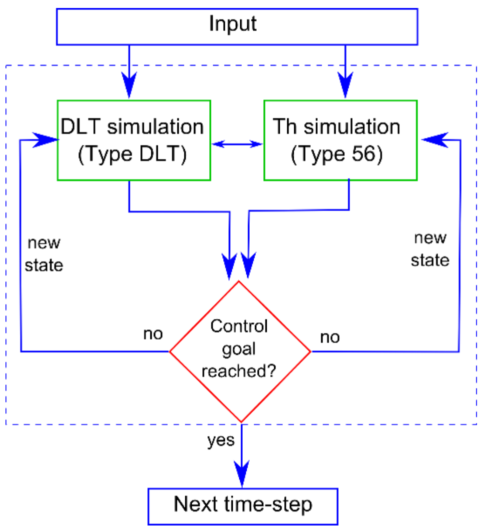


Fig. 8 – Flow chart of the iteration process between daylighting and thermal simulation within each time step

The control algorithm is not incorporated into the Type_DLT, but implemented through the "Equation" functional blocks that TRNSYS offers by default. This has the advantage that the Type_DLT does not need to be recompiled every

time the control strategy has changed and can thus be reused more easily by the user.
Fig. 8 shows the general workflow of the process. Both the daylighting (Type_DLT) and the thermal (Type56) simulations take their inputs. Then, the BSDF data and the Types' outputs are passed to a control "Equation" (a special functional block of TRNSYS in which an equation system can be defined) that modifies the shading states. By default, TRNSYS iterates until all Type outputs have reached convergence. Only then does it advance in time by performing the next time step.

## 2.5 Test model

A very simple but representative model has been chosen to show the capabilities of the Type_DLT. It consists of a single, box-shaped thermal zone, taken from a real project of a shopping mall located in Genoa, Italy (lat. 44.41°, long. 8.85°). The weather file used in the simulations has been taken from the Meteonorm database. The box dimensions are 50 m x 134 m x 7.4 m. It is located 4 m above ground level (Fig. 9).

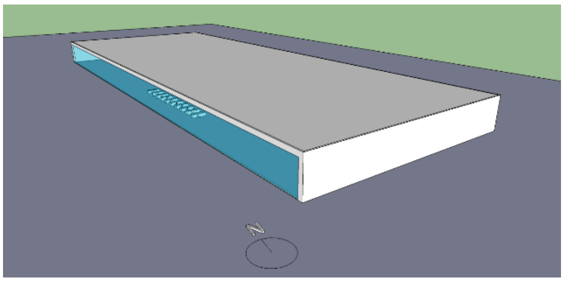

Fig. 9 – Geometry of the daylighting model

The surfaces facing north and south are modelled as adiabatic. The other surfaces are all connected with the outside. The west façade has a glazing area of 132 m x 6.3 m.
Two geometric models have been built, a simpler one for the thermal simulation and a more detailed one for the daylighting simulation. Both models have been drawn with Google SketchUp and exported to TRNSYS and Radiance respectively.
Eleven sensors have been located in a row in the working planes of the cash registers, 5 m from the façade, 0.8 m from the floor, and 1 m distant from each other (Fig. 10). The sensors disposition has been chosen in order to guarantee the visual comfort on the workplace.

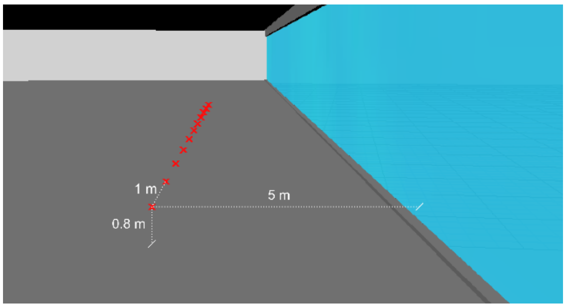


Fig. 10 – Grid of daylighting sensors

The surface reflectance factors used for the daylighting simulations can be seen in Table 10. Wall constructions are shown in Table 11.

Table 10 – Surface reflectance factors

| Surface | Reflectance factor |
|---|---|
| Internal wall | 0.5 |
| Ceiling | 0.8 |
| Floor | 0.2 |
| External wall, ground | 0.35 |

Table 11 – Wall constructions

| Surface | Thickness [m] | U [W/m² K] |
|---|---|---|
| Wall | 0.3 | 0.367 |
| Roof | 0.59 | 0.207 |
| Floor | 0.36 | 0.353 |

The glazing consists of two panes (4-12-4) with low-e coating and argon filling. It has a U value of 1.36 W/m² K, a solar heat gain coefficient of 0.568 and a visible transmittance of 0.810.
The external shading system consists of venetian blinds which can be pulled up and down and whose slats can be tilted at angles ranging from zero (horizontal) to 60 degrees. The slats are 200 mm wide with a spacing of 180 mm and a rise of 20. The surface reflectance is 0.7.

### 2.5.1 Control strategies

We have tested and evaluated the Type_DLT's capabilities by comparing two different controls of the CFS (cf. Table 12). The first control aims at optimizing the energy saving (*Th-Control*), the second at optimizing the visual comfort (*DLT-Control*).

*Th-Control* aims to increase the energy saving and thermal comfort by controlling the solar gains. In the cold season (15th of October – 15th of April) the trigger is the internal air temperature: if it is below 21°C, blinds are pulled up in order to maximize the solar gains. If the internal air temperature exceeds 23°C, blinds are pulled down. The latter condition has been added because people inside the shopping mall will probably be heavily dressed and in motion. During the warm season *Th-Control* closes the blinds whenever the incident solar radiation on the façade exceeds 55 W/m², in order to reduce the cooling load. The daylighting-based *DLT-Control* controls the daylight passing through the CFS by acting on the slat angle in such a way that the internal illuminance measured by the sensors (cf. Fig. 10) is always kept within the useful illuminance range as per LEED v.4 protocol (Link03).

Table 12 – Thresholds used to control the CFS

| Season | Control | Threshold |
|---|---|---|
| Cold season | *Th-Control* | 23°C (21°C) |
| Warm season | *Th-Control* | 55 W/m² |
| All year | *DLT-Control* | 300 – 3000 lux |

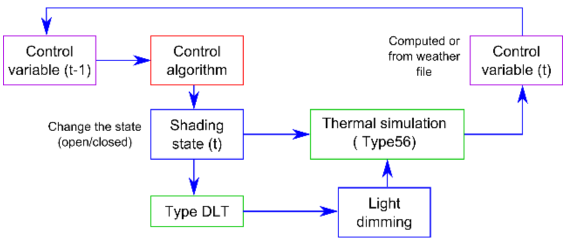


Fig. 11 – *Th-Control* algorithm

*Th-Control* gets the solar irradiance incident on the façade from the weather file (warm season) or the indoor air temperature from the Type56 (cold season). Then, it evaluates the shading state (blinds up or blinds down and closed, that is, with a slat angle of 60°) and passes it to Type_DLT and Type56 for the thermal and daylighting simulations (Fig. 11). The illuminance calculated by the Type_DLT is used to dim the artificial lighting.

In the *DLT-Control* algorithm (Fig. 12), the control receives as input the illuminance from the Type_DLT and an initial shading state that corresponds to the blinds pulled up. If the illuminance measured by the sensors is below 3000 lux, the initial shading state is kept. Otherwise, the blinds are pulled down with a horizontal slat angle. If the measured illuminance is still above 3000 lux, the slat angle is gradually changed from 0° to 60° in steps of 15° until the illuminance is below 3000 lux. In case daylighting provides less than 500 lux, artificial lighting is added to reach exactly this amount (as lights are dimmable). Otherwise, artificial lighting is switched off.

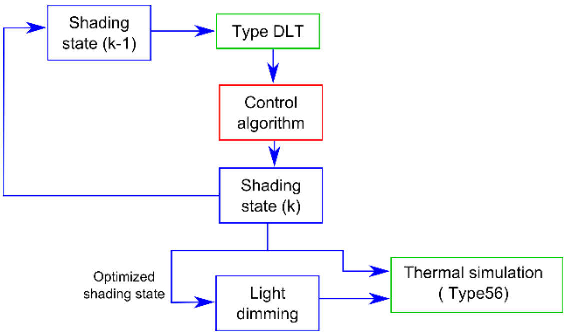


Fig. 12 – *DLT-Control* algorithm

Once the optimal shading state is found, the control passes the information to the Type56 for the thermal simulation.

Both the window and the shading device have been created with Window 6.3 from LBNL, as well as the BSDF data files for each shading state.

As this work is at an early stage, the thermal simulations have been conducted with a simplified approach using the Type56, not implementing BSDF-based calculations. The solar gains have been multiplied by a shading factor Fc calculated according to equation (1.1) from the Solar Heat Gain Coefficient (SHGC) computed in Window 6.3.

$$Fc = \frac{SHGC_{CLEARGLASS} - SHGC_{CFS}}{SHGC_{CLEARGLASS}} \qquad (1.1)$$

### 2.5.2 Schedules and internal gains

The shopping mall is open from 8 am to 8 pm. Occupation during the day ranges from 50 to 1000 people. Setpoint and setback in the cold season are 17.5°C and 14°C, respectively. In the warm season, the setpoint is 24°C. Dehumidification takes place for relative humidities above 60% during opening hours. The heating and cooling system has a maximum power of 120 kW and is turned on (off) one hour before (after) opening hours. The mass air change rates are 7.35 kg/m² h during opening hours and 3.00 otherwise, according to EN 10339. The internal gains are shown in Table 4. The lighting power is relative to 500 lux. For 85% of the floor surface, corresponding to the internal area of the shopping mall, artificial lighting provides 400 lux. In the remaining strip near the glazed façade (15% of the floor surface), artificial light is dimmed according to the amount of daylight in order to provide 500 lux on the working plane.

Table 13 – Internal gains

| Typology | Gain | Unit |
|---|---|---|
| Persons | 185 | W/person |
| Artificial lighting | 10.5 | W/m² |
| Fridges | -9.4 | W/m² |

## 3. Results

First, we compare internal illuminances on the working plane and shading states (Fig. 15 and Fig. 16). As expected, the *DLT-Control* guarantees visual comfort all the year thanks to the broad range of shading states available. Glare and insufficient lighting are effectively avoided. The *Th-Control* optimizes the solar gains, in order to improve the energy saving and the thermal comfort, but without considering the glare problems during the cold season or the gains caused by the artificial lighting during the warm season in order to compensate for insufficient daylight.

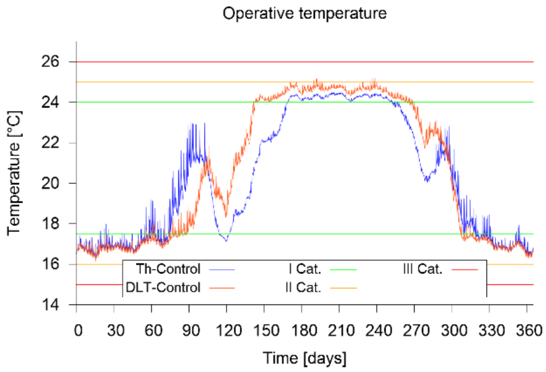


Fig. 13 – Hourly operative temperature. Both controls respect the design limits suggested by EN 15251. However, the *Th-Control* tends to stay closer to the first category, thus providing more comfort.

Observing the operative temperature (Fig. 13), thermal comfort is quite high for both controls. However, looking at the Percentage of Persons Dissatisfied (PPD) in Table 14, it can be seen that the *Th-Control* provides a more comfortable environment during opening hours except for category I, which is intended for sensitive environments, such as hospitals and nursing homes.

Table 14 – PPD values. Percentage of operative hours over the year in which the PPD complies with the categories reported in EN 15251.

| Control | I cat. | II cat. | III cat. |
|---|---|---|---|
| | PPD < 6% | PPD < 10% | PPD < 15% |
| Th | 44% | 68% | 90% |
| DLT | 52% | 57% | 80% |

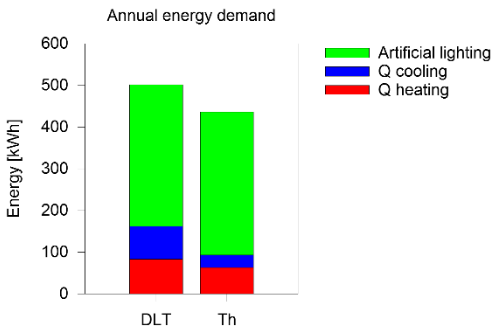


Fig. 14 – Annual energy required for heating, cooling and artificial lighting depending on the control. *Th-Control* requires substantially less energy for heating and cooling than *DLT-Control*.

The energy demand (Fig. 14) confirms our hypotheses regarding the control strategies. The *Th-Control* saves more energy in terms of heating and cooling. On the other hand, artificial lighting requires about 1% more energy, as blinds are pulled down during the warm season in order to reduce the cooling load. *Th-Control* provides energy savings for heating and cooling of about 70 MWh/year with respect to the *DLT-Control* that instead saves a small amount of electricity for artificial lighting equal to 2.25 MWh/year. The differences in terms of energy demand between *Th-Control* and *DLT-Control* are 24% for heating and 62% for cooling. Therefore, the major energy savings are obtained during the warm season. However, closing the blinds also if glare is not a problem significantly compromises the visual comfort. On the other hand, keeping the blinds pulled up during the cold season causes serious glare issues and reduces the energy demand by "only" 24%.

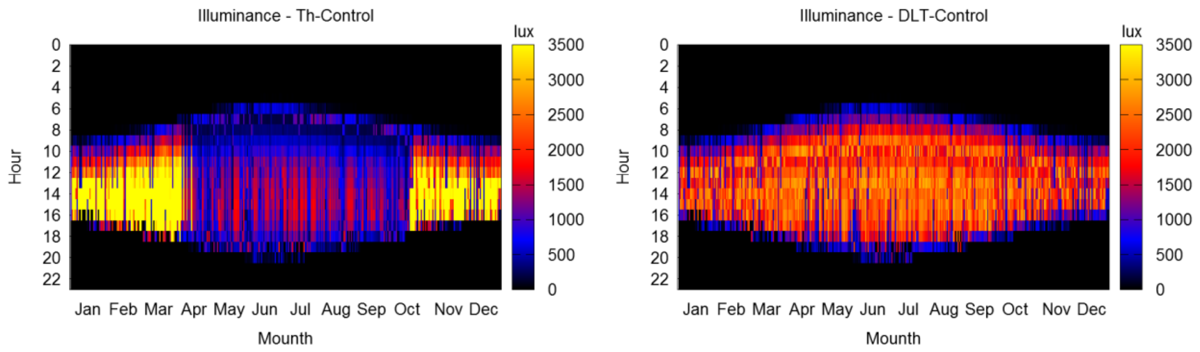


Fig. 15 – Maximum measured internal illuminance. Yellow areas indicate glare conditions. *DLT-Control* provides always a useful amount of daylight for the working activities. *Th-Control* tries to reduce the energy demand and to improve the thermal comfort by keeping the blinds pulled up during the cold season, thus enhancing the solar gains, and by keeping the blinds closed during the warm season in order to avoid an overheating of the zone. However, this strategy substantially deteriorates the visual comfort, especially during the cold season where glare is frequent.

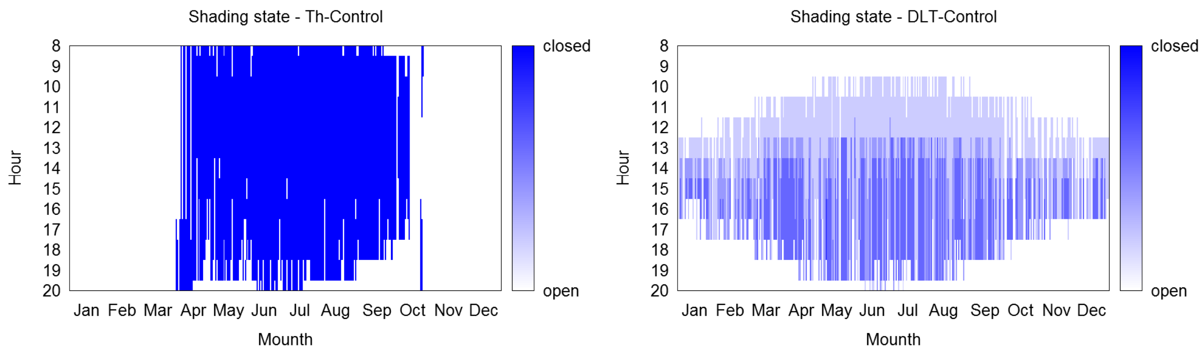


Fig. 16 – Hourly shading schedule. The several states available to the *DLT-Control* allow for a better control of the incident daylight, hence providing optimum illuminances in the range from 300 to 3000 lux.

## 4. Conclusion

We have presented a tool able to perform integrated energy and daylighting simulations of complex fenestration systems (CFS). The tool consists of a novel building block for TRNSYS called "Type_DLT". The Type_DLT uses the BSDF data characterizing the CFS to perform accurate daylighting calculations with Radiance's three-phase method. The method is involved from TRNSYS at each time step during the dynamic building simulation in order to compute illuminances on the working planes. The thermal simulation as well as the control of the CFS is performed in TRNSYS external to the Type_DLT, giving the user maximum flexibility regarding the control strategy, which can be based on both thermal and daylighting parameters.

We have demonstrated the capabilities of the tool by implementing two different controls of a CFS. The thermal simulation is still simplified insofar as it excludes the BSDF. Instead, it is based on the shading factor. Nevertheless, the results are promising and proved to be consistent with the hypotheses made about the control algorithms.

## 5. Acknowledgments

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