Modelling of complex fenestration systems – application of different toolchain approaches on real case scenarios

Abstract

This paper presents a comparative study among simulation tools in their capabilities of evaluating complex fenestration systems in terms of their thermal and daylight performance. Two powerful and flexible toolchain approaches based on EnergyPlus and TRNSYS including third-party tools are analysed in detail and their procedure in model setup are shown. By investing into comparative simulations, capabilities of both toolchains are highlighted and pro- and cons are discussed within this paper. By comparison against measured data, the ability of both toolchains to predict real case scenarios is shown. Satisfying alignment has been achieved for both tools in energy performance prediction (cooling loads, temperatures) as well as daylighting predictions (illuminance levels). Remaining deviations show the sensibility in used model definitions, used data as well as tool handling.

Introduction

The role of CFS modelling

Trends in implementing complex fenestration systems (CFS) in the modern architecture of non-residential buildings are driving the need for improved methods and validated tools for planning and engineering purposes. Especially for highly glazed building facades, the detailed modelling of CFS plays a major role in enabling reliable simulations for thermal and daylighting performance predictions as well as for comfort evaluation.

Models development to evaluate CFS within building energy simulation tools has increased significantly in recent years (Kirimtat et al. 2016). Although the number of tools is increasing, workflows including important aspects like high modelling flexibility, usability and efficient runtime while preserving detailed results is still rarely available – particularly in the field of CFS modelling (Loonen et al. 2016).

Numerous case studies are published in literature, examining the potential of CFS under various climate conditions and room scenarios (Gong et al. 2016; Santos et al. 2018; Bustamante et al. 2015). However, clear and proved workflows in how to gain the required model information as well as how to setup a simulation model for a coupled thermal and daylighting analyse of complex facades are still rare.

At the same time the utilization of daylight in buildings has gained a significant relevance in reducing the electrical energy demand for artificial lighting as well as optimizing the overall energy demand for heating and cooling (Pyonchan et al. 2009). Evaluating building façade systems in the early stage of a design is crucial in order to meet low energy requirements and highest comfort levels in the operation.

Overview on simulation tools for CFS evaluation

The challenge is to define a reliable workflow to evaluate the performance of CFS. Nowadays, several software exist to perform dynamic energy and daylighting simulations for CFS. These tools rely on complex models, which require deep knowledge and simulation skills by the user and often do not offer a co-simulation environment. Moreover, either for the part of daylight simulation as well as the part of thermal simulation of CFS, simplifications are made in the modelling to enable a numerical representation with a reasonable effort in providing input data, model setup and simulation runtime.

For this reason, the use of a trustworthy procedure to simulate CFS and the awareness of the likely error that could occur by using such detailed models is essential for a conscious design of energy efficient buildings.

In (Loonen et al. 2016) the current status, requirements and opportunities on evaluating adaptive facades with the most powerful and validated simulation tools (EnergyPlus, ESP-r, IDA-ICE, IES VE and TRNSYS) is shown. Based on this work, two of the mentioned software packages have been analyzed in course of this research and with specific regards to check their capabilities for a coupled energy and daylight evaluation of CFS.

In the last years, several widely used building simulation tools have extended their ability to perform coupled daylight and thermal evaluations for CFS based on Radiance Three-Phase Method (3PM) (Saxena et al. 2010) and the ISO15099 standard (EN ISO 15099). Even though most of the methods claim to enable an integral approach to increase the overall efficiency concerning daylight and energetic aspects, just a view of them allow timestep-based feedback loops between the thermal and daylight simulation routine. However, this is a crucial aspect for developing improved control strategies and optimizing thermal and visual aspects of a complex façade in detail and close to real conditions.

For the EnergyPlus simulation kernel, serveral graphical user interfaces (GUIs) exist, most of them open source and non-commercial. The probably most widely used is OpenStudio (v.2.7), which enables an energy-, daylight- and glare evaluation of CFS using the 3PM (Guglielmetti 2015). Nevertheless, the functionality is limited as it does not allow to insert user-defined bi-directional scattering desitribution functions (BSDFs) for thermal and daylight calculations as well as no adaptive shading states according to daylight and thermal conditions. Instead of a timestep-based coupling, OpenStudio precalculates annual illuminance schedules for each window group (windows, which are equally controlled) as well as for the control of a simplified shading (Fc-factor). A powerful and flexible apporach is connecting EnergyPlus via using the Grashopper plugins Ladybug and Honeybee with Rhinoceros. Beside the Radiance Five-Phase Method (Lee et al. 2018) it also enables userdefined BSDFs for the thermal and daylight calculation. Howerver, a compiled energy and daylight optimization on timestep basis is still not implemented.

IDA ICE (version 4.7 and higher) allows the smplified calculation of daylight factors and illuminance values for several thermal zones, userdefined sensor grids as well as different sky models. By (Karlsen et al. 2015) a method is presented to couple IDA ICE with Radiance using the 3PM. Nevertheless, a timestep-based coupling between thermal and daylight evaluation is also not possible.

IES VE and ESP-r enable simplfied daylight calculations based on the radiosity method as well as rayracing technique by using Radiance. Also there, the integrated daylight module is rather for calculating the daylight-responding artifical light demand instead of detailed coupled simulations. Algorithms for detailed CFS analysis are not included.

TRNSYS involves since version 18 additional daylighting functionalities within Type56 using Daysim. Additionally it enables a detailed thermal modelling of the CFS using the latest model implementations based on a combination of bidirectional scattering distribution functions (BSDFs) and the ISO15099 standard (Hiller and Schöttl 2014). The Grasshopper-based platform TRNLizard enables parametric modelling with focus on coupled thermal and daylight analysis (Frenzel and Hiller 2014).

Nevertheless, also in Type56 daylight calculations are primarily used for calculating the daylight-responding artificial light demand as well as enabling dynamic shading strategies based on a simplified Fc-factor.

To perform a compiled thermal and daylight analysis of CFS, the Artlight routine was developed and implemented as a new TRNSYS-Type (Hauer and Geisler-Moroder 2017). Artlight showed firstly and with success the capability of a time-step based coupling of thermal and daylight simulations. In combination with the new Type56-BSDF model, TRNSYS enables an accurate evaluation of shading elements and daylight redirecting components in terms of visual and thermal performance, paired with the development of enhanced control strategies.

Toolchain approach for coupled thermal and daylight evaluation of CFS

Among all tools of the undergone tool screening, EnergyPlus and TRNSYS are those, which provide the most of the necessary functionalities to perform a coupled thermal and daylight evaluation. Based on these tools, two toolchain workflows (ref. Figure 1) have been defined starting from the shared geometry platform Rhinoceros. The free available Grasshopper plugins Ladybug and Honeybee connect EnergyPlus and Radiance, while TRNLizard in combination with Artlight connects TRNSYS with Radiance. In Rhinoceros the geometrical modeling is done, via Grashoopper the model set up as well as the transition into the simulation input files to perform the simulations in EnergyPlus (*.idf) respectively TRNSYS (*.d18, *.b18).

This toolchain approach guarantees a common databasis to enable comparative evaluations of the gained results.

Beside different tool handling approaches, the methods and databasis behind both toolchains are similar. In terms of flexibility, both tools allow advantages and disadvantages for indiviual tasks. By investing into comparative simulations, capabilities of both toolchains are highlighted and pro- and cons are discussed within this paper. By comparison against measured data, application of the toolchain on real case scenarios are shown.

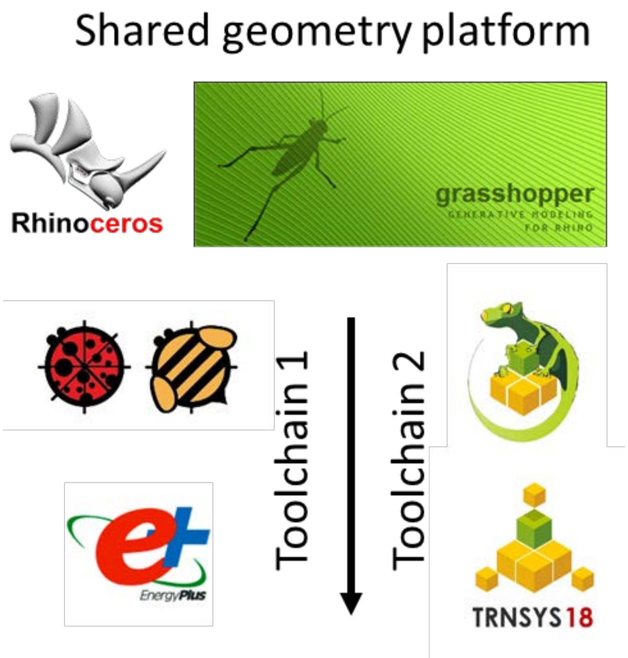


Figure 1: Toolchain workflow for evaluating CFS

A major reason that most tools come up with a scheduled model input instead of instantaneous timestep coupling is due to time and data intensive simulation effort, as the 3PM workflow has to be executed at least once within each simulation timestep. The loss in flexibility by precalculated illuminance values and shading states has to be accepted thereby.

Simulation workflows

In following subsections, the modelling capabilities of the tools involved in both toolchains are explained in detail and compared. Moreover, the thermal-daylighting interaction capabilities are discussed.

Rhinoceros – TRNLizard/Artlight - TRNSYS

Since TRNSYS18, a free plug-in for Grasshopper named TRNLizard was released, which allows to perform parametric thermal and daylight simulations based on a 3D-geometry in Rhinoceros. It combines the advantages of the parametric architecture from Grasshopper tools with the powerful solving engine of TRNSYS kernel. By the modular structure of the TRNLizard, it provides a greater flexibility compared to the classical Simulation Studio interface. Starting from a pre-defined template for a single-zone simulation, it also allows to include user-defined components (Types). Within this tool comparison, Rhinoceros is used as geometrical platform to setup the geometrical model and the TRNLizard plug-in is used to setup the energy model for the thermal simulation. For this study, Artlight was implemented as user-defined component in TRNLizard.

With Artlight, a coupling of the thermal modelling TRNSYS with the daylight modelling in Radiance is realised. The daylight simulation routine is based on the Radiance 3PM, while the detailed thermal modelling of the CFS is done using the latest model implementations in Type56 since TRNSYS 18.

Artlight is linked with the radiation processor (Type15) for the environmental input data as well as with the multizone building model (Type56) for the coupled daylight and thermal modelling. The structure of the Artlight-routine is shown in Figure 2.

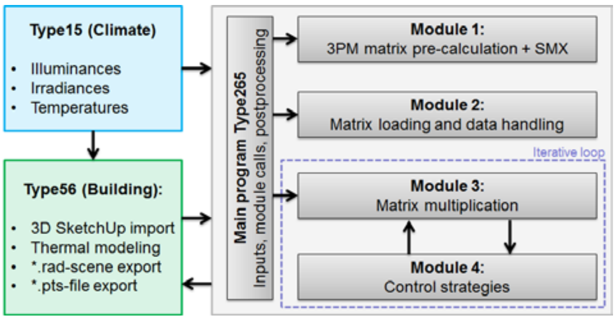


Figure 2: Structure and input-output of Arlight

Module 1 can either use the exported files from Type56 or a manually created Radiance scenes to generate the view matrices and the daylight matrices. As a default, the daylight matrix is calculated using the Reinhart MF:4 subdivision of the Tregenza sky (2306 patches).

The view matrix has to be calculated separately for each window part and for each orientation. Using Radiance tools, a user-provided *.epw-file can be converted via the *.wea-file format into a sky matrix (*.smx). The BSDF data for the transmission matrix has to be provided separately for each window subdivision and sets of blind positions by the user. They can be generated with external tools (WINDOW7, genBSDF).

To enable a fast calculation, all necessary matrix data to perform the daylight simulation has to be loaded into the RAM before the first simulation timestep. The data loading, caching and flexible storage (re-)allocation depending on the actual simulation setup is done in Module 2.

$$Z = \begin{bmatrix} 1 \\ .. \\ 2306 \end{bmatrix}^T * \begin{bmatrix} 1 & 145 \\ .. & .. \\ 2306 & .. \end{bmatrix} * \begin{bmatrix} 1 & 145 \\ .. & .. \\ 145 & .. \end{bmatrix} * \begin{bmatrix} 1 & s \\ .. & .. \\ 145 & .. \end{bmatrix} \quad (1)$$

In Module 3, the whole 3PM matrix multiplication given in eq. (1) is processed in a repeating loop depending on the number of window (subdivisions) and façade orientations. As a result, the timestep-based illuminance and luminance values are analysed, if they achieve the given threshold criteria shown in eq. (2) and eq. (3). Index number “s” represents the number of sensor points.

$$Illuminance: \left[\frac{\sum_{i=1}^{s} E_i}{s} \geq 500lx)\right] \xrightarrow{then} true \quad (2)$$

$$Luminance: \left[\sum_{i=1}^{s} (L_{s,o} \leq 5000\frac{cd}{m^2})\right] \xrightarrow{then} true \quad (3)$$

Different implemented control strategies further allow running the coupled simulation either focussing on thermal optimization or daylight optimization of the situation in the room.

Rhinoceros –Honeybee – Energy Plus

Honeybee[+] is an improved version of Honeybee legacy, which allows for extensive analyse of daylighting performances of CFS. In fact, the tool includes the several matrix methods of Radiance (Subramaniam, 2017), and allows to employ BSDF with different resolutions (i.e. Klems and Tensor-tree) as well as a 3D geometry of the shading device. Honeybee[+] offers a default control strategy based on interior illuminance level, either global or direct. Other controls can be defined by modifying the python code of the *dynBlindSchd* component, but this requires a coding capability by the user. Alternatively, a csv file with the shading configuration can be addressed.
Concerning the thermal modelling, even if EnergyPlus allows for analysis of CFS by means of ISO15099 coupled with BSDF for the optical part, it is not possible to directly use this module in the Honeybee components.

A customization of the idf file is required to import the BSDF into Honybee and activate the Complex

Fenestration State object. The procedure includes two steps:

1. From the idf file containing the BSDFs and the other fenestration system information, the section Construction:ComplexFenestrationState has to be extracted, and connected as *EPconstruction* to the window component.
2. The remaining information in the idf has to be set as *addittionalString* input to the *runEnergySimulation* component.

The control of Complex Fenestration State con be done through EMS (Energy Management System) object within EnergyPlus. Nevertheless, the EMS has not been yet implemented in Honeybee, this lack limits the applicability of the tool for dynamic CFS that require BSDF data to be characterized. If standard shading system are employed (i.e. venetian blinds, roller shade, performed mesh and switchable glazing), the several shading control types of EnergyPlus can be set in the *EPWindowShades* component.

An interaction between thermal and daylighting physics is not possible during simulation run-time. Information are shared as schedule after one of the simulation has completed. In particular, energy and daylighting simulations can share schedules for the shading activation and daylight-responding artificial light demand. In this sense, Honeybee is user-friendly since the user is not required to manipulate or post-process the data from one simulation to the other.
Nevertheless, this functionality prevent the possibility to define multi-objective control strategies that involve simultaneously thermal and daylighting parameters, such as interior air temperature and illuminance values.

Simulation test cases

In this section, the undertaken simulation test cases are described. To check both toolchain approaches against each other, two major comparative settings have been defined: (1) on a theoretical basis with a shared geometry model and (2) an individual comparison of both toolchain workflows against measured data.

Shared geometry model: PASSYS cell
For the theoretical model comparison, a geometrical box model representing the PASSYS outdoor test stand at University of Innsbruck (ref. Figure 3) is used, as it is also needed for the second comparison against real-case measurements with an installed test façade.

The geometry represents an office box with the dimensions of 4.98 m x 2.77 m x 2.73 m. The south-oriented façade involves three façade areas (FA) including an opaque part (FA1) and two transparent façade parts in the middle (FA2) and the top (FA3) of the facade. Both parts can be equipped with different shading systems and can be also controlled independently.

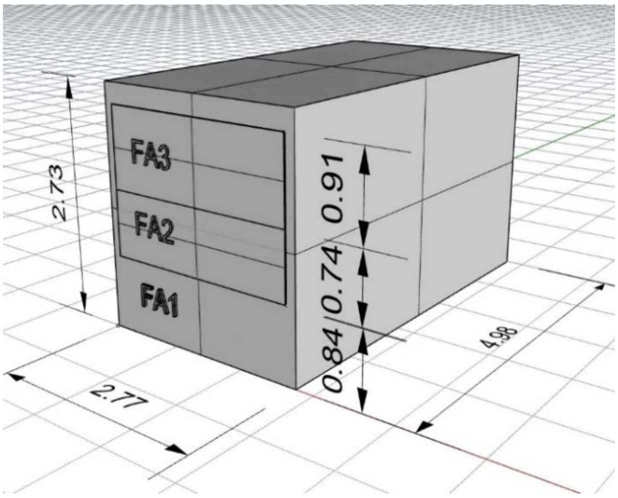


Figure 3: Sketch of the PASSYS test cell model in Rhinoceros

Theoretical comparison
For the theoretical comparison of both proposed simulation toolchains, the PASSYS box was modelled with constructions for walls, roof and ceiling based on theoretical values from literature. All surfaces are modelled with external boundary conditions (wind and sun exposed) except the backside wall, which is modelled adiabatic towards the adjacent service room. Other settings like ventilation, infiltration and internal gains set inactive in order to reduce modelling influences. Heating and cooling set points are set constantly to 20°C respectively 26°C. For the simulated location of Innsbruck, the EnergyPlus weather file (*.epw) from EnergyPlus website is used.

Measurement comparison
For the real case comparison, monitoring data from the PASSYS outdoor test stand from two separated test phases including a shaded and non-shaded façade setting are used. Climate data is available in a 3-minute interval from the weather station on site including ambient dry bulb temperature and incident radiation in horizontal and vertical (south) orientation – separated into a direct and diffuse component.

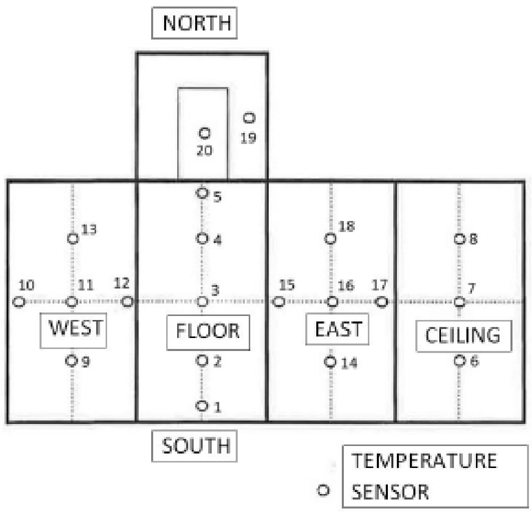


Figure 4: Sensors installed in the PASSYS cell envelope

For the thermal model comparison monitoring data is evaluated for inside and outside surface temperatures of walls, floor and roof, room (ref. Figure 4), air temperatures in 3 different height levels as well as power loads for heating, cooling and internal gains.
For the daylighting comparison, two horizontal illuminance sensors positioned along the centreline of the room towards the room depth with 1.5 m (near) and 4 m (far) distance from the façade installed.

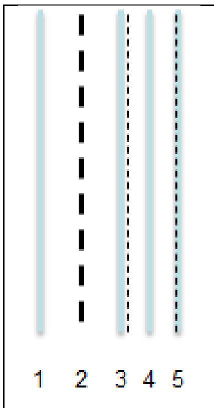
Installed test façade

During the monitoring phase, a closed cavity façade with two separate venetian blind systems (ref. Figure 5) was installed in between of an impingement glazing and a 3-pane insulation gazing unit towards inside.

Figure 5: Installed monitoring facade at PASSYS-cell

For monitoring phase 1, the facade is not shaded (retracted blinds in FA2 and FA3). For monitoring phase 2, the façade states in shaded condition: FA2 is equipped with a downwards curved, diffuse shading blind, FA3 is equipped with an upwards curved, reflective blind forcing specular daylight reflection towards the depth of the room.

Table 1: Monitoring facade setup (WINDOW7)

	Pos	ID	Name	mm
	1	65009	Float glass	7.7
	2		Air & System	80.0
	3	65010	Float glass (with lowE)	8.8
		9	Argon/Air (90%/10%)	16.0
	4	65011	Float glass	3.8
		9	Argon/Air (90%/10%)	16.0
	5	65010	Float glass (with lowE)	5.8

Simulation model setup

In this section, the detailed setup of the façade model within both simulation toolpaths is described as well as the fit of the thermal cell model to match the real-case situation of the PASSYS cell.

Facade model setup

For the detailed thermal modelling of CFS within the multizone building model, both investigated toolchain workflows use similar procedures. Since TRNSYS 18, a new model routine based on BSDF are available (Hiller und Schöttl 2014). The standard window model in TRNSYS, which is based on one-dimensional angular dependent values for transmission, reflection and absorption, is still available. In contrast, the BSDF model enables a detailed modelling for the multiple scattered reflection and transmission, which is significant for blind systems, especially in case of specular daylighting systems.

In TRNSYS as well as EnergyPlus, the modelling is separated into shortwave radiation modelling by the pre-calculated BSDF data and the interrelated longwave radiation modelling according to algorithms defined in the ISO15099. This standard is currently still the most comprehensive and available modelling standard for complex glazing systems incorporating blinds.

To gather the system data for the model definition in TRNSYS and Energy Plus, WINDOW7 was used as third-party and free-to-use tool from LBNL as a shared data base to describe the optical glazing properties, using entries from the IGDB (ref. Table 1). For modelling the shading blinds in detail, the genBSDF tool within Radiance was used to simulate a Klems BSDF based on Geometry and Material description of the blind (ref. Table 2).

By importing the created BSDF into WINDOW7 as user defined shading layer, an overall system BSDF was created by combining it with the glazing layers.

Table 2: Specification of used blind systems

Parameter	System - FA2	System – FA3
width	60 mm	60 mm
spacing	52 mm	34 mm
rise	4.6 mm	6 mm
ε_{front}	0.88	0.04
ε_{back}	0.88	0.88
$material_{front}$	RAL9016	Miro3
$material_{back}$	RAL9016	RAL9016

PASSYS cell model fit to measured data

In order to calibrate the theoretical model with the real test box, a measurement period of two weeks (calibration phase) was used to match the construction setup with the real conditions. By using GenOpt, the thicknesses of the different construction layers were varied by using the measured room temperature as target function for the optimization process. By this, the overall U-value of the envelope as well as their thermal capacitance were optimized.

The boundary conditions of the PASSYS cell were measured over a period of two weeks (4th of January 2016 to 18th January 2016). The parameter identification problem optimizes the root mean squared value of the overall difference between measured data (ref. Figure 4 with inside surface temperature of 5 envelope surfaces and air temperature) and simulated data.

For building performance, analysis error can be defined as shown in equation (4) by the difference between a predicted value and a measured value. In the present case, the error calculated for summation of the indoor air temperature and inside surfaces temperature averaged in the test room.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(ma_i - sa_i)^2 + \sum_{i=1}^{n}\sum_{j=1}^{5}(ms_{ji} - ss_{ji})^2}{n}} \quad (4)$$

ma_i = measured air temperature
sa_i = simulated air temperature value
ms_{ji} = measured inside surface temperature for different wall orientations
ss_{ji} = simulated inside surface temperature for different wall orientations

To solve the parameter identification, hybrid generalized pattern search algorithm with particle swarm optimization algorithm was used. Using this algorithm, the cost function mentioned in the previous section was parametrized.

The parametric identification of this model reduces the thermal capacitance of air by 20%. On the other hand, insulation thickness of the insulation material was decreased on most of the wall except the ceiling. The upper bound of the ceiling thickness is 0.4 m in the literature and reached the peak at the end of the optimization process. This is because the ceiling was entirely exposed to solar radiation of the PASSYS-cell assuming that heat gain through ceiling was greater compared to the other wall constructions. Wall to service and floor experiences the maximum decrement in terms of thickness of the insulation layer, almost 50% in both cases. As the PASSYS cell is lifted above from the ground by pillows, the outside surface of the floor is not in contact with the ground. Besides, thickness of concrete layers with high thermal mass have been also decreased to reduce the overall thermal capacitance of the model.

After the optimization process a cross-check period was used to validate the optimized model. The correspondence between measured and simulated room air temperature for the cross-check period reached a remaining root mean square deviation of 0.98 K.

Simulation results and analysis

In following subsections, the results for the theoretical model comparison between both toolchain approaches as well as the comparisons against measurements is shown.

Theoretical model results

In a first step, both toolchain approaches are tested based on the theoretical PASSYS model using the literature values for the construction layers. Also for the façade model setup, the same dataset was used according to the description in the previous chapter.

Two cases have been evaluated: for case 1, the theoretical PASSYS model was modelled using external boundary conditions for all walls (except the northern wall, which is adjacent to a service room). Beside this, the convective heat transfer coefficients for all surfaces (inside and outside) are calculated in EnergyPlus and used as input in TRNSYS. Physical parameters like solar absorption and longwave emissivity are set equally.

Table 3. Case 1 - Ideal heating and cooling loads

Case 1	EnergyPlus		TRNSYS	
	heating	cooling	heating	cooling
Wh/m2	10340.3	8646.59	12725.56	10461.29
kWh/m2	10.34	8.64	12.72	10.46
rel. dev.	20.68%	18.99%		

For case 1, the results show significant differences of 20.68 % for heating and 18.99 % for the cooling energy demand between both toolchains. TRNSYS estimates clearly higher demand compared to EnergyPlus.
To improve the situation, in case 2 the surface outside temperatures of all outdoor walls (except the south façade) – calculated by EnergyPlus - have been used as temperature boundary condition input for the external walls in TRNSYS. By this approach, the differences in the results between both tools have been reduced significantly for the heating demand to 5.29 % and for the cooling demand to 0.54 %. Therefore, the model setting of case 2 is used for further theoretical analysis.

Table 4. Case 2 - Ideal heating and cooling loads

Case 2	EnergyPlus		TRNSYS	
	heating	cooling	heating	cooling
Wh/m2	10272.06	8646.60	10833.02	8601.29
kWh/m2	10.27	8.65	10.83	8.60
rel. dev.	5.29%	0.54%		

For case 2, Figure 6 shows the match for the free floating room temperature between both toolchain approaches. In a yearly trend, slightly higher deviations have been shown in winter months (October – March). In general, the value for the rRMSE based on a yearly simulation is low with 4.72 %. Beside the sensitive room air temperature, also the operative room air temperature corresponds well between both tools.

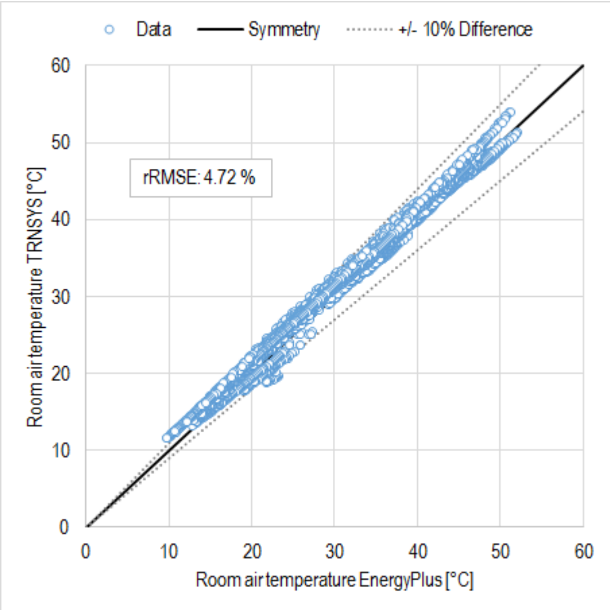


Figure 6: Comparison of sensitive room air temperature

A similar comparison between both toolchain approaches is shown in Figure 7 for the resulting inside surface temperature of the glazed façade. Except of some particular higher deviations, the rRMSE based on the yearly simulation result is again low with 4.78 %.
For this comparison, in EnergyPlus the spectral window model is used, while in TRNSYS the new Type56 BSDF model is used. Switching in TRNSYS to the DOE-model caused higher deviations in the results.

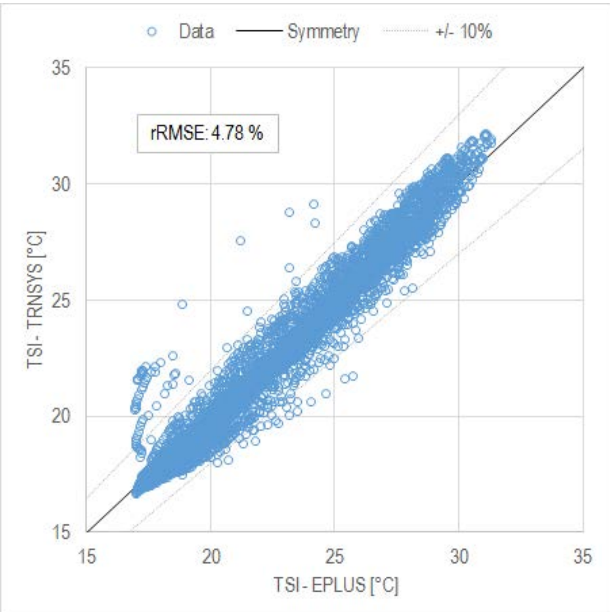


Figure 7: Comparison of inside glazing surface temperatures for the glazed situation

In Table 5 minimum, maximum and mean values are shown for the inside glazing surface temperature. For the case without blinds, FA2 and FA3 shows identical results through the same setting. The mean values corresponds well between both toolchain approaches with 0.1 °C. Also the differences for the maximum and minimum value lower than 1 °C.

Table 5: Statistical values for the glazed situation of the theoretical model comparison

	EnergyPlus		TRNSYS	
	FA2	FA3	FA2	FA3
Max [°C]	31.31	31.31	32.15	32.15
Min [°C]	16.93	16.93	16.69	16.69
Mean [°C]	22.75	22.75	22.65	22.65

For the comparative case with blinds in both façade areas, the correspondence of the inside glazing surface temperature between both toolchain approaches is shown. In this case, also Energy Plus is using now the integrated BSDF model including ISO15099 standards for the complex glazing modelling. EnergyPlus shows slightly higher temperatures in this case then TRNSYS.

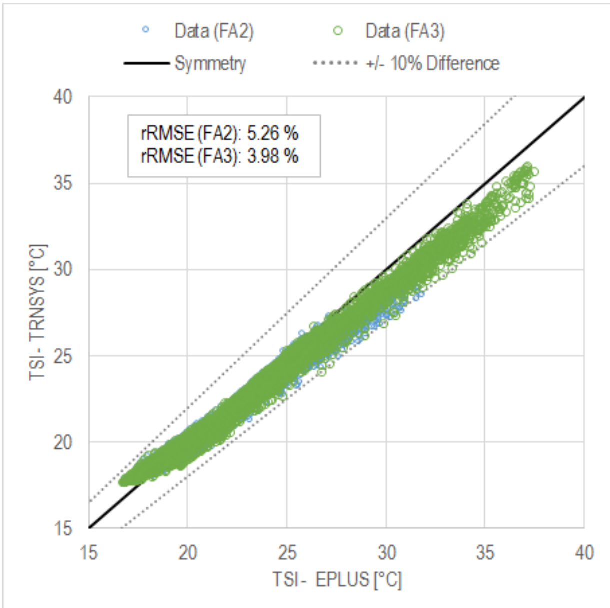


Figure 8: Comparison of inside glazing surface temperatures for the shaded situation

The maximal and minimal temperature between both toolchain approaches differs now up to 2 °C for both façade parts. Nevertheless, the mean temperature value is within 0.5 °C difference. Also the rRMSE for both blind parts are low with 5.26 % respectively 3.98 %.

Table 6: Statistical values for the shaded situation of the theoretical model comparison

	EnergyPlus		TRNSYS	
	FA2	FA3	FA2	FA3
Max [°C]	32.80	37.49	30.88	35.96
Min [°C]	16.76	16.74	17.61	17.64
Mean [°C]	23.18	23.80	22.81	23.45

For the theoretical model comparison, hourly illuminance values calculated by Artlight (TRNSYS) and Honeybee (EnergyPlus) are compared. As both algorithms base on the Radiance 3PM and use the same input matrices (SMX, DMX, BSDF, VMX), similar results have to be expected. As shown in Figure 9, the daily profile for the 1st of January and for the shaded situation shows a perfect correspondence of the results.

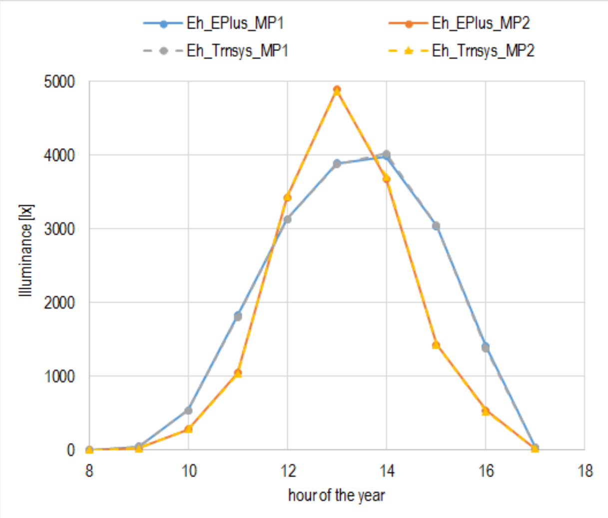


Figure 9: Comparison of illuminance results for the shaded situation

Comparison against measured data

For the comparison against measurement, the box model of the PASSYS cell from the previous theoretical comparison was overtaken. The box was again modelled with outside surface temperature as boundary condition. Instead the modelled surface temperature, the measured outside surface wall temperature from the monitoring phase is used, which also corresponds to the model setup during the optimisation process. The south wall including the testing façade had to be modelled as external wall including solar radiation and temperatures.

The radiation measurement was done for the global and diffuse part on the horizontal (situated next to the PASSYS cell) as well as on the vertical (directly next to the measuring façade). EnergyPlus is restricted to horizontal radiation input data (direct-normal, diffuse), while TRNSYS also allows to use vertical measured radiation data (global, diffuse) as input for Type56. EnergyPlus is using the Perez model to calculate the vertical radiation, while for TRNSYS directly the vertical measured radiation is used. In Figure 10, a comparison of the global radiation measured in the façade compared to the calculated one by EnergyPlus is shown. It shows a reasonable accordance for the comparative purpose with an rRMSE of 4.18 % for the measurement period 1 (without blinds).

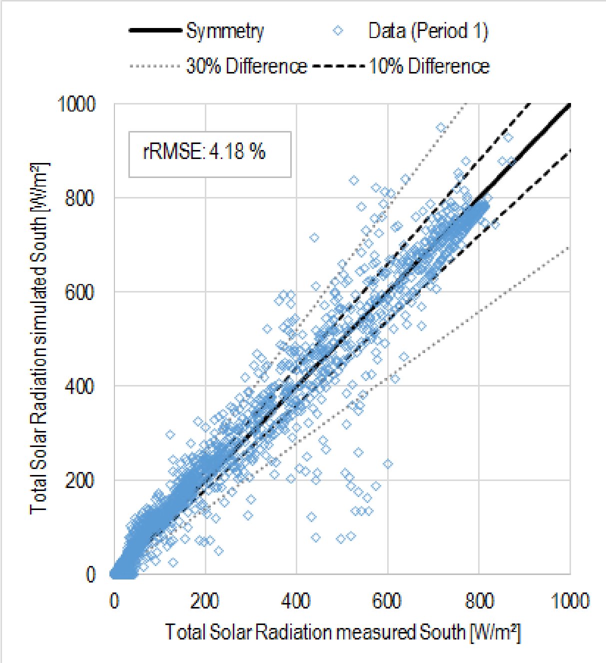


Figure 10: Comparison of the solar radiation input for the test-facade

Also for the measurement comparison, a case without shading (gathered blinds) as well as a case with active shading (FA2: shading blinds with 0°, FA3: redirecting blinds with 0°) has been analysed. In Figure 11 the total transmitted solar radiation through both façade areas are compared. TRNSYS shows slightly higher transmittance values in the morning and evening hours, while the daily peaks corresponding well.

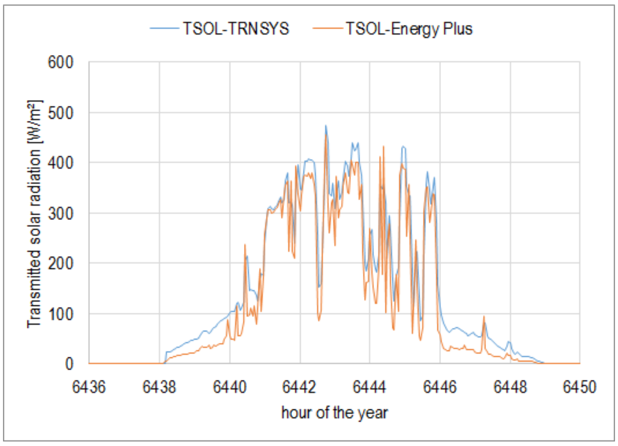


Figure 11: Transmitted solar radiation for the glazed situation

In Figure 12 the same comparison is shown for the total solar transmitted in case with blinds. Significant differences in the instantaneous values between EnergyPlus and TRNSYS are shown. While the thermal BSDSF model in TRNSYS interpolates between the neighbour patches, EnergyPlus takes the actual value of the patch hit by the sun. Nevertheless, the integral value of the day is similar.

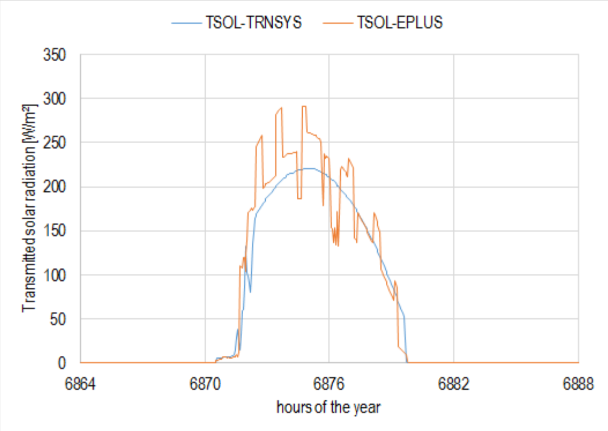


Figure 12: Transmitted solar radiation for the shaded situation

The comparison of measured and simulated illuminance values shows that a satisfying correspondence could be found for days with diffuse conditions. The used daylight simulation models are similar to the theoretical comparison. The comparison against measurements is evaluated only with TRNSYS and Artlight, as shown in the theoretical comparison, the daylight algorithm in both tools are identical. In Figure 13 the comparison between simulated and measured results (Case 1: only glazing) show a good agreement with an rRMSE of 10.77 % for the façade near measurement point (MP1) and an rRMSE of 5.46 % for the façade far measurement point (MP2). For MP1, the simulation is slightly overestimating the illuminance values compared to the measurement.

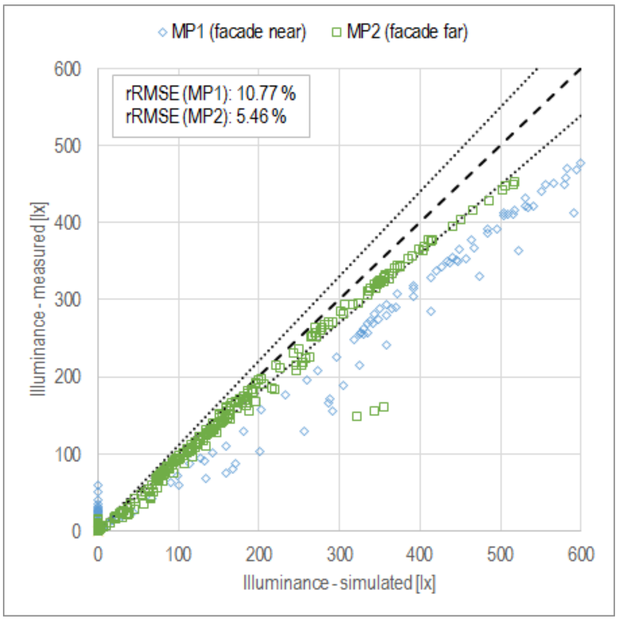


Figure 13: Comparative illuminance values - glazed situation

Also for case 2 (FA2: shading blind, FA3: redirecting blind) the results are satisfying for both measurement points (ref. Figure 14). For both cases, at days with high parts of direct solar radiation the simulation clearly overestimated the illuminance values compared to the measurement. This issue is still under research, nevertheless it seems to be strongly connected to errors in the measurement of the direct and diffuse radiation components.

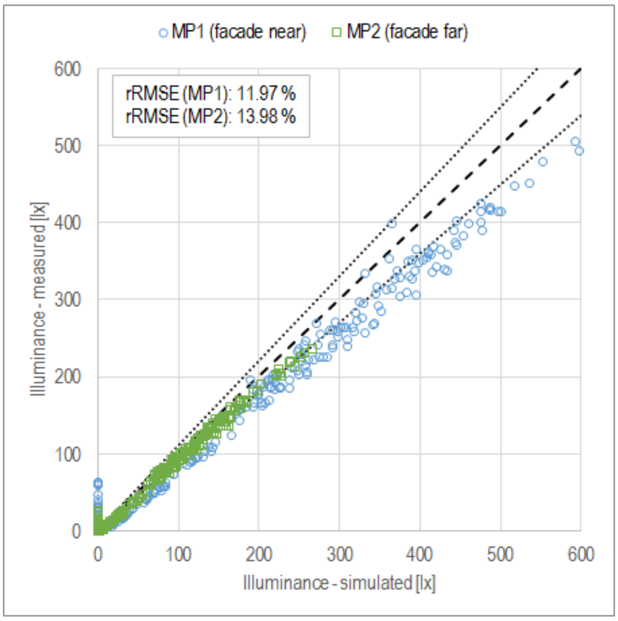


Figure 14: Comparative illuminance values - shaded situation

For comparing the simulated and measured cooling load during the operation of the PASSYS cell, the measured room air temperature was used as target function in the simulation, which was reached within each time step by setting ideal heating and cooling in the simulations.

Figure 15 shows a 2-days trend of the instantaneous values (3min interval) as well as the averaging hourly trend of the cooling loads for the glazing situation. It includes the measured values during the PASSYS operation as well as the simulated cooling loads by TRNSYS and EnergyPlus.

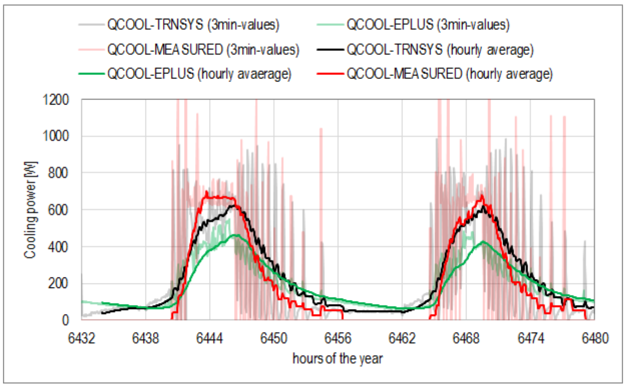


Figure 15: Instantaneous cooling load - glazed situation

The high peak values are resulting from continuous on-off operation mode of the cooling unit, caused by the high cooling power installed in the PASSYS cell. Similarly, TRNSYS reacts by assuming an ideal cooling system. A detailed comparison of the instantaneous cooling peaks shows a good agreement between simulated values in TRNSYS and measurement. Other than TRNSYS, EnergyPlus does some averaging of the output values, which reduces the peaks in the resulting cooling load.

In general, the simulated values in TRNSYS are closer to the measured results, while EnergyPlus underestimates the cooling load significantly. Compared to TRNSYS, the results from EnergyPlus show higher cooling loads during the night times, which can be caused by higher thermal capacitance. Nevertheless, this effect was improved significantly after optimizing the thermal model towards the measurement data using GenOpt.

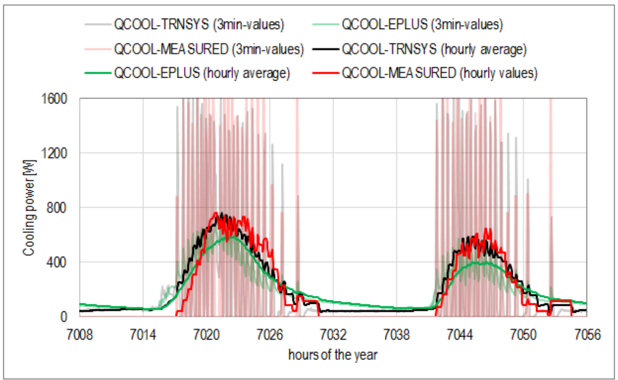


Figure 16: Instantaneous cooling load - shaded situation

For case 2 using shading blinds, Figure 16 shows the comparison for another 2-days trend. Also in this case, TRNSYS corresponds well with the measured values, while EnergyPlus is underestimating the cooling load. Still, both toolchain approaches show clearly the ability, to represent the measured situation with high accuracy.

Conclusion

With both proposed toolchain workflows, two powerful and highly flexible approaches have been shown and applied successfully on theoretical as well as real-case scenarios. Allowing Rhinoceros as well as WINDOW7 as a shared platform for geometry modelling and CFS data setup hence the common approach. Nevertheless, differences occurred in the theoretical comparison although all influencing model data and parameters have been adjusted. Reasons for this are due to different modelling routines and algorithms within the used tools.
The gained results for the measurement comparison for thermal comparison as well as for daylighting results are promising and show a high reliability of the models. Especially after optimizing the thermal model, results improved significantly. Detailing the reasons for remaining differences will be part of further studies.

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