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M4.1 Analysis of calculation approaches for complex fenestration systems

WP4. Modelling, T4.1 Tools for the coupled simulations

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1 Introduction

Implementing Complex Fenestration Systems (CFS) in the modern architecture of non-residential buildings is a trend driving the need for improved methods and validated tools supporting the design. Especially for highly glazed building facades, the detailed modelling of CFS plays a major role 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 are still rarely available – particularly in the field of CFS modelling (Loonen et al. 2016).

This report covers the topics of: (i) improvements of simulation models for a coupled thermal and daylight evaluation of complex façade systems; (ii) their comparison against other tools as well as measured data. The work was developed by the FACEcamp partners in Work Package 4, Task 4.1.

2 Objectives

The overall goal of the reported activities have been to improve the existing tools for the simulation of daylight, glare, and energy applied to the Complex Fenestration Systems (CFS) technologies.

An overview on existing simulations tools is provided including enhanced methods to evaluate façade performances. A set of modelling activities has been done to enhance the simulation capabilities for an integrated thermal and daylight evaluation of complex fenestration systems including also the daylight non-visual impact. All involved partners have brought in their individual expertise from the different fields of façade modelling (energy performance, thermal and visual comfort, non-visual effects and circadian entrainment). Through a close research cooperation within this working task, already existing knowledge in the façade modelling has been exploited and further strengthened. The established FACEcamp toolchain matrix will contribute to future services of a possible competence centre as well as for planners and consulters.

Finally, a key aspect for spreading the adoption of advanced modelling tools for CFS was to create simplified guidelines that can summarise the available approaches for stakeholders needing models and simulations. Such guidelines are reported in Milestone M4.3.

3 Methodology

The following main aspects have been addressed to improve the modelling capabilities towards a better thermal, visual and non-visual characterization of a complex façade system.

- Creation of a tool matrix highlighting the most capable and widely used simulation tools to address a coupled thermal and daylight evaluation.
- In-deep analysis of the simulation tools TRNSYS18 + TRNLizard and EnergyPlus + Ladybug/Honeybee and elaborating a “toolchain approach” to enable coupled thermal and daylight evaluation of facades.
- Comparative simulations among a reference test case using the “toolchain approach”.
- Comparison of the simulation tools against long-term monitoring data from the PASSYS cell at UIBK.
- Improved analysis of secondary heat fluxes through CFS and development of a calculation method for a detailed analysis of secondary heat fluxes based on CFD analysis (with possible evaluation of vented and non-vented cavities with complex lamella systems

4 Results

4.1 Simulation tools matrix

Nowadays, several building performance simulation (BPS) tools exist to support coupled thermal and optical performances prediction of Complex Facades Systems (CFS). Nevertheless, performing such analysis is a challenging task and information on possible source of errors and pitfall as well as procedures for a good practice are not available or partially complete. Additionally, several tools rely on complex models, which require deep knowledge and simulation skills by the user. Frequently, such complex models request a detailed characterization of the elements comprising the fenestration system, which add preliminary calculation phases to the actual simulation.

Table 1 summarizes the capabilities of the stat-of-the-art BPS tools (e.g. Energy Plus, TRNSYS, IDA-ICE, IES-VE and ESP-r) for perform dynamic energy and daylighting simulations for CFS. This table is an extension of a previous work (Loonen et al. 2016), which adds relevant information for a complete CFS performances analysis: detailed information on the thermal and daylight models for CFS used by each tools, parametrization and optimization, additional tools for pre-processing.

In the last years, several widely used BPS 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 integrated approach to increase the overall efficiency concerning daylight and energy-related aspects, just few of them allow timestep-based feedback loops between the thermal and daylight simulation routine. However, this is a crucial aspect to design comfortable and efficient buildings, e.g. for developing improved control strategies and optimizing thermal and visual aspects of a complex façade systems in detail.

Parametrization and optimization function are widely used in the last years to allow designer exploring numerous design solutions and to find optimal cases. Most of the tools report in Table 1 offer the possibility of parametrize and apply optimization function to the model; nevertheless, a complete parametrization, which involves also the building geometry, is only available for the tools integrated in the Grasshopper environment (i.e. Energy plus and TRNSYS). Grasshopper, in addition to a complete parametric environment, offers the interoperability with other plug-ins for co-simulation, data analysis and visualization, use of multi-objectives genetic algorithms.

According to the analysis performed and the façade technology studied, different pre-calculation can be required. The characterization of the shading component is a fundamental requirement for a correct use of detailed thermal and optical models. Table 1 report the main pre-processing tools, while further information on the procedures for component characterization can be found in FACEcamp M4.3 ‘Modelling guidelines for Complex Fenestration Systems’.

In the next chapter, two main BPS tools, i.e. Energy Plus and TRNSYS, are investigated in detail by means of two different toolchains that include the use of the common platform Rhino3D/Grasshopper.

Table 1. Tool matrix (part 1, first six columns)

Software	Conduction solution method	User Interface	Source code access and modification	Control simulation capabilities	Physical domain integration	Daylighting algorithm
EnergyPlus v9.2	CTF, Finite difference	IDF editor, DesignBuilder, Comfen, OpenStudio, Simergy, Sefaira, AECOsim, Ladybug Tools, DIVA4	free, open-source	Presets, Time-scheduled, Energy Management System (EMS)	Thermal, visual, airflow, HVAC	Splitxflux, (Delight)
TRNSYS v18	CTF external models for FD available (Type260, Type399)	TRNBuild, Simulation Studio, TRNLizard,	commercial, open-source (except Type56)	Presets, time-scheduled, time-step user-defined equations in Simulation Studio	Thermal, visual, airflow, HVAC	Backward Raytracing, DAYSim, Radiance file export
IDA ICE v4.8	Finite difference (FD, dynFD)	Standard- and Advanced level interface	commercial, open source, user-defined modules can be added	Presets, Time-scheduled, control macros	Thermal, visual, airflow, HVAC, CFD	Radiosity, Raytracing (Radiance-integration)
IES VE	Finite difference	integrates different calculation modules in one user interface	commercial, no source code access, no user-defined modules	APpro - rule based control of a building system	Thermal, visual, airflow, HVAC, CFD	Radiosity, Raytracing (Radiance-integration)
ESP-r	Finite volume variable thermo-physical properties	no user interface	commercial, open-source, code modifiable	Presets, Time-scheduled	Thermal, airflow, HVAC	-

Table 2. Tool matrix (part 2, final five columns). *[1] façade component characterization, [2] 3D geometry characterization*

Software	Thermal analysis of CFS	Daylighting analysis of CFS	Parametrization and optimization	Pre-processing tools	Further comments
EnergyPlus v9.2	ISO15099 + BSDF, schedule surface and absorption gains	3-phase method (OpenStudio)	Full factorial (jePlus), Genetic algorithm (Grasshopper)	WINDOW, Radiance[1] Sketch-up, Rhinoceros[2]	Options for modelling adaptive facades are significantly limited when the simulation engine is accessed through one of the third-party GUIs
TRNSYS v18	ISO15099 + BSDF	DAYSIM, 3-phase method (TypeDLT, ArtLight)	Full factorial (jePlus), GenOpt, Genetic algorithm (Grasshopper)	WINDOW, Radiance[1], Sketch-up, Rhinoceros[2]	
IDA ICE v4.8	ISO15099	3-phase method coupling exiting (but not published)	Internal full factorial and optimization functions (beta)		Adaptive features and control strategies (control macros) can be directly added to the mathematical code; it allows the control of various building systems, including facade actuators.
IES VE	-	-	Full factorial (Parametric Tool) and optimization (Hone)		The daylight module can be only used for dimming light, no shading control; the CFD module can only use the results from the thermal module - not vice versa; APpro - it enables the simulation of rule-based control of a building system
ESP-r	CFS model by Lomanowski and Wright Advanced optics model by Kuhn	3-phase method coupling exiting (but not published)			Strong developing community, several new functions for model adaptive behaviour in the building shell implemented; Disadvantage: weak documentation of new functions, non-user friendly interface; allows construction material properties changing with temperature and humidity; coupling modules to Radiance for daylight analysis existing, but expert knowledge necessary

4.2 1D simulation toolchains

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 analysis 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), besides the fundamental role in internationally renowned certification protocols such as LEED, BREEAM, and WELL. Evaluating building façade systems in the early stage of design is crucial in order to meet low energy requirements and highest comfort levels in the operation. 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 are essential for a conscious design of energy efficient buildings.

Nowadays, several simulation tools exist to perform dynamic energy and daylighting simulations for CFS. In chapter 4.1 of this report, the initial work is presented in starting with a wide tool comparison in the field of CFS evaluation. Nevertheless, several 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.

Within this subtask it was the challenge to define a reliable and useful workflow to evaluate a multi-objective optimization of complex fenestration systems including energy- and daylight simulations. One main aspect was to go for tools, which are widely spread in the community and offer flexibility in terms of tool interoperability and common databases.

In Figure 1, an overview of the full proposed FACEcamp toolchain is shown. It integrates the three different main aspects for a full CFS evaluation - Energy, Daylight visual and non-visual):

- **Toolchain 1:** Rhino → Ladybug/Honeybee (Radiance) → EnergyPlus OpenStudio → LARK
- **Toolchain 2:** Rhino → TRNLizard/Artlight (Radiance) → TRNSYS18 → LARK
- **Toolchain 3:** Rhino/IFC → DALEC

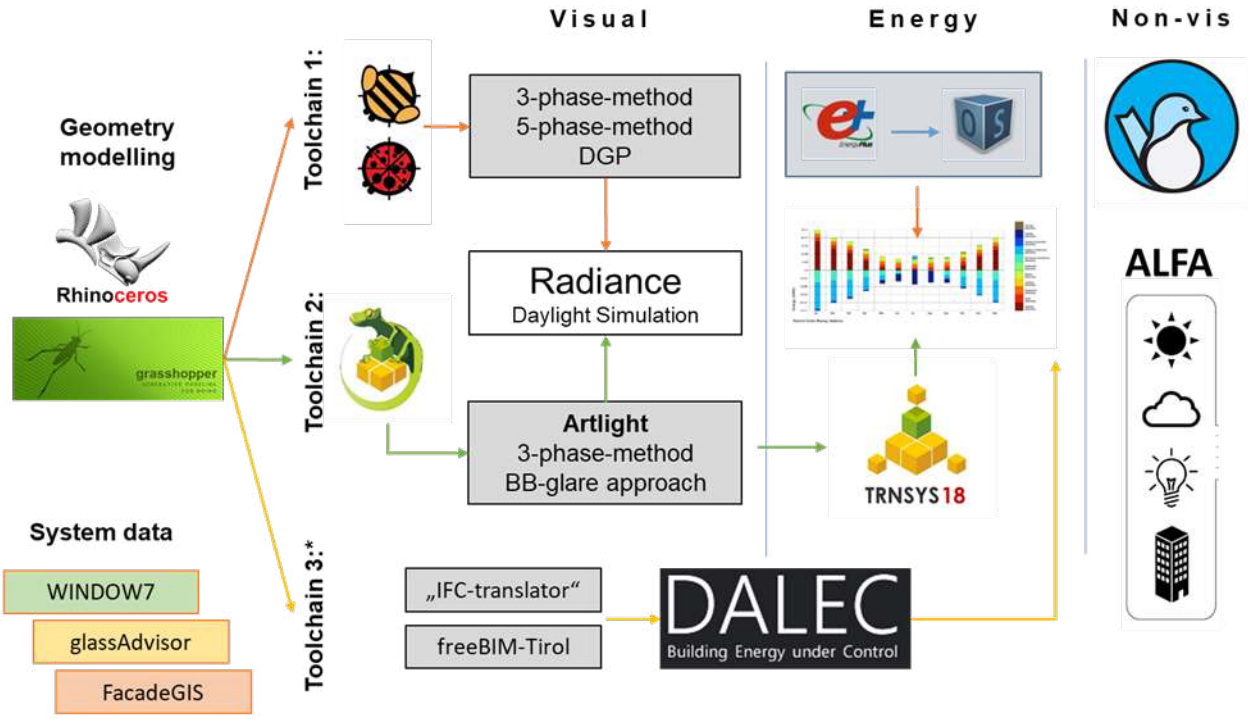

Figure 1: FACEcamp simulation toolchain for complex facade systems

Toolchain 1 and 2 follows a detailed modelling approach including Radiance-based daylight simulations as well as dynamic energy simulations in EnergyPlus and Radiance. Furthermore, via Grasshopper it is also possible to include the non-visual modelling using the free available Tool LARK. Toolchain 3 is intended as early stage design evaluation, DALEC enables a combined thermal and daylight evaluation of complex façade systems based on a single-zone model.

4.2.1 Toolchain 1 and 2: tool comparison for a coupled thermal and daylight evaluation

Among all tools which underwent screening, EnergyPlus and TRNSYS are the tools, which are most widely used and provide the necessary functionalities to perform a coupled thermal and daylight evaluation. Based on these tools, two toolchain workflows 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. The geometrical modelling is done in Grasshopper, the model set up as well as the transition into the simulation input files to perform the simulations in EnergyPlus (*.idf) and TRNSYS (*.d18, *.b18) has been implemented via Grasshopper.

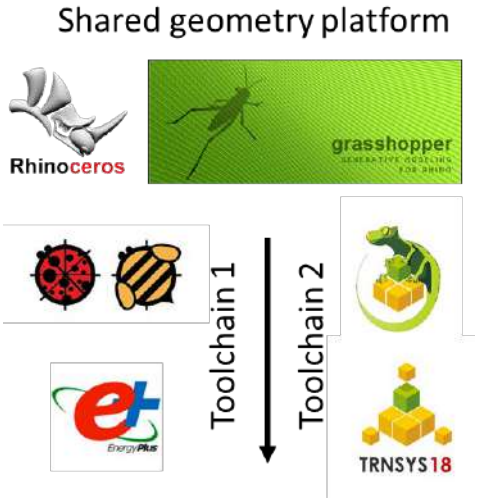

Figure 2: Energy and Daylighting toolchain workflow for evaluating CFS

(1) For the **theoretical model comparison**, a geometrical box model representing the PASSYS outdoor test stand at University of Innsbruck (ref. Figure 3) has been implemented in the toolchains and used for the comparison against real-case measurements. The test façade is characterised by a daylight redirecting system

(2) 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.

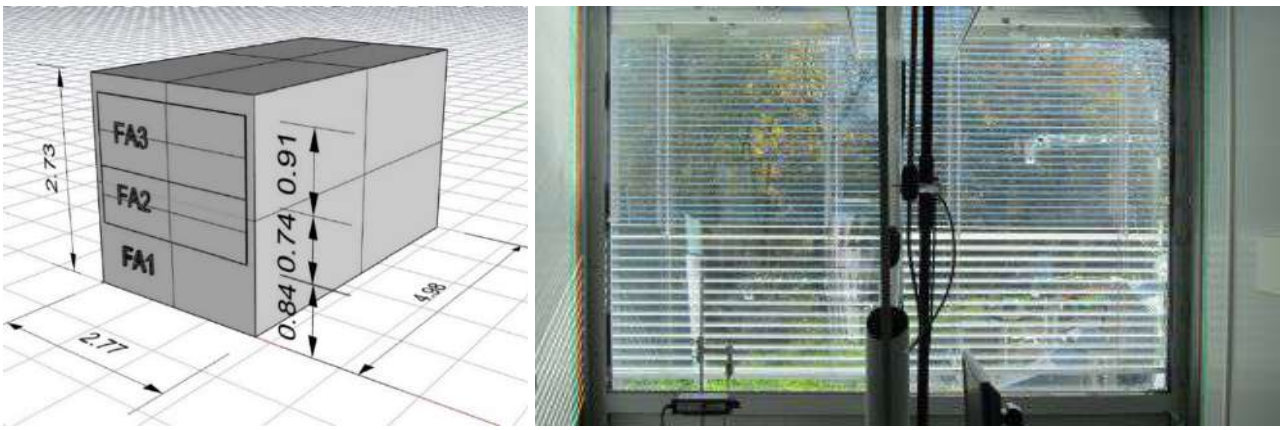

Figure 3: Sketch of the PASSYS test cell model in Rhinoceros (left); Installed facade at PASSYS-cell (right)

In both investigated tools TRNSYS and 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 the most comprehensive and widely used modelling standard for complex glazing systems incorporating blinds.

For the evaluation, in a first step both toolchain approaches have been tested based on the theoretical PASSYS settings, using the literature values for the construction layers. For the comparison against measurement, the (already validated) box model of the PASSYS cell from the theoretical comparison was overtaken. The box was again modelled with outside surface temperature as boundary condition and realistic construction definitions, gaining from an optimization process. In particular, the measured outside surface wall temperatures from the specific monitoring phase were used. The south wall including the testing façade has been modelled as external wall including solar radiation and temperatures.

In Figure 3 on the left part the scatter plot of the results for the room air temperature at the theoretical model comparison is shown, while the right side shows a comparison of the inner surface glazing temperatures in the same case. Both results are satisfying and go in line with a low deviation in the yearly heating and cooling loads. Nevertheless, a strict alignment of the model settings in both tools

was necessary to get a satisfactory correspondence. For the daylighting part, shown in Figure 4, especially for diffuse days a good correspondence could have been achieved between simulation and measurement. In case of the compared heating and cooling loads shown in Figure 5, the simulated values in TRNSYS are closer to the measured results in the PASSYS cell, while EnergyPlus underestimates the cooling load significantly.

Detailed information's about the comparative study and all results achieved can be read in (Hauer et al, 2019).

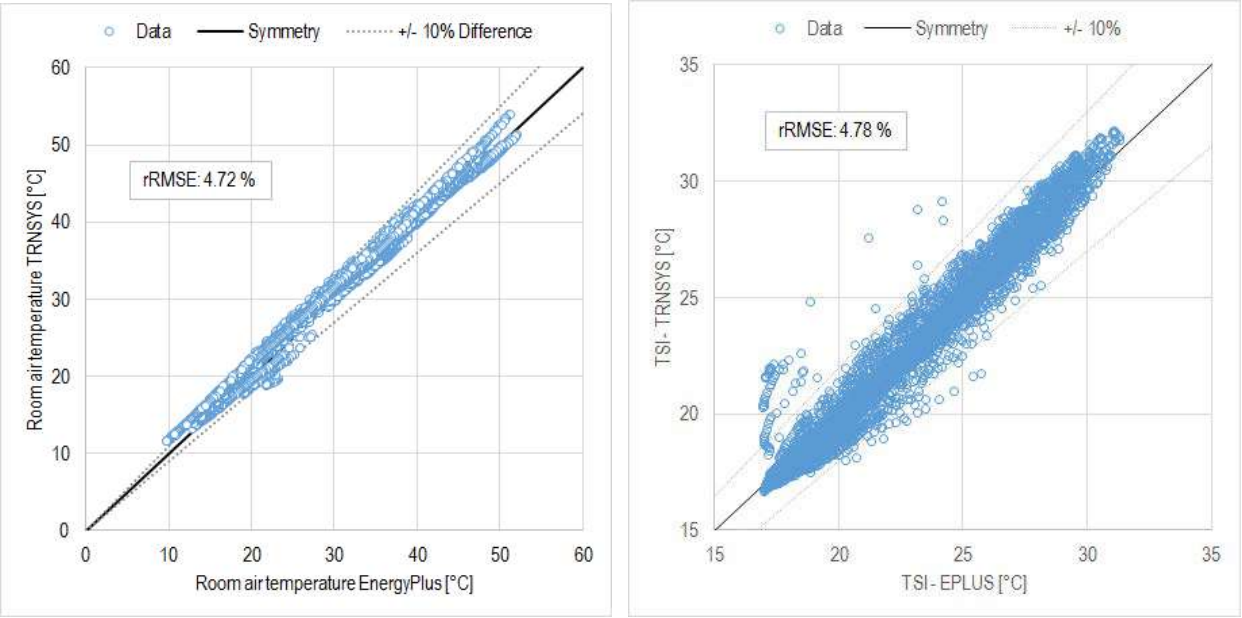

Figure 4: Comparison of sensitive room air temperature (left) and glazing surface temperature (right)

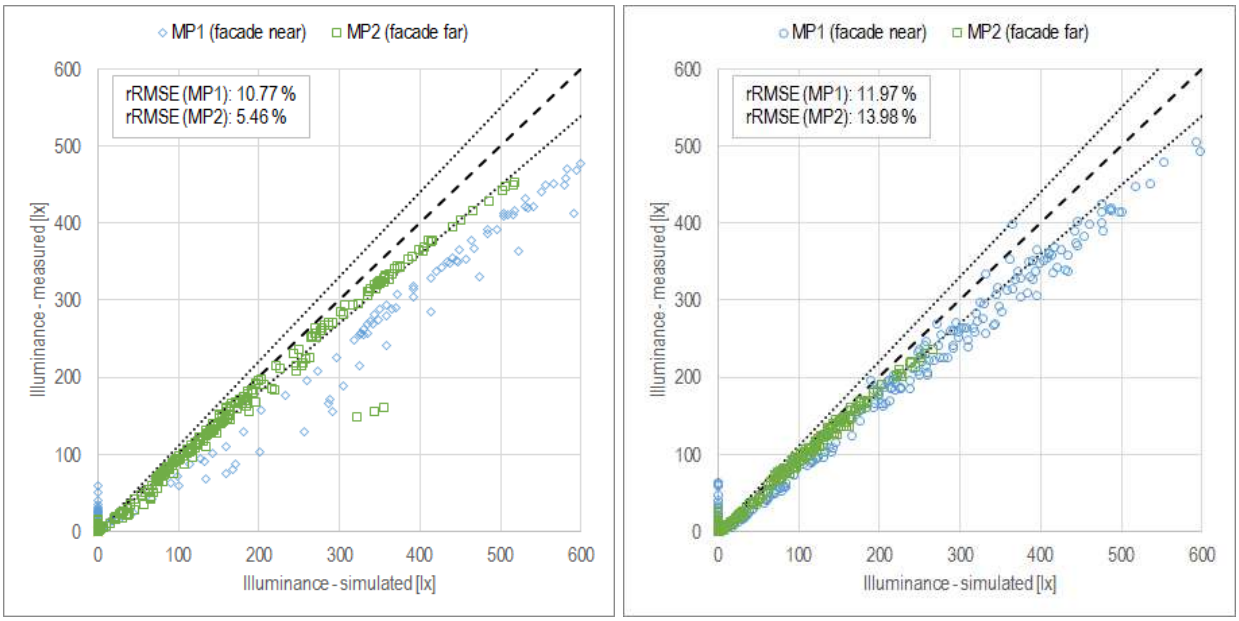

Figure 5: Comparative illuminance values - glazed situation (left) and shaded situation (right)

4.2.2 Toolchain 3: Simplified modelling tool DALEC for early-design evaluation

In addition to Toolchain 1 and 2, which focuses on complex tools enabling detailed evaluation of complex façade systems including non-visual comfort, Toolchain 3 includes the webtool DALEC – "Day- and Artificial Light with Energy Calculation" (www.dalec.net), which enables an easy and fast evaluation of different façade solutions. With DALEC an online concept evaluation tool for lighting designers, architects, building engineers and building owners has been developed by Bartenbach

together with Zumtobel Lighting and the University of Innsbruck. Although easy to use, the software accounts for the complex thermal and lighting processes in buildings and allows a simple evaluation of heating, cooling and electric lighting loads. Not only energy, but also user behaviour is considered, and visual and thermal comfort is evaluated (glare, overheating frequency).

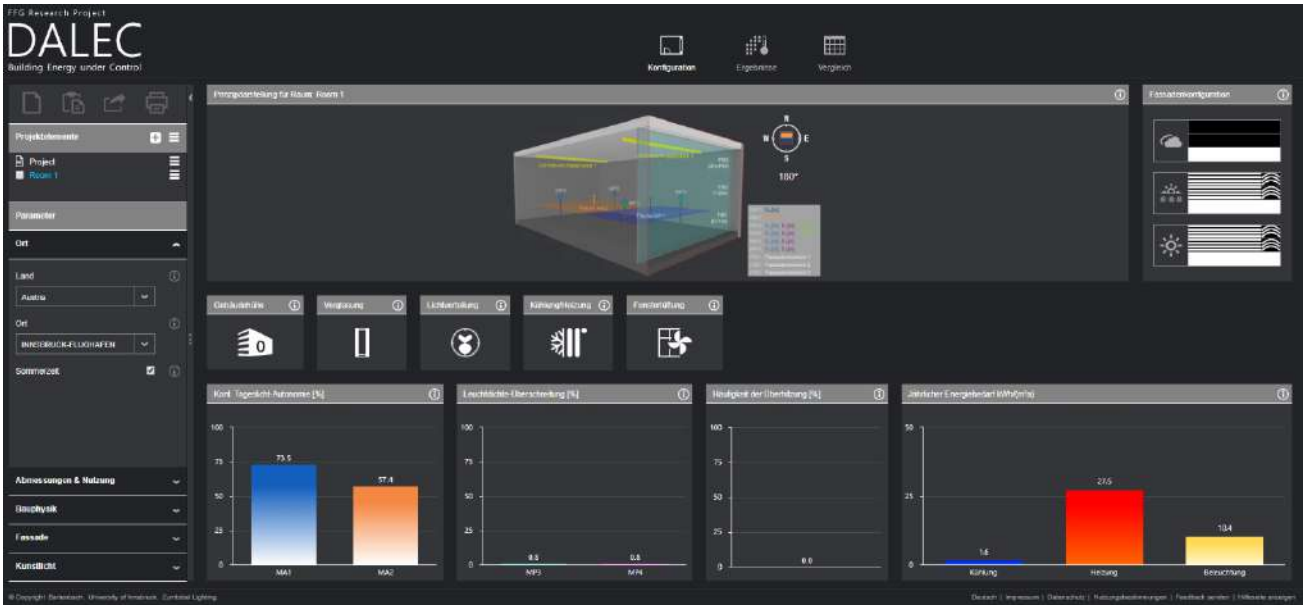

Figure 6: The DALEC web interface – www.dalec.net

During FACEcamp, DALEC was validated and compared against bunch of other simulation tools. Several Results are collaboration activities in the IEA SHC Task 56 on Solar Envelopes and will be published in the Deliverable Report of Subtask C in May 2020. Bartenbach as well as EURAC as Task coordinator have been involved intensively in those activities and a fruitful knowledge transfer from the FACEcamp activities have been made within the task consortium.

Also, in FACEcamp, first proof-of-concepts have been made by coupling DALEC with Rhino as a geometry platform. While the official DALEC version is applicable via the Web-Interface, an integration into the BIM-environment via IFC will be established soon. Therefore, a plug-in for Revit is developed in order to specify the needed data in a Revit model to run a DALEC-calculation.

4.2.3 Modelling Non-visual effects of daylight

To include also the aspects of non-visual light effects, intensive investigations have been made to extend to toolchain approach. Due to the common platform Rhinoceros/Grasshopper for geometrical and parametrical model setup, the two available tools ALFA and LARK have been investigated in detail within Task 4.3 (see Report M4.4 on Modelling of non-visual effects of daylight), and is therefore only mentioned shortly in this report.

LARK, a plugin for Grasshopper developed by the University of Washington in collaboration with ZGF Architects LLP, and **ALFA** (Adaptive Lighting for Alertness) developed by Solemma.

ALFA LARK

After a tool comparison, LARK was chosen for an integration into the FACEcamp toolchain, as it is

(1) directly implementable as Grasshopper workflow (and therefore easily combinable with TRNLizard or Honeybee) and

(2) free of charge as well as an open source tool

A full and adaptable workflow has been established and integrated into the FACEcamp toolchain (see Figure 1).

4.3 2D and 3D analysis of CFS

Besides the three toolchains described below, a fourth one based on CFS modelling procedure has been conceived and developed, aiming at characterizing CFS at a more detailed geometrical scale, considering the bi- or tri-dimensional temperatures' fields.

Complex Fenestration Systems are characterized by advanced shading systems, with for example complex geometries and highly reflective surfaces, whose optical and thermal performance depend on the angle of incidence of solar radiation. In addition to the complexity of the shading system itself, the CFS could also be characterized by different types of cavities such as naturally ventilated ones. All those peculiarities have to be covered by adequate thermal and optical models. However, the current most widespread thermal calculation models for fenestration systems are based on the standard ISO 15099 (EN ISO 15099), that refers to standard geometries for blinds, like screens parallel to the windowpane or venetian blinds with flat geometries and ideal diffusely reflecting surfaces. Furthermore, the conductive and convective heat transfer within the cavities is computed with a pressure drop model applied to a layer-by-layer approach. This model is based on the opening characteristics of the shading layer that's assumed to be parallel to a windowpane. This hypothesis is not adequate in case of venetian blinds and other types of shading systems with big openings (Hart et al. 2017). In addition to that there are limitations in the applicability of the ISO 15099 to different cavity layouts including wider closed ones or open and naturally ventilated ones. Furthermore, professionals of the façade construction industry are interested in assessing the components' critical temperatures and the fenestration's behaviour under real dynamic operating conditions and in representative extreme ones.

Due to all these limitations in the current thermal models for fenestration systems, a new modelling approach for assessing the thermal performance of CFS has been developed. This methodology has been applied to different types of fenestration systems, both standard and complex. The resulting key performance indicators (KPI) have been compared with those obtained with commonly used calculation tools, like WINDOW 7 and TRNSYS 18, both based on the algorithms of the standard ISO 15099 (Demanega et al. 2018; Demanega, 2018). Moreover, the validity of the new modelling approach was investigated by comparing simulation results with in-situ measurements of a commercial Complex Fenestration System under dynamic conditions (Demanega et al. 2019).

In the developed modelling procedure, solar radiation is treated apart from fluid flow and heat transfer. In particular, solar radiation is treated with a detailed optical model based on ray tracing and using the software Radiance (Ward, 1994) and a modified version of the Three-Phase Method (McNeil, 2014) that describes the way light passes through a fenestration system. For this application, the aim was not to compute the transmitted light but the absorbed radiation (Demanega et al. 2019), as shown in Figure 7.

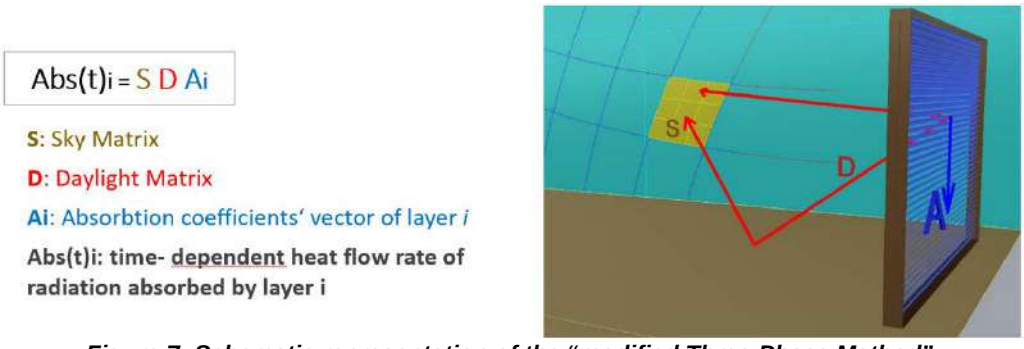

Figure 7: Schematic representation of the "modified Three-Phase Method".

In a second step, the coupled heat transfer and fluid flow was computed with a CFD simulation using the Finite Element (FEM) software COMSOL Multiphysics. The absorbed fraction of solar radiation resulting from the optical calculation was also included in the CFD simulation. Regarding the CFD simulation, the use of different turbulence models has been investigated and a comparison with a Finite Volume (FV) software ANSYS Fluent was done (Demanega et al. 2018).

Since the modelling approach was applied to two fenestration systems, standard and complex, and the simulation results were compared with measurements and results from other calculation tools, both in stationary and dynamic conditions, the description of the results can be subdivided into different parts.

4.3.1 CFD+Radiance approach versus WINDOW 7 in stationary conditions

For standard fenestration systems, a very good correspondence between the results from the ISO 15099 based software WINDOW 7 and the CFD+Radiance modelling approach could be found. The relative difference for the U-value and g-value was in both cases below 1%. Indeed, in case of complex fenestration systems, higher discrepancies emerged: for the U-value, the relative difference was of 8.0%, while for the g-value relative errors of up to 30% emerged. This result highlights the importance of a detailed optical calculation for CFS.

4.3.2 CFD+Radiance approach versus TRNSYS 18 in dynamic conditions

The heat flux on the façade room-side face resulting from the CFD+Radiance approach was compared with results from TRNSYS 18. A similar trend of the heat flux could be noticed and the peak values were comparable, however an evident time-shift of around one hour between the results of the two approaches emerged. This is due to the fact that the ISO 15099 (EN ISO 15099) based thermal model used within TRNSYS 18 does not take into account the mass and the resulting thermal inertia of the glazing components. This is confirmed by the fact that heat flux is perfectly in phase with the global vertical irradiance measured inside the room. This problem has been encountered also in another study (Hauer et al. 2017). The comparison of the calculated heat flux with the CFD+Radiance approach and TRNSYS 18 for one clear sky day in February is shown in figure 9.

4.3.3 CFD+Radiance approach versus in-situ measurements in dynamic conditions

To verify the validity of the modelling approach, a comparison with in-situ measurements performed on a commercial CFS installed on the west façade of the Living Labs of the Free University of Bozen-Bolzano was done. The experimental setup included thermocouples, pyranometers, heat flux plates and a temperature-controlled measurement device to determine the undisturbed, transient heat flux through transparent components (Hauer, 2017). Figure 8 shows the measurement setup for the CFS.

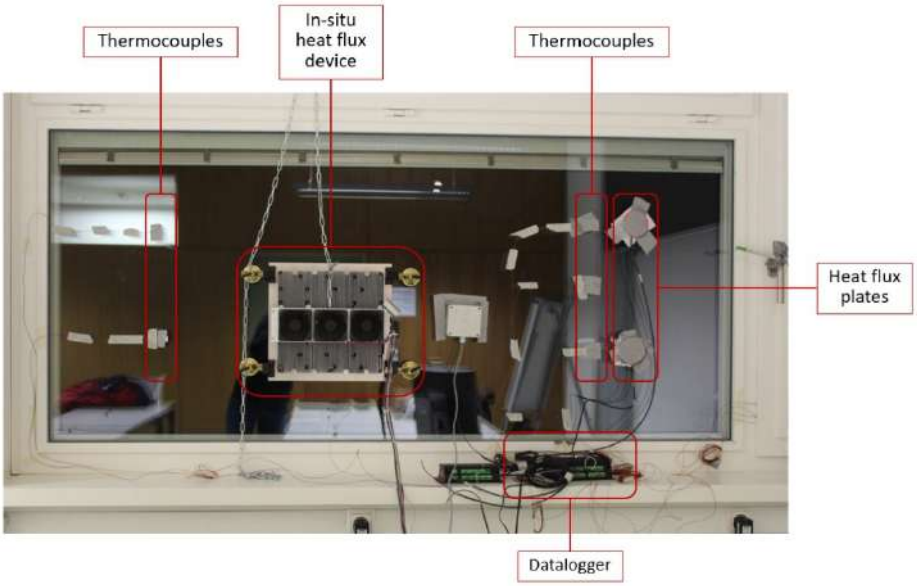

Figure 8: Measurement setup for the CFS

The comparison between the total heat flux on the room-side face measured with the heat flux plates and the in-situ heat flux device and the simulated one was performed, in order to validate the simulation against the measurement approaches (Figure 9). From this comparison, a good correspondence between the two approaches emerged. As already mentioned, the CFD+Radiance

approach is able to appraise the inertial effect of fenestration systems that consists in a time-shift of around one hour between the peak irradiance and the maximum solar gain on the room-side face.

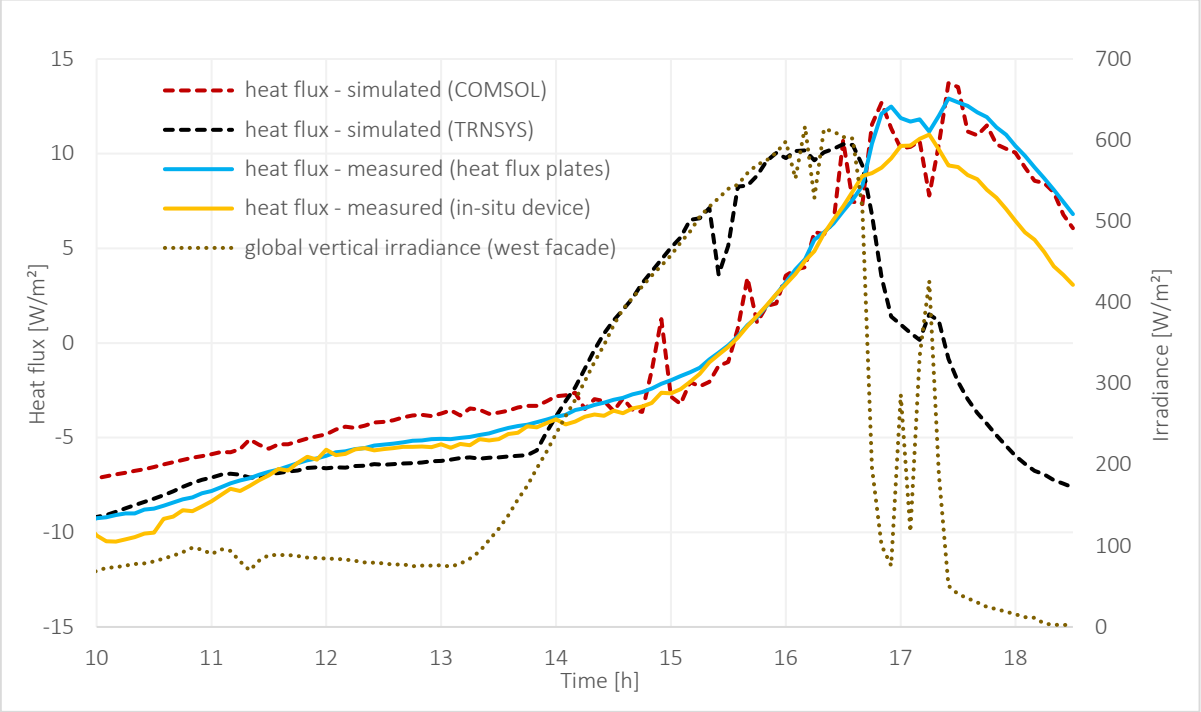

Figure 9: Comparison of simulated and measured heat flux through the CFS.

In addition to heat the heat flux, the CFD-based methodology gives evidence on the temperature and velocity distribution within the cavity and along the solid components of the CFS (Hand, 2019). This allows to account for the components' temperatures, to assess maximum and minimum temperatures and to evaluate the air flow rates in ventilated cavities. For instance, figure 10 shows the temperature distribution of the CFS for different times of a clear sky day in February. Even if the external air temperature is around 15 °C, the upper part of the cavity reaches temperatures of around 50 °C.

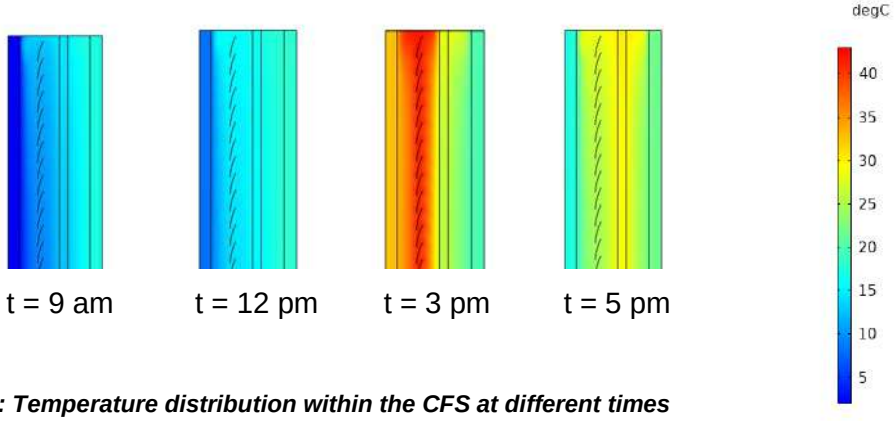

Figure 10: Temperature distribution within the CFS at different times

The coupling of CFD simulations with the separately computed effect of solar radiation, emerged to be a valid modelling approach for assessing the thermal performance of complex fenestration systems. This modelling approach could be appropriate for a detailed analysis of fenestration systems, in order to assess specific properties, as for example the air flow rate in the cavity, secondary heat fluxes or the maximum temperature reached by a component of the facade (e.g. glazing sealants, air, lamellas, etc.).

From the numerical modelling of CFS emerged that the solar absorption has a significant impact on the fluid flow in the cavity, the solar heat gains and the components' temperatures (Demanega, 2017). The impact of the complex behaviour of the lamellas on the heat transfer with solar radiation is well

represented by the detailed optical modelling, which is essential to appreciate the complexity of the shading system. In case of deeper cavities and even ventilated ones, the accurate modelling of the fluid flow is essential to assess the real performance of the fenestration system.

5 Conclusions

Thanks to the FACEcamp activities on modelling, a review of available modelling and simulation tools for Complex Fenestration System (CFS) has been done. Thermal, visual and non-visual comfort, besides energy, have been considered as main requirements.

Three specific toolchains at system level have been improved and verified one against the others and validated against measured data. Moreover, one further toolchain has been defined to study the secondary heat fluxes at a finer scale, dedicated to the assessment of the temperature, heat flux, air velocity and pressure multi-dimensional fields.

The FACEcamp Milestone M4.3 reports a practical summary on a simulation tools selection, with their main features and how to use such toolchains.

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