COMBINED THERMAL AND LIGHT SIMULATION METHOD FOR DAYLIGHT UTILIZATION

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1. Abstract

This paper describes the development and implementation steps of a combined thermal and light simulation. The thermal analysis is performed in TRNSYS. The light model includes detailed simulations of the daylight system done with the so called “three-phase daylight coefficient method” in RADIANCE.

Beside the development of enhanced methods for thermal simulation of complex daylight systems in combination with standard components in TRNSYS, the main focus is to develop a coupling model between both parts. The new simulation method allows the development and evaluation of fenestration systems with regard to thermal and visual criteria, thus the coupling should allow minimizing heating and cooling demand with simultaneous consideration of visual aspects.

Exemplarily a newly developed, complex daylight system is modeled and analyzed in comparison to a reference system with state of the art exterior venetian blinds. Additionally to the system comparison the capability and accuracy of the developed simulation methods on different systems and further developments are discussed.

2. Introduction

The façade, as an interface between the outdoor and indoor climates, is a decisive factor for energy consumption of a building. It controls the influence of daylight, influx of solar energy and heat flow. Apart from energy the facade is also a significant factor for visual and thermal comfort. Light is the most important information medium (visual perception) and demands on the illumination of work places are becoming more prevalent.

While energy for heating demand is reduced due to daylight and artificial lighting in winter, the need for cooling is increased in summer as the electricity for illumination must be re-cooled by electricity. During the course of the research project “Multifunctional Plug and Play Façade” (Streicher, W., Müller, M., 2009) it has shown that the aspect of daylight utilization and artificial lighting out of the façade is not sufficiently taken into account.

Therefore, the project “Licht aus Fassade” (LichtAusFassade, 2009) contains the development of energy-based optimized concepts for the provision of daylight and artificial lighting from the façades for interior spatial areas. The aspects of thermal and visual comfort as well as the energy requirements for heating and cooling are evaluated for a new daylight system.

3. Method

3.1. Reference Room

For the validation of the developed simulation methods a standard design for the reference room is defined. Likewise the developed concept of the daylight system of the façade is based on this reference room.

The main focus on the room definitions are related to different user aspects. Depending on the organization form it differs in terms of room geometry, daylight usage, location of inner rooms or façade-oriented rooms and building materials. With the definition of a double office room many relevant aspects are covered. Based on this usage the geometry, the properties of the environment surfaces and the user characteristics are defined.

The geometrical dimensions in Figure 1 are related to already existing definitions in the MPPF-project and to a standard reference room from *Bartenbach LichtLabor*. The façade consists of a parapet including the technical equipment of the MPPF and a large window area, which offers all opportunities for an advanced daylighting system. The definitions of the interior objects are according to Neufert (2009).

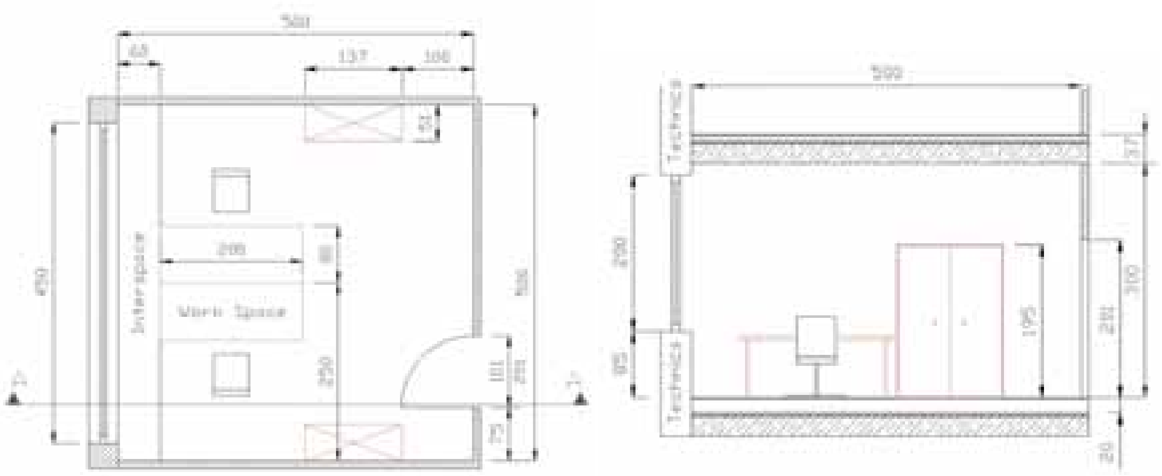

Fig.1: Reference room

The reference room definitions also include structural-physical aspects (wall mounting, U-Values...), lighting aspects (absorption coefficients, transmission values), user characteristics (attendant persons, internal loads, air change rates…) and typical interior as listed below.

Parameter	Definition	Source
Climate	Graz, Austria, south oriented	
U-value wall U_{wall}	0.15 W/m²K	Assumption
U-value window U_{window}	0.8 W/m²K	Assumption
Window surface	9 m² (Width: 4.5 m, Height: 2 m)	Assumption
Glazing part on the façade area	60 %	SIA 2024
Sensible heat emissions	70 W/person (at 24 °C)	SIA 2024
Average moisture discharge	80 g/(h person) (at 24 °C)	SIA 2024
Operating hours:	Monday to Friday – 7 a.m. to 6 p.m.	SIA 2024
Internal loads (equipment)	9.6 W/m²	SIA 2024
Room temperatures	21 °C (heating), 26 °C (cooling)	SIA 2024
Ventilation - air change rate	0.96 h^{-1}	SIA 2024
Visual reflectance of ceiling/walls/floor	80 % / 50 % / 30 %	Assumption
Luminous efficacy of artificial light	40 lm/W	Assumption

According to SIA 2024 and its full load hours the profiles for internal gains and humidity are calculated. Figure 2 shows this calculated weekly profile of specific internal loads by persons and equipment. Internal gains by means of artificial lighting are an input from the coupled simulation.

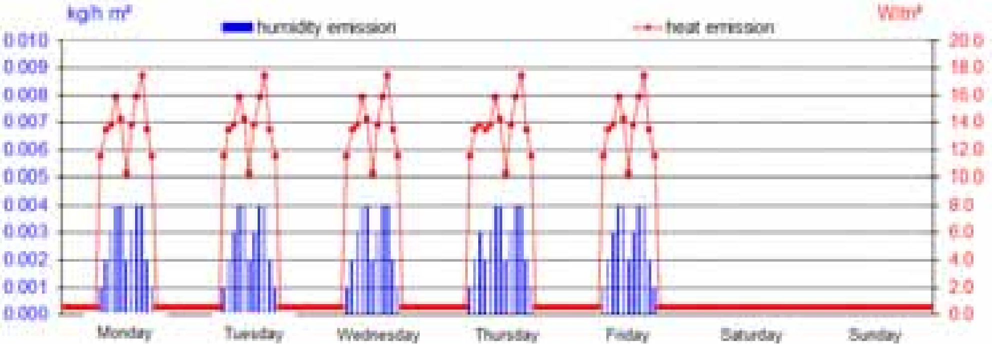

Fig. 2: Loading profile according to SIA 2024

3.2. Simulation methods

Separated thermal and light simulations of complex daylight systems with state of the art programs and models are challenging tasks. All the more this is true for combined simulations and thus no methods of simultaneous evaluation of thermal and visual behaviors exist. Therefore a new approach with linked thermal and lighting simulations is implemented, which enables significant validations of fenestration systems.

Thermal- and light simulation models build up the basics for this work. In a further step the main objective is to develop a coupling method, which allows parallel and iterative calculation of both parts.

Thermal Simulation

Based on standard models in TRNSYS three methods are implemented to represent the thermal behavior of daylight systems. The main focus is the external load due to radiation. The reference room is modeled in the building model of TRNSYS (Type 56). This type allows simulating standard applications like internal or external shading devices by shading factors. To simulate complex shading blinds it is necessary to extend this method by more detailed thermal models.

The developed models are directly coupled to the building model. The calculation of the energy input, including transmission and secondary heat flux through the window, is performed external and linked as input - separated in wallgain and internal gain - to Type 56 (Fig.3). For these simulation models the window of Type56 is totally shaded (fc=1).

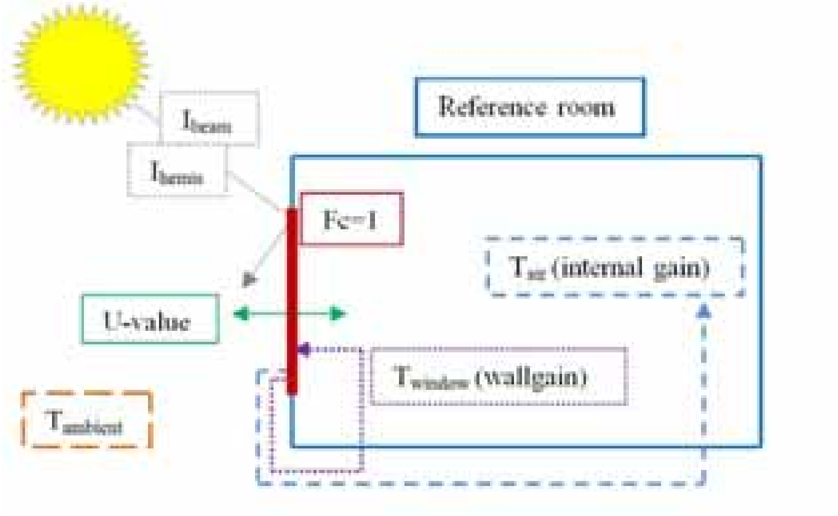

Fig.3: Energy input through internal gain and wallgain representing the solar gains for g-model and Abs-model

The internal gain is implemented as fully radiative gain to the air node of the zone. It represents the transmission gain through the system and takes the interaction of absorbing short- and long wave radiation exchange between the surfaces into account.

The secondary heat flux of the window is indirectly modeled as wallgain. As a result of this wallgain the inner glass pane is heated up and results in an equivalent combined heat flux. The glass temperature also affects the U-value and thus the heat losses through the window. In fact the calculation of this wallgain is the major key in the following steps.

The correct interpretation of the wallgain is an essential point with two criteria:

- Energy: losses through the window surface (U-value) and gains through secondary heat flux
- Surface temperature and its effects on comfort

For an appropriate modeling of external radiation it is crucial to analyze the annual energy flux characteristics of windows. In a first step external radiation through a standard window without a shading device is implemented. The influences on this characteristic were carried out with several studies under constant conditions (radiation intensity, angle of incidence, temperature differences between inside / outside, convective heat transfer coefficients). The introduced three models are based on these studies.

The models, called g-model, Fc-model, and Abs-model, mainly differ with respect to:

- Calculation method of wallgain and internal gain
- Implementation in Type 56

The models include a dependency of two angles to consider different g-values due to angle dependent reflectance characteristics and emission factors. The thermal models also consider different positions of the shading blinds. The energy input through the systems is calculated separately for beam, sky and ground radiation.

g-model:

Solar radiation on the window surface is reduced by the overall g-value (daylight system + window) for the beam and diffuse radiation part. Thereby the theoretically incoming radiation through the shading system is determined. The calculation of the secondary heat flux is done separately for beam and diffuse radiation.

An advantage is that through the direct calculation method the results correspond directly to the measurements. It is optimal for fast setup with reliable results. It has to be taken into account that a slightly overestimation of the secondary heat flux is given.

Fc-model:

This approach is similar to the g-model. An overall shading factor is calculated by the g-values of the window and of the complete system (eq. 1), which is comparable to the external shading factor (Fc). The reduced external radiation through this shading factor is treated as external radiation. It is equivalent to the radiation passing the daylight system.

$$F_C = \frac{g_{system}}{g_{window}} \text{ (eq. 1)}$$

This model works efficient enough for external blinds. Furthermore it is more reliable for standard system, because of a moderate regulation of different thermal influences.

Abs–model:

A more detailed approach is the Abs-model. It allows the implementation of specific window data, such as absorption coefficients of panes and blinds, emission coefficients, etc. Therefore the opportunities for modeling integrated window blinds are higher.

The modeling concept correlates directly to the g-model with external calculation of the radiation and separation in wallgain and internal gain. The wallgain includes, additionally to the g-model, a separate calculation of the temperature increase and radiation exchange between the panes.

The high number of required data results in an extensive validation for every single system. For the actual developments this model shows already sufficient results in modeling elementary systems. For more complex systems it requires further developments especially in terms of interpretation of the secondary heat flux.

Light simulation

Physically correct daylight simulations are computationally demanding already for a single situation. Thus, annual simulations with full renderings at each time step are hardly feasible. Ward implemented methods within the RADIANCE lighting simulation tool (Ward and Shakespeare, 1998) that allow efficient annual daylight simulations even for complex fenestration systems.

The basic idea is to use the daylight coefficient approach and pre-calculate unit coefficients before the annual simulation. These coefficients are then linearly combined for each time step of the year according to the respective luminance distribution of the sky. To enable such linear combinations both the continuous sky distribution and the bidirectional scattering distribution function (BSDFs) of the daylight system have to be discretized into patches. For the sky patches either a discretization into 145 segments by Tregenza or Reinhart subdivisions of Tregenza patches into 577 or 2305 regions are used. The BSDF of the daylight system is discretized into 145 ingoing and 145 outgoing directions according to Klems' subdivision of the hemisphere that yields approximately equal illuminances for each patch at constant luminance. It is important to notice that luminances are averaged within patches and thus spiky BSDFs will be smoothed. However, as the total luminous flux transferred through the system is correct, the mean work plane illuminances that are evaluated are correctly simulated.

Detailed information about the methods used for annual daylight simulations with RADIANCE are given by Ward et al. (2011) or McNeil (2011).

The BSDFs of the daylight system can be determined by measurements or by computer simulations e.g. using a commercial non-sequential ray-tracing engine. For each technically different part of the system and for each state of these parts the BSDF has to be defined to allow for the calculation of daylight passing into the room. These lighting data generally are specified for CIE standard illuminant D65 representing a phase of daylight with a correlated color temperature of approximately 6500K and applying V(λ), the spectral luminous efficiency function for photopic vision.

Additionally for the thermal calculations the angular dependent solar heat gain coefficient (SHGC, g-value) has to be determined for all the parts and different states of the daylight system. This can be done by extensive measurements in a climate chamber supported by simulations for direct solar radiation. Other approaches require the calculation of the solar radiation transmitted through the system and the radiation absorbed at the different components of the system. This allows especially adapted thermal programs to calculate the total radiation passing into the room. All these solar data have to be known for each incident direction of the radiation and for all the different parts of the system and for each state of these parts.

Coupling: Thermal simulation – Light simulation

The thermal model was build up in TRNSYS. The light simulation as a self-contained part is done by RADIANCE and implemented in the TRNSYS Simulation Deck by a new Type (Type205). This Type calls a Fortran subroutine, which communicates - depending on the iteration steps - several times with the light simulation scripts. This Type manages the iterative calls of RADIANCE and provides the artificial light gains for Type 56 as internal light gain. The internal light gains are calculated by continuously adding artificial light to daylight to reach a mean illuminance of 500 lux at the work plane. A luminous efficacy of 40 lm/W is assumed for the artificial light.

For the control strategy TRNSYS plays the master role, as the iterative routine is already integrated in TRNSYS. At every single time- and iteration step, Type 205 calls RADIANCE and transfers the required simulation data and the actual tilt angle of the daylight system from the previous iteration step. Depending on the control strategy TRNSYS also returns a thermal request, which allows TRNSYS to interact with the light control strategy. The light control strategy for the two examined daylight systems is described in detail in the following section. If the room temperature is out of a defined range, Type 205 recalls RADIANCE in an iterative call with a thermal request for changing the blade position to achieve less or more gains to avoid cooling or heating, respectively. However, the control strategy is implemented in a way that lighting guidelines are always dominant to avoid glare caused by thermal requests.

Daylight Systems

The daylight systems (Fig. 4) that will be exemplarily compared are exterior venetian blinds (Tab. 1) representing a widely-used system and the newly developed, patented "Alar Lamella" inside a casement window (Bartenbach, 2009; Bartenbach LichtLabor GmbH, internal reports).

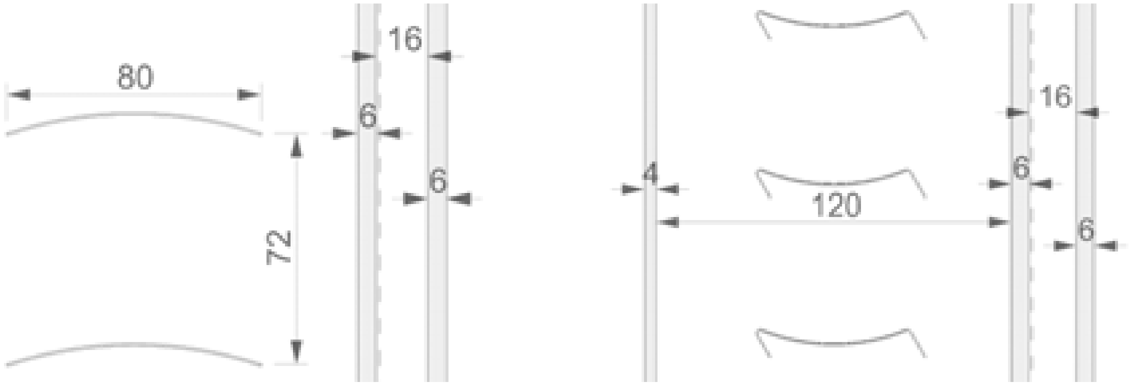

Fig. 4: Sketches of daylight systems: Exterior venetian blinds (left), "Alar Lamella" inside casement window (right). Dimensions are given in mm.

In both systems the lamellae are rotatable to provide glare protection as well as thermal control. Thus, solar radiation can be shaded in summer and solar heat can be gained in winter. The "Alar Lamella" is a multifunctional system with two different zones: Perforated lamellae with a film for glare protection (Tab. 2) allow a good view to the outside; solid lamellae (Tab. 3) are mounted in the upper part to utilize sunlight and thus minimizing the need for artificial light during daytime.

The control strategy of both systems is designed to maximize the input of daylight, to prevent glare by high luminance and at the same time to minimize heating and cooling loads.

The venetian blinds are opened as much as possible as long as glare is not an issue. According to the standard EN 12464 luminance values higher than 1000 cd/m^2 should be avoided in the field of view and in mirrored positions for computer desks making the control strategy rather restrictive. At the same time the tilt angle of the lamellae is chosen to prevent direct sunlight penetrating into the room between the lamellae.

Basically the same strategy applies for the "Alar Lamella" too. Additionally the perforated lamellae are completely closed in summer, when direct sunlight hits the façade. The solid lamellae are controlled differently in summer and winter to account for sun shading and solar gains, respectively.

Tab. 1: Characteristics of venetian blinds

Characteristic	Venetian Blinds		
Tilt angles [°]	0	45	75
Normal solar transmittance [%]	43.08	12.12	0.96
Diffuse solar transmittance [%]	20.05	13.88	3.59
Normal SHGC [-]	0.516	0.197	0.071
Diffuse SHGC [-]	0.292	0.223	0.101

Tab. 2: Characteristics of "Alar Lamella", perforated

Characteristic	"Alar Lamella", perforated						
Tilt angles [°]	0	15	30	45	60	75	90
Normal solar transmittance [%]	34.99	32.78	28.03	23.28	13.05	7.78	5.55
Diffuse solar transmittance [%]	21.34	20.87	19.03	16.47	12.48	7.78	4.07
Normal SHGC [-]	0.429	0.416	0.368	0.319	0.193	0.130	0.102
Diffuse SHGC [-]	0.294	0.291	0.271	0.240	0.191	0.133	0.087

Tab. 3: Characteristics of “Alar Lamella”, solid

Characteristic	“Alar Lamella”, solid						
Tilt angles [°]	0	15	30	45	60	75	90
Normal solar transmittance [%]	34.37	33.22	29.35	25.61	9.42	3.38	0.17
Diffuse solar transmittance [%]	21.98	21.91	19.78	16.64	11.23	4.38	0.12
Normal SHGC [-]	0.421	0.419	0.377	0.338	0.144	0.067	0.028
Diffuse SHGC [-]	0.296	0.297	0.272	0.234	0.167	0.082	0.028

4. Results

4.1. Thermal interpretation

The interpretation of the thermal results is mainly done in comparisons of energy balances, temperature curves and comfort criteria. Beside the validation of the simulation methods by comparison of the single methods the validation of both systems is the main focus. For the interpretation only results from the g-model and Abs-model are relevant due to higher reliability.

Energy balance

Figure 5 shows a comparison between the reference system (REF) and the daylight system “Alar Lamella” (Alar). Following variations with strict light control (light) and runs with thermal response (therm) are compared as well as g-model (g) and Abs-model (abs).

For the reference system the divergences between Abs-model and the g-model are very little – only slightly higher solar gains due to overestimation of the secondary heat flux at the g-model cause a higher cooling demand. This results in a deviation of 2 % between these two models in annual energy balance.

Simulation REF_therm-g shows a clear reduction of the artificial light demand due to increased solar gains by implementation of the thermal request in the control strategy.

With the daylight system “Alar Lamella” a significant reduction of the artificial light demand and a reduction of cooling and heating demand, beside a higher use of solar gains, is reached.

Regarding the “Alar Lamella” simulations with the Abs-model an overall deviation in the energy balances of around 8%, compared to the g-model, is shown. This is the reason why Alar_light-abs indicates the lowest cooling demand. For further steps the models have to be adapted in more detail to reduce the deviation.

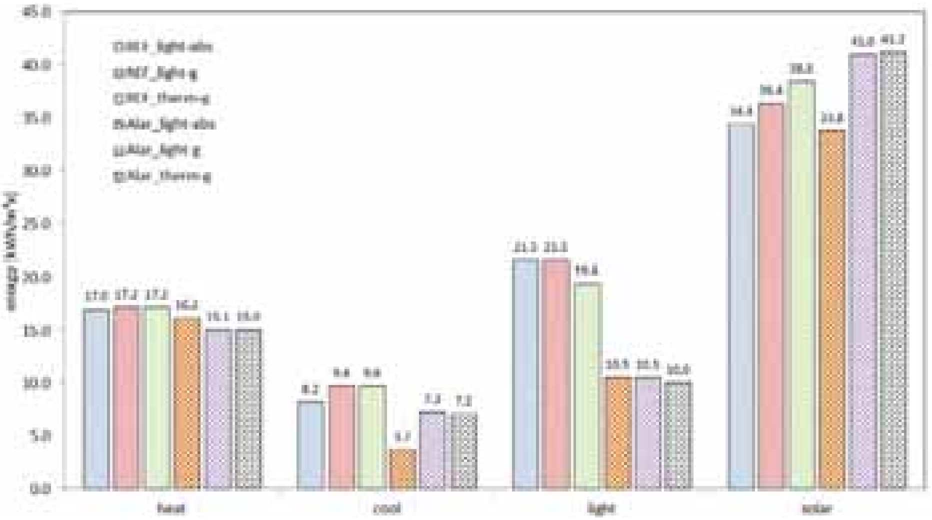

Fig. 5: Model and system overview in energy balance

Temperature curve

The operative room temperature (TOP), simplified as average of air temperature and surface temperatures of the surrounding, shows an annual range between 21°C and 27°C. There are only slightly differences at higher temperatures between both systems. The inner window surface temperature (TSI) differs especially in the colder period through a higher use of solar gains of the daylight system and the lower U-value of the system. In Figure 6 the operative and inner surface temperature are illustrated as annual temperature duration curves.

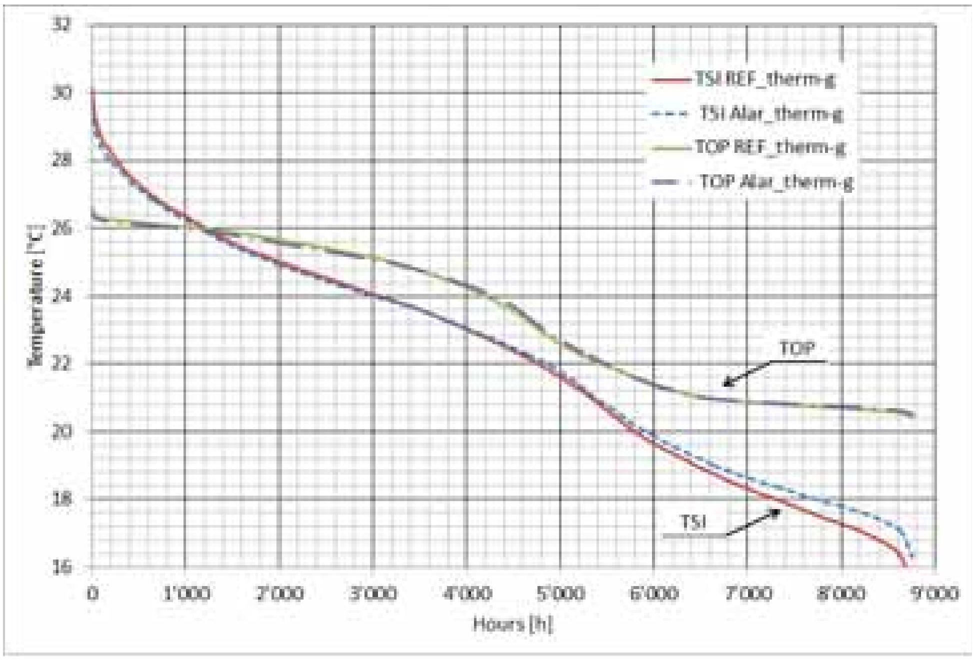

Fig. 6: Annual temperature curves - operative room temperature (TOP) and inner window surface temperature (TSI)[°C]

Comfort Criteria

In Table 4 a comparison of the most important results, regarding comfort criteria during the hottest annual hour, are listed. There are no significant differences between all values of the reference system and the “Alar Lamella”.

Tab.4: Comfort criteria: Inner window surface temperature, radiation asymmetry (R_Asym), predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD, according to ISO 7730) for the highest temperature during a year

	TSI max [°C]	**R_Asym** [°C]	**PMV** [-]	**PPD** [%]
REF_light-g	30.15	4.5	0.94	23.65
Alar_light-g	29.69	4.1	0.89	21.55

4.2. Light interpretation

Illuminance

Sufficient daylight supply in terms of workplane illuminance levels is a main criterion for the daylighting of office buildings. According to the standard EN 12464 a minimum of 500 lux is required on work planes in offices. Figures 7 and 8 show the annual mean horizontal illuminance values on the work plane for the venetian blinds and the “Alar Lamella” system, respectively. Throughout the year higher values are obtained from the “Alar Lamella” caused by the highly specular surface of the solid part as well as the perforation of the part that allows view to the outside. Table 6 shows that using the restrictive control strategy described above leads to a daylight autonomy of about 27% for the “Alar Lamella” whereas additional artificial lighting is needed with venetian blinds for more than 99% of the year. The significant difference in amount of daylight at the back of the room (sensor positioned 1m from back wall) indicates the superior ability of the highly specular, solid part of the “Alar Lamella” to redirect light into the depth of the room.

All results in Figures 7 and 8 and Table 6 are obtained from the simulations with interactive requests from TRNSYS (simulation method “therm”) and are truncated to the operating hours. The days of the year are running from left to right, the hours of the day from bottom to top. The numbers in Table 6 are related to a total of 2720 hours where daylight is available during office hours according to the test reference year.

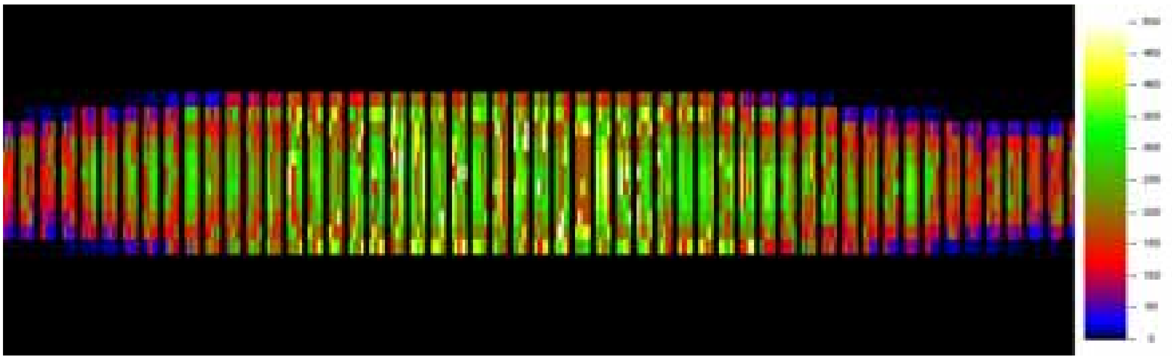

Fig. 7: Annual mean horizontal illuminance [lux] on the work plane for the venetian blinds

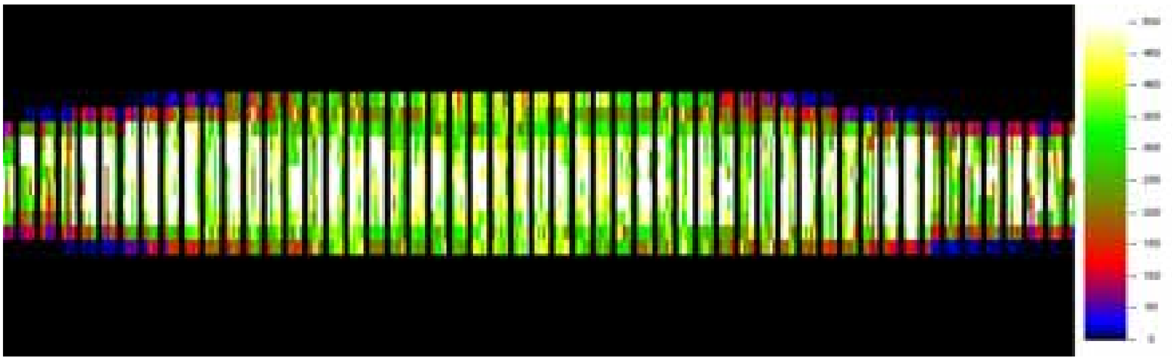

Fig. 8: Annual mean horizontal illuminance [lux] on the work plane for the “Alar Lamella”

Tab.6: Daylight characteristics of systems related to illuminance

	Venetian Blinds	**“Alar Lamella”**
Mean illuminance on work plane above 500 lx	10 hrs (0.37%)	744 hrs (27.35%)
Mean illuminance at back of room above 300 lx	0 hrs (0.00%)	215 hrs (7.90%)

Luminous efficacy

Luminous efficacy describes the amount of radiant flux that is perceived as light by the human eye. The spectral luminous efficiency function for photopic vision$V(\lambda)$ is used to convert from radiometric to photometric units and leads to a maximum luminous efficacy of 683 lm/W for monochromatic green light at 555nm. Luminous efficacy for skylight is approximately 100 lm/W while sunlight yields about 120 lm/W. With spectrally selective low-E coatings applied to glazings these values can be further increased.

For fenestration systems luminous efficacy is an important index as it indicates the thermal gains brought into the building through daylight. Thus, especially for office buildings high efficacy levels are desired as they represent increased daylight supply at the same heat input.

Figures 9 and 10 show the annual luminous efficacies for the venetian blinds and the “Alar Lamella” corresponding to an annual mean of 48.9 lm/W and 68.9 lm/W, respectively. Compared to the specular “Alar Lamella” the diffuse venetian blinds yield lower values throughout the year. Expectedly, the luminous efficacies of both systems highly correlate with the respective tilt angles of the lamellae.

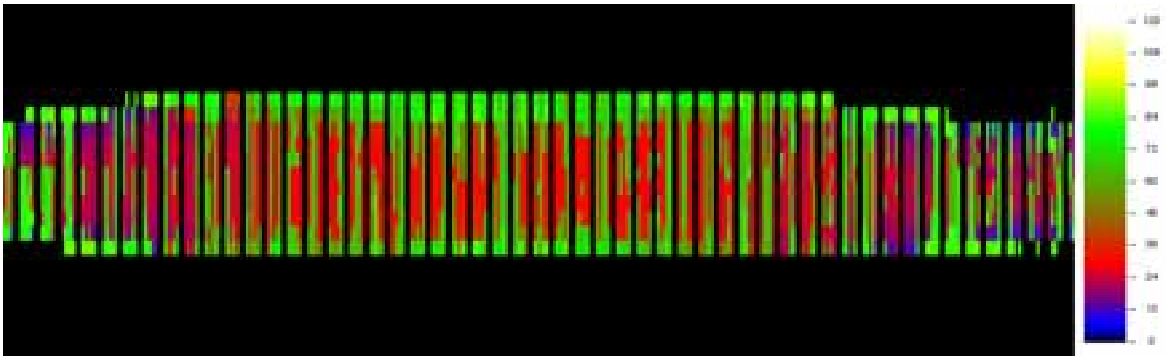

Fig.9: Annual luminous efficacy [lm/W] for the venetian blinds

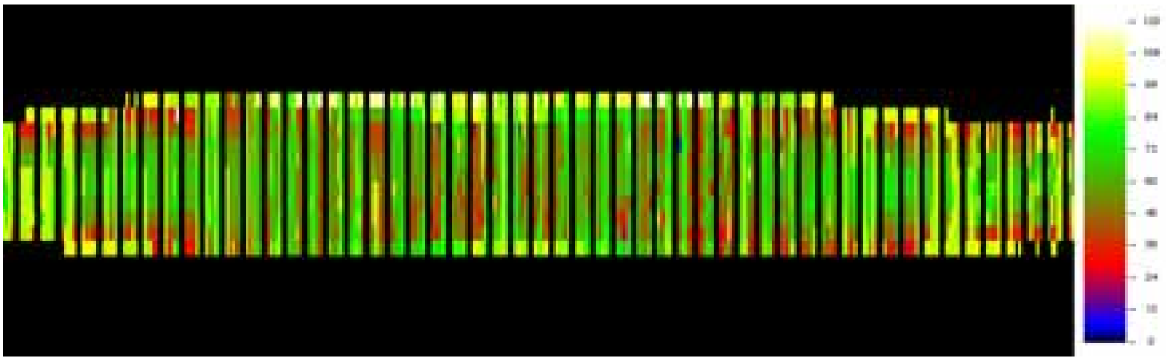

Fig.10: Annual luminous efficacy [lm/W] for the “Alar lamella”

Tilt angle dependencies

Table 7 shows simulation results split up for the various tilt angles of the daylight systems. For the venetian blinds, including interaction from TRNSYS does not significantly change the percental fraction of the single tilt angle occurrences. However, the positions of the “Alar Lamella” are influenced by the thermal requests. The main tendencies are to open the perforated lamellae from 90° to 75° and to close the solid lamellae from 60° to 75°.

As described above, the luminous efficacy highly correlates to the tilt angle of the daylight system’s lamellae. At smallest tilt angles (open positions) the luminous efficacy is highest, decreasing with larger blade rotations. Generally, the “Alar Lamella” yields higher efficacies than the venetian blinds. Expectedly, the fully closed (90°), solid “Alar Lamella” depicts an exception because nearly all the light is reflected, but still some thermal loads (secondary heat flux) are brought into the room. However, the low SHGC for this system setting indicates that these loads are not decisive in absolute values.

The SHGC (eq. 2) given in Table 7 is calculated in a simplified way from the thermal simulations as

$$SHGC = \frac{wallgain+int.gain}{ext.radiation} \text{ (eq. 2)}$$

Especially the solid “Alar Lamella” yields a high range of possible SHGCs from 0.043 to 0.327 (factor 7.6) according to the tilt angles. The venetian blinds and the perforated “Alar Lamella” yield lower dynamic range with factors of about 3.5 each.

Tab.7: Simulation results for daylight systems depending on tilt angles of the lamellae

	Tilt angle [°]	**Occurrence without TRNSYS interaction [%]**	**Occurrence with TRNSYS interaction [%]**	**Mean luminous efficacy [lm/W]**	**Mean calculated SHGC [-]**
Venetian blinds	0	15.6	15.5	82.18	0.259
	45	37.5	37.5	64.46	0.156
	75	46.9	47.0	25.51	0.073
“Alar Lamella”, perforated	0	19.8	19.9	91.54	0.312
	15	0.2	0.3	90.09	0.278
	30	1.5	1.6	91.31	0.245
	45	6.3	6.7	91.61	0.196
	60	2.1	4.0	82.18	0.153
	75	0.5	9.2	67.49	0.114
	90	69.6	58.3	51.09	0.089
“Alar Lamella”, solid	0	17.6	17.6	102.50	0.327
	15	3.3	3.3	100.99	0.322
	30	3.6	3.6	99.89	0.255
	45	16.1	15.9	94.72	0.186
	60	46.4	41.8	74.40	0.098
	75	6.9	12.4	37.14	0.052
	90	6.1	5.4	1.86	0.043

5. Discussion

The application of the enhanced method of combined thermal and light simulation implicates a huge amount of data acquisition and high CPU effort. It is time and CPU expensive, but the indispensable comparison between complex daylight systems is feasible. The results have to be discussed out of two points of view, namely the thermal and light aspects.

The developed models present respectable results for standard systems, such as venetian blinds, based on thermal considerations. For more complex systems the results between the models diverge slightly more although the thermal behavior is represented appropriately. For further projects and developments the models, especially the Abs-model, has to be optimized.

Nevertheless the comparison of the standard system and the “Alar Lamella” is carried out with the developed models. The results show the advantages of the daylight system regarding to heating, cooling and artificial light demand. The difference in comfort criteria is in the range of the uncertainty of the models and no clear conclusion can be drawn.

The “Alar Lamella“ outperforms the venetian blinds not only concerning thermal indices, but also with respect to lighting aspects. The results from the combined thermal and light simulations show a superior behavior in terms of mean work plane illuminance, daylight autonomy and luminous efficacy. Moreover, with the increased dynamic range of the SHGC of the solid “Alar Lamella” solar gains can be effectively controlled.

6. Acknowledgment

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