A NEW MODEL FOR SMART WINDOWS WITH MOVABLE PLANE MIRROR-ARRAYS AS A BASIS FOR ENERGY MINIMIZING CONTROL

Alexander Schwank[1], Jürgen Schmid[2], Anton Maas[3]

[1] University of Kassel, Department of Efficient Energy Conversion
[2] Fraunhofer Institute for Wind energy and Energy Systems (IWES), Kassel
[3] University of Kassel, Department of Building Physics and Centre for Sustainable Building (ZUB), Kassel

1. Introduction and motivation

The energy demand of buildings maintains one of the highest shares of the primary energy demand in Germany. It is used mainly for heating, cooling and for lighting. Controllable windows with solar-redirecting mirror systems can greatly influence the solar energy flows and distribution to the inside. The development of Micro-Mirror-Arrays (Viereck, 2011) within smart windows as such a device inspired this work by providing various possibilities to controllable windows, e.g. separate angular settings of different areas within the window, variable orientation of the mirror structures relative to the window and variable structure geometry. The control of smart windows meets different situations resulting in different set points. In high temperature conditions solar heat sources lead to higher cooling loads of a building resulting in a higher energy demand, and vice versa for cold temperatures. The need to illuminate a room and to provide a glare shield and a good view outside is related to the presence of people (Fig. 1). The functionality of the window is strongly linked to the changing outside conditions like sky radiance distribution and temperature. These examples show the high necessity of an automatic controlled window in terms of energy minimisation.

A key part of developing an energy minimizing control strategy is having a valid model of the mirror structures as solar-redirecting system within the window. Some requirements to such a model are as follows: it should enable an integral approach evaluating solar heat sources and daylight distribution. The integral algorithm should make it possible to examine the system control. The use of an adapted programme basis, which makes control analysis possible, is preferable. Even for whole year runs the simulation times should be manageable. It is beneficial to have a limited number of input parameters.

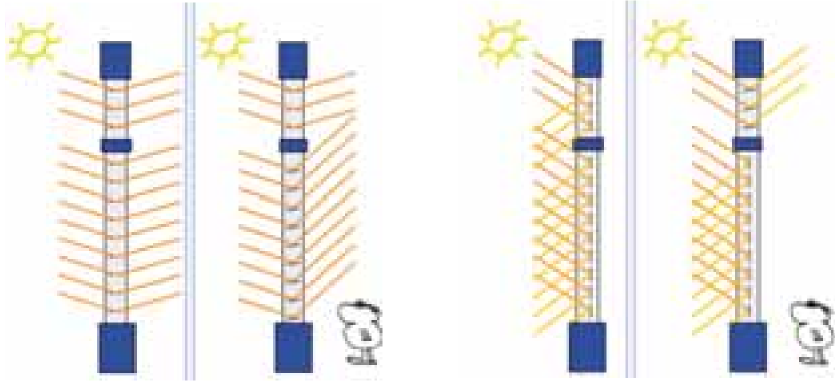

Fig.1: Visualization of concepts using mirror-arrays as solar-redirection system for glare shield and a better light distribution (left) or for heat protection and illumination (right) [Viereck et al (2009)]

2. State of the Art

The energy of a building is dominated by its energy requirements for heating and cooling and for artificial lighting. Thus a model for developing an energy-minimizing-control should be able to predict the heat and light flows through a window system and its distribution within the building. Starting point is to model the sky radiance and luminance distribution, followed by a part that describes the optical and thermal behaviour of the window and its coatings. This includes the radiation and light redirection system. Finally a routine to model the distribution of the solar flux within the building has to be considered.

Vartiainen (2000) compared several luminous efficiency models and pointed out how important the use of an accurate model is. According to his findings the models of Perez et al (1990 and 1993) are the best in describing the real conditions as they showed much more realistic results than the other models, especially for overcast sky conditions which are dominating in Europe. Thus the present paper focuses on programs which are able to use the Perez models.

A key point is the coupling of external to internal daylight distribution. A sophisticated approach is tracing the rays with a program like Radiance (Larson and Shakespeare, 2003). Mardaljevich (1997) and others validated the program Radiance for several different building geometries and shading devices. The results are detailed and close to real situations. The disadvantages of this program are a relatively extensive simulation time and big efforts to determine a whole cluster of various parameters.

Another approach to predict the internal illumination distribution is the radiosity-method (e.g. Müller (1997)). Originally, this method was developed to model radiative heat transfer. One important assumption is to treat all surfaces´ reflectivity as perfectly diffuse. The advantage of this approach is a much shorter simulation time. On the other hand, no specular reflections may be analyzed. For higher complexity of the building geometry the required simulation effort rises rapidly.

Tregenza (1983) introduced a method called *daylight factor* approach, which is capable to accelerate the simulation speed of ray-tracing simulations by decoupling the transfer function of the window-redirection-building system from the sky radiance distribution. Reinhardt (2001) compared the accuracy of the results and the simulation speed of different radiance based approaches to model the daylight distribution and additionally introduced an optimized approach using daylight-factors and Radiance. With this optimized approach, analysing complex light redirection systems with different angular and area settings would make it necessary to simulate each single configuration in advance before starting e. g. whole year runs. This again leads to extensive simulation times. Additionally, there is no possibility to facilitate the algorithm, because Radiance acts like a black-box. The optical and thermal properties of windows, its frames, glazings and coatings are collected in sophisticated programs and databases like WIS, WinDat (2011).

Nielsen et al. (2005) introduced a daylight distribution model for the early phase of building design which is a mixture of ray-tracing and radiosity method, resulting in short simulation times and an acceptable amount of input data. It uses the window system characterisation provided by WIS. The validation showed a good agreement for isotropic optical materials and relatively grand errors for systems including shading devices. Solar-redirecting devices are not taken into account. WIS includes a simplified model to characterise light-redirecting devices. Jäger (2005) adapted an algorithm formally used in thermal calculations to describe in detail the behaviour of different solar-redirection systems. A limit of both algorithms is however, that the azimuthally dependence of the incoming irradiation is not taken into account and that just horizontally orientated structures are examined.

Integral approaches are facing the task to couple thermal and lighting simulations or to integrate them within one program. The program ESP-r developed at the University of Strathclyde, Scotland is a thermal simulation tool coupled with radiance lighting simulations. The thermal model is used to extract radiance inputs. The routine uses the daylight factor approach.

Hviid et al (2008) introduced a new integral model for the early design process of buildings. It is a *Matlab* based programme which links the thermal and the visual part within one integral programme. Some analysis on the effect of control is undertaken as well. The routine of Nielsen et al (2005) is used to model the solar-radiation and light-redirecting-system and the light distribution in the building, with the effects already mentioned above.

2. Goals

The key motivation is to identify the energetical potentials of windows with solar-redirection systems. As a basis it is crucial to identify an energy minimizing control. In order to make a valid control analysis it is necessary to have a valid mathematical model. This should contain at least the parts thermal transmittance, light transmittance and distribution and user needs.

The state of the art showed that the existing algorithms that were found are only partially useful to solve this kind of question. There are just some integral approaches, containing all the aspects that were mentioned. The key point is the light and its distribution within the building. On the one hand, the *Radiance* and Ray-Tracing based approaches, are too slow for this variety of different settings of the solar-redirection system (angular settings and settings of controlled areas). Furthermore, they don't deliver the possibility to make logical analysis (blackbox problem). Inherent to this approach is the use of distributed programs and models, which makes it more difficult to make an integral control analysis. On the other hand the algorithm is fast but not adequate enough to describe the effects of a specular solar-redirection system (Nielsen et al 2005, Hviid et al 2007).

The goal of this work is to close a part of the gap in modelling variable, specular solar-redirection systems, subsuming the solar-transmittance, the redirection effects and the distribution inside the building. Within a tolerable simulation time, the model should deliver the solar-transmission properties of such a system and the irradiance distribution on a reference plane. Later on the extension to illuminance distributions is quite simple.

3. Model Description

In the following, the model is called *solREflexiq*. First assumptions and simplifications are mentioned. The analysis within this paper is focusingthe solar radiation. Using a valid luminous efficiency model this of course can be generalized to illumination aspects. The analysis assumes a completely specular reflection. Diffuse reflections from the mirror structures have to be added later on using already existing algorithms (e.g. Nielsen (2005), Jäger (2005)). This model is about plane structures. The inside areas, like walls and ceilings are perfectly diffuse reflectors (Lambertian diffuser). This analysis is dealing with structures that are comparable to the Micro-Mirror-Technology, but scaled up in size and neglecting the bended elements. These are called mirror-arrays (ma). The model also neglects the effects of light diffraction. The sun and the sky segments are treated as point sources.

3.1. View-Factor-Relation model of plane structures

The key challenge is to predict how the orientated radiation is processed within the mirror arrays, how much of the incoming radiation to the window plane is passing and if it is redirected. A new model for windows with movable plane mirror-arrays is presented in this paper. It is based on an approach of ray-tracing, vector algebra and the balance of areas. Analysing one single array-segment is generalized to the repeating structures. Using the outside radiance or luminance and the angular direction relatively to the window as an input the algorithm delivers as outputs the angular dependent solar- and light transmittance of the solar redirection system. Additionally, it models the illuminance and irradiance distribution at an arbitrary reference plane within the building. It is capable to calculate azimuthally dependencies as well as arbitrarily orientated mirror structures. This fast algorithm is meant to be integrated in one program with thermal simulation routines and other main effects, like glare shield. The algorithm is implemented in Matlab Simulink in order to have a good basis for future control development (Mathworks (2010).

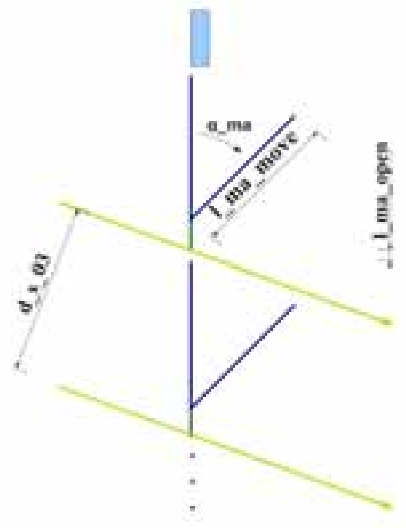

Fig. 2: Schematic drawing of the mirror-arrays side view including nomenclature. Movable mirror part (blue), fixed mirror part (green), solar rays (yellow). l_ma_move (length of the movable mirror), l_ma_fix (length fixed mirror), l_ma_open (length open part).

The starting point of the algorithm is to predict the shares of visible MMA areas (movable, fix, open) from the direction of the solar rays. These visible areas depend on the configuration of the mirror arrays and their angular setting, as well as on the view direction in elevation and azimuth. Fig. 2 shows two array segments in side view. Obviously, the distance between two solar rays (d_s_03) is not equal to the sum of the height of the open (l_ma_open), the fixed (l_ma_fix) and the movable part (l_ma_move). Assuming the sun as a point source the view direction can be treated as the sun-view-angle or in the model of Tregenza the view angle of an arbitrary sky element. Assuming the windows normal direction south and a slope angle of 90 degrees, the elevation α_s and azimuthally position γ_s is then equivalent to the viewing direction.

Fig. 3 illustrates this effect for horizontally structured mirror-arrays with an angular setting of 45° (azimuthal view position γ_s=-5°). For the sake of simplification, the mirrors are not interrupted in the beginning. It can be observed α_s=60° that no radiation from this direction will pass the mirror structures directly. Only the fixed (green) and the movable parts (blue) are visible. At α_s=20° there is additionally a directly transmitted part. Further diminution to α_s=-20° reduces the visible area of the movable part and increases the open-direct part significantly. At α_s=-60° the upper side of the MMA's is not visible any more, but only the bottom part (slightly lighter blue)

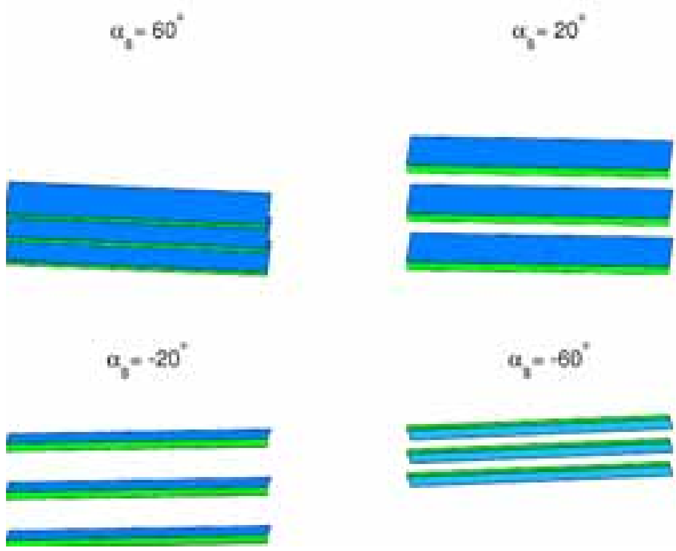

Fig. 3: Different elevation view angles from horizontally structured mirror-arrays with tilt angle of 45 degrees (nearly azimuthally-perpendicular)

Fig. 4 shows a side-view schematic drawing of the different mirror array parts and their indices. E.g. the straight line limiting the upper part of the movable row has the index 1.

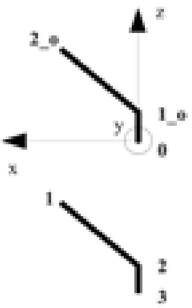

Fig. 4: Side view of two rows of the mirror array with indices: 0) Basal-line and lower end-line of upper fixed part, 1) upper end-line movable part, 2) upper-end-line fixed part, 3) lower-end-line fixed part

The key challenge is to determine the distances between the parallel solar rays hitting defined parts of the mirror arrays (e.g. d_s_02 determines the distance between the solar ray hitting the centre and the one hitting the upper part of the fixed row). The visibilityshare of the fixed, the movable and the open part is thus determined by putting the linked distance into relation to the maximal distance of one single structure element (d_s_03). This relation will be called ψ-Factor, e.g. the Factor of the fixed element ψ_fix is calculated like in eq. 1. The other ψ-Factors are calculated in the same manner.

$$\psi_{fix} = \frac{d_{s_{23}}}{d_{s_{03}}} \qquad \text{(eq. 1)}$$

The radiation which is led through the mirror-arrays for this share results in multiplying incoming radiation (I_in) on the window plane with this ψ-Factor and the reflectivity (ρ_ma) of the mirror-material (eq. 2). The determination of the shares' directions passing through the mirror-arrays will be explained in the next section.

$$I_{move} = \psi_{move} * \rho_{ma} * I_{in} \qquad \text{(eq. 2)}$$

The figure 5 shows the three general situations that are separated in this concept in 2-dimensional view. In case a) the solar radiation penetrates the structures so steeply, that no part passes through the mirror arrays directly. The distance d_s_02 is a measure of the movable share, whereas the distance d_s_23 is linked to the fix part. Case b) shows a situation where all the portions are existent. The distance d_s_01 is a measure for the open share. In Case c) there is no visible upper part of the movable arrays thus the movable parts are equal to zero. A part of the radiation, which comes through the open part, hits the backside of the upper row-segment. Another fraction hits the fixed part.

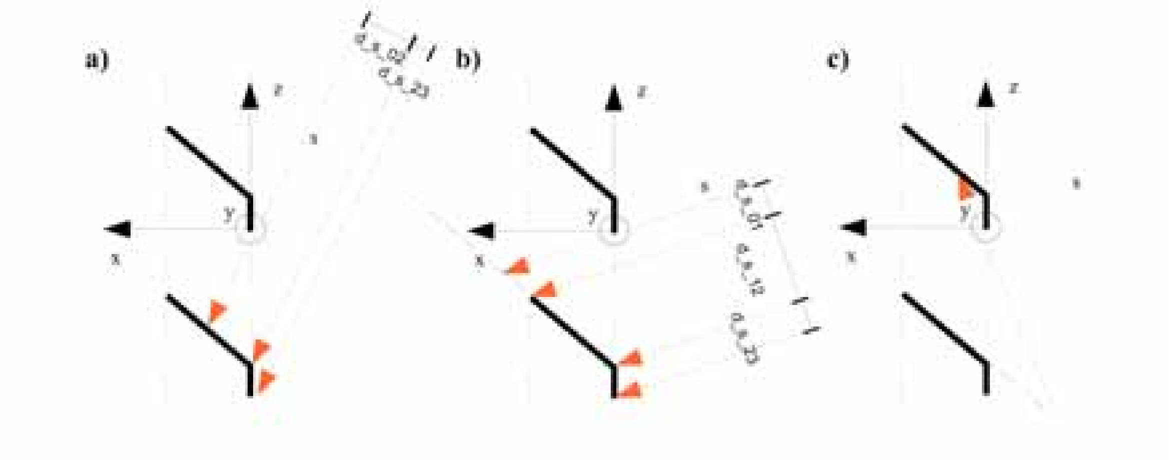

Fig. 5: Three different situations in 2-d view (red arrows coming from the radiation source): a) Situation without an open part b) situation with open part c) situation without a visible share of the upper side of the movable mirror-element.

The radiation is traced further on through the mirror-arrays. Fig. 6 shows the principal fine structure. As already mentioned, the open share splits in an open-direct and an open-backside-movable part, which strikes the backside of the above movable mirror row. The fixed share does not split off. The movable share divides into the movable-reflected and the movable-open part. The movable-open part exists, if the movable mirror part is interrupted. The movable-reflected part is the redirected share. It goes directly inside or outside the building or is reflected to the back of the above mirror row.

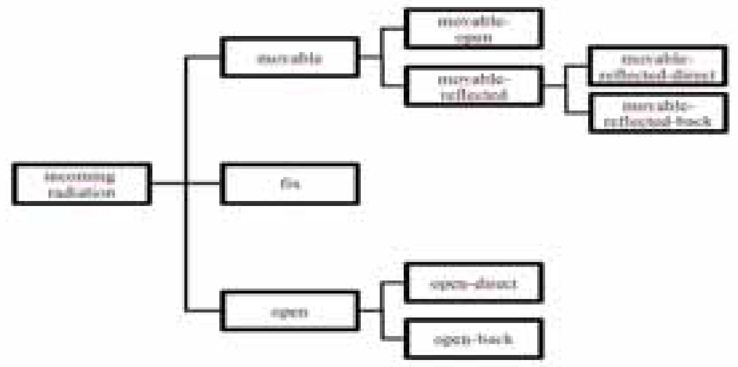

Fig. 6: Principal drawing of the radiation shares which are taken into account. Main: open, movable and fix part.

Up to now the question where the solar ray is intersecting the defined straight line could be ignored, assuming that the rays were hitting the structures azimuthally perpendicular. Now this 2-dimensional logic will be generalised for the 3-dimensional case. Fig. 7 visualizes the general interdependencies. In this case the radiation doesn't penetrate azimuthally perpendicular (γ_s=-30° and α_s=35°) and additionally the structures are rotated in the window plane (rotation angle δ_ma=-30° from the horizontal). Four solar rays are included. The green line marks the rotation of the mirror-array structures. The intersections from all the solar-rays with the straight lines representing the mirror-arrays parts have to be located on this line. Exclusively in this case the complete height of the mirror-array is relevant.

3.2. Specular redirection algorithm of arbitrary plane structures

In order to calculate the specular direction of the reflected radiation from arbitrarily oriented, plane mirrors the following approach is used: A set of three equations is to be solved, which is determining its Cartesian vector components. Whenever possible, normalized vectors are used in order to simplify the calculation. The incoming ray and the normal to the mirrors surface enclose an angle φ. Second, the outgoing solar ray and the incoming one enclose the angle of two times φ. These two conditions can be interpreted as scalar products. Finally the incoming ray and the mirrors-normal are building a specific plane. The outgoing ray is also within this plane. Mathematically this may be treated in following way: the cross product of the incoming ray and the mirrors-normal is determined. The scalar product of this vector and the outgoing ray must be zero. From these three equations the three components of the outcoming ray can be determined.

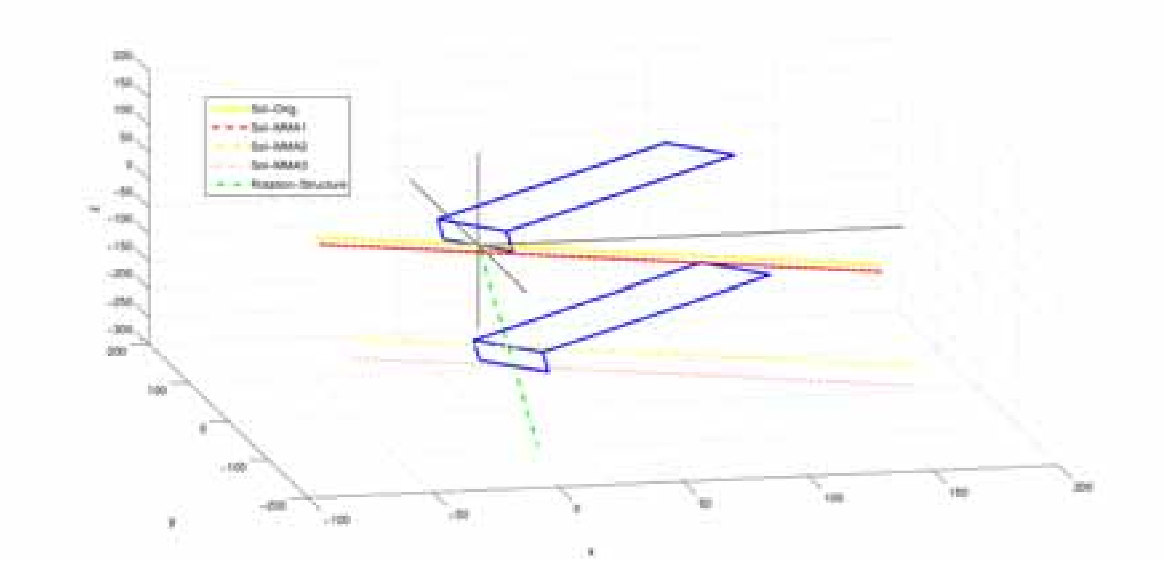

Fig. 7: General concept explanation in 3-dimensional view (angles: solar azimuth γ_s=-30°; solar elevation α_s=35°; slope movable mirror β_ma_mov=45°; rotation mirror-array structures δ_ma=-30°)

3.3. Radiation distribution within the building

The concept of the radiation distribution to an arbitrarily located and oriented reference plane inside the building is likely the concept of Nielsen (2005) a mixture of ray-tracing and the radiosity method. The rays from the corner of the relevant window area are traced in the direction of the outgoing radiation part (e.g. movable-open) in order to find representative intersection points on the room-limiting-areas (ceiling, walls, floor). The algorithm is the following: first it is checked whether the direction of the radiation is above or below horizontal. If it is below, the radiation tends to hit the floor, the side walls or the back wall. In this case, only the radiation which is directly transmitted to the reference plane is validated. The reflected radiation from the floor is neglected (see also the assumption just upward to vertical facing reference surfaces). That means that second reflections are not taken into account.

The part which is reflected above the horizontal line tends to hit the ceiling, the side walls or the back wall. If the lower end of the window is higher than the reference plane, this part won't hit it directly. In the standard case it will not hit the reference plane directly. The oriented rays coming from the window corners, which are above the horizontal, will hit the ceiling plane anywhere, not necessarily within the margins of the real ceiling. Connecting these points will result in a parallelogram. Its main centre can be determined. Following the radiosity method, this is the point from which the reflected part is being sent to the receiving reference surface. If this point is located within the margins of the ceiling, it is already the relevant point.

Otherwise, a connecting straight line between the middle point of the window element and this point will be constructed and the intersection to one of the real walls is determined. In this case, this intersection point is the relevant senderpoint. In case of a grand window area, the algorithm allows to split this area in several sub-areas and to use the same procedure as described above. Depending on the number of sub-areas this will lead to more exact results and a longer simulation time.

4. Plausibility

The following plausibility analysis will be based on a standard case: length of the fixed part l_ma_fix= 1.58 cm, movable part l_ma_move=7.89 cm and open part l_ma_open=0.53 cm. The angular setting of the mirror-arrays is β_ma=45°. For simplification, in the standard case the mirror-arrays movable part is one uninterrupted part. Thus the moveable open part is equal to zero.

The analysis diagram on the right side of Fig. 8 shows that the open-direct part starts at a solar altitude angle of below 30°. This can also be observed in the visualization on the left side where the open part is locked at 60° and open at 20°. At below -45° the movable-reflected-direct part ends and the open-backside part starts. At this point one starts to look from the bottom to the movable mirror parts. From -20° to 0° solar altitude angle one part of the movable-reflected part directs to the back of the above located mirrors.

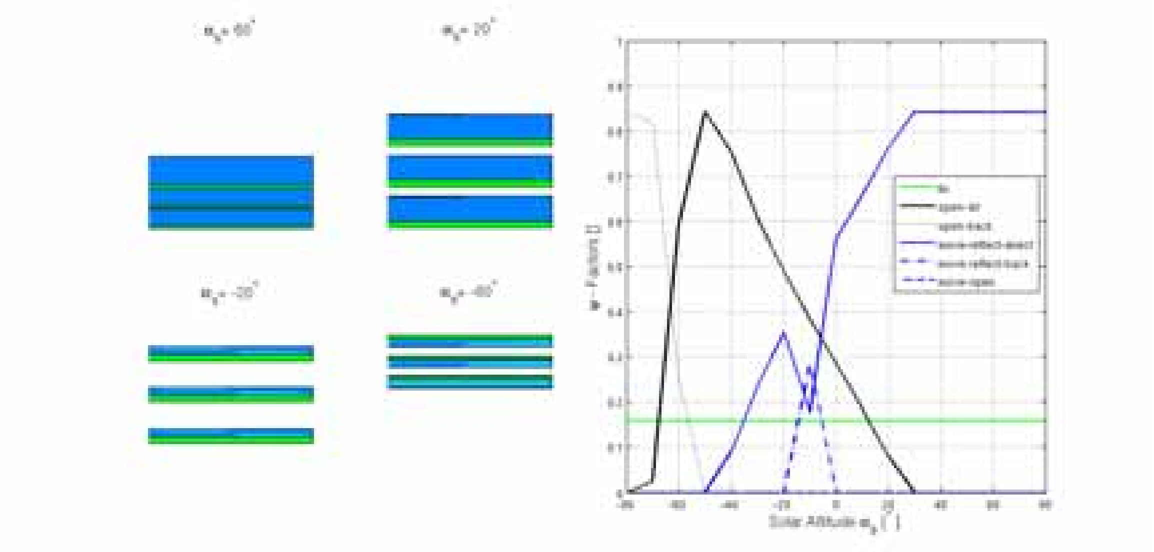

Fig. 8: Azimuthally perpendicular view angle with variable solar altitude angle. Right side: visualization; left side: analytical solution by the algorithm

The situation if the solar altitude angle is kept (20°) and the azimuth angle is variable is shown in fig. 10. From an azimuthally perpendicular position at an altitude angle of 20° there is still an open-direct part. Below -50° and above 50° there is none. Thus even in horizontal configuration the azimuthally dependency of the ψ-factors cannot be neglected. A 2-dimensional analysis leads to substantial errors mainly for steep azimuth angles.

An analysis of mirror-arrays which are rotated -45° within the window plane in fig.11. The altitude angle in this case is variable. Compared with the horizontal situation the open-direct part starts already below 40°. There is no situation where the movable-reflected part is directed to the bottom of the above row and a much smaller band where the direct part is heading to this place.

4. Validation

The previous section showed some comparisons to get an idea of the plausibility of results. In this section the validity of the numbers will be checked. The results of the new model will be compared with *Radiance* results. The configuration of the test is as follows: Artificially, in *Radiance* a dark sky is created that consists of a sun resulting in solely beam radiation from one direction. The reflectance of the ground is set to zero. Thus the radiation comes exclusively from one defined direction. The radiation hits a room configured as shown in Fig. 11. This room is configured like in VDI 2078 (1996), but the window is determined to 1m² in order to get a relatively defined solar radiation situation inside the building. The mirror arrays are in standard configuration as already described. In this artificial case the window panes are neglected .

This validation consists of three main steps:First, the solar-flux which reaches the outside surface of the window is validated. Second, the solar-flux which reaches the ceiling is compared in location, intensity, and distribution. Finally, the irradiance distribution on a reference plane is validated. Thus the validation covers three models: the mirror-array model for transmission, the one for the direction and the model for the radiation distribution inside the building.

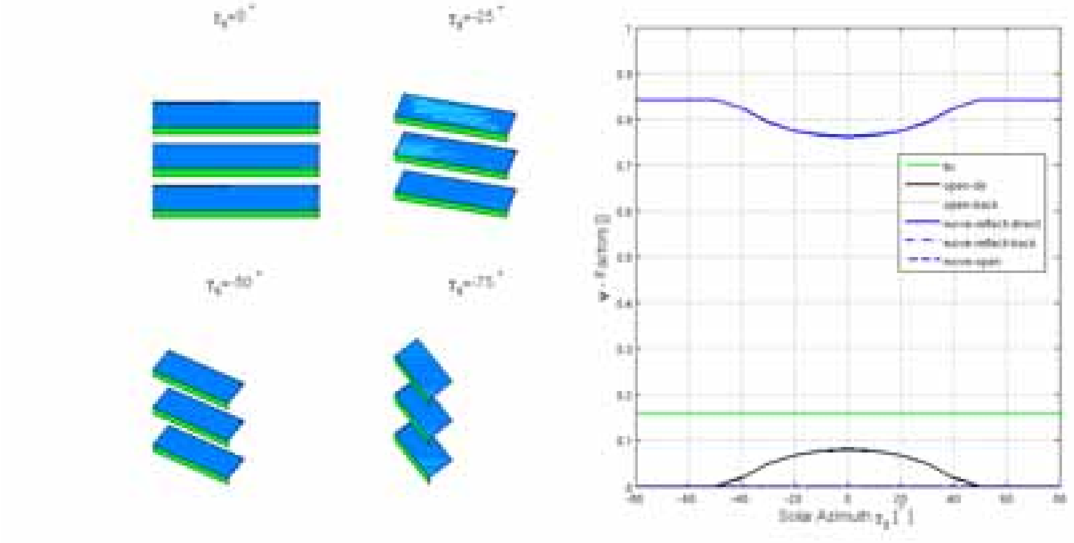

Fig. 9: Visualization and analysis diagram of the mirror-arrays at a solar altitude of 20° and variable azimuth angle.

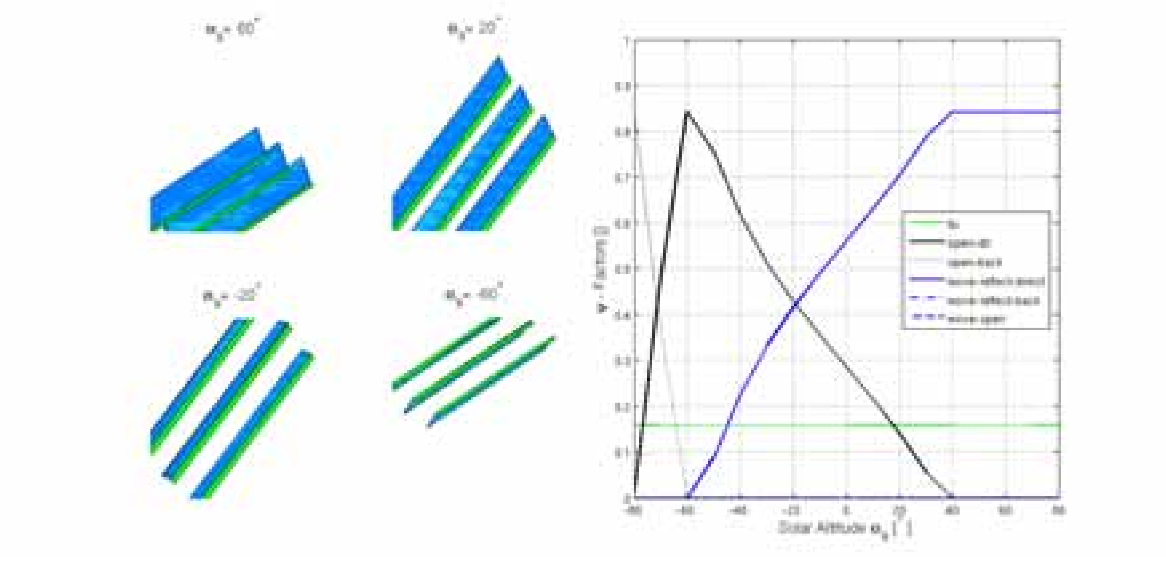

Fig. 10:Analysis of mirror-array structures that are rotated -45° in the window plane for different altitude angles

As input an irradiance of 750 W/m² on an outside horizontal plane is chosen. Thus the solar radiation flux on the window plane varies, depending on the angular conditions. In this case of validation the following situation will be analysed: Solar altitude angle 30°, solar azimuth 0°, mirror-arrays standard configuration, horizontal with a slope angle of 80°, and mirrors without absorption.

In this case the solar flux which reaches the 1-m²-window is around 1299 W. Fig.12 shows a visualisation and ψ-Factors-analysis for this situation. As a result of the new model the fixed part has a share of 15.8%, the movable-direct of 58.6% and the open-direct of 25.6% resulting in a total of 100%. There is no movable-reflected part on the backside of the row above.

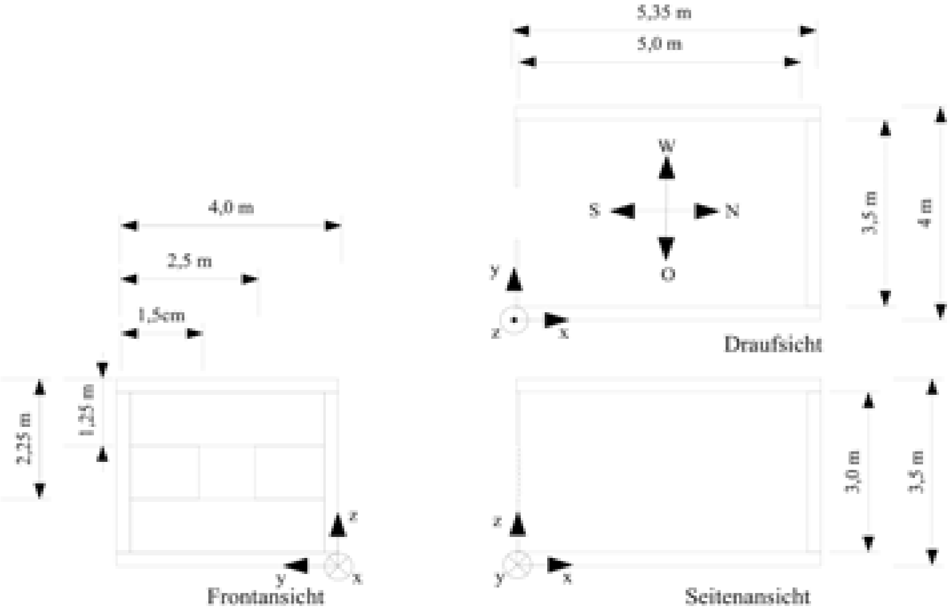

Fig. 11: Configuration of the analyzed building.

Going further to the transmission of the solar flux to the building, Fig. 13 shows what the situation looks like in a *Radiance* picture. The reflected part of the movable mirror-parts (movable-direct) can be found on the ceiling, whereas the open-direct part is transmitted to the floor. This part intersects the reference plane between 0.26 m < x < 1.99 m.

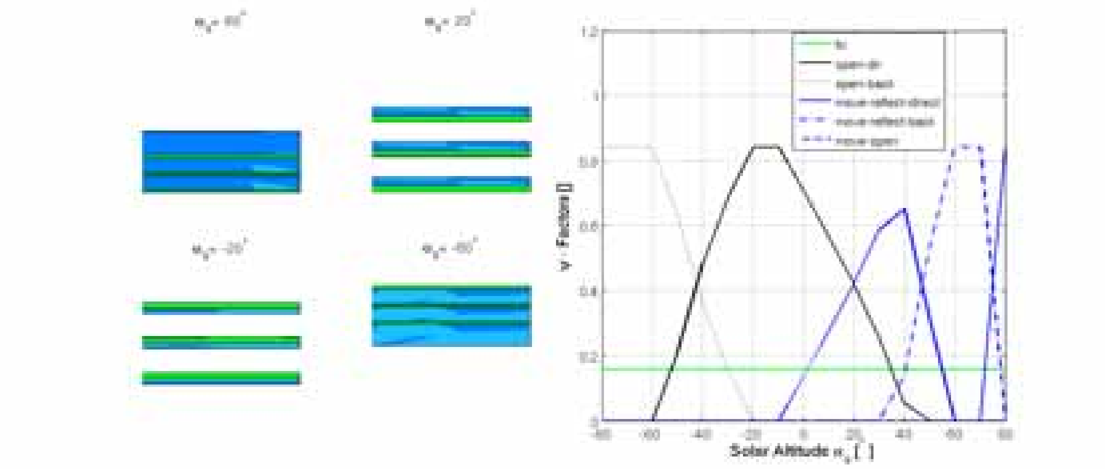

Fig. 12: Visualization of the mirror-arrays and analysis diagram for a mirror-slope-angle of 80°

A comparison of irradiance distributions at the ceiling plane is shown in Fig. 14. The rectangular shape of the new models compared with the *Radiance* distribution field results from assuming the sun as a point source. The integrated solar flux calculated for the Radiance Model in this situation is 840 W compared to 760 W in *solREflexiq*. This is a deviation of around 9.4 %. A reasonable explanation for this effect are the secondary reflections within the room, mainly from the floor.

It is substantial to know about the distribution of solar flux on a reference plane, e. g. to predict the illuminance level. Figure 15 shows this distribution on a plane in 85 cm height and orientated upwards (positive z-direction). The comparison shows a quite similar distribution shape with a nearly parallel location of the results. This leads to high relative errors in the locations with low irradiance. The reason for this effect could be the neglected secondary reflections.

Artificially the reflectance of the walls and the floor is set to zero the situation differs in the following way: the integrated solar flux on the ceiling in Radiance is now 2.8 % lower than the solREflexiq result. It results in an irradiance distribution on the reference plane as shown in Fig. 16.

Fig. 13: Radiance picture of the situation in fisheye perspective: α_s=30°; γ_s=0°; standard configuration of mirror-arrays

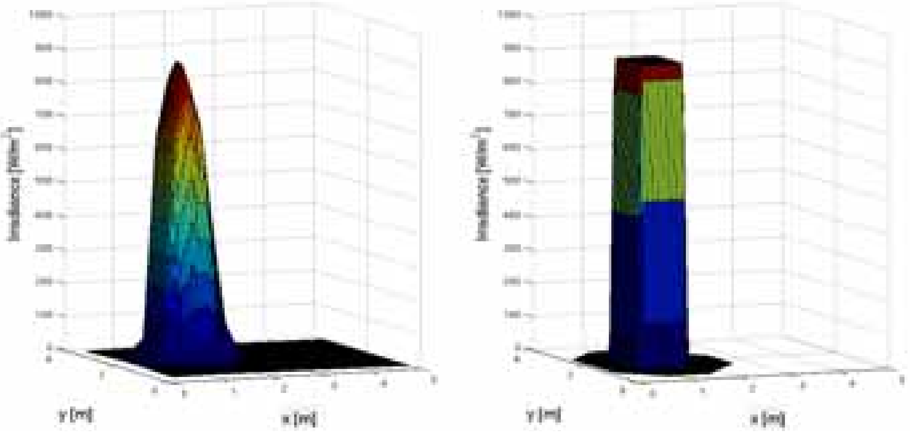

Fig. 14: Distribution of irradiance on the ceiling in Radiance and solREflexiq

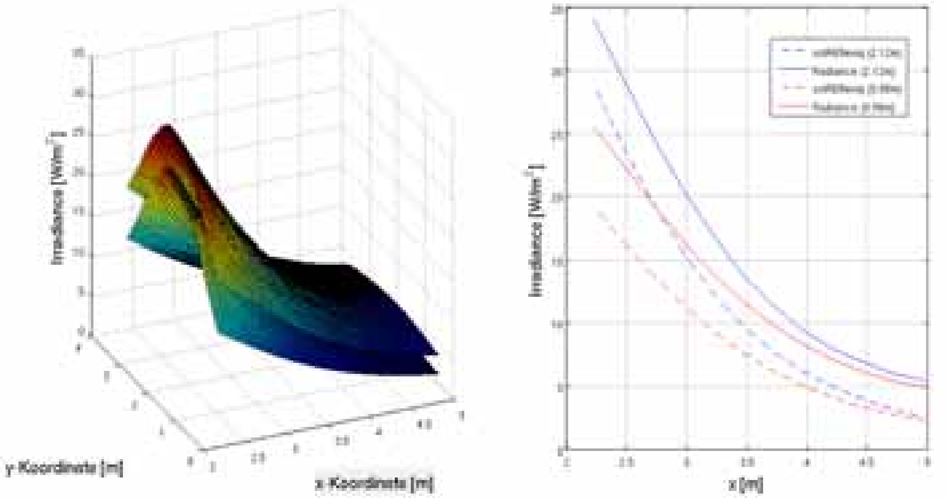

Fig. 15: Comparison of irradiance distribution in Radiance and solREflexiq on the reference plane

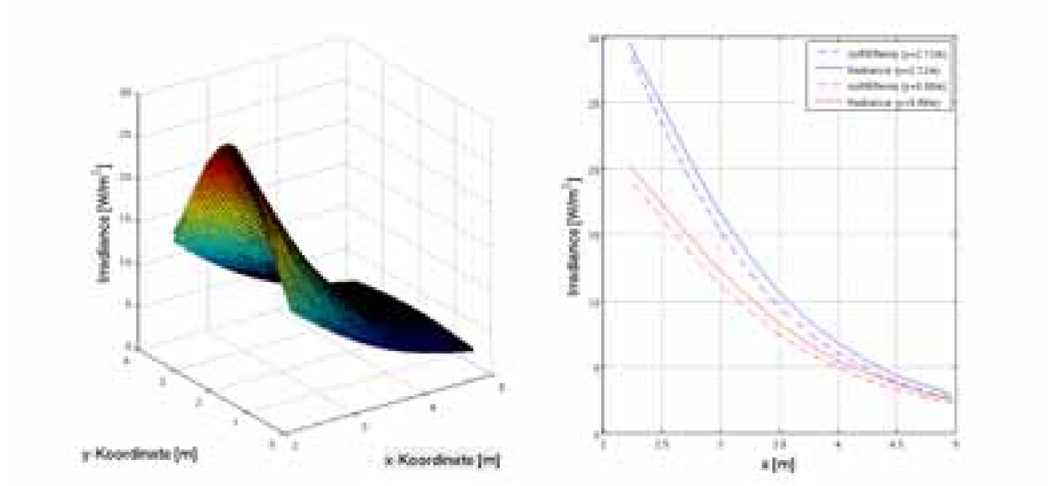

Fig. 16: Same as Fig. 15, but without secondary reflections form the floor and the walls

5. Results

The model *solREflexiq* is able to deliver a variety of different results and possibilities of analysis. As an example, the solar transmission rate depending on the solar altitude can be determined. Fig. 16 shows a solar-transmission field for an azimuthally perpendicular situation. The variables are the slope of the movable-mirror part (α_ma), and the solar altitude angle (α_s). It shows, that there is a relatively straight line between the solar altitude angle -80° and the mirror-slope-angle of 80°, where the solar-transmission of the mirror-arrays change very quickly from a very low level on the left side to a very high level on the right side of this line. The detailed shape of this border line is quite complex and a good basis for further investigations and systematic understanding. The range of the solar-transmission rate is between 0 and 84.1%. The high end is determined by the hight of the fixed element. In order to come to a sophisticated control concept, it is now important to check the direction of the out-coming redirected solar-rays.

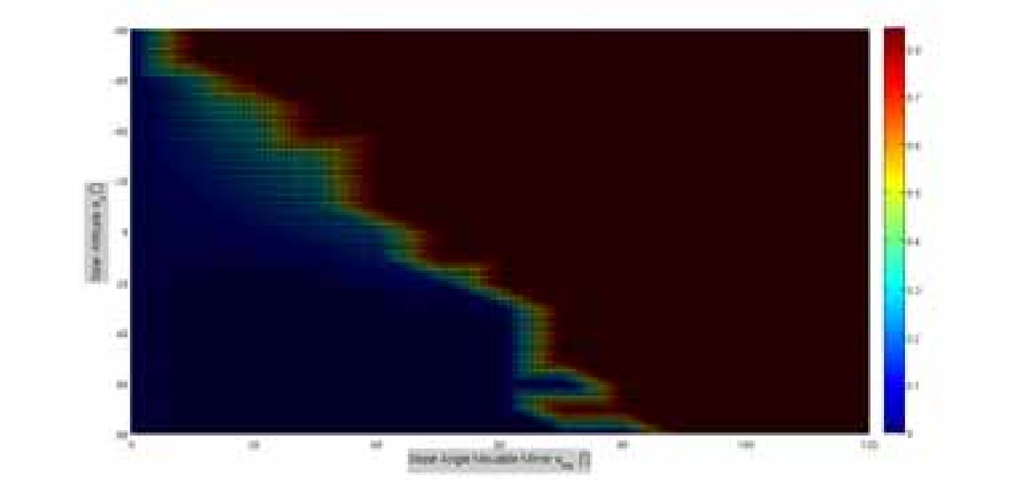

Fig. 16: Solar-Transmission-Rate of the mirror arrays in Standard configuration (solar azimuth 0°)

6. Summary

A new model, called *solREflexiq*, to evaluate the energy related effects of specular, plane, and arbitrary oriented solar-redirection systems is introduced. It also consists of an algorithm for the distribution of solar flux into the building which is comparable with other algorithms that are already in use. It is a mixture of methods: ray tracing, radiosity, and balance of areas. *solREflexiq* is one step to link the effects of daylight distribution, thermal effects, and other side conditions in order to find an energy-optimized control strategy and to evaluate the whole year energy effects of those systems. The approach is motivated by the development of micro-mirror-arrays and uses their geometrical relations as an example. The plausibility contains mainly the comparison between visual and numerical analysis. It gives an idea of the possibilities for analysing the properties of these kind of structures. It showed that, even for horizontally oriented solar-redirection systems, a 2-dimensional analysis is not accurate for steep azimuth angles. Following visual and numerical analysis there is a substantial influence of the azimuth angle to the transmission properties. The validation of *solREflexiq* with *Radiance* showed a relatively high relative error for the irradiance distribution on the reference plane. The assumption was approved that this deviation was a result of the neglected secondary reflections of the floor and the walls. Subtracting those reflectances in *Radiance,* the comparison of the results shows a very similar shape and a low relative error throughout the whole room. This leads to the result, that the algorithm for the mirror-arrays and for the distribution from the ceiling to the reference plane is validated. The algorithm for the other secondary reflectance has to be improved. As a result a solar-transmission field dependent on the solar altitude and the mirrors setting angle was extracted. This shows the analytical possibilities of *solREflexiq offering* a basis for a coming control development of smart windows.

7. Outlook

Some more validation of the new model *solREflexiq* has to be done, e.g. for different configurations of the mirror system and different solar positions. Further analysis of different mirror-array configurations can lead to adapted and optimized designs. It would be beneficial to generalize the approach of plane to bended structures. The coupling of a sky-radiance and illuminance model will lead to realistic situations. Introducing glass-panes with certain coatings will make different window and systems comparable. It would be useful to evaluate other configurations of plane mirror systems, e. g. existing integrated plane macro jalousie systems. The coupling of a thermal routine will open the possibility to conduct integral analyses of control strategies and energy optimization. Simplified algorithms to model glare shield and a satisfactory view outside would integrate the model in the user's context. Finally, investigations on the optimized size of intelligent windows containing solar-redirection-systems would be valuable: probably this will lead to larger window areas and much more use of daylight inside buildings, while saving primary energy.

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