Evaluation of daylight performance in scale models and a full-scale mock-up office

Dilay Kesten[1*], Sebastian Fiedler[2], Felix Thumm[1], Andreas Löffler[2] and Ursula Eicker[1]

[1]*Centre of Applied Research - Sustainable Energy Technology (zafh.net), Stuttgart University of Applied Sciences, Stuttgart, Germany;* [2]*Department of Architecture and Design, Stuttgart University of Applied Sciences, Stuttgart, Germany*

Abstract

The best way to improve daylight performance is to take a closer look on the behaviour of lighting the interior of sample building spaces. Scale models are commonly used to assess daylighting performance of buildings using an artificial sky for purpose of research and teaching as well as practice. In this paper the daylight assessment performance of the artificial sky at the Stuttgart University of Applied Sciences, Department of Architecture is evaluated. A method was developed, which allows analysing the main sources of errors by progressive stages. To analyse the main sources of error, comparisons were undertaken between the full-scale mock-up office, physical scale models and computer simulation models. The field measurements were performed in a South–South-East faced full-scale mock-up office. The four photosensors were placed on the middle axis of test office and scale models and the illuminance was measured from these points. The luminance distribution of the sky and the sun at the time of every single measurement was recorded with a luminance camera and fisheye lens. The computer simulation model was created in the Radiance program and used especially to archive sensitivity analyses of modelling errors. This study is an attempt to identify the main sources of experimental errors occurring in the assessment of building daylighting performance by means of scale models. It is aiming to find a correlation between luminance distribution of the sky and outside direct illuminance and internal illuminance levels and describes a strategy for energy efficient lighting design.

Keywords: daylight assessment; scale model measurements; artificial sky

*Corresponding author:
dilay.kesten@hft-stuttgart.de

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1 INTRODUCTION

The reduction of building energy consumption and increase of user comfort by means of intelligent daylighting design gain more and more importance.

To achieve these goals, it is essential to assess the daylight performance of buildings in early stages of the design process. Simulation models can be used to asses the annual energy consumption for electric light or the impact of daylight on the thermal behaviour of the building. This is not possible with the analysis of scale models under an artificial sky [1]. But scale models allow an intuitive and direct approach to the given task and working in small groups on the same model. The impact of changes in a scale model can be seen and evaluated immediately, while the impact of changes made in a simulation model has to be recomputed. Depending on the complexity of the building this can take up to some hours or more [2,3]. Hence the artificial sky is an important tool for the assessment of daylighting performance in early design stages, when geometry and material are not yet defined in detail, and for teaching purpose.

However, creating an accurate physical model is not easy and can cause major errors. In the previous studies the difficulty of accurately reproducing internal reflectance and some other common error sources in daylighting performance assessment was identified. According to Love and Navvab results, the general estimation of daylighting performance in physical models differed by 10–50% from that of the real building (full-scale space) depending on the fenestration types and photometer position in the space [4].

As well as the geometric and photometric properties of the scale models, Cannon-Brookes' study pointed out other physical parameters, such as maintenance and dirt in the building. This study showed that relative divergences of 10–25% can happen, for example, if the surface reflectance of the scale model is not accurate [4].

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This paper describes a methodology to analyse the daylight performance using full-scale mock-up office and different scale physical models under effect of various daylight sources. The comparisons of daylight measurements have expressed different profiles. Synthesis of these results leads to investigate the source of errors in order to determination of the daylight performances at the Stuttgart University of Applied Sciences, Department of Architecture. Unlike precedent studies about scale model measurements this methodology includes measurements in a real test room of scale models under outside conditions and under the artificial sky as well as additionally computer simulation modelling for sensitivity analysis [5–7].

2 EXPERIMENTAL METHODOLOGY

The major aim of the methodology is to assess the daylighting performance of scale models in real sky, artificial sky and computer-designed sky to quantify the experimental errors. It allows analysing the main sources of errors in progressive stages by comparing measurements in a test room and scale models under real sky types (clear, overcast), simulated standard sky types and mapped real sky values. Figure 1 shows scheme of the experimental procedure in this study.

In a first step simultaneous measurements of work plane illuminance for overcast and clear sky conditions are undertaken in a full-scale test room and scale models placed under identical outdoor daylighting conditions. The luminance distribution of the sky and the direct horizontal illuminance (in case of direct sunlight) at the time of every single measurement are recorded with a luminance camera and illuminance sensors. In a second step the luminance distribution and the setting for the sun is transferred to the artificial sky and the scale models are measured under reproduced outside daylight conditions.

The measurements were done with models of different scale (1:10, 1:20 and 1:50) and for three different facade systems (Venetian blinds with daylight guiding equipment, horizontal louvres and light-shelf). Facade systems of full-scale mock-up office can be seen in Figure 2.

The comparison of the test room and the scale models under the same outside conditions allows isolating and quantifying the errors due to model building, i.e. material and geometry (scale). The comparison of the models under the artificial sky and the same models under outside conditions allows isolating and quantifying the errors due to the performance of the artificial sky, i.e. sky type.

The test room is obstructed by surrounding buildings. To quantify the impact of the external obstructions additional measurements of the scale models are undertaken on top of a high rise building (Max-Kade-Building) near the test room site. Some measurements are also compared with computer simulations with identical settings.

2.1 Test room

The test room is located in an office building near the city centre of Stuttgart, Germany. The two-storey building is commonly used by the University of Stuttgart and the Stuttgart University of Applied Sciences. The test room is located on the ground floor and facing the parking area. The facade is orientated towards South–South-East (154.5° from North).

The interior of the test room was very inhomogeneous, which would have complicated the model building and caused additional errors in the measurements. Therefore the test room was remodelled. The walls' and ceiling's original surfaces—profiled metal sheeting and timber panels—were covered with plasterboard and painted white. The heavily soiled linoleum floor was covered with a blue-grey carpet; the window frames and the door were painted white.

After remodelling the test room dimensions are $2.31 \times 5.84 \times 2.08$ m (width × depth × height). Floor plan and sections of test room are shown in the Figure 3b.

2.2 Scale models

The scale models built for the measurements differ in scale and material. There are models of the test room and the three facade systems in scale 1:10, 1:20 and 1:50. They represent commonly used model scales for detailed facade (1:10), room (1:20) and building design (1:50).

Different aspects were analysed in each scale. Models of the Venetian blinds and louvres were built with opening angles of

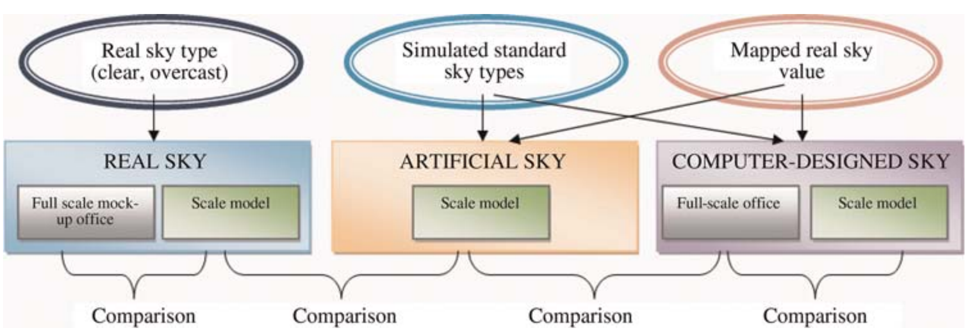

Figure 1. *Scheme of the experimental methodology.*

Figure 2. *(a) Venetian blinds; (b) horizontal louvres; and (c) light-shelf.*

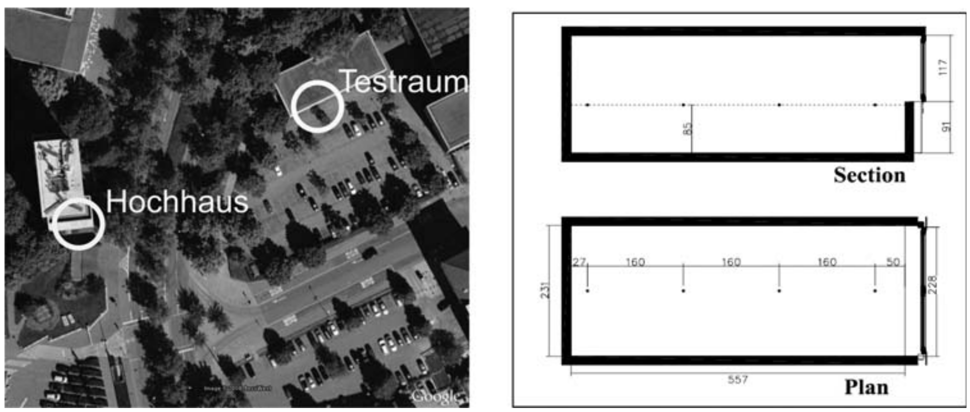

Figure 3. *(a) Site plan (test room in circle) and (b) floor plan and section of the test room.*

0° (horizontal) and 45° in scale 1:10, to analyse the impact of the facade system's adjustment. The influence of model material was analysed in scale 1:20. Therefore two models of the test room were built, one with model material and the other one with the original materials that were used for the remodelling of the test room itself. The facade system models in scale 1:20 were built in three different material versions: original material, good but uncommon model material and common model material. All model building materials were carefully chosen to match the photometric properties of the original materials. For that purpose the reflectance and transmittance of more than 200 different model building materials and the original materials were determined with a Perkin Elmer Type Lambda 19 spectrometer. The results were collected and displayed in a catalogue that supports students when building daylighting scale models. Table 1 shows all materials used in the test room and the scale models and their photometric properties.

The glazing of the test room was not modelled. The transmittance of the glazing was measured before every measurement series with a Gossen Mavolux lux-meter. Thus the angle-dependent transmittance could be considered as a correction factor in the analysis of the scale model measurements.

The best position for the scale models was the window of the room adjacent to the test room. The horizontal middle axis of the test room window and the scale model window were on the same height. The scale models facade was carefully aligned with the test room facade, but with an overhang of ~10 cm to avoid shadowing effects by the facade system rack.

2.3 Sky luminance distribution

The sky luminance distribution was recorded with a TechnoTeam LMK mobile luminance camera and a Nikon FC-E8 fisheye converter. Since the view angle of the luminance camera was restricted to ~150°, it was not possible to measure the luminance distribution of the whole sky vault with one picture. Therefore a series of four pictures per measurement had to be taken, which took ~1 min 20 s. For transferring the sky luminance distribution into the artificial sky, it was partitioned into 145 regions according to Tregenza's model [8].

2.4 Illuminance measurement

The illuminance was measured at four points (respectively, two points when the 1:50 scale model was used) on the middle axis of the test room and the corresponding points in the scale models. Figure 4a and b shows the setting in the test room and in a scale model (scale 1:20). In cases of direct sunlight on the test

Table 1. *Photometrical properties of full-scale mock-up office and physical scale models.*

Component	Material	Scale	ρ_{tot} (%)	ρ_{dif} (%)	ρ_{dir} (%)
Wall, ceiling	White paint on plasterboard (RAL 9010)	Original	89.97	89.79	0.18
	Museum quality mounting board, natural white[a]	All	90.47	90.20	0.28
	Finnboard[a]	1:20	82.20	80.40	1.80
	Grey paperboard	1:20	45.53	45.37	0.16
Window frame, door	White paint on wood	Original	89.42	88.45	0.97
	Museum quality mounting board, natural white	All	90.47	90.20	0.28
Carpet	Carpet, grey-blue	Original	19.44	19.42	0.02
	Rag-felt board AF, grey-blue	All	19.08	19.02	0.06
Venetian blinds	Grey paint on aluminium (RAL 9006)	Original	53.20	47.80	5.40
	d-c-fix aluminium self-adhesive film[a]	1:20	49.12	46.19	2.92
	Grey paperboard[a]	1:10, 1:20	45.53	45.37	0.16
	PET-G patterned sheet, printed (line pattern 1.0 mm)[a]	1:50	–	–	–
Louvres	Aluminium E6 EV1	Original	72.71	67.49	5.22
	3M Scotchlite reflecting film 3210[a]	1:20	65.16	59.70	5.47
	Aluminium sheets (0.5 mm)[a]	All	59.49	43.25	16.24
Light-shelf (specular)	Aluminium sheets	Original, all	80.67	45.52	35.15
Light-shelf (diffuse)	White paint on film coated plywood (RAL 9010)	Original, all	90.47	90.46	0.01
	Museum quality mounting board, natural white[a]	1:20	90.47	90.20	0.28

[a]For material description, see www.modulor.de.

room facade the horizontal direct illuminance was recorded and transferred to the artificial sky. This was done by measuring the horizontal total and the diffuse illuminance with an unshaded and a shaded illuminance sensor, respectively. The difference of these two values is the horizontal direct illuminance.

All illuminance measurements were taken with PRC Krochmann illuminance sensors Type MI (Mini). These sensors' dimensions of ~25 × 25 × 7 mm (width × depth × height) are very small, which makes them particularly suitable for scale model measurements. The sensors were carefully calibrated under the artificial sky. Since the SI-photocells in the sensors are temperature-sensitive, the calibration was done for different temperature profiles. The temperature-dependent measurement errors were eliminated by recording the temperature of the sensors and using correction factors when analysing the measured data.

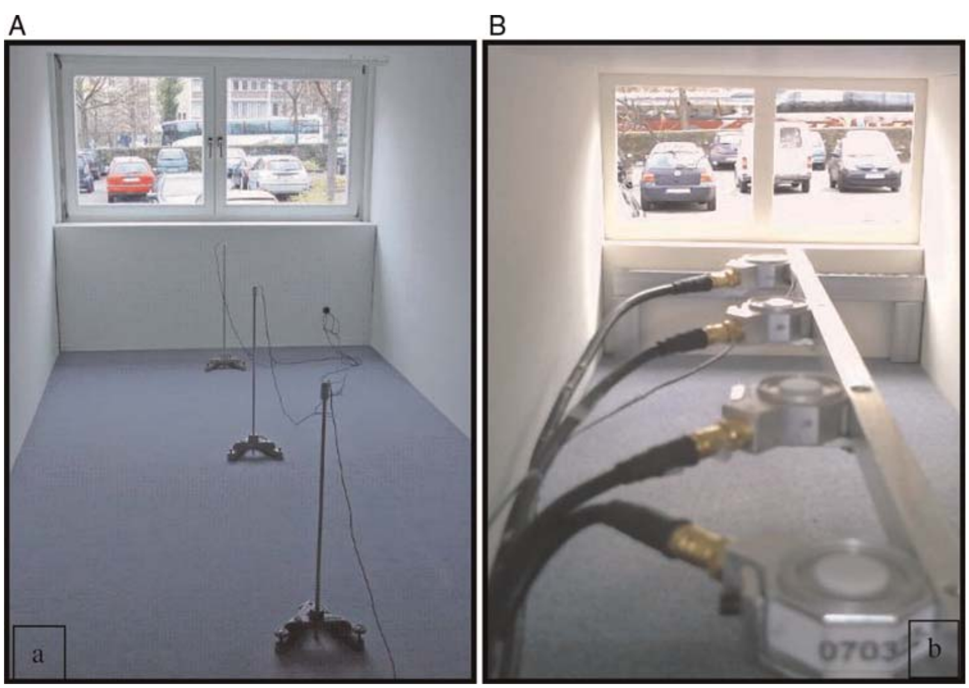

Figure 4. *Measurement settings: (a) in test room and (b) scale model.*

2.5 Artificial sky and sun

The artificial sky at the HFT Stuttgart has a diameter of 4.20 m (Figure 5). The sky luminance distribution according to Tregenza's model is simulated with 360 dimmable fluorescent lamps behind a translucent vault. The maximum horizontal illuminance in the middle is ~25 000 lux. The sun is represented by a horizontal and vertical movable parabolic mirror with a halogen bulb.

The control system allows setting the International Commission on Illumination (CIE) standard sky types and uniform sky for every time and location. An extension to the control system makes it possible to import measured luminance distributions and set the sun according to measured horizontal direct illuminance levels.

Since the maximum luminance of the artificial sky (~2500 cd/m^2) and sun (~7800 cd/m^2) are much lower than in outside conditions, the measured data have to be scaled down. The halogen bulb of the artificial sun is the weak point. For simulating measurements with direct sunlight on the test room facade, the scaling factor often has to be set to 5% or less. With the scaling factor being so low, the artificial sky has great problems simulating a given luminance distribution accurately. To avoid this, some measurements in the artificial sky were split up into two measurements: one with the sky vault lamps only and higher scaling factor and one with the artificial sun only and low scaling factor. The results were summed up and then compared with the outside measurements.

Figure 5. *The artificial sky and sun at the HFT Stuttgart.*

2.6 Computer simulation modelling

The Radiance program was used to determine the interior space illuminance within the computer simulation. The measured performance of the full-scale mock-up office, physical models and three-dimensional simulation models were compared. The sensitivity analyse was done in Radiance to better understand the error sources on daylighting performance.

2.6.1 *Modelling of real sky with radiance*

In the Radiance modelling, the continuous real sky is the reproduction of actual measured luminance distribution of natural sky. The sky luminance levels were determined at each time of measurement with a digital SLR camera. According to Tregenza method, sky I divided by 145 patches. The image processing software determines the luminance of each sky patches. In addition, for each measurement, the entire vertical illuminance was recorded. This measurement gave information about whether it was a sunny or a diffuse day.

2.6.2 *Modelling of the artificial sky in radiance*

The artificial sky of the HFT Stuttgart was modelled in Radiance. In this sky model, the patches have relatively 'sharp' edges and can be seen as significantly different luminance levels from each other. Figure 6a shows the modelling of the Radiance–Tregenza sky. The original 145 circular discs of the Tregenza sky are replaced by 145 trapezoidal surfaces, because the artificial sky is also completely enclosed and does not consist of 145 individual panels with circular voids between the surfaces. In Figure 6b, the trapezoidal Tregenza surfaces and the 1:20 model of the test room with a light-shelf is shown. The 'edges' of the individual patches are seen clearly due to their different luminance levels. Figure 6c shows the Radiance model of the artificial sky with the sun. The blue circle is the diameter of the parabolic reflector of the artificial sky. The smaller red circle corresponds to the true diameter of the sun. The opening angle corresponds to the real sun angle of $2 \times 0.25°$.

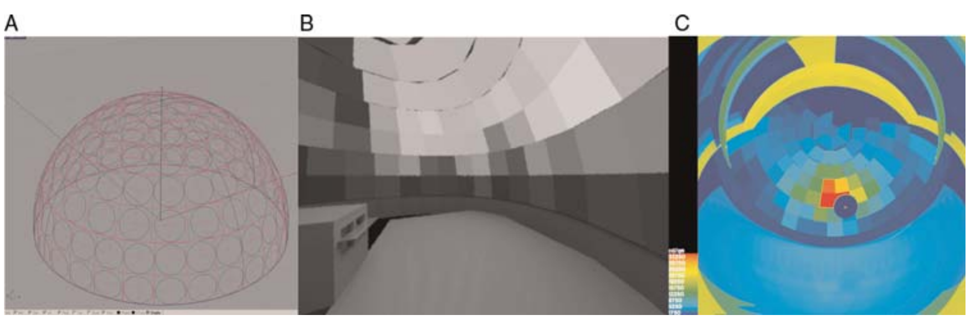

Figure 6. *(a) Modelling of the Tregenza sky in Rhino; (b) Radiance model of the artificial sky; and (c) Radiance of the artificial sky with sky direct sun.*

3 EXPERIMENTAL RESULTS

Inside the physical scale models and full-scale mock-up room, measurements were taken on four points (1:10 and 1:20) and two points (1:50), respectively, on the middle axis of the room to evaluate internal illuminance. In this paper, the authors concentrate on the most significant findings of their experiments. The results are dealing with the impact of sky conditions and the impact of surrounding buildings.

3.1 Impact of surrounding buildings

Figure 7 indicates a comparison of illuminance measurements in a 1:20 scale model under cloudy sky conditions in the artificial sky and under natural circumstances. The columns show the deviation of the measurements in the artificial sky compared with the measurements under real sky conditions. The first measurement was taken on top of the Max-Kade-Building, i.e. without obstruction affecting the daylight performance. The second and third measurements were taken on the test room site, i.e. with obstruction by the surrounding buildings. While all measurements show an underestimation of illuminance levels in the artificial sky that has the tendency to increase with the distance from the measurement point to the window, the deviations of the measurements with obstruction are lower than in the measurements without obstruction. Since the obstruction is likely to be a serious error source, this seems to be an unexpected result. The ‘better’ results in the measurements with obstruction can be explained by the luminance distribution of the artificial sky. The obstructed sky patches are simulated with a much higher illuminance than measured outside. This is because there are no separations between the sky patches, thus every sky patch is influenced by the neighbouring ones, even if they are switched off. The higher luminance of the obstructed sky patches is an extra error source, but partly compensates the general underestimation of the artificial sky.

To have identical sky conditions, measurements between the test chamber and the corresponding model, as described in this section, always carried out different results. The reason of this diversity can be the placement of the physical model next to the testing room. In order to understand surrounding effect on the daylight performance, three dimensional simulations of the test room and 1:20 scale model were evaluated (see Figure 8 (middle)).

Figure 8 (left) and (right) shows the view from the first measurement point towards the outside. The difference between the visible sky sections can be recognized from the image. Owing to the different sizes of the sky sections and the surrounding buildings, there may be variations of the illuminance level of the measurement points. It is an error, with comparative measurements between test office and model, which cannot be prevented. The deviation between the two values, especially at the rear measuring points may well account for more than 10%.

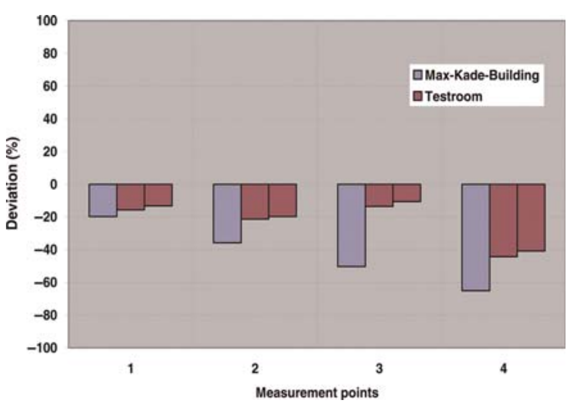

Figure 7. *Deviation of illuminance levels between artificial sky and natural sky circumstances comparing the impact of surrounding buildings.*

3.2 Impact of sky conditions

Figure 9 presents the illuminance level deviation between the 1:20 scale model and the full-scale mock-up room with light-shelves under natural sky conditions (cloudy and sunny skies). In cloudy sky, the measurements in the scale model do not greatly deviate from the full-scale room measurements of each measuring point. However, also the illuminance sensor size can influence the illuminance level.

Under clear sky, depending on the scale of the model, the sensor can be partly affected by the direct sunlight. Considering the fact that the illuminance metre dimension is always the same, but the scale of the model may be changing, different results may be achieved.

The measurements (Figure 10) between the 1:20 scale model under the artificial sky and the 1:20 scale model under natural sky with light-shelves show that the trends under

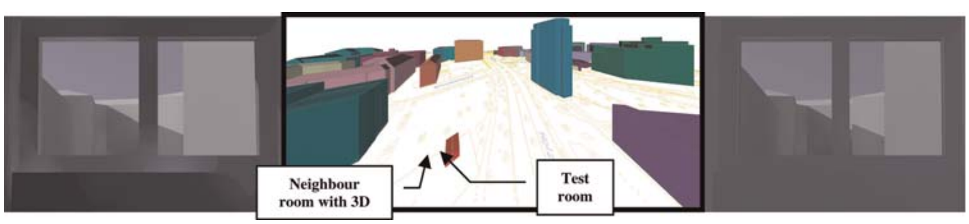

Figure 8. *Three-dimensional model of the test room with surrounding buildings: (left) view from the window in the model and (right) test area (Radiance simulation).*

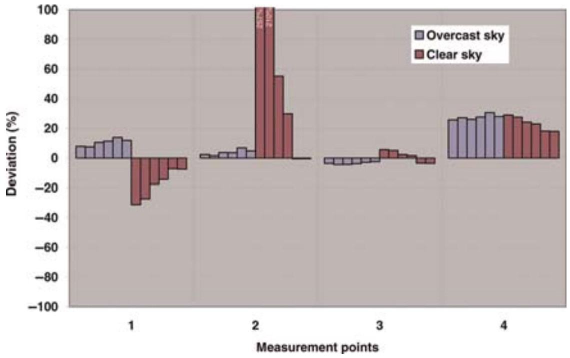

Figure 9. *Deviation in natural sky circumstances between the 1:20 scale model and full-scale mock-up office comparing the impact of sky conditions.*

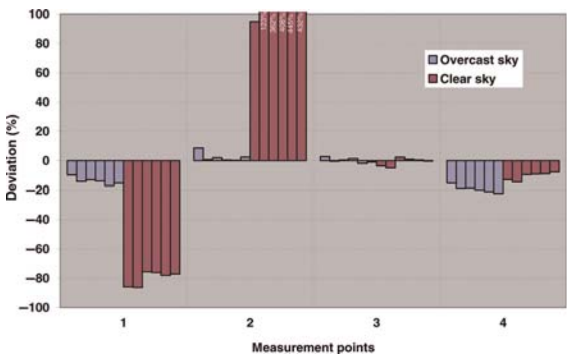

Figure 10. *Deviation between artificial sky and natural sky circumstances comparing the impact of sky conditions.*

cloudy sky are similar, whereas under sunny sky the sun rays strike directly the first measurement point of the model under the natural sky and the second point of the model under the artificial sky. If measurements are carried out under a sunny sky in combination with shading systems (here a light-shelf is used) measurements will react very sensitive. Especially at the first and second measurement points a significant deviation can be realized.

4 CONCLUSION

Various experimental uncertainties are involved in this kind of measurements. Since the artificial sky and scale models are used for the assessment of daylighting, errors cannot be avoided, but need to be detected and minimized by the development of measurement rules and strategies.

In the scope of this work, several design alternatives were evaluated. The results exposed that the surrounding buildings affect the daylighting distribution within the space. Illuminance level on the measurement points are reduced from window side to the rear of the room without obstruction. Obstruction shows a significant impact on illuminance levels especially between the measurement points 2 and 3.

Moreover, changing sky conditions cause fluctuation in daylighting distribution. This fluctuation is more remarkable under the sunny sky conditions than under cloudy sky conditions.

In this study, the scale model measurements in natural and artificial sky conditions allow the assessment of the quantity of daylight with different facade systems in different sky types and their transfer into real situations. Openings were modelled accurately in the scale models and to minimize the error glazing was not used. After the measurements a glazing correction factor was used to compare the full-scale mock-up building and scale models. Some local rules application (like sensor wires pass thought the rear wall) can cause accuracy of measurements problems.

To increase the accuracy and find out the certain problems, more measurements must be taken (in similar and/or different conditions). Those measurements will be helpful to define errors and find out the correlation between each impact.

Further work is required on comparison of software simulation results and measurements results comparison. According to software simulations, electricity demand (related with daylighting) heating and cooling load will be evaluated.

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