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The use of a full scale mock-up office and different scale model measurements to assess daylight performance

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The daylighting design of buildings has a major impact on their energetic performance and the occupants comfort. Appropriate solutions offer a stimulating view to the outside, avoid glare and contribute to the reduction of the buildings electrical consumption by substituting and displacing artificial light and decreasing cooling loads. 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 comparison to simulation tools the experimental work on scale models under an artificial sky offers a concrete and intuitive approach to daylight design, especially in early design stages and teaching. 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, that allows analyzing the main sources of errors by progressive stages. In a first step simultaneous measurements of work plane illuminance for cloudy and sunny sky conditions were undertaken in a full scale test room and scale models placed under identical outdoor daylighting conditions. The luminance distribution of the sky and the sun at the time of every single measurement was recorded with a luminance camera and illuminance meters. In a second step the luminance distribution was transferred to the artificial sky (according to Tregenza´s model) and the scale models were measured in the artificial sky under reproduced outside daylight conditions.

Keywords: Daylight Performance Assessment, Full-Scale Mock Up and Scale Model Measurements, Artificial Sky

1. Introduction

Daylighting design is one of the most important aspects in architecture. While the “correct and magnificent play of volumes under light”, atmospheric and staged use of light and appropriate illumination of rooms have always been on the designers task list, reduction of building energy consumption and increase of user comfort by means of intelligent daylighting design gain more and more importance [1].

To achieve these goals, it is essential to assess the daylight performance of buildings in early stages of the design process. This can be done by computer simulations or by using scale models analyzed under an artificial sky and sun. Both methods allow performing analysis for any location and time. Predefined sky conditions (usually CIE clear, cloudy and overcast sky) make the results comparable and reproducible. While computer simulations allow an easy and accurate input of geometric and photometric parameters, the building of a precise scale model and the choice of appropriate materials require some more effort. 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 (except for the partial daylight factor method under a scanning sky simulator described in Michel & Scartezzini) [2]. 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 [3, 4]. 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 purposes.

This paper describes a methodology to evaluate the daylighting assessment performance of an artificial and the implementation to the artificial sky at the Stuttgart University of Applied Sciences,

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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 [5-7].

2. Experimental Methodology

The major aim of the methodology is to assess the daylighting performance of scale models in natural and artificial sky conditions as well as 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 conditions and under the artificial sky.

In a first step simultaneous measurements of work plane illuminance for cloudy and sunny 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 façade systems (Venetian blinds with daylight guiding equipment, horizontal louvers and light shelf). 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 to 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). Figure 1a shows the site plan of the study area.

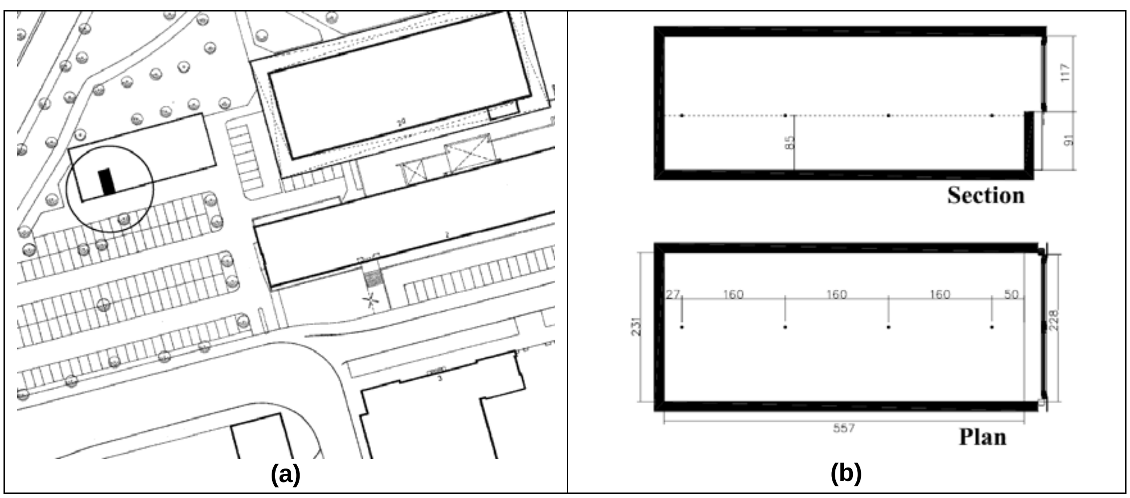

Figure 1a. Site plan (test room black in circle) 1b. Floor plan and section of the test room

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 x 5.84 x 2.08 m (width x depth x height). Floor plan and sections of test room are shown in the Figure 1b.

A rack in front of the test room façade allows the installation of three different façade systems: Venetian blinds with daylight guiding equipment, horizontal louvers and a light shelf. The Venetian blinds and the louvers can be adjusted in different angels. The light shelf is covered with aluminium sheet on one side and painted white on the other side. It can be adjusted with either the specular (aluminium sheet) or the diffuse (white paint) side upwards.

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 façade systems in scale 1:10, 1:20 and 1:50. They represent commonly used model scales for detailed façade (1:10), room (1:20) and building design (1:50).

Different aspects were analyzed in each scale. Models of the Venetian blinds and louvers were built with opening angles of 0° (horizontal) and 45° in scale 1:10, to analyze the impact of the façade system's adjustment. The influence of model material was analyzed 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 (from samples of the manufacturers), 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.

Since the scale models can not be placed at the same position as the test room, the sky view factor for the illuminance meters in the test room and the scale models are different. To minimize the errors caused by this effect, different scale model positions were simulated using a 3D-CAD model [6].

Table 1. An adequate caption to inform the reader

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*	all	90.47	90.20	0.28
	Finnboard*	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*	1:20	49.12	46.19	2.92
	Grey paperboard*	1:10, 1:20	45.53	45.37	0.16
	PET-G patterned sheet, printed (line pattern 1.0mm) *	1:50	-	-	-
Louvres	Aluminium E6 EV1	original	72.71	67.49	5.22
	3M Scotchlite reflecting film 3210*	1:20	65.16	59.70	5.47
	Aluminium sheets (0.5mm) *	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*	1:20	90.47	90.20	0.28
*for material description see www.modulor.de					

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 façade was carefully aligned with the test room façade, but with an overhang of approx. 10 cm to avoid shadowing effects by the façade system rack. Placement of the model can be seen in Figure 3.

Figure 2. Measurement settings test room

2.3 Sky luminance distribution

The sky luminance distribution was recorded with a TechnoTeam LMK mobile (Rollei d30 flex) luminance camera and a Nikon FC-E8 fisheye converter. The best position for the camera was also analyzed with the 3D-CAD model mentioned above. The camera was positioned in line with the scale model's vertical middle axis and approx. 50 cm below the window's horizontal middle axis. (Figure 2)

Since the view angle of the luminance camera was restricted to approx. 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 approx. 1 min. 20 sec., and were analyzed using the TechnoTeam software LMK2000. 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 3 (a) and (b) show the setting in the test room and in a scale model (scale 1:20).

(a) (b) (c)

Figure 3. Measurement settings (a) in test room (b) scale model and artificial sky and sun in HFT Stuttgart

In cases of direct sunlight on the test 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 respectively a shaded illuminance sensor. 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 approx. 25 x 25 x 7 mm (width x depth x 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 analyzing the measured data.

2.5 Artificial sky and sun

The artificial sky at the HFT Stuttgart has a diameter of 4.20 m (Figure 3 (c)). 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 approx. 25,000 lux. The sun is represented by a horizontal and vertical movable parabolic mirror with a halogen bulb.

The control system allows setting CIE clear, cloudy, overcast 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 (approx. 2500 cd/m2) and sun (approx. 7800 cd/m2) are much lower than in outside conditions, the measured data has 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 façade, 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 to the outside measurements.

3. Experimental Results

Inside the physical scale models and full scale mock up room, measurements were taken on 4 points (model scale 1:10 and 1:20) respectively 2 points (model scale 1:50) 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 model building material properties, sky conditions and the impact of surrounding buildings.

3.1 Impact of surrounding buildings

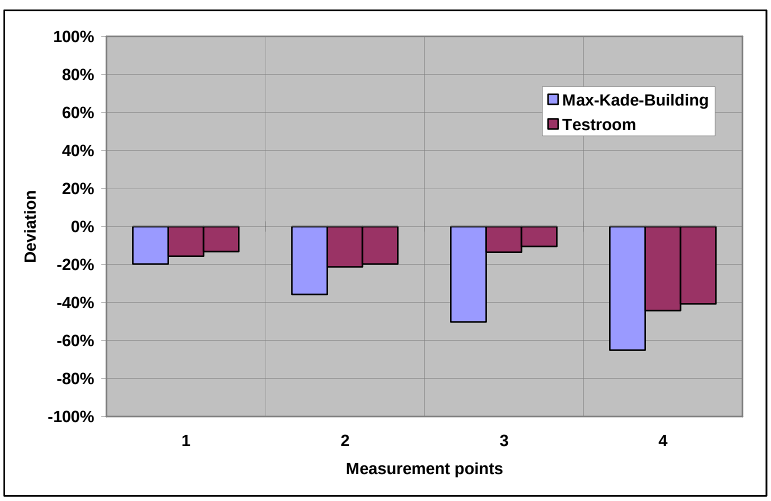

Figure 4. Deviation of illuminance levels between artificial sky and natural sky circumstances comparing the impact of surrounding buildings

Figure 4 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 to 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 measurement was 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 which 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 and 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.

3.2 Impact of sky conditions

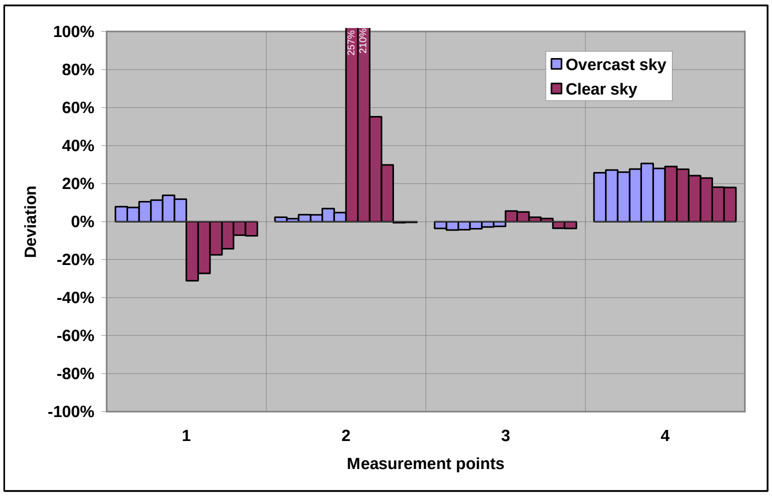

Figure 5. Deviation in natural sky circumstances between the 1/20 model and full scale mock up office comparing the impact of sky conditions

Figure 5 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 have not much deviation 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 sun light Considering the fact that the illuminance meter dimension is always the same, but the scale of the model may be changing different results may be achieved.

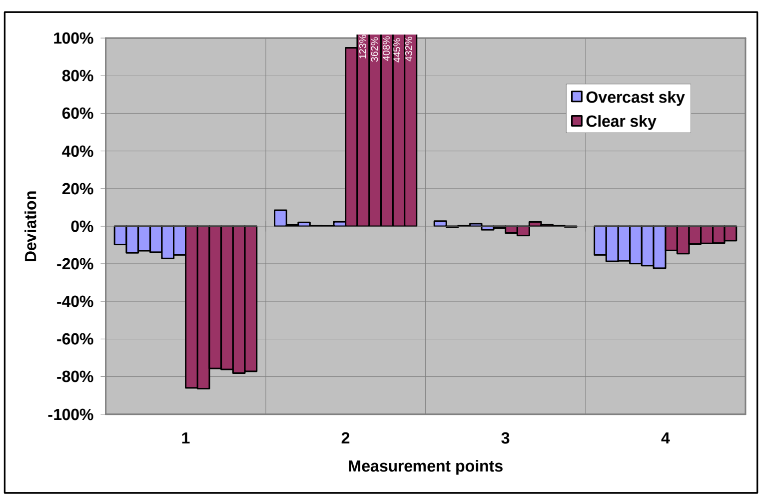

Figure 6. Deviation between artificial sky and natural sky circumstances comparing the impact of sky conditions

The measurements (Figure 6) between the 1/20 scale model under the artificial sky and the 1/20 model under natural sky with light shelves show, that the trends under 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 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 point a significant deviation can be realized.

3.3 Impact of model building material properties

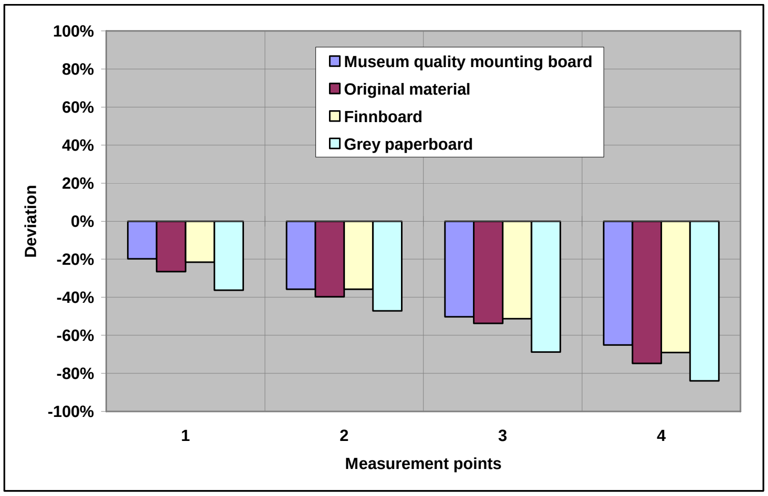

Figure 7. Deviation between 1/20 model in natural sky and artificial sky comparing building material properties without any other influences

The measurement results (Figure 7) which were obtained under cloudy sky conditions show similar trend in all material types between the 1/20 scale model under artificial and natural sky,. These measurements are not affected by any other influences for instance; by obstruction, façade systems or sky conditions.

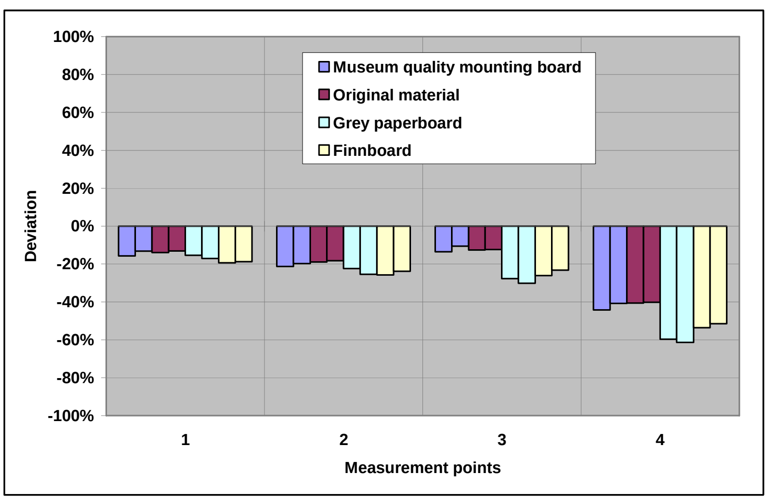

Figure 8. Deviation between 1/20 model in natural sky and artificial sky comparing building material properties without surrounding building effects

Figure 8 shows the comparison between the 1/20 scale model under artificial sky (cloudy) and 1/20 scale model under natural cloudy sky conditions. The shading affects of the surrounding building were taken into consideration in these measurements. The different deviation in percent at each measurement point, from point No.1 near the window to point No. 4 in the back of the room is described. As a general trend the deviation increases with the distance of the measurement point to the window. An explanation for this result could not yet be found. The authors assume that effect results from the difference between the sun spectrum and the halogen lamp spectrum as well as the spectral reflection properties of the model material. Further measurements will be taken to verify this assumption.

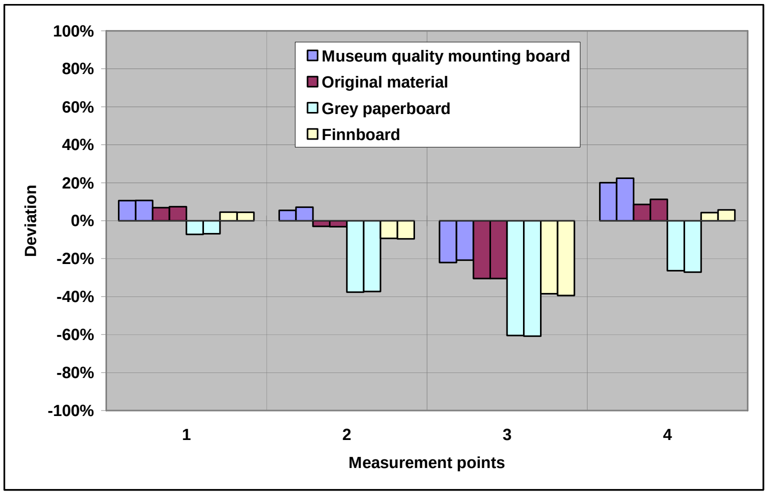

Figure 9. Deviation between 1/20 model and full scale mock up office in natural sky conditions comparing building material properties

From the graph in figure 9. can be concluded, that the mean illuminance levels on the measurement points show different characteristics in dependency on the used materials. This graph presents a comparison of the illuminance values deviation under natural cloudy sky conditions between the 1/20 scale model and the full scale mock up room. Depending on the material specification different trends can be seen. At the first point near the window the scale model with original material has an approximately 7% higher illuminance value than the full scale model,. At the second and third point, negative differences can be seen. That means that the mock up room is brighter than the model by 5% and 31 % respectively. At the measurement points with a bigger distance to the light source, the scale model room measurement point illuminance level is 10% higher than the values measured in the mock up room.

4. Discussion and Conclusion

The research shows the daylighting assessment results, received from measurements in a full scale mock up room and different scale models under natural and artificial sky conditions with different materials and façade systems.

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 can not be avoided, but need to be detected and minimized by the development of measurement rules and strategies.

According to the results of this work, experimental errors can be classified into three categories:

- Scale Model Errors: size of scale models, geometry of model, sensors location, edge joints, colour and material reflection, openings and external obstruction definition [9]
- Artificial Sky Errors: horizon line error [10], parallax error [11], luminance distribution
- Luminance Camera Errors: Sky view factor, shadowing effect, analyzing software

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 (Figure 4.). Obstruction show a significant impact on illuminance levels especially between the measurement point 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 (Figure 5 and 6).

Illuminance deviation results from figure 7 show a decreasing trend along middle axe of the room and only small changes according to the type of the material under unobstructed overcast sky conditions.

The luminance level doesn't reach a high uniformity and is not close to theoretical values. The errors on measured illuminances are high and must be correlated with new measurements and simulation works.

In order to get accurate results from scale buildings, it is necessary to integrate all the rules before starting the research. Some of the general rules can be defined, such as the influence of geometry or building material properties. The other rules are local and can be summarized as sensor location, dimension of model and technical and optical attributes of equipments [3].

In this study, the scale model measurements in natural and artificial sky conditions allow the assessment of the quantity of daylight with different materials and different façade systems in different sky types and their transfer into real situations. General rules were applied to the research, the materials were chosen with respect to colour and reflection coefficient which are same or close to full scale material values. 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.

In order to obtain results from the artificial sky and sun in HFT Stuttgart, the next step would be to compare the results with other artificial dome skies, sky scanning simulators or mirror skies in Europe with same scale models.

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