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Daylight enhancement and lighting retrofits in educational buildings

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Abstract: According to the International Energy Agency, lighting makes up about 19% (~3000 TWh) of the global electric consumption. Often the lighting energy savings cannot be provided in new buildings with new lighting systems. Therefore, major potential in lighting energy savings can be found in the existing building stock (older than 25 years). Educational environments such as schools, colleges, universities /campuses cover a significant percentage of the existing non-residential building stock. This study focuses on lighting solutions for the retrofitting of educational buildings, with a particular emphasis on two University lecture halls which are located in Turkey/Konya and Germany/Stuttgart. Evaluations of the pre-retrofitting lighting performance are based on the measurements and observations. After a detailed performance analysis, the best lighting retrofitting options were identified. The retrofitting scenarios were simulated in virtual environment and their impact in terms of identifying the most efficient are discussed. The cost of retrofit estimation is done using the Relight tool which is developed as a part of IEA- SHC Task 50 Subtask C.

Keywords: Lighting retrofitting; daylighting; campus; education buildings.

1. Introduction

The place of learning should be a secure, safe and comfortable environment conductive to teaching and learning. The students, teachers and lecturers are more alert and ready to work if appropriate comfort conditions are provided. All educational spaces should use the available daylight as the primary light source. Good lighting provides the best visual effectiveness, minimizes the use of energy while giving people satisfaction.

Recent studies have estimated that European schools contribute 15% of the public sector carbon footprint. It is assumed that approximately 20-30% of energy use comes from artificial lighting in educational buildings. This is a current important research topic, revealing more environmental and sustainable educational buildings. The primary energy consumption of schools in Luxemburg has increased due to the higher electricity usage (Thewes *et al.*, 2014). The trend of increasing electricity use in Scottish schools was discussed by Dobson and Cater (2010), while approximately 46% of total electricity demand of the American educational buildings is from office equipment and lighting (Appel, 2010). Most of these studies try to detect the efficiencies and potential improvements which allow reduction in energy use.

The lighting for a lecture hall must supply the correct amount of light during the day. Tasks and activities are generally carried out on a table/desk or on white/blackboards. Therefore, good horizontal and vertical lighting is essential. Furthermore, controllable lighting and shading systems should be able to adapt lighting conditions when visual equipment, (i.e., data projectors), are used. Even though daylight contribution is significant for educational spaces, it is of variable nature and mostly provides only a portion of the required light level.

Glare is a common problem in classrooms and lecture halls, which happens when part of the visual scene is much brighter than the overall brightness of the rest of the field of view. Glare can be divided into two types: Disability glare, defined as a decrease in a visual performance due to light scatters within the eye; and, Discomfort glare, a subjective feeling of disturbance. Although the glare issue has been studied over a long period, there are still many unresolved questions. One common finding is that people consider a bright surface as disturbing. It is also believed that some glare can be tolerated if the work place contains a view to the outside (Osterhaus, 2001; Velds, 2000; Wienolds and Christoffersen, 2006).

2. Method

The main aim of this study is to investigate the effect of daylight availability on visual comfort and estimate potential savings on lighting electricity in educational spaces. Interior daylight illuminance measurements were carried out in lecture halls at the Stuttgart University of Applied Sciences, Germany and KTO Karatay University, Turkey. The unobstructed horizontal outdoor illuminance data and the internal measurements were acquired simultaneously. During the monitoring of the luminous environment, a user satisfaction questionnaire (IEA-SHC-Task 50 Subtask D3) was answered by students. The purpose of the questionnaire was to obtain inputs such as the indoor comfort levels of occupants in the context of light intensity. High Dynamic Range (HDR) imaging was used to collect luminance information at the lecture hall in Stuttgart. All collected momentary illuminance, luminance data, computer simulation outputs such as climate based annual lighting analysis and occupant feedback through questionnaires were used to evaluate visual comfort and glare.

In a first step, the luminance and illuminance in the lecture rooms with daylight and artificial light were measured. In Konya, the measurements were conducted during the last week of May 2015, with illuminance levels recorded every 15 minutes. The illuminance measurements in Stuttgart were taken three times a day, on a weekly basis, during the winter semester. The luminance measurements were performed with a high dynamic range (HDR) camera with a fisheye-objective. The images were evaluated with the LMK 2000 software. In both locations, all illuminance measurements were taken with HOBO illumination/temperature data loggers (U12). This device has a range of 0 – 320,000 lx and an accuracy level of ±2.5% at 25^{o}C.

As daylight factor (DF) threshold measures are not sufficient to assess the daylight performance, climate based daylight modelling was used to analyse the lecture rooms. In order to conduct climate based daylight modelling, standardized meteorological files were used for specific geographical locations. Three computer simulation tools were used to model the daylight performance for the present study. Three dimensional geometries, including the rooms' surroundings were built in Ecotect Analysis 2011. The numeric simulation results were also visualized via the same tool. Radiance 3P7 for Windows was used for current moment daylighting analysis. Climate based annual lighting analysis were performed via Daysim 3.1 for Windows (Daysim 3.1, 2013). Additionally, energy analysis of the existing lighting system and suitable renovation suggestions including cost comparison was generated by reLight.

It is reliable to have measured data and comparable simulated data to assist the investigation and analysis of a space (Maile T. *et al.*, 2010). Nevertheless, the complexity of the lighting environment requires documentation of user experiences to better understand the nature of the light and especially to discover unpleasant occurrences such as glare, distribution of light intensity use of control systems etc. To obtain data, students were asked to fill in a user questionnaire (IEA-SHC-Task 50 Subtask D3). All collected data was digitalized and analysed in an excel spreadsheet and the average score was found for the questions.

2.1. Room(s) description

The study was carried out in two lecture halls in Konya and Stuttgart in the month of May, 2015. The lecture halls have different dimensions and are furnished differently. Therefore different measuring grids were used for each lecture hall: in Konya a 3x3 grid, in Stuttgart a 4x4 grid. However, measurement results of both can be easily compared considering the general room form.

2.1.1. Stuttgart, Germany

The test space is a lecture hall in Building 3 of the University of Applied Sciences Stuttgart, Germany, geographically located at 48°68'N latitude and 9°22'E longitude. The duration of sunshine varies between 1300 and 2000 hours, while the global radiation varies between 780 and 1240 kWh/m^2. During the winter, Stuttgart`s daylight can range from 8 and a half to 9 hours. In summer the average amount of daylight is almost 16 hours.

Figure 1: Bird's-eye view of the building and floor plan of the lecture room in Stuttgart

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The main facade of the lecture room is oriented towards Southwest. The test room dimensions are 10.1 m x 9.7 m x 3.8 m - width x depth x height). Location of the building and floor plan and of the test room is shown in the Figure 1. The centre of each desk was selected as a measurement point, this results in grid dimension of 1.60 m x 1.60 m in the lecture hall. Window-to-wall-ratio of the lecture hall facade is 40%. The room surface reflectance values are: $R_{ceiling}$ = 80%, R_{walls} =50%, R_{floor} = 30%, $R_{furniture}$ = 50%. The windows consist of two layers of clear glass resulting in visible transmittance (Vt) of 72%.

2.2. Konya, Turkey

Figure 2: Layout plan of KTO Karatay University and floor plan of the measured classroom in Konya.

The classroom from KTO Karatay University, as shown in Figure 2, was located in Konya, Turkey at 37°52'N latitude and 32°35'*E*. Konya is a city in the Central Anatolia Region of Turkey. The average duration of sunshine is 2630 hours and the global radiation varies between 760 and 2530 kWh/m^2a. Winter has an average of 9 and a half hours of daylight in Konya and in summer the average amount of daylight is 14 and a half hours.The facade of the measured classroom is oriented towards west. The dimensions of are 10.50 m x 9.45 m x 3.60 m - width x depth x height). Window to wall ratio of the lecture hall façade is 60%. Floor plan and sections of measured classroom are shown in the Figure 3. The surface reflectance values are obtained from on-site auditing: $R_{ceiling}$ = 85%, R_{walls} =65%, R_{floor} = 35%, $R_{furniture}$ = 50% and Window Visible Transmittance = 72%.

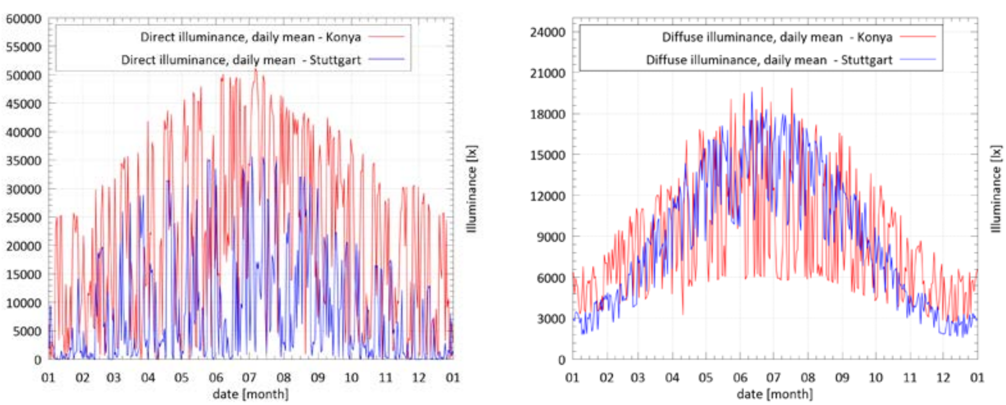

Figure 3: Daily mean direct normal illuminance and daily mean diffuse horizontal illuminance values of Konya and Stuttgart.

2.2. Illuminance distribution

In order to quantify the daylighting performance of the lecture halls, it is helpful to see the differences between illuminance data for each city. Figure 4 represents the diffuse horizontal illuminance and the direct normal illuminance magnitude difference between Konya and Stuttgart. According to the data, it was observed that both direct and diffuse illuminance values are higher in Konya than in Stuttgart.

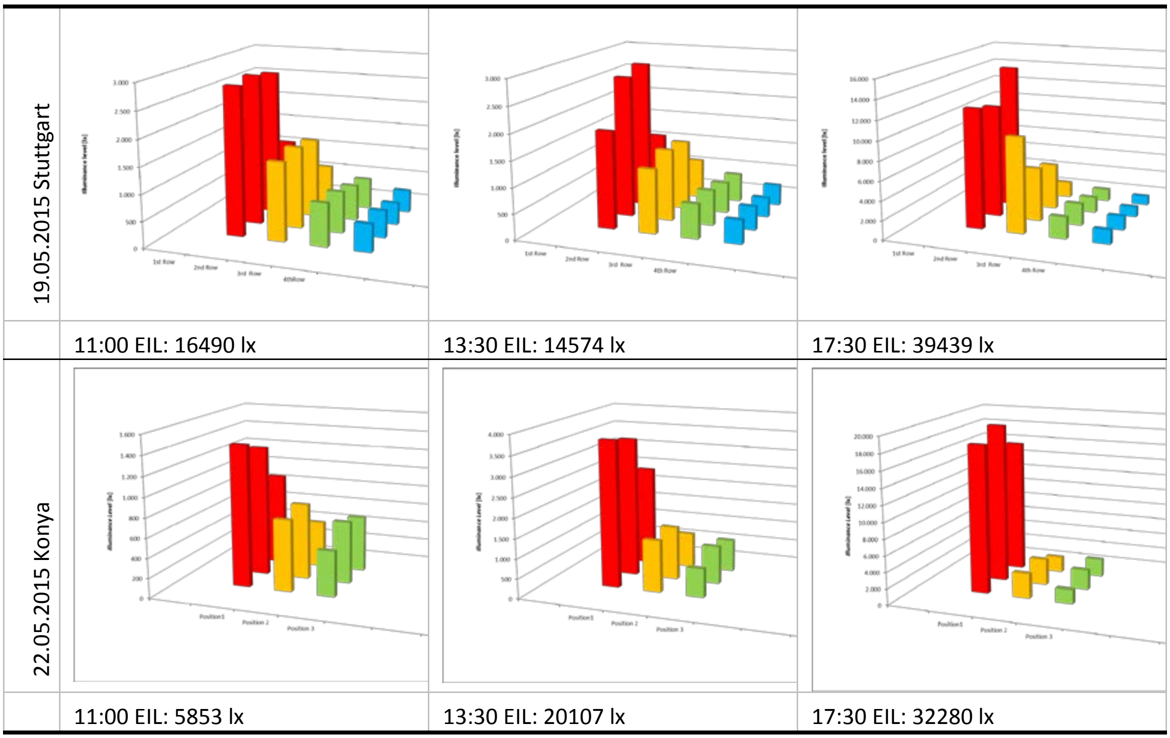

Figure 4: Horizontal illuminance at working plane grid in Stuttgart and Konya.

Inside the lecture halls, measurements were taken on sixteen points (Stuttgart) and nine points (Konya), respectively, to evaluate internal illuminance. In this paper, the findings of the first experiments are presented. The results deal with the impact of geographical position and sky/ climate conditions. Figure 5 indicates a comparison of illuminance measurements in two lecture rooms under different sky conditions on similar days. Measurements were taken at 11:00h, 13:30h and 17:30h.

The columns show the illumination level of each measurement point. Unobstructed horizontal exterior illuminance levels (EIL) were also measured and noted in to the Figure 4. Under cloudy sky, the illuminance levels do not greatly differ between the first measurement row and the rear rows of the room. Under clear and sunny sky, the sensors were affected by direct sun light and shadow in both lecture halls. This effect causes high illuminance level differences between measurements points and may be the main cause of the glare problem. Moreover, in daylighting distribution was observed under changing sky conditions (clear, cloudy, and covered). Under sunny sky the fluctuation is more remarkable compare to cloudy sky conditions.

2.3. Existing lighting system inspection and suitable renovation suggestions

To enable a precise analysis, it is essential to adequately assess the existing lighting system. The reLight tool (V1.04) was used to evaluate the existing lighting system, to provide suitable lighting renovation suggestions and to cost each of the different proposals.

First, a simplistic qualitative analysis of the lecture halls, (i.e., room proportion, facade type), was completed. The main space usage categories were defined and the pre-parameterization and verification logic was established to ensure that no invalid data sets were created. Relevant system components such as lamps, control equipment and luminaires were created within the database together with their characteristic values for energy use and efficiency. As a second stage, the lamp and luminary properties were defined. Additional information, for instance; typical service life of lamps and/or the necessary illumination level for the different spaces were also added to the database. To provide renovation options with a comparative analysis, appropriate lamp and spatial data was input into the relight (V1.04) application. Finally different renovation options per lecture room were combined into an overall renovation, in order to obtain optimum energy and/or cost-efficiency results and viewed in a graphical format.

3. Results

3.1. Luminance and illuminance distribution from the observers' point of view

During the monitoring of the luminous environment, the user satisfaction questionnaire (IEA-SHC-Task 50 Subtask D3) was answered by students. The questionnaire consists of four parts: general questionnaire (remarks and light level questions); light experience questionnaire; daily experience; and, semi-structured interview. The general questions were rated from 1 (Low/little) to 7 (High/ Much). In the semi-structured interview, questions covered attitudes and behaviours, light environment, control system and eye symptoms.

In Konya, 50 students were part time users of the classroom, with 8 hours per week. 80 % of the students found the lighting level in the room and on the desk satisfactory or better than satisfactory. On the other hand 30% of the students mentioned bright areas and glare problems. Half of the students found the classroom and lighting control system unsatisfactory and not good enough. They describe lighting experience of classroom as light, pleasant, colourless, strong, spread, warm, clear, monotonous and bright.

In Stuttgart, 14 students answered the questionnaire during the measurements. 36% of the students rated the light distribution with 3 and 64% were rated 4. The light environment defined as middle and the lighting system optimization was not necessary required. 9% of the students didn't find any gloomy areas in the lecture room. 55% of them rated the gloomy areas with 7, 27% of them with 4 and 9% with 3. Bright area was assessed with 4, from 27 % of the contributors. 9% were not affected by bright areas. 27 % of the respondents found glare as a problem and rated the outcome with 4 or 5.

3.2. Daylight autonomy and electric lighting use

Climate based annual daylight simulation were completed in Daysim 3.1, with illuminance values analysed using the “Useful Daylight Illuminance” (UDI) scheme (Nabil and Mardaljevic 2005). UDI is the annual occurrence of illuminance across the grid system that considered in three categories, namely; illuminance level less than 100 lx, greater than 100 lx and less than 2000 lx, and greater than 2000 lx.

Figure 5 shows the related UDI distributions for the two lecture halls in this study. UDI>2000 is meant to represent times when an oversupply of daylighting might lead to glare and / or visual discomfort. The useful daylight indicates for the lecture rooms are; in Stuttgart 87% and in Konya 65%. The UDI100-2000 that represents “useful” daylight was achieved with 6% in Stuttgart and only 1% in Konya.

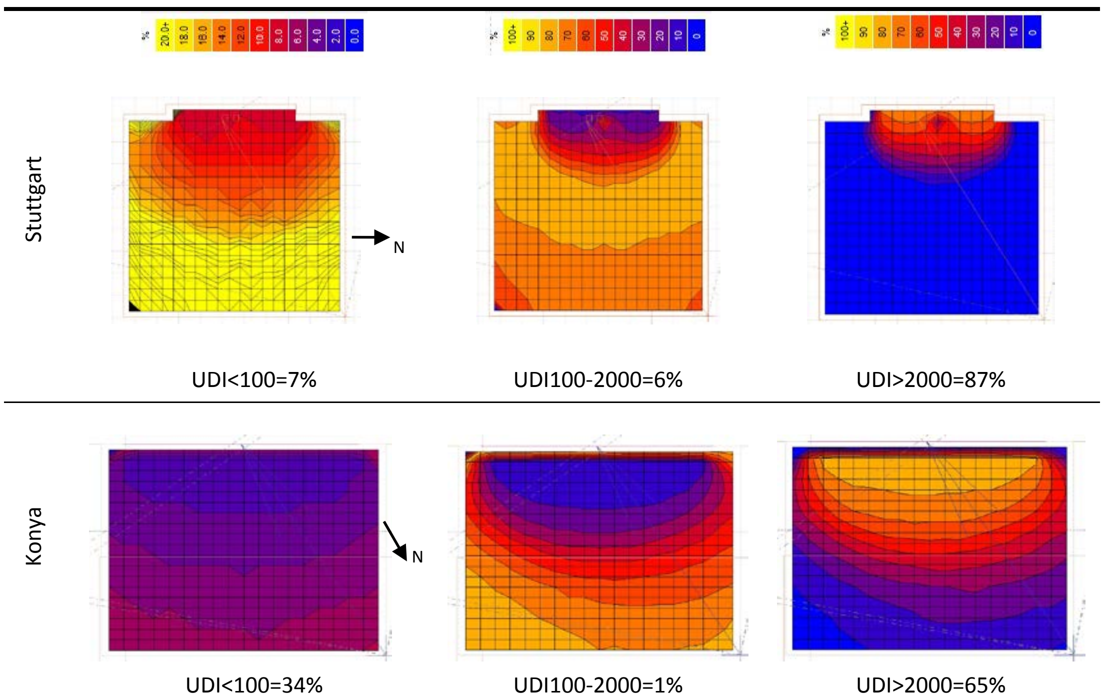

Figure 5: Useful Daylight Illuminance comparison.

500 lx were specified as the daylight autonomy threshold and 65% of all illuminance work plane sensors have a $DA_{con\ 500}$ above 60% in Stuttgart .The investigated space in Konya 100% of all illuminance sensors have a $DA_{con\ 500}$ above 80%.

3.3. Possible lighting solutions and cost of retrofitting variations

The existing lighting systems (B) of both lecture halls are defined in Table 1. The best way to reduce the cost of the operating an older lighting system is to replace it with a newer, more efficient one. This can be achieved with upgrading the lamps, ballast, fixtures and control systems(http://www.facilitiesnet.com).

Four different retrofitting alternatives were calculated using reLight and compared them in order to attain lower energy use and save utility costs. In the first retrofitting suggestions (V2a), the number of the luminaries stayed the same but lamp types were changed (per luminaire Stuttgart: 30.8 W and 2262 lm, price: € 134, Konya: 37.0 W und 3900 lm, price: 280 €.) The second alternative, (V2b), provided similar illuminance levels on working plane with less luminaires and lamps (Stuttgart: 59.4 W and 4550 lm, 150 € Konya: 59.4 W and 4500 lm, 162 €). In the third alternative (V3), additional to the second one, the daylight and occupancy control system were proposed. For sun and glare protection, a light-directing system was proposed as a supplementary system to the lighting control system, in fourth alternative (V4).

In Stuttgart, the existing system's total cost including investment, energy and service/maintenance over the 20 years period is 57.52 €/m^2. With first retrofitting alternative, the energy and service cost can be saved but investment cost are high compare to existing system. The total energy costs are 30% lower in second alternative. Using of the control systems and sun/glare protection systems 20.5 % and 15.5% of the total costs can be saved.

Table 1: The existing lighting system of the lecture halls in Stuttgart and Konya.

	Stuttgart	Konya
Area[m²]	74.06	99.22
Installed power[W]	1065.0	1140.0
energy demand [kWh/a]	1135.9	1211.4
Annual service costs (approx.) [€]	35.6	69.6
Annual energy costs (approx.) [€]	227.2	242.3
Maintenance the existing system (approx.) [€]	450.0	450.0
User profile	Lecture hall /classroom	Lecture hall /classroom
Window Area Fraction of Wall Area[%]	40	60
Mounting Style	Mounted	Recessed
Type of lighting	Direct	Direct
Luminaire shape	Rectangular (long)	Rectangular (middle)
optical system	Glossy grid	Glossy grid
Number of luminaire	15	15
Number of lamps per luminaire	1	4
Lamp type	T8 fluorescent lamp	T5 fluorescent lamp
Ballast	Magnetic	Electronic
Lamp power [W]	58	18
Solar shading	No sun/ glare protection	No sun/ glare protection
Lighting management	No lighting management	No lighting management

Comparing the total costs in Konya, the alternative costs are higher than in Stuttgart. That means less cost reduction can be provided by suggested retrofitting alternatives. The saving potential is 18 % in the second, 7.5% third and just 1.6% in the fourth alternative.

In order to evaluate the influence of the retrofitting alternatives on the energy balance, the primary energy is calculated. The annual primary energy demand comparison is given in Figure 6. The highest energy demand is needed in existing conditions for both locations. The difference between the third and the fourth alternative is small even though the lowest primary energy demand has been sustained from different retrofitting scenarios in Konya and Stuttgart. The comparison between V2a and V2b leads to the following conclusion: In Konya, there is a large reduction in energy demand by using energy efficient lamps. On the other hand, a higher reduction in energy demand was observed in Stuttgart, by using 8 efficient luminaries instead of 15 and T5 lamps.

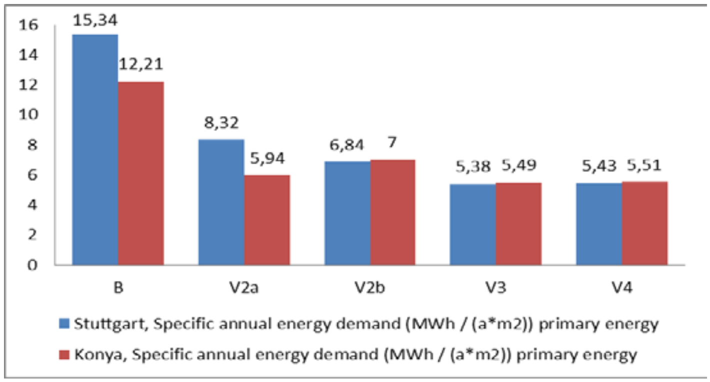

Figure 6: Specific annual primary energy demand comparisons for retrofitting alternatives.

4. Discussion and Conclusion

Based on the literature review, it was established that there is a large amount of energy consumption from artificial lighting in educational buildings. At the same time, it is strategic to explore and quantify the benefits of daylight contribution and compare the energy saving from retrofitting alternative lighting systems.

Nowadays, there are increasingly capable lighting simulation tools available for comparing the performance and energy efficiency of lighting systems. In this study, the daylight availability and visual comfort conditions were calculated and evaluated by users in two different lecture halls in Germany and Turkey. This method included the definition of the energy efficiency potential via analysis of the existing situation by measurements and questionnaire, evaluation of software tool outputs and the comparison of retrofitting scenarios. The analyses of the daylight availability and energy saving potential of existing lighting have been evaluated based on real use conditions in order to understand the positive and negative attributes of the system of the system. During the measurements, the following weak points were found: the lack of the measurement equipment (different numbers of sensors were used in the lecture halls), the lack of a luminance camera in on location (Konya) and sometimes inconsistent answers of respondents.

After monitoring the existing situation, the lecture halls were modelled in a computer environment, with annual daylighting simulations undertaken for both locations. The outputs like Daylight Autonomy and Useful Daylight Illuminance, which indicate the percentage of occupied hours when sensor point was above or between certain lux thresholds, were displayed and compared. According to the simulation results, the predicted annual lighting energy demand in the investigated lecture room in Stuttgart is 22.1 kWh/m²a. In Konya the predicted annual lighting energy demand is 7.9 kWh/m²a. In both cases the installed specific lighting power is 11.48 W/m².

The large windows do not mean that the light is automatically better. It causes mostly glare problems which could be eliminated by using of sun/ glare protections elements such as lamellas and blinds. The luminance camera was used in Stuttgart to quantify the luminance level and evaluate the glare. However the absence of the luminance camera in Konya, meant the comparative glare analysis couldn't be completed but is planned for the future.

The energy saving percentage for the retrofitting scenarios was calculated for each location. Besides energy efficiency of the lighting system the productivity and satisfaction of the users are important, especially in lecture halls of university buildings. Considering the result of the user satisfaction questionnaire it is possible to conclude that the main visual discomfort is caused by disability glare in the classrooms, perceived especially in places close to the windows. For this reason shading systems are recommended.

In conclusion, the retrofitting of the lighting system generally assures a more efficient use of artificial lighting, the proper daylight contribution and a higher visual comfort level. Moreover, in order to improve the daylight limitations; more illuminance and luminance levels can be provided in different time of the year and under various sky conditions. Finally, in order to improve the computer model characterisation; user behaviour definition can be monitored.

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