

EULISP

Evaluation and User Assessment of Lighting Systems Performance

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1 Abstract

During the planning process of buildings the energy consciousness and the visual comfort is getting more and more important. Since there are new daylighting systems on the market which promise to increase both - energy savings and visual comfort - there was no possibility to check these promises or to plan these systems.

For that reason new procedures to assess performance and user acceptance have been developed. New innovative systems have been selected and investigated. A suitable **testing procedure** has been developed to get the necessary optical and thermal data. The systems have been tested in scaled models, 1:1 rooms and in optical laboratories. A fully turnable 1:1 twin test room at Fraunhofer ISE has been built during the project. With that facility, comparable system data are collected. Actually it is used to evaluate new blind systems for industrial partners. At BLL new test rooms for performing the objective testing and for measuring the illuminance distribution have been set up. Together with the new developed objective testing procedure, these rooms are used for getting performance values. In the Philips rooms different controls for artificial lighting are investigated and user assessments are performed.

Computer models for some of the new systems have been developed out of the laboratory measurements. The validation of the models with the 1:1 system measurements has been successful. Due to general restrictions of the simulation programs, it is impossible to model all types of systems now. Further developments on the simulation programs are necessary.

For the **energy savings prediction** a combined thermal and lighting simulation procedure has been developed, based on well defined optical and thermal models.

A new procedure to investigate **acceptance** has been developed, based on photorealistic representation of computer-simulated scenes (SVR), which creates the impression of 3-D-virtual reality for the observer. A lot of calibration measurements were needed to get the correct luminance and color distribution. **User assessments** in real offices and in SVR have been performed. The results show a good correspondence for the SVR results, especially for glare and brightness issues. One of the main results is the non-existence of a glare or comfort index, because the range of answers is extremely broad.

For a lot of the available systems it is now possible to evaluate the important issues **user acceptance** and **energy savings**.

2 Objectives and introduction

It is widely accepted today that carefully planned use of natural light for indoor lighting has positive effects on the overall building energy demand due to the fact that e.g. in modern office buildings lighting may account for as much as 50% of it. Therefore, the goal is to use as much daylight as possible. Because of the variable nature of daylight and in order to avoid visually unacceptable conditions, this must be done in a controlled way, which is possible using advanced design tools and/or advanced daylighting systems. It requires also an electronic control of the supplementary artificial lighting. The performance of such combined systems is not yet understood in a quantitative way. With this project a method for the evaluation of this performance is developed.

Two issues are crucial for the success of any integrated daylighting/controls system:

- the **energy savings** and
- the **user acceptance**.

Without user acceptance, the system won't work, because unsatisfied users will always find ways to override and therefore destroy it. Without energy savings, systems will hardly be sold. This project provides the tools to assess both of the above-mentioned critical issues. Four systems are evaluated both in practice and under laboratory conditions. The evaluation includes both energy saving potential and user acceptance. In this way a method for the **performance prediction** of real systems on the basis of "simple" laboratory tests is developed.

The overall system performance is evaluated in direct comparison to conventional systems, i.e. windows with manual control. The performance evaluation includes the artificial lighting system and the appropriate controls. The comparison was performed in defined, unused full-scale test rooms. These test rooms have been set up for the project, and the entire measuring equipment has been installed. In order to provide methods for future comparative evaluation studies, parallel investigations using scaled models under an artificial sky and computer simulations were carried out, compared to the test room results and modified. The established data and methods was the basis for the development of an **evaluation standard** and a **test procedure**.

The user reaction is a field widely neglected, most probably because of its complexity. First research activities in this field are going on at the project partner's institutions. One of these methods is based on computer simulation by creating a static virtual reality. This is important for the inclusion of natural daylight in subjective test procedures: it is the only way to ensure reproducible test conditions. Another method is questioning office workers under specific

conditions. The advantage of this is that the subjects are in a real environment with their work, movements etc.. A third method uses the objective testing of persons with respect to measurable criteria.

Having both at hand: a standardised test procedure and a reliable user assessment prediction, it is now possible to make realistic assessments of the energetic impact of daylighting technologies on buildings.

3 Partnership and addresses



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4 Technical description

4.1 Selection of 2-4 integrated daylight systems (Task 1)

For the project, new systems as well as common systems have been tested. In following table, all tested systems are listed together with the type of testing:

System	1:1 ISE measurements	1:1 user assessments	RAD-Model	SVR	Objective Testing	Physics	Energy Simulation	Scale Model
Venetian Blinds	+	-	+	+	+	-	+	+
Venetian Blinds with LUXSENSE	-	+	+	-	-	-	+	-
Venetian Blinds with TRIOS	-	+	+	-	-	-	+	-
Fish	+	+	+	+	+	+	+	+
y-glass	+	-	-	-	-	+	-	+
sloped ceiling	+	-	+	-	-	n.a.	-	+
Lumitop	+	-	-	-	-	+	-	+
No System	+	-	+	-	-	n.a.	+	+

Table 4.1.1: **Table of systems : Which kind of tests were performed**

1:1 ISE measurements:	Illuminance measurements performed at ISE 1:1 test facility
1:1 user assessments:	User assessments in offices at ISE, Philips and BLL
RAD-Model:	Simulation model for RADIANCE was developed
SVR:	User Assessments in a static virtual environment were performed at ISE
Objective testing:	Performance tests of persons were performed at BLL and ISE
Physics:	The specific system was also measured in laboratory facilities
Energy simulation:	The energy saving potential was determined by using simulation tools
Scale:	Scaled model investigation have been done at TNO and BLL

In following paragraphs, the tested systems are described.

4.1.1 Standard venetian blinds

The venetian blind system is one of the real standards in daylighting. It is used in a very wide range of different dimensions, situations, materials and control strategies.

The basic concept is the shading function of a horizontal structure. The shading effect depends on the inclination of the lamellas. It is possible to close the

lamellas in such a way that there is no direct sun entering the room, i.e. complete sun protection.

Usually the lamella surfaces reflect some of the incident light. This leads to a certain amount of transmitted diffuse light that depends mostly on the surface characteristics and the inclination of the lamellas. The transmission of lamella systems may be reduced to zero depending on the shape of the lamellas. So the venetian blind is also useful as an anti-glare system.

Venetian blinds are used in front of the glazing, behind the glazing and also inside the isolation glazing, i.e. between the glass panes. Most lamellas are made of metal (very often special alloys) with a predominantly diffuse colored surface. There are also systems available based on plastics for indoor use. Special types are also available with highly specular surfaces.

For EULISP, a standard system behind the glazing is selected. The system is LUXAFLEX 6036 (off-white) and is manufactured by HUNTER-DOUGLAS.

4.1.2 Reflecting, light guiding elements ("FISH")

The whole window is divided into two sections: an upper part with a fixed daylighting system and a lower part with a moveable sun/glare protection system. It is new on the market. They have been developed for the Brundtland Centre Focus 21, one of the JOULE II projects and are just now in realisation.

Upper window part

The system consists of two components. Both components are integrated into the double glazing. The daylight redirecting is done by a fixed reflective element (see Figure 3). The horizontal lamellas have a special shape and highly specular surfaces. They transmit diffuse daylight from the sky to the upper half of the room.

The system has no sun shading function. Therefore it is necessary to install a second component for sun shading. This second component is realised as a roller blind in front of the light directing system.

Lower window part

In the lower window part the major task is to have a reasonable sun and glare protection system with the possibility of contact to the outside. For that reason a movable light directing lover is used. The reflective upper surface is oriented to the outside resulting in a highly effective sun shading and glare reduction effect.



Figure 1 + 2: Light guiding property and section of the "Fish" System

4.1.3 Architectural solution

For an architectural solution the partners agreed to have an inclined ceiling at the window side of the room. This is the most common practice and a solution that is often easy. The ceiling inclination is about 45°.



Figure 3: Architectural solution: Sloped ceiling

4.1.4 Sundirecting Glass

The system consists of acrylic profiles stacked one upon another between two sheets of glass. It is used to guide the direct sunlight to the ceiling, where it is reflected down to the working plane without glare. When used as a sundirecting rooflight in an atrium, the direct sunlight is spread and guided down into the atrium space. The system depends on total reflection and there is no dispersion of the light. The light is not only reflected in the vertical plane, but also in the horizontal plane so the light can reach the depth of a room for all solar positions without movable parts in the facade. The vertical deflection is achieved by the shape of the acrylic profiles and by a sinusoidal surface located where the light leaves the element. This system was chosen for the project, because it is a brand new system and seems to have good market chances. The product name is LUMITOP and is manufactured by Vegla, Aachen. The system was developed by the Institut für Licht und Bautechnik of FH-Köln. It was in-

tegrated into the upper window part. In the lower part a normal blind system as glare protection was installed.

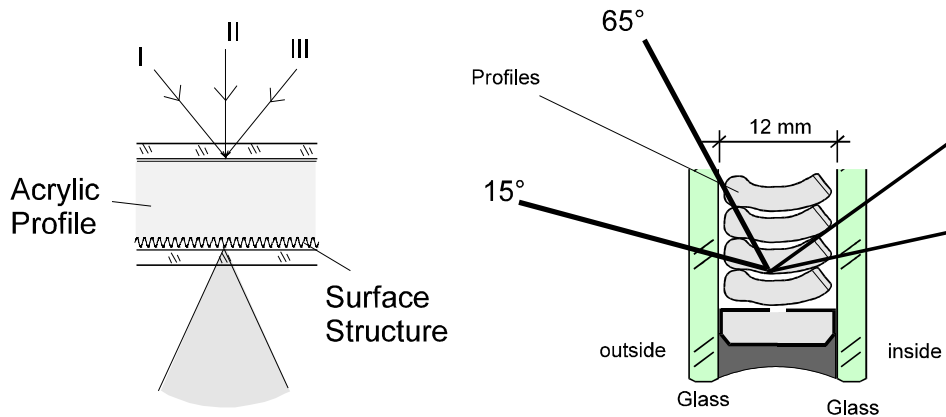


Figure 4 + 5: Horizontal and vertical section of LUMITOP

4.1.5 y-glass

The principle of this system is shown in the following figure. In-between a glazing there is an inlet out of PMMA. This inlet has special properties due to its production process. During the extruding of this plastic, extremely homogeneous bubbles are introduced into the material. These bubbles are horizontal tilted. If a ray hits the interface PMMA-(air)bubble, total reflection occurs and the light is redirected.

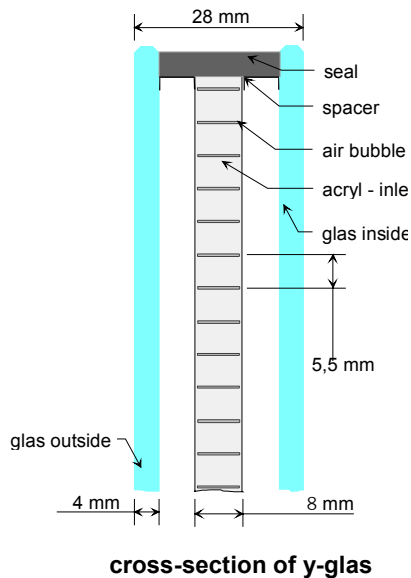


Figure 4.1.1: Principle of the y-glass system

4.1.6 Lighting and Control Systems

Luminaires with lighting control per luminaire

The artificial lighting system supplies a maximum illuminance on the working plane of 800 lux. Used was a ceiling -mounted direct lighting systems with 4 luminaires, HF-dimmable as commonly used in lighting practice. The luminaires were of type TBS 300/2.58 M6 (twin-lamp luminaires with a M6 type mirror).

The lighting is controlled per luminaire (e.g. type Luxsense), combined with controllable blinds. The luminance of the window and the working plane is controlled (5 sensors). There is no possibility for the user to adjust anything.

Luminaires with lighting control per room

The lighting systems are of the same type as above. Lighting control is for the whole room (TRIOS system). In this case, the user can adjust the level on the working plane and/or the luminance of the window.

4.2 Design and construction of the test facility (Task 2,5)

4.2.1 General

The purpose of the test facility is to get comparative measurements and performance evaluation of the systems. The idea is to have a divided, flexible container with two identical room layouts: one for the system under investigation and one with a conventional system (e.g. window + venetian blinds). The major effort in designing the test facility was to find a cost-effective solution for the construction, especially after termination of the lease of the institute's test area. Therefore only one feasible place on the roof on an existing building was left.

4.2.2 Location and dimensions

The test facility is erected on the roof of a 16 m high office building in Freiburg, Germany. There are no obstructions and the orientation of the test facade can be varied. This has been achieved by designing a rotating substructure between the roof and the test rooms.

Both rooms are 3.65 m wide and 4.6 m deep. The total height of the rooms is about 3m. There is a false ceiling installed which has a variable distance to the roof. The facade is divided in an upper, "light guiding" part and in a lower, "look through" part. The facade is designed as adaptable as possible, that means e.g. every type of glazing up to 50mm thickness can be installed. It is also possible to remove the hole facade for testing special facade types.



Figure 4.2.2: Photo of the test rooms



Figure 4.2.3: Example of luminance measurements

4.3 Design and installation of the monitoring equipment

4.3.1 Indoor illuminance

Both rooms are equipped with 12 illuminance sensors each:

- 4 horizontal sensors are regular distributed in the middle on the ceiling. (Positions from the facade: 60, 175, 290, 400 cm)
- 4 other sensors, one vertical and three horizontal, at work plane height, can be moved across the room with a step motor (ISEL 2 phase step motor), so that the whole room can be scanned within one minute.
- 2 pairs of vertical sensors are fixed on the wall facing the window. Each pair contains a shielded and an unshielded vertical sensor. The vertical shielded sensor is mounted at 1,20m height and "sees" only the window. The other vertical shielded sensor at 2,20m height "sees" only the upper part of the window. These shielded sensors can be used to determine the general luminance of the daylight system.

4.3.2 Facade luminance

For luminance measurements we are performing spot measurements with a MINOLTA Luminance meter LS100 and taking additional photos of the scene with a CCD-Camera (Kodak DC50). The results of these spot measurements are automatically placed into the photos. An example is shown in the following figure.

4.3.3 Electric Energy consumption

The energy consumption of the artificial lighting is monitored separately for each luminaire group (two luminaires). This power - voltage converter is developed and calibrated at the institute. The output signal is 1V per 100W. The maximum power to be monitored is 1 kW. The accuracy is about $\pm 1\%$.

4.3.4 Outdoor sensors

The Fraunhofer Institute for Solar Energy Systems ISE in Freiburg, Germany, participates in the 'International Daylight Measurement Programme', a world-wide action initiated by the International Illumination Commission (CIE). A 'general class station' is operated on the roof of the institute building. On this basis, 10-second samples of different meteorological parameters are available. For the EULISP project the values of the following sensors are used:

- ambient horizontal illuminance, type LMT BAP
- ambient temperature, type: Thies Pt100 thermometer
- global horizontal irradiance, type: Kipp & Zonen CM 11 pyranometer
- direct normal irradiance, type: Eppley NIP, mounted on 2AP tracker
- diffuse horizontal irradiance, type: Kipp & Zonen CM 11, shaded

This weather station is located within a distance of about 50m from the test facility. The access to the actual data is possible via networking. In addition to this, the vertical illuminance in facade plane is measured by a LMT illuminance measuring unit BAP for outdoor installation.

4.4 Real office installation (Task 7)

4.4.1 Introduction.

This documentation describes the location, design and interior of the two EULISP test rooms that have been built in a research building of Philips Lighting in Eindhoven, the Netherlands.

Part of the EULISP project is the capability to make simulations of the lighting conditions inside the testrooms both in daylight and night-time conditions.

4.4.2 Description of rooms and exterior environment.

Location

The test office is located at the ground floor (1 m above street level) of a single story building in Eindhoven, The Netherlands. The windows are facing West, with a view out that is partially obstructed by a low storage building (height 3 m above street level) at a distance of 5 m from the facade.

Dimensions

The building facade contains a window area reaching from 0.9 m to 4 m above the floor over the total width of the room. In the base case a false ceiling is installed at 2.8 m above the floor. To enhance the daylight contribution in the

room it is possible to extend the window to 4 m above the floor and install a light redirecting device. The room is 3.65 m wide and 5.4 m long. It has light walls, 'normal' carpet, and a white ceiling. The window contains standard clear double glazing.

Furniture

The "standard" furniture is placed in a "standard" way, with a desk and a conference table. When the office is used by a subject it contains office equipment, such as a telephone, a personal computer (network connection has been provided), and a printer if needed. The office is furthermore "decorated" with posters at the walls and a small cupboard to make the office look as realistic as possible.

Artificial lighting

For the artificial lighting a direct installations was installed. This system consists of four luminaires of the Philips type TBS 300/2.50 M6 (twin-lamp luminaires with a M6 type mirror), which are recessed in the ceiling. This is considered to be a "standard Western European" lighting solution. The luminaires contain 2 fluorescent lamps, operating on high frequency ballasts, with a colour temperature of 4000K and good colour rendering ($R_a = 80$). The lamps are dimmable to 3% of the light output. The artificial illuminance at the desk has a maximum value of 1000 lx.

Artificial Lighting control system

Two different artificial lighting control systems can be used in the room, one luminaire based and one room based system:

Luminaire based system.

This control system has a photocell and automatic daylight linked dimming in each luminaire, the commercial type name is Luxsense. The luminance of the relevant area underneath the luminaire is controlled, the lamps are dimmed when the luminance exceeds a certain value. The luminaires can be combined with controllable venetian blinds. The blinds control the luminance of the window, which is measured by a separate sensor. The system is designed to be used fully automatic without possibility for the user to adjust anything.

Room based system.

This is a lighting control system for the whole room, named TRIOS. With this system one photocell which measures the luminance of a certain area is placed above the desk. The system can be combined with controllable blinds. The blinds control the luminance of the window, which is measured by a separate

photocell. In this case the user can adjust the level on the working plane and/or the luminance of the window by means of an infrared remote control unit.

4.4.3 Monitoring

Data are collected with a specially developed piece of equipment, a combination of a data logger and a control unit, which can be programmed and read out remotely by means of a modem and a PC. Illuminance is measured at each minute at several positions in the room. Horizontal illuminance is measured at the desk, and at the conference table, vertical illuminance is measured at the wall in front of the desk, behind the desk and at the rear wall, next to the door, all at "eye level" (1.5 m above the floor). The spectral sensitivity and the angular dependence of the photocells is known.

The presence of the subject is detected by infrared movement receivers.

All settings of the artificial lighting, the use of the remote control and the setting of the blinds are also stored in the unit.

4.5 System Monitoring

4.5.1 Monitoring in ISE Test facility (Task 8 a)

Measurements are performed only at clear sky and overcast sky conditions. Measurements at cloudy skies are not comparable because of the enormous variety of the luminance distribution of the sky. Especially a comparison to the simulation is extremely difficult for the cloudy sky, because the exact cloud distribution cannot be modelled out of the radiation measurements. The used sky model of Perez is very accurate concerning a yearly analyses, local clouds at a special position can't be modelled. For that reason, a full day measurement as demanded from the IEA-task 21 is not suitable for getting the energy demand, because the scaling from short term (day) measurements to a whole year energy demand is quite difficult and inaccurate. The more accurate way is the exact modelling of the systems and performing yearly simulations.

For the overcast sky at least two different orientations are used. As sky validation both measurements should have quite the same daylight factor distribution. For the clear sky at least four different orientations to the sun are used. The sun height is 20° and 60°, the azimuthal angle between facade and sun is 0° and 45°. Out of these four orientations the typical light distribution for high and low sun positions can be determined. It also turned out to be suitable to use a special configuration for comparing the full scale measurements with the simulation and the scaled model measurements. In this configuration the lower window part (look through part) is totally closed, so that the light distribution is only influenced by the daylighting elements.

4.5.1.1 Results

Overcast sky

For an overcast sky, all tested systems show worse properties than the normal glazing - which is different to the promise of the manufacturers (see Figure 4.5.1). The behaviour is caused by two factors:

1. The total visible Transmission of two of the systems is considerable lower than the transmission of the conventional glazing
2. The light, that will be redirected onto the ceiling, is scattered diffusely with an efficiency of 80% on its surface. Additionally half of this scatted light will be lost by leaving the room again through the glazing (Law of Lambert). To avoid this phenomena, a direct reflecting or forward scattering ceiling material has to be used.

System	Visible Transmission ($t_{hh,v}$)
Conventional Glazing	0.69
Y-Glass	0.72
FISH-System	0.31
Lumitop	0.34

Table 4.5.1: Visible transmission values of the measured systems

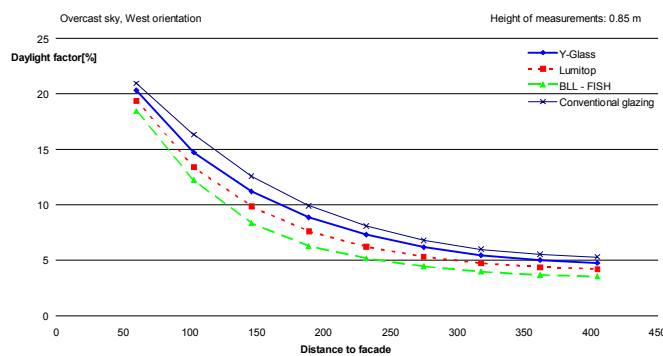


Figure 4.5.1: Daylight factors for all measured systems for an overcast sky

For the clear sky measurements all systems improve the level of illuminance - except the y-glass system which causes direct glare. This direct glare can be seen as a peak illuminance in 4.05 m depth in Figure 4.5.2.

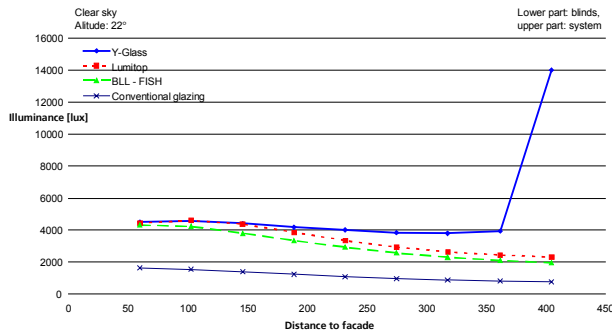


Figure 4.5.2: Light distribution for clear sky conditions of the check of systems

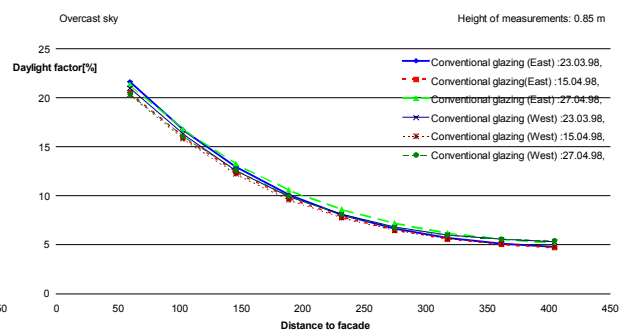


Figure 4.5.3: Daylight factors for the conventional glazing: the reproducibility of the overcast measurements

Another big issue was to measure reproducible properties of the elements. Because of the great variety of the sky luminance distribution one has to be careful performing the measurements. For the overcast sky conditions we found, that before the measurements will take place the rough sky luminance has to be checked. The zenithal luminance has to be about three times higher than the horizontal. If this is fulfilled in the sky area that is important for the measurements, the measurements can be performed. Remembering the relative accuracy of the sensors of about 4%, the results shown in our overcast measurements:

Clear sky

For the clear sky condition it is much more difficult to create comparable boundary conditions. For example the sun altitude for the low sun position (20°) is changing rapidly over the time (15th May: 6min/degree). Because we have to perform at least 4 measurements per sky condition (normal to sun, 45° to sun, lower part closed, lower part blinds), the altitude could change about 3° in 15 minutes - which changes the light distribution.

Summary

All systems have been measured. We found some important recommendations, which have to be fulfilled before starting the measurements. All important recommendations are included in the tasks "Parameter Identification" and "Development of Evaluation Standard and Test Procedure".

4.5.2 Monitoring in BLL test rooms

4.5.2.1 Full scale test facility at BLL

In the frame of an extension of the laboratory of Bartenbach LichtLabor at Aldrans a new full scale test facility was designed. The same facility was used for the system monitoring and for the performance tests with subjects.

4.5.2.2 Description of the full scale test facility

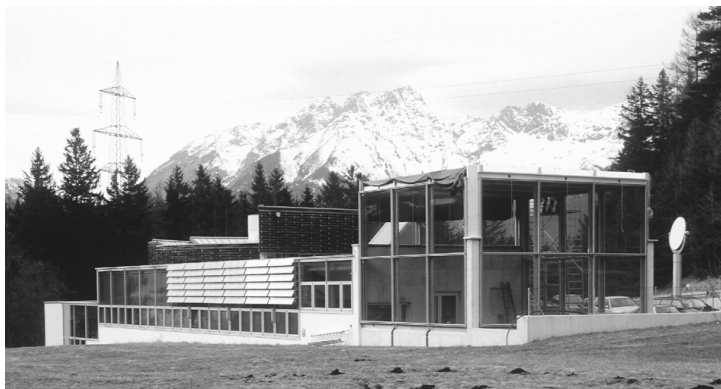


Figure 4.5.4: Laboratory building and the full scale test facility, seen from the south-east position.

The experimental room is a clear envelope with a minimum of static construction. The different test rooms are separately erected inside this envelope. So it is possible to change to different room situations very fast and cheap. The tested daylighting system consists of two different components in the upper and lower part of the window. As the construction of the test-facility does not allow to change the single pane glazing, the „Fish“-system was mounted behind the glazing. The textile sun shading device is situated between the glazing and the „Fish“-device.

4.5.2.3 Results of the daylight measurements



Figure 4.5.5: Photographs of the BLL test rooms

The two pictures above show the two test rooms. The left one is with the standard venetian blinds and the right one is with the „Fish“ system in the upper window. Beside the two different facades the rest of the room is completely the same.

During the equinox period a number of measurements have been carried out. But only two of them are chosen for further evaluation. These are the dates for 24th February as an overcast day and 23th April as a clear day.

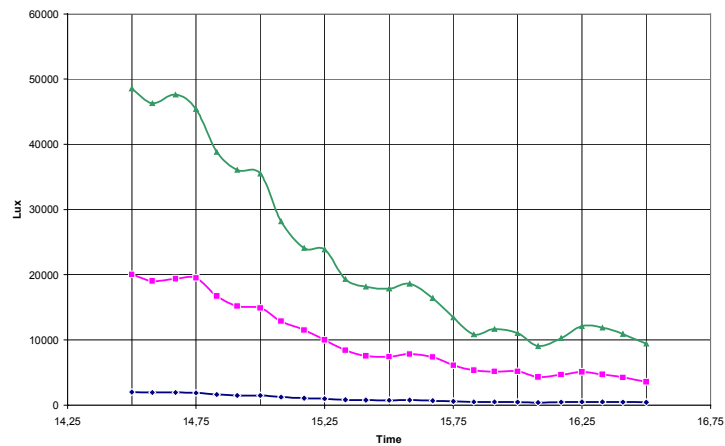


Figure 4.5.6: Measurements on a cloudy day (24.2.1998)

The raw results are shown in the following diagrams. The diagrams show the benefit of the fish system as a difference of the lighting level on the horizontal plan on working high.

Both systems are adjusted in such a way that there is nearly the same luminance level on the facade.

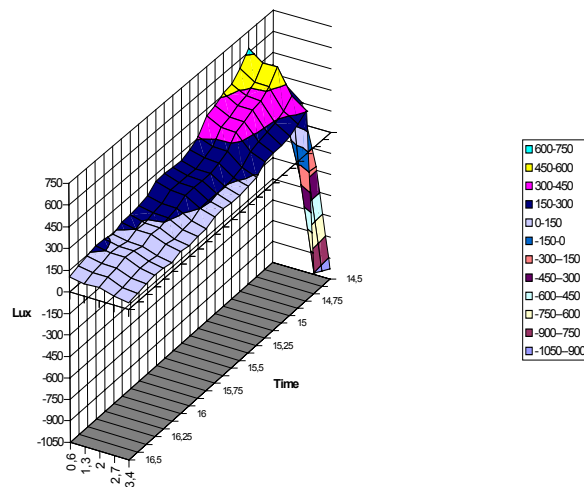


Figure 4.5.7: Luxlevel difference between fish and reference on a cloudy day. The data were collected on 24.2.98. There is a more or less constant winning over the whole day.

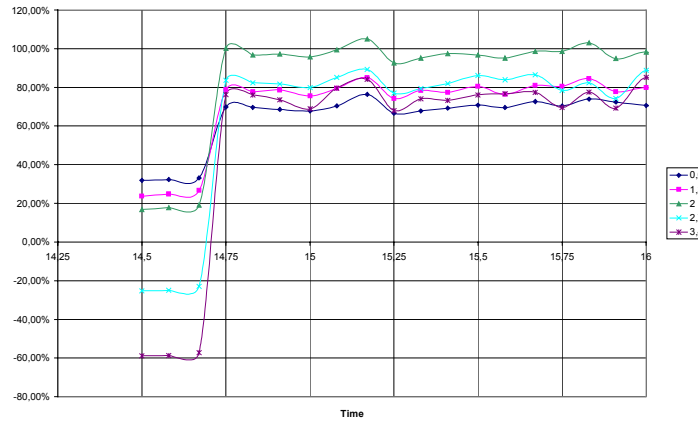


Figure 4.5.8: Luxlevel difference between fish and reference on an overcast day. The data were collected on 24.2.98

Above diagram shows the difference between the two room along the time of the day for the overcast day. The sensor positions are shown in different curves as parameters. If we forget about the measurement before 14,75 (this are wrong results due to an open door) we get a very constant difference. This means we really are allowed to use the daylight factor for comparison which leads to a much more simpler diagram.

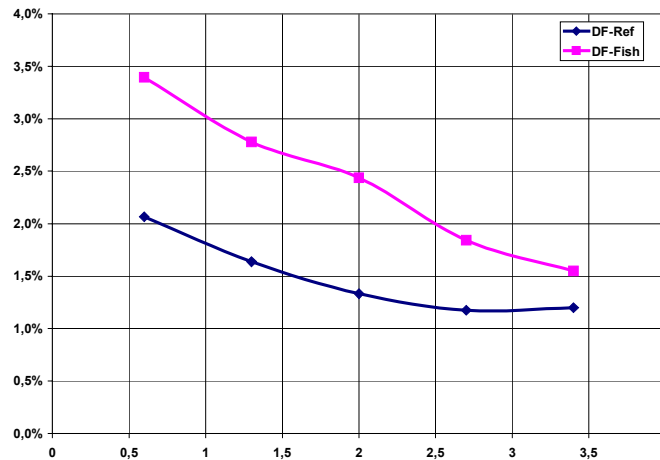


Figure 4.5.9: Daylight factors for the two systems

4.5.2.4 Summary of the BLL measurements

The measurements show a much more complex behaviour of the systems for clear sky conditions than under overcast sky. For a complete evaluation of a facade it is absolutely necessary to check overcast and clear conditions. Using such methods it is important not to forget that the results are only true in the actual context. The shown benefits from the Fish-System are only true if we use the louver of the reference room also for the overcast sky to reduce the brightness of the window.

4.5.3 Monitoring in Philips test rooms

4.5.3.1 Sloped ceiling

Layout of the room

In the Eulisp testroom the daylight contribution has been enhanced by extending the window to a height of 4m above the floor. The window part of the ceiling has been put at a slope of 45 degrees over a width of 1.2m. The window now consists of a lower (normal) part and an upper part. Both can be covered separately by venetian blinds.

The sloping ceiling made it very difficult to mount luminaires close to the window. A pending luminaire under the sloping ceiling nearly cancelled out the effect of the extra window on the daylight contribution.

Daylight measurements

The daylight has been measured simultaneously in the room with the sloping ceiling and the adjacent, identical room where the ceiling was left unchanged. The measurements took place with different weather types and with different settings of the venetian blinds. The venetian blinds in front of the normal (lower) window were set at exactly the same angle in both rooms.

Discussion of the results

In all cases the extra window caused the daylight contribution to increase with respect to the reference, normal ceiling. The increase, however, depends strongly on the setting of the venetian blinds.

In the following table the average increase of the illuminance at the desk and at the table is given for the different settings of the venetian blinds:

	no venetian blinds	venetian blinds horizontal in front of the lower window	venetian blinds horizontal in front of the lower and upper window
desk illuminance	10%	50%	50%
conference table illuminance	50%	60%	20%

Table 4.5.2: Average increase of the illuminance level for the sloped ceiling

From this table it can be seen that without venetian blinds the increase in daylight contribution is the highest in the back of the room (conference table), at

the desk the increase is only 10%. When the venetian blinds are placed horizontally in front of the upper and lower window the increase is highest at the desk. But when the upper part of the window is left open and only the lower part is covered with horizontal blinds the gain is the highest, 50% extra at the desk and 60% at the conference table, compared with the reference room with horizontal blinds.

It should be noted however, that the angle of the blinds is a critical parameter, a slight adjustment can destroy the effect. And when the sun shines on the window the blinds should be closed totally.

4.6 Objective testing of persons

In order to avoid the disadvantages of purely subjective methods in a technical evaluation of daylight and artificial light systems, the Bartenbach LichtLabor developed new test methods which can determine objectively and quantitatively the visual or psycho-physiological stress connected with VDU work, depending on different lighting conditions. Daylight and artificial lighting systems were tested with these methods and compared by using the performances achieved by the test subjects. Some highly significant differences in performance done under the individual lighting systems become apparent and demonstrated that the visual stress or the physical or physiological fatigue from an ergonomic viewpoint depends largely on the lighting conditions at the workplace. This holds true for daylight systems (glare protection, re-directing lamellae, clear window as a control condition) as well as for purely artificial lighting systems where especially the choice of colour temperature of the light and the used control gear (conventional or electronic) determine the resulting performance. Optimised lighting also positively affects the productivity and economic for the design of workplaces that take the human factor into account.

4.6.1 Introduction

For about two years now the perception-psychology department of the Bartenbach LichtLabor in Aldrans near Innsbruck has done systematic research on the influence of different lighting variations in offices on the psychophysical or mental stress of people who work at VDUs. Great emphasis is placed on the objective and quantitative measurement of visual stress versus relief in an actual performance situation. The test methods which were developed measure each time one specific partial performance from the wide range of visual tasks that are connected to VDU work. Under the conditions of installed daylight and artificial light system, these test methods measure, among others, the following performance variables:

- certainty of perception and speed of perception for VDU work,
- degree of attentiveness,

- stress capacity of attentiveness,
- attainment of an overall perspective of the VDU,
- detailed stimulus differentiation,
- concentration capacity,
- carefulness in looking back and forth between screen and manuscript,
- certain factors of short-term memory.

Based on the data of these variables, lighting systems are compared with each other in order to analyse the stress factors and to determine which lighting conditions are the most favourable for minimising visual stress. The tests were done under virtual field conditions in order to eliminate the disadvantages of a classical field study and to benefit from the advantages of a lab study. For this purpose, actual office rooms were constructed as test rooms in which the lighting systems could be changed and where desired and undesired influence factors could be systematically controlled and altered: for example, the position of a seat within a room (facing the window or turned sideways), the reading conditions of VDUs (colour or monochromatic, positive or negative representation, tests with or without manuscripts, manuscripts on a stand or on a desk, glossy or matte manuscripts). In connection with lighting systems, the influence of these variables on the performance or the development of performance was measured using the methods described below.

Up to now, these tests has been carried out only in the Bartenbach's laboratories. For using this tests in the EULISP testrooms, they had to be adapted to the field conditions. The adaptation was necessary especially for the user interface and the operating system, which is now Windows. With this version of the testsoftware it should be possible to carry out such tests in every possible environment.

4.6.2 Description of tests and measured variables

4.6.2.1 Objective measurements of performance

Although it is insightful to establish to what degree differences in evaluation and acceptance can be verified by quantitative data for performance, and although subjective evaluation might serve as a secondary control tool, priority must be given to quantitative measurement of performance levels and their comparison.

It was for this purpose that the test methods listed below were developed by the Bartenbach company. This required a development stage that lasted a year because the theoretical criteria for quality (reliability, validity, objectivity) had to

be optimised through calibration, and because we also had to establish an appropriate degree of difficulty.

The close relation of the visual test demands to actual VDU work ensures that the results can be generalised vis-à-vis the actual demands of real work (external validity). The test subjects were compensated for their participation; a factor which led to a corresponding motivation and a willingness to make an effort.

The analysis included seven test methods whose individual variables each measure a significant essential component of mental or visual stress (or relief) in connection with the lighting of workplaces (here mostly VDU stations).

4.6.3 Fatigue measurements

Inadequate lighting represents a physiological and psychological interference factor whose effect of stress begins relatively early in the unconscious, but is experienced consciously only as it increases.

With the choice of the cybernetic flicker blending frequency analysis, a method was chosen which could measure quantitatively and objectively the vegetative-cerebral degree of fatigue of test subjects in connection with VDU work and with dependence on installed luminaires.

The controversy surrounding this method might be due to the fact that the current adaptation condition of the eye is given too much weight with individual or single measurements. This influence was reduced to a statistic inconspicuousness by taking pre-test measurements after a phase of adaptation to the room that lasted 5–10 minutes during which the test subjects were informed about the course and the goal of the tests. In addition, only arithmetic averages from measurements of 30 people were compared and used in further calculations; in this way a so-called >runaway< could not noticeably influence the average.

In order to analyse the fatigue gradients over time, the vigilance measurements were carried out before and after the tests. The time span of 4–5 hours in between was necessary to complete the entire battery of tests. Because the flicker blending frequency depends on the size of the stimulated area in the retina, the blending frequency was measured throughout for three flicker point sizes. Furthermore, the measurement is done cybernetically, meaning that the blending frequency is approached both from increasing and decreasing directions.

For each test subject, six individual fatigue values were measured on the basis of the flicker blending frequency analysis. The differences (i.e. gradients) between the measurements before and after were then used for the statistical da-

ta analysis. Positive as well as negative values (differences) are possible because, with a high blending frequency, a low degree of fatigue can be recorded and on the other hand a decreasing blending frequency goes hand in hand with increasing, mostly still unconscious fatigue.

If a negative fatigue gradient is designated here as >recovery<, e.g. with eVG [electronic control gear], it does not signify a steady decrease of visual fatigue but rather a statistic average which indicates an evenly high and constant cerebral level of activity (vigilance).

4.6.3.1 Questionnaire

In addition to the objective tests also a questionnaire was used. Results of a questionnaire show a subjective experience about the room. These results are to be compared to the results of the objective tests. For this reason the subjects had to answer a questionnaire after the objective tests. This was carried out in Aldrans and also in Freiburg.

The questionnaire was divided into different sections:

- 1) After the instruction (written and verbal) some important biographic dates were asked. These were sex, age a.s.o. Also the use of spectacles was collected here.
- 2) Then some questions followed about the general preferences of the subjects concerning lighting situations for working conditions.
- 3) Next were the questions about the overall lighting conditions of the single testroom. A part of this section was also a semantic differential. This tool allows to measure the emotional acceptance of the specific room. So also the intuitive relations to the room were measured.
- 4) The last section focused on the lighting conditions of the working desk. That means most of the questions had to do with the reading conditions on the VDU screen and on paper.

Throughout the whole questionnaire a six steps rating scale was used. The opposite poles were marked with the corresponding extreme answers. The questionnaires of Aldrans and Freiburg were a little different due to the different situations of the test rooms. For comparisons of the results only these questions are used which were identically in both.

4.6.4 Tests performed

	Clear Sky		Overcast Sky	
	B	A	B	A
Aldrans	"Fish"-System textile sun shading (upper part) Reflective louver closed (lower part) N=14	White Louver in front of facade (whole window) Closed to prevent from direct glare N=15	"Fish"-System no sun shading (upper part) Reflective louver horizontal lamellas (lower part) N=16	White Louver in front of facade (whole window) Opened to trans- parency to the ground N=14
	C		D	
Freiburg	"Fish"-System no sun shading (upper part) with closed louver (lower part) N=22		"Fish"-System no sun shading(upper part) without louver(lower part) N=55	

Table 4.6.3: System configuration at different locations and sky types (N ... Number of subjects per test room condition)

4.6.5 Example for the questionnaire results:

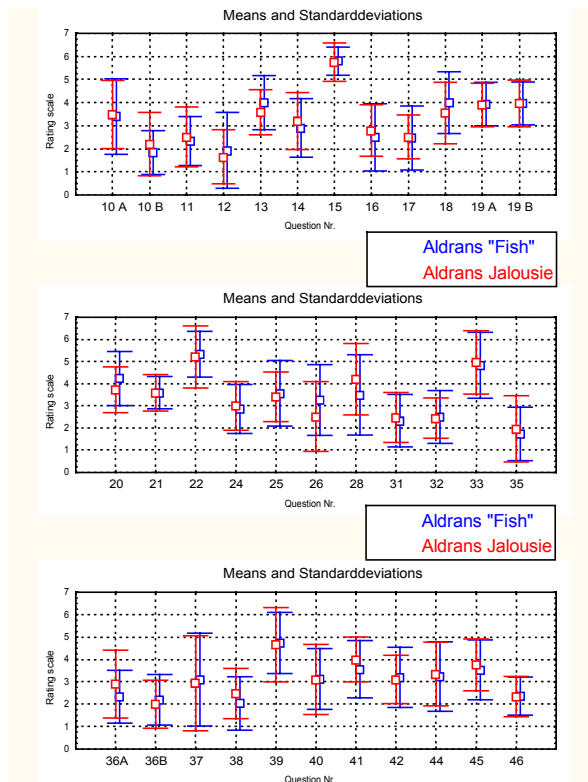


Figure 4.6.10: Questionnaire: ALDRANS : No significant differences in assessments throughout

4.6.6 Comparisons Aldrans - Freiburg

4.6.6.1 Example for objektive tests : Sensitivity to changing contrasts an the screen display

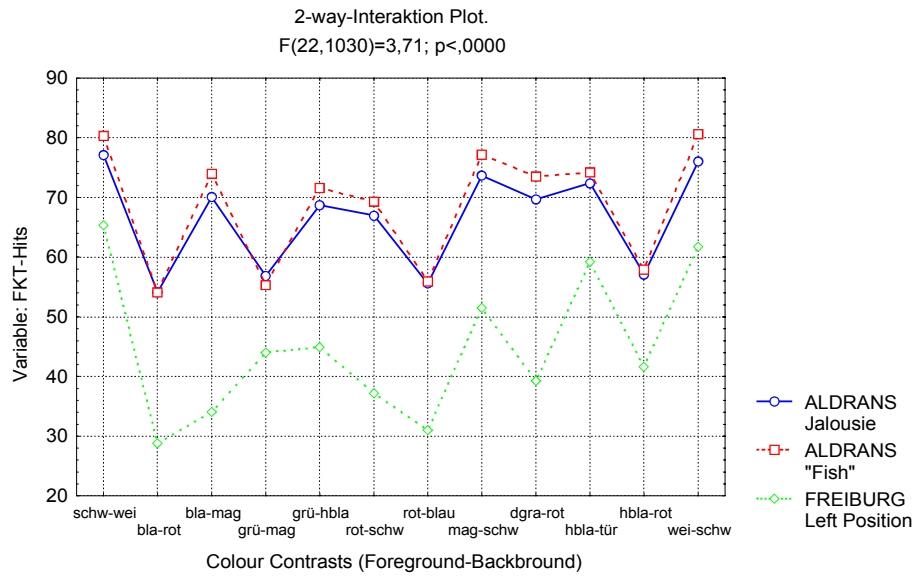


Figure 4.6.11: Sensitivity to changing contrasts an the screen display

4.6.7 Example for questionnaire results

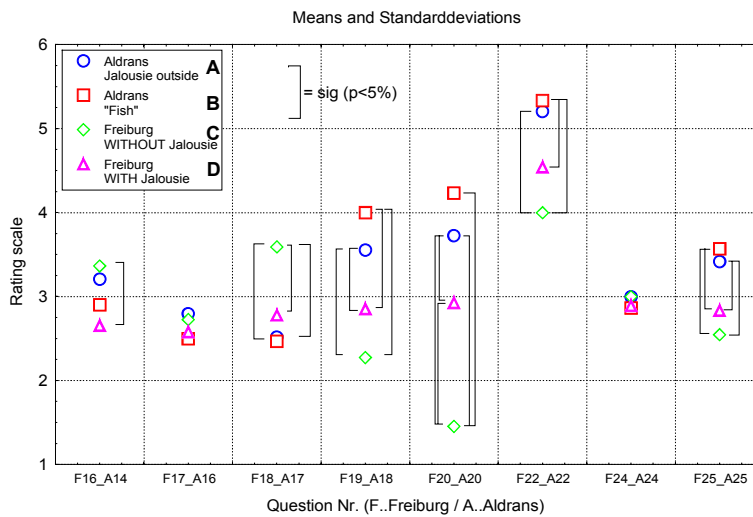


Figure 4.6.12: Means and standard deviations of the questionnaire

4.6.8 Discussion of the results and conclusions

- a) With the help of both, the objective tests and the subjective questionnaire, it is possible to evaluate lighting conditions from an objective and subjective point of view.
- b) It can be seen, that it is very important to structure the results in a useful way in order to get useful statements. For example there are no statistic relevant differences in the Aldrans results between the fish and the louver as long as we do not take apart the clear and the overcast days. If we look at them separately there are significant differences for the clear day but none for the overcast. There is a significant lower performance for the louver under the clear sky condition. This is true for the objective tests and also for the fatigue measurements.
- c) There are no significant differences out of the questionnaires (concerning the above comparisons). Here we have to keep in mind that both weather conditions are included in the results. It can be assumed that there are differences if the two weather conditions are analysed separately. This should be done in the future.
- d) It seems to be very critical to compare such results between different test room locations. Due to the different conditions man have to be very careful in interpreting the differences. But it can be clearly seen that there are significant differences between the results in Aldrans and Freiburg for the Fish-System. Although the system itself was the same, the lower part of the window was treated in a different way. If we compare the results without care about the weather there is a significant lower performance for the left position in Freiburg and a significant longer processing time for both positions. If we take apart the two weather conditions, we can see that the difference comes from the overcast sky. The difference was, that for this condition the louvers in the lower part of the window were taken away in Freiburg but only opened in Aldrans. It can be assumed that the significant lower performance in Freiburg was due to the lack of glare control under overcast conditions.
- e) Similar results can be found in the comparison of the questionnaire. The acceptance of the Freiburg rooms concerning transparency are significantly better than the Aldrans rooms. But at the same time the subjects complain about glare and also about a bad light distribution.
- f) All the results seem to be quite logical and also fit quite well to results from earlier tests.

4.7 Modelling and simulation of systems (Task9)

4.7.1 Description of the daylight simulation program

The daylighting conditions inside the test facility have been simulated using the well known simulation program RADIANCE. This program is today's most advanced ray-tracing program for analysis of daylight situations.

The program was developed at the Lawrence Berkeley National Laboratory in Berkeley, California, USA. This program operates according to the so-called "backward ray-tracing" method: Starting from the eye of an imaginary observer, view rays are sent into the scene, with each individual view ray being followed until it hits a light source, a path which may include several reflections from various surfaces. The energy-relevant and colorimetric information is determined from each single view ray. This information corresponds to the luminance (units cd/m^2). If a large number of view rays are sent through an imaginary "screen" in front of the observer's eye, the individual luminance values can be used to build up a photo-realistic image (see "visualisation" below).

As the aim is to investigate the daylighting quality in offices, direct radiation from the sun and zones of the diffusely radiating sky form the light sources. A physically correct daylighting simulation, which is not restricted to a purely schematic representation of this temporally variable and spatially very extended, diffuse light source, is possible with RADIANCE. Results from the lighting simulations include information on the distribution of luminance and illuminance values in the modelled environment.

A representation of the luminance values, corresponding to the perception of a hypothetical observer with a given perspective, is called a "visualisation" of the scene: the "brightness" (luminance, cd/m^2 or $\text{lm}/\text{sr}/\text{m}^2$) of each position is correlated with its spatial co-ordinates. The visualisation corresponds to a photo of the real scene. However, the reproduction media used cannot display the full range of luminance values. Paper prints, photography, computer monitors, video-film or slides are not capable of reproducing the wide range of brightness which the eye - within a fixed adaptation state - can perceive.

For this reason, luminance distributions can also be presented as "false colour images", for example. Certain colours are allocated to certain brightness ranges. The resulting image no longer corresponds to the visual impression, but this approach allows regions of great brightness, which would appear as a uniform white field in a photo, to be displayed with greater differentiation.

Whereas luminance values indicate how much light is reflected from one point in a certain solid angle, the illuminance values (in $\text{lux}=\text{lm}/\text{m}^2$) indicate how much light from all directions within a hemisphere is incident on a point on a certain surface (normally at working height, oriented horizontally). The calcula-

ted illuminance distribution provides information on the amount of light and its distribution within the room.

Summarising the following main goals of a daylight simulation:

- Photo-realistic visualisation of the test facility at a specific orientation with a distinct sky condition at a specific date
- Analysis of discrete luminance values within a photo-realistic visualisation of a specific scene
- Overall representation of prevailing luminance values (falsecolour)
- Analysis of illuminance values at discrete positions inside the scene
- Overall representation of prevailing illuminance values (isolux).

All displayed illuminance values were measured in desk height (0.85 m).

4.7.2 Simulation models

The RADIANCE simulation environment allows to model transmitting materials in different ways. The most intuitive modelling is to make a geometrical model. The structure is built by a 3-D model, the physical behaviour is described by reflectance values, transmission etc. But there exist some limitations in the geometrical modelling of redirecting materials :

- **small structure:** If the material consist of small structured elements, the backward raytracing is unable to find light sources with small opening angles like the sun. That means, the rays are followed through the material, but they do not hit the sun. Therefore the energy flux through that material is underestimated dramatically.
- **scattering and multi-scattering:** Most of the known materials reflect the light not completely direct, they scatter more or less the incoming light. In some case multiple scattering properties are given - which makes it quit impossible to describe the whole system correctly.
- **manufacturing tolerances:** In many cases we know the different layers of the material and know theoretically the light transmittance through the element. But in reality, all layers are produced with a more or less certain precision. Adding several layers leads then to unpredictable optical behaviour.

For the described limitations, RADIANCE offers another type of modelling: The BRDF-models. The bi-directional-reflection-transmission-function (BRDF) describes the light distribution of the whole system for all incoming light directions. This function can be determined either by measurements or by numerical models.

4.7.2.1 Geometrical models

Wall, windows, doors, frames, furniture and blinds of the test facility have been modelled as geometrical model. That means, the geometric description of these models have been set up by using CAD-software (ARCHI-CAD 5.0). The material properties have been measured and converted into the RADIANCE format.

The blinds have been modelled by using the manufacturers drawings in combination with the genblinds-function of RADIANCE and reflectance measurements of the plain material. The lamellas are of 35 mm width, slightly curved (TYPE Luxaflex 6036) and beige-white with a hemispherical reflectivity of approximately 75 % (RGB values: $r=0.715$ $g=0.803$ $b=0.746$)

All opaque material have been modelled as lambertian diffusor. The glazing is an ordinary glazing with a visible transmission of $\tau_{vis} = 0.7$.

A visualisation of the test facility's computer model is given in the following illustration (July 14, 8:27, south orientation, mainly diffuse sky, 166 W/m^2 visible horizontal diffuse irradiation; horizontal venetian blinds):

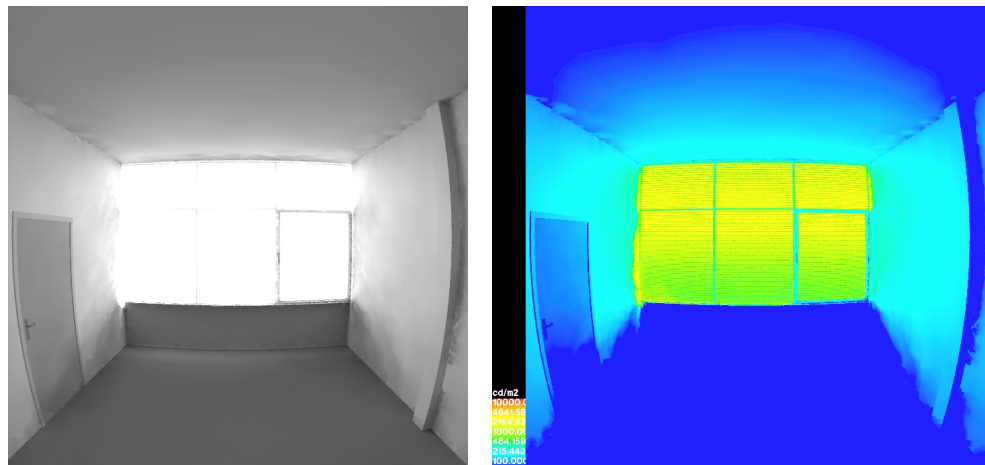


Figure 4.7.1 & 4.7.2: Visualisation and luminance distribution for the Freiburg test facility: Blind system, horizontal tilted

4.7.2.2 BRTF - models

So far, we have described how to model a standard window or opaque materials in RADIANCE. The capabilities of RADIANCE however, extend beyond the simple materials, and allow the user to specify a complex scattering material. By this we subsume both translucent materials (Aerogels, white diffusing glass etc.) and light-redirecting materials (refracting or reflecting materials). For both types the scattering is described by the bidirectional-reflection-transmission-function (BRTF), which has to be known for the specific material. It is either measured by a gonio-photometer or numerically calculated by raytracing. For

most material types both methods have been used to cross-check between measurement and physical model for the material. The implementation in RADIANCE differs for the two material types:

Diffusely scattering materials are modelled without much trouble, since they are effectively a (more or less) diffusely emitting light source on the inner layer of the window. Their emittance changes with outdoor conditions (e.g. sun-position and luminance, shading etc.), which is fully taken care of in the inner workings of RADIANCE. The user specifies the BRTF as a term of standard functions (e.g. sin, cos, gaussian) and step functions (e.g. if). The best combination is the smallest set of functions modelling the key characteristics of the BRTF, which is usually very close to the physical model of the light transport inside the material. An ideal diffus scattering material is characterised by a constant BRTF, but this is rarely found in real materials.

Light redirecting materials show a BRTF, which is considerable non-diffus: The redirecting of light correlates with a strong peak in the BRTF. An ideal mirror would be modelled by a delta-function (infinitely small and high peak). However, any existing window materials used for redirecting light are not ideal, since they either use curved mirror elements or the surface of the elements scatters to some extent. They are characterized by a localized, highly peaked BRTF function. Measuring and modelling of such functions is considerably more complicated than for the above mentioned diffusely scattering materials.

The Lumitop material exhibits an extraordinary scattering behaviour, which is not possible to model with any existing, standard BRTF models. For this material, a specially adapted mathematical model was developed. It is directly based upon the measured BRTF, which, due to the refined angular resolution of the available data, was precise enough to include a great amount of detail. The mathematical model smoothes the detail, as far as it is not important for the daylight simulation. This incorporates both the averaging of the BRTF for a non-infinitesimal window and the extent of the sun source solar disc.

The Lumitop material was designed to redirect light towards the ceiling, regardless of its incident direction on to the outside surface of the material. We present the BRTF in the following three visualisations of the measured data: The outgoing hemisphere is projected on a flat circle, which is a standard way of plotting angular dependant data. For normal incidence (lumitop:0+0), light is in fact redirected towards a direction, which for a standard mounted window correlates with the ceiling of the room. For an incident direction of 30 degrees (which, for a south facing window, would correlate with a sun azimuth of 150 degrees, 0 deg altitude) the redirected peak shows a skew (note the asymmetrical peak). For 45 degrees a large portion of the light is still redirected, but a second peak appears.

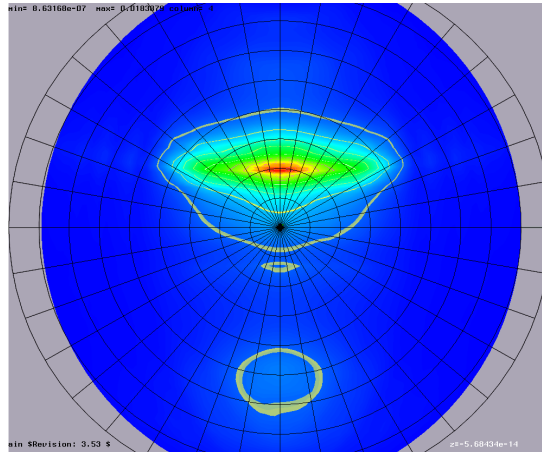
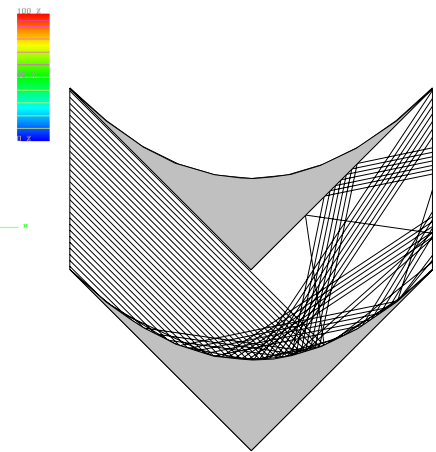
Figure 4.7.3: Measured BRTF for an incident direction of 0° 

Figure 4.7.4: External forward raytracing through FISH element

Many bi-directional measurements of the different systems were carried out. With that data computer models have been created. This was done by fitting 3-dimensional functions onto the measured data. Because the innovative systems have a strongly varying behaviour for different light incidents, the functions have to fit for all possible light incidents.

But it came out, that the simulation program RADIANCE has basic restrictions. Up to now it is not possible to simulate diffuse scattering materials like LUMITOP in combination with diffuse light sources like the sky. Because the diffuse part of the daylight is extremely important for the light distribution in the room, no model validation for diffuse scattering materials is possible with the latest version of RADIANCE. Therefore we had to skip the validation of models for the LUMITOP and Y-glass system at this point. An extension of the RADIANCE program to the diffuse sky for BRTF-Materials is necessary and planned.

For systems having one symmetry axis in the horizontal, a new way of modelling of special elements were developed to have at least this group of materials inside this project. This works basically for the FISH System. The idea is to model the systems externally and to perform a forward raytracing through that element. This raytracing is done in one degree steps and for all possible incident directions - vertical to the element surface. This is restricted to elements, which have one symmetry axis in the horizontal. The results of these external raytracing procedures are coupled with the actual sky distribution. The result is a luminance distribution for the daylighting element which includes the part coming from the diffuse sky. This luminant element is placed afterwards into the RADIANCE simulation environment.

4.7.3 Validation of the models

In this chapter, measurements in the test rooms are directly compared to the simulation results. For the validation of the daylighting elements, which are normally used only in the upper part of the window, in the first step all other parts of the window were covered during measurements to minimise influence from other light sources. With that knowledge, the models have been adapted.

The Comparisons using the same rendering parameters and the full facade models are presented for following representative facade and sky configurations:

	Facade type	Orientation/ Sun Position	Sky Type
A	Simple window	South	Overcast
B	Venetian blinds, closed	20°	Clear
C	Venetian blinds, closed	43°	Clear
D	Lowered ceiling (2.175 m)	North	Overcast bright
E	Lowered ceiling (2.175 m)	West	Overcast
F	Sloped ceiling	North	Overcast bright
G	Sloped ceiling	West	Overcast bright
H	Fish system	20°	Clear

Table 4.7.1: Extract of the validation simulations

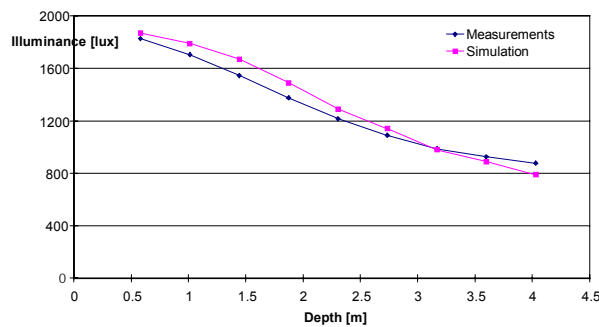


Figure 4.7.5: C: Venetian blinds closed, clear sky, 43° sun position

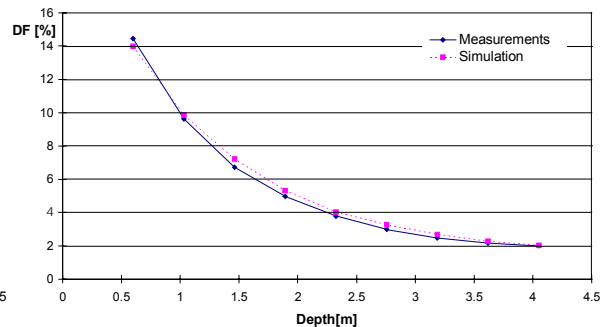


Figure 4.7.6: D: Lowered ceiling, north, overcast sky

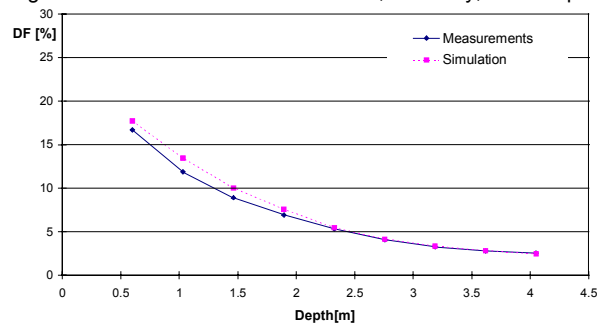


Figure 4.7.7: F: Sloped ceiling, north orientation, overcast sky

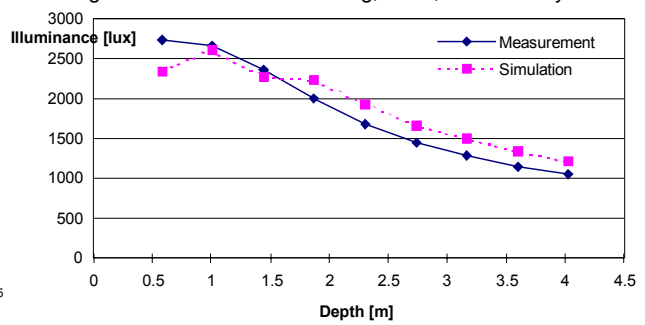


Figure 4.7.8: H: Fish system in upper window, overcast sky

All above diagrams show good accordance between measurement and simulation. This means, these models are validated and can be used for the energy prediction and the virtual reality assessments.

4.7.4 Visualisation of the models

As described, RADIANCE also offers to present the results as visualisations. In the following figures are shown representative visualisations from the Freiburg test facility and the Eindhoven test offices.

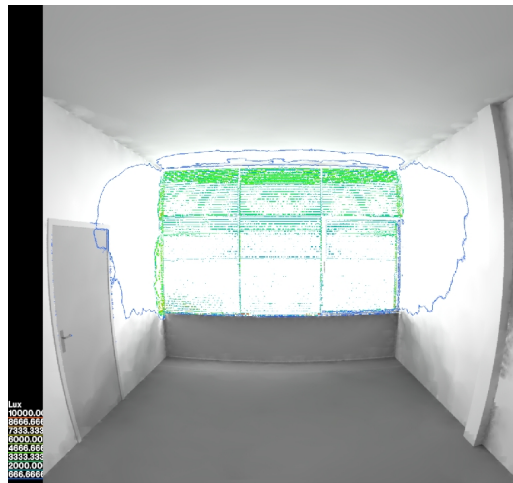


Figure 4.7.9: Illuminance distribution for the Freiburg test facility: Blind system, horizontal tilted



Figure 4.7.10: Top view with illuminance distribution during day (only daylight: overcast sky) for the Eindhoven test offices

4.8 Scaled model investigations (Task 10)

4.8.1 Introduction

This chapter describes scale model measurements performed for the EULISP project. In this project a number of ways to evaluate daylight conditions are compared. One of these evaluation methods is scale model testing under an artificial sky. Other methods include full scale office rooms, computer simulation with the Radiance models and Static Virtual Reality.

The scale model measurements described here are given for the two variants of Eulisp test rooms in Eindhoven (in the following called the Philips-model) and the test room in Freiburg (in the following called the ISE-model).

The measurements have been performed in two laboratories, at Bartenbach Lichtlabor (BLL) in Aldrans (Austria) and at the TNO-TUE Centre for Building Research (CBO TNO-TUE) in Eindhoven (the Netherlands) using two types of artificial skies both having the luminance distribution of the CIE overcast sky. These measurements are meant to compare the results between the laboratories and to compare with simulations and measurements in the full scale rooms under a real sky.

4.8.2 Experiments

4.8.2.1 The artificial sky at CBO TNO-TUE

A number of the tests are performed under the artificial sky of the TNO- TUE Centre for Building Research in Eindhoven, the Netherlands. This artificial sky is a so called Mirror Box which simulates a CIE overcast sky. Due to the 140 dimmable 50 W fluorescent lamps levels up to 15.000 lux can be achieved under this sky. This enables detailed research on complex daylight systems where often (such as in atria) a large fraction of the incoming daylight is lost. High levels are then required when reliable measurements have to be made. The temperature of the lamps and ballasts used in the mechanically ventilated ceiling of the artificial sky stabilises after about half an hour. This means that after this half hour period the light output of the sky is very stable. In this experiments fluctuations where within 0.3% shows the measured luminance distribution of the artificial sky. This has been done using a Sky Luminance Scanner which measures the sky dome in 2227 points. The measurements show that the luminance distribution agrees very well with the luminance distribution of the (theoretical) CIE overcast sky.

4.8.2.2 The artificial sky at BLL

The artificial sky consists of 393 luminaires mounted on a half sphere. The luminaires can be controlled in groups of 4-8 depending on the elevation angle.

They are equipped with dimmable 230V tungsten halogen lamps with diffuse glass.

The illuminance distribution used for the measurements is CIE overcast sky. The daylight factor is measured with a row of PC-controlled photometer heads (DIN 5032 class B) inside and outside the model. One photometer is mounted on top of the model and nine photometer heads are placed inside the model 8.5 cm above the floor (= 85 cm), in a distance of 5 cm. The value of vertical illuminance on the rear wall is taken in a height of 12 cm (= 1.2 m).

In the artificial sky at BLL the sun is simulated with a parabolic shaped reflector with a diameter of about 1 meter. This reflector is equipped with a tungsten halogen lamp of 1000 W. With this configuration it is possible to have a quite good parallel beam of the sun but it is not possible to reach the original illumination level.

4.8.2.3 The scale model used at CBO TNO-TUE.

The standard full scale room is a normal office room of 3.6 x 5.4 x 2.8 meters (W x D x H) as it used at Philips lighting in Eindhoven. The second version is a room of the same dimensions but with a sloping ceiling in the first quart of the room. The facade is 4 meters high. From the facade the ceiling slopes with towards normal ceiling height of 2.8 meters at a distance of 1.3 meters from the facade.

The scale model is a one to ten copy of these rooms in Eindhoven having the same reflection factors as the original one. The model has interior dimensions of 36 x 54 x 27 centimetres. Prior to the scale model work these factors were measured. A sample of the original carpet is used in the scale model to have the same reflection factors. The walls have a (rather high) reflection factor of around 80 %. The ceiling has a reflection of 90 %.

The scale model has been used unfurnished and with a single layer of clear floatglass. The effect of the clear double glazing is mainly an 9 % lower daylight factor in both cases.

To create realistic for the site of the real test rooms (see report on simulations for photographs, site plan and other details) the measurements are done with a simulated obstruction of 2 meters high, parallel to the facade and 5 meters out of the facade. The measurements have been done with and without a light redirection device provided by BLL.

4.8.2.4 Data of the 1:10 scale model at BLL.

Scale model measurements are taken in two different models. A smaller one with a flat ceiling is a copy of the ISE test room in Freiburg and a bigger one

with sloped or flat ceiling a copy of the Philips test rooms. The Philips room was additionally equipped with a construction simulating the influence of the ground and the building in front of the facade.

Reflection factors inside the models (floor / walls / ceiling): 0.1 / 0.85 / 0.85

Reflection factor of ground and obstacle in front of the facade: 0.20

The window consists of single glazing with approximately 9% window frames.

4.8.2.5 Black and white (b&w) model

Along with the measurements performed by TNO and BLL comparisons were carried out between the different results. As some of the measurements showed rather high differences, it was decided to build another model which should be tested in both institutes. The model was constructed in a way that it was easy to transport and also to change the reflectance of the surfaces between white and black. There were no furniture and also no framing of the window simulated. The model was equipped with a single pane glazing. No other daylighting systems were checked with this model. The task was just to make sure, that the identical model gives the same results in the two different skys.

4.8.2.6 Comparison of the Measurements

Most of the measurements for the Philips-model and the Black and white model were carried out by two institutes. The following section compares the corresponding results.

a) Measurements for the Philips model

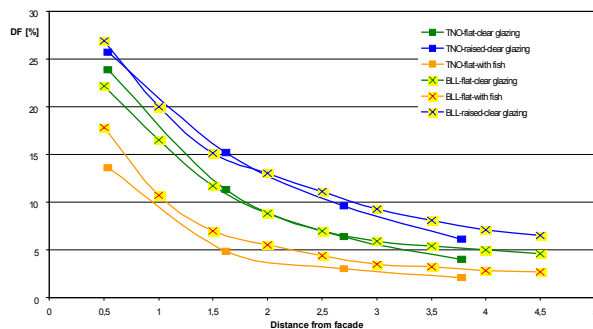


Figure 4.11: Comparison of the results for the Philips model

b) Measurements for the b&w model

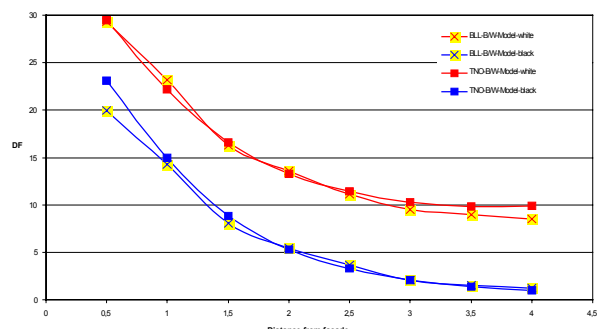


Figure 4.12: Comparison for black and white model

4.8.2.7 Discussion of the results

The test with the black and white model shows a very good correspondence of the results. This is a very important result, due to the very different concept of the two artificial skies which were used in this measurements.

There are a surprisingly high difference for the first measurement point with the black model. Having the other results in mind this is probably a fault reading during measurement. There is another much smaller difference in the depth of the room with the white surfaces. One of the possible explanations for this effect is a slightly higher reflective ground in front of the TNO model. Also interesting is, that a similar difference can be found in the comparison between the measured and the calculated results. As the black and white model test showed a very good correspondence the different results for the Philips room can not be caused from the different sky types.

For the two measurements without systems, there are higher results in the depth of the room from BLL. As the results in the centre of the room and also close to the facade correspond much better it can be assumed that there are differences in the reflectance values of the surfaces.

The over all difference for the measurement with the Fish system is higher compared to them without systems. If we assume a difference in the reflectance values between the two models this can be expected. The Fish systems redirects the whole daylight to the ceiling and so it is distributed by reflections on ceiling and walls.

The overall differences are within a range of +/- 10% without systems and within +/- 15% with systems. Local differences can be found up to 25%.

4.8.3 Conclusions of the scale model investigations

The results of the measurements of BLL and CBO TNO-TUE are slightly different. As in experimental practice a number of causes for these slight differences can be found. The main sources are:

- reflection factors of the walls and ceilings differ lightly
- simulation of window framing
- reflection factor of ground and obstacle
- precision of luminance distribution of the artificial sky
- precision of photometers
- positioning of photometers

From the comparisons to the simulations with Radiance and the results of the black and white model the differences in the models itself seems to play the most important role. Especially light redirecting systems seem to be more sensitive to the finish of the model.

4.9 Determination of the energy saving potential (Task 12)

4.9.1 Introduction

For the determination of the energy consumption of a building, normally a dynamic simulation of the thermal behaviour for a one year period is necessary.

Dynamic means that the values of the variables describing the actual state of the building are dependent on the values of former states. Several building simulation programs are available for this task. Most of them calculate the total energy demand for a given building or room taking into account the energy for heating, cooling and artificial lighting. As input these programs need the building geometry, weather data and user behaviour.

But most of these thermal simulation programs are not able to simulate the influence of complex light redirecting elements for the daylight situation inside the building. This has to be calculated by a separate daylight simulation program. But the daylight situation inside the office shows an impact on the energy demand, due to interaction of artificial lighting or shading devices with the illuminance level inside. That means the electric energy required for artificial lighting and thus the internal thermal loads depend closely on the results of a daylighting simulation.

Therefore a combined dynamic thermal and light simulation is necessary to determine the influence of daylighting elements or shading control strategies for the total building energy demand.

Two different approaches for this task have been used in this project. First a feed-back coupled combination of the thermal simulation program TRNSYS and the lighting simulation program RADIANCE for entire year simulations. Second a direct coupled combination of the ESP-r simulation program with RADIANCE for a closer look how artificial lighting can be influenced by daylight depending on different lighting strategies.

4.9.2 Feed-back coupled dynamic thermal and light simulation using TRNSYS and RADIANCE

4.9.2.1 Classifying the irradiation data

The basic idea to reduce the number of necessary RADIANCE simulations is to classify similar sky luminance distribution functions. A criteria for the quality of the classification is the standard deviation of the calculated global irradiance with respect to measured values. For example, dividing the direct irradiation in 6, the diffuse irradiation in 3 classes and the sun's Zenith angle in 35 classes will reduce the number of needed RADIANCE runs to a maximum of $6 \times 3 \times 35 = 630$. In practice, the number will even be much lower, because not all combinations exist in reality (e.g. almost no diffuse light for very low Zenith angles will never happen for some locations). So the actual number depends on the climate data used for the simulation. For the GERMAN TEST REFERENCE YEAR Freiburg (GTRY 7) only 355 of the 630 possible combinations are realised, with a standard deviation of 36 W/m^2 in global irradiance only. This results in a reduction for the simulation time of almost an factor 7 compared to all 2400 office hours. After having done these 355 daylighting simulations you have do

distribute the results to the corresponding 8760 hours of the year. A computer program was developed at ISE to do this classification for a given data set and reorganising the RADIANCE results for the TRNSYS simulation.

With this pre-work done you can do combined thermal and daylighting simulation for a whole year period.

4.9.2.2 Feed-back coupled simulation

Feed back- coupled simulation means that the results of the thermal simulation may influence the daylight simulation and vice versa. TRNSYS and RADIANCE do not work together directly, but the output of one program is used as an input for the other. For example imagine a control strategy for the thermal simulation program which closes blinds for heat protection if the room's temperature exceeds 26°C or close them only for glare protection if the direct solar irradiation on the window exceeds 150 W/m². On an intermediate day at a certain hour TRNSYS decides to leave the blinds open. This information is passed to RADIANCE which will perform the raytracing simulation without blinds in front of the window. The calculated illuminance value for the wanted sensor position (e.g. the desk) is given back to TRNSYS to decide whether artificial light is necessary or not (with a dimmed system: how much light), what will affect the thermal status of the room. This may result in a different blind position, making a second RADIANCE run with closed blinds necessary.

Therefore an iteration loop is performed. That means, if TRNSYS is started for the first time, it stores all the information about the 'first guess' blinds position in a file, which is read by a program that invokes automatically all the needed RADIANCE simulations (depending on sky class and blind position). The resultant illuminance values are used as input for the next TRNSYS run, which may cause other blind positions and therefore new RADIANCE simulations. This is done until no more changes in the blinds positions occur. Then TRNSYS is called for the last time, having all information about the lighting situation and giving now correct values for the buildings energy demand.

4.9.2.3 Simulated examples of daylighting elements

Combined simulations have been carried out for the following systems:

- for a very common inner blind system, measured, modelled and validated for this report
- for the FISH system, without textile sun protection
- for a combination of these two systems, FISH system in the upper part of the window, blinds in the lower
- reference-case, only double glazing

The office is just a typical two person office: 3.65 m wide, 5 m deep, two big windows, two small windows above (for a different daylighting system). It is orientated south and there are no obstructions outside. All other walls are connected to similar office 'cells'. There are two persons in from 8 h to 18 h, 5 days a week, using two standard computers. Heating and cooling setpoints are 20°C and 26°C (from 22 h to 6 h only 16°C for heating). The location used is Freiburg, 48° North, 7.25° East. The corresponding weather data used is the GERMAN TEST REFERENCE YEAR Freiburg (GTRY 7). The office is well insulated and the windows are double glazings.

For the RADIANCE model, the following material properties were used: ceiling 70 % reflectance, walls 50 %, floor 20 %, desk 30 %. The window has transmission of 75 %.

4.9.2.4 Shading setpoints and lighting control

For the blind system, three different positions are possible : up, that means no shading at all, medium for glare protection, realised with horizontal lamellas and closed for heat protection.

For the FISH system, which was used here as an example without the textile sun shading, there is of course only one position, so no decision has to be made from TRNSYS.

The blinds are activated in the following cases: the direct irradiation exceeds 150 W/m² in window plane: this will cause the horizontal position for glare protection. If the room temperature exceeds 26°C the blinds are closed totally for heat protection. Of course are these positions not compulsory, intermediate positions are possible in reality, but this is a necessary compromise between accuracy and computing time.

For the whole year simulations, the lighting strategy used for this examples is fairly easy: the light is not dimmed, it is only switched on or off the whole room, depending on the lighting level on the desk. Illuminance values on the desk (85cm high) below 500 Lux causes the lights to be switched on.

4.9.2.5 Results

For this simple example, the differences very small. Only for the cases with a controlled blind system, the amount of needed heating energy is a little bit higher. In that case, the blinds were closed for glare protection, but heating is needed in this hour. This effect compensates partly the energy savings during the summer, which you can see at the total energy demand for the whole year.

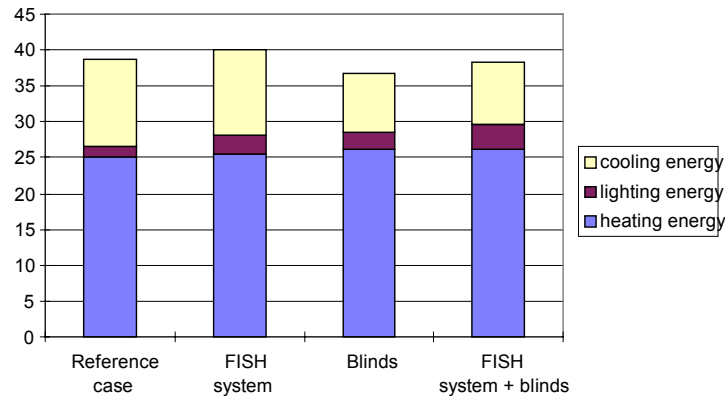


Figure 4.13: Total energy demand for the different systems

The results of the electric power needed for artificial lighting are discussed in the next section, where we have a closer look at some days focusing on artificial lighting.

The higher amount of needed energy for the FISH-system has its reason in the lack of shading in the summer months, but consider it was modelled without the movable textile shading device, which is normally installed for that reason. With this exterior shading the savings in the cooling energy would be higher.

Due to the compensation between winter and summer energy balances and the poor lighting strategy (only on or off), the differences for the whole year energy balance are not very big. But for better lighting strategies the saving potential can be much higher, as we will see in the next section.

4.9.3 Combined simulations using ESP-r and RADIANCE

The objective of this work is to investigate the feasibility of a combined simulation of thermal behaviour and lighting conditions of a building. Daylight responsive control of lighting will reduce the internal heat gain at hours with the highest cooling loads (summer). This can lead to a reduction of the needed cooling capacities. The simulations are aimed to determine whether this type of effect exists and is significant in magnitude.

4.9.3.1 Program description

An interface between RADIANCE and ESP-r has been developed by Milan Janek in Glasgow (Scotland). The main part of it is a script that is called from the thermal simulation program ESP-r for each timestep. Then a RADIANCE scene is built including a sky luminance description based on the climatic data supplied by ESP-r. This luminance distribution function is generated using the Perez sky model. That means, in opposite of the TRNSYS-RADIANCE coupling,

ESP-r waits at each timestep for the RADIANCE results, so only one run of the thermal simulation is needed.

The Radiance calculation is essentially for the determination of the sensor signal for the sensor installed in the room that is used to control the artificial lighting. In this test a ceiling mounted sensor is assumed with a geometry matching the TRIOS sensor which was installed in the real test rooms. Based on this sensor signal two control strategies, on/off switching and an integral-reset (TRIOS) system are compared with a system without controls (permanently on).

4.9.3.2 Results

This direct coupled simulation was carried out for some days in 5 minute steps, with focus on the electric lighting demand. Figure 4.14 shows that an intelligent lighting strategy can save a big amount of electric energy and in summer avoid cooling loads too. The integral-reset strategy needs significant less energy than the on/off control.

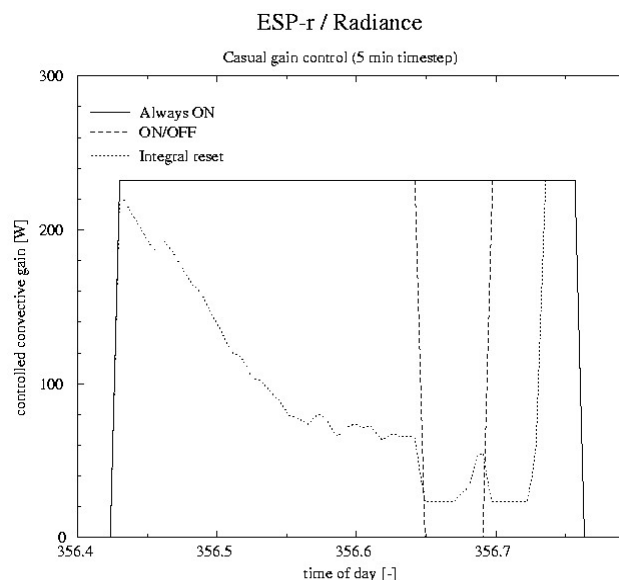


Figure 4.14 The electric energy needed for lighting on a mostly cloudy winter day for different lighting control strategies

Because it was a mostly cloudy day the on/off control switched the light off for only one hour. In this hour, the integral-reset strategy leads to a small amount of energy more than the on/off switch, but for the rest of the day it needs less energy, because it adds only the light which is needed to reach a certain illuminance level.

This kind of combined thermal and daylighting simulation (ESP_r/RADIANCE) is very convenient to examine the impact of different electric lighting strategies, but can be very time consuming, especially if

complicated daylighting systems are installed to. Therefore it is necessary for each problem to decide which simulation method is suited the best.

4.9.4 Conclusions

The most important conclusion is that it is difficult to say, system A performs better than system B, because the impact of a daylighting system on the energy balance of a building depends on many factors:

- geographical and climatical position of the building
- the orientation of the rooms
- obstructions through buildings or trees nearby
- design of the room (especially the room depth)
- rooms usage: target value of the illuminance that is needed (e.g. office or floor)
- rooms usage : occupancy hours (e.g. office hours or half day school)
- whole year energy efficiency or seasonal accents (hotel, summer school)
- mainly energy aspects or emphasis on visual comfort

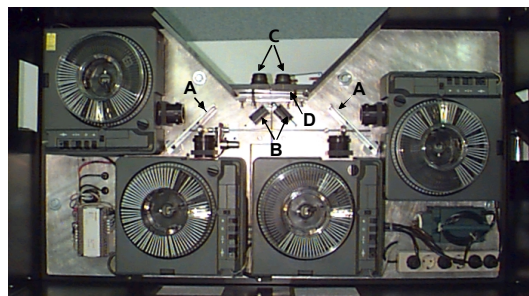
That means, that it is only possible to decide for a certain, well defined problem which system is the most suitable by doing a detailed energy simulation. Depending on the problem one of the two above mentioned combined simulation methods has to be chosen for that task.

4.10 Set up static virtual reality (SVR) (Task 13)

4.10.1 General description of SVR

The SVR (Static Virtual Reality) is an apparatus for high resolution stereo projection to create realistic impressions of simulated scenes. The idea is to project the results of the daylighting simulation as realistic as possible to the subject. That means, that the simulated luminances should correspond to the occurring luminances in the projection. It is clear, that there exists a physical limit of the maximum luminances being reproducible. But the slide-projection is the reproduction method with the highest possible contrast available for a reasonable price.

The projection should also cover the whole view area of human's eyes. For that reason the scenes are projected as close as possible to the eyes of the subject. The subject has to look through oculars on the "screen". As can be seen in the following picture, four slide projectors are used. These four are necessary to have a smooth transition from one scene to the next without having a black screen for a short time. And it is also very important for the eye adaptation and being comparable to have this smooth transition. This smooth change of scenes has been realised by two mechanically moving mirrors, which flips between two slide projectors.



A: Moving mirror
B: Fixed mirror

C: Ocular lenses
D: Projection foil

Figure 4.15: Top view of the SVR: Four projectors create a virtual reality on the screen, which can be watched through ocular lenses

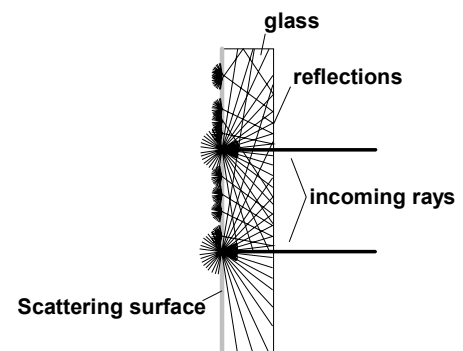


Figure 4.16: Multiple scattering of glass due to internal reflections: unsharpness

4.10.2 Projection Screen

The first task of the set up was to find a suitable screen material for the SVR. The wished "ideal" properties are:

- high transmission for getting high luminance values
- lambertian diffusor for a homogeneous bright screen
- thin material for getting a sharp picture

After testing lots of different glass types (milk glass, fritted glass, painted) it was clear, that the thickness of the screen is important for the sharpness. In the following figure is shown what happens, if a "thick" material as glass (e.g. 3mm) is used: On the scattering surface, several rays are scattered backwards. These ray will be reflected on the other, transparent side, too. This procedure happens several times so that one ray will be splitted into lots of rays and this leads to an unsharp picture. One solution is to use a thin, scattering foil out of plastic.

The used foil is very thin ($< 0.1\text{mm}$) and scatters good. The hemispherical transmission of it is about 45%. The maximum luminance value reachable is 9000 cd/m^2 (without any slide).

Due to the fact, that the light is not parallel, the screen is not homogeneously lighted. That means in the center the screen is brighter that at the edge. The difference in brightness from center to the edge is about 35% and too high for ignoring. Therefore test measurements have been performed to get a function for this behaviour. This function is now taken into account at the exposing process from the rendered picture to the slide.

4.10.3 Film material

The next step was to take the behaviour of the film material into account. To understand from what kind its behaviour is, the principle of a slide projection has to be explained. The slide projection is a subtractive projection method. That means for generating a specific colour, several bands of wavelengths have to be filtered out of the incoming light. For example to get a red picture, the green and blue colour have to be filtered out. To filter out a colour means to absorb or reflect respective wavelengths. But this does not mean, that all of (in this case) the red light is going through the slide. There is also an amount of (in this case) red light being absorbed. And last but not least the amount of red light is not only influenced by the "red particles" in the film material. But also the green and blue particles influence the amount of red light going through a slide. To characterise the exact behaviour of the film material (all known films have a slightly same behaviour) hundreds of slides have been exposed. For exposing slides directly from files, the ISE has a Matrix QCR-z camera. All types of 8 bit rgb-colour-pictures can be exposed with that camera directly from a file. For the test procedure, uniform pictures with definite rgb-values have been created. This have been done for the basic colours (red, green, blue), their complementary colours (cyan, yellow, magenta) and for white (red=green=blue). This set of 7 colours have been created in 16 steps from 0 to 255 for the rgb-value. These slides have been inserted into the SVR and the respective luminances have been measured. Studying these curves two main problems can be determined:

1. The Addition of the red green and blue luminances does not correspond to the white value. (Reason: Subtractive projection).
2. Exposing the film with the basic colours leads to a saturation using rgb-values greater than 200. This does not occur for the yellow and white colour. This means using the normal exposing method, the whole possible brightness range cannot be used.

Solving the second problems leads to multiple exposing of the slides and using a better film material (KODAK EPN 100 professional), which has the triple prize of normal slide films.

4.10.4 Generation of definite luminances

4.10.4.1 Calibration the slide exposing look up table (LUT)

This procedure uses the normal ra_tiff colour mapping.

For that reason an optimum combination of exposure and gamma value for the filtering was looked for in the first step. Thousands of program calls were performed to find a combination, which changes quickly in the lower luminance ranges and slowly in the higher ones. Because of the maximum restriction of the slide projectors of 10000 cd/m², this working range is in-between 0-10000 cd/m². Decisive for choice of the combination of exp=-6, gamma=4.8 was, that there is a great change in the output value (RGB-value) in the most important lower ranges (up to 500 cd/m²).

In a second step, the properties of the film material and the projection way had to be considered. For that reason, hundreds of slides, exposed with definite 12-bit RGB-values, had been measured. Finally, we calculated look up tables (LUT) for the different projector types(see Figure 4.17).

Using this calibration, we measured a display accuracy of about 15%.

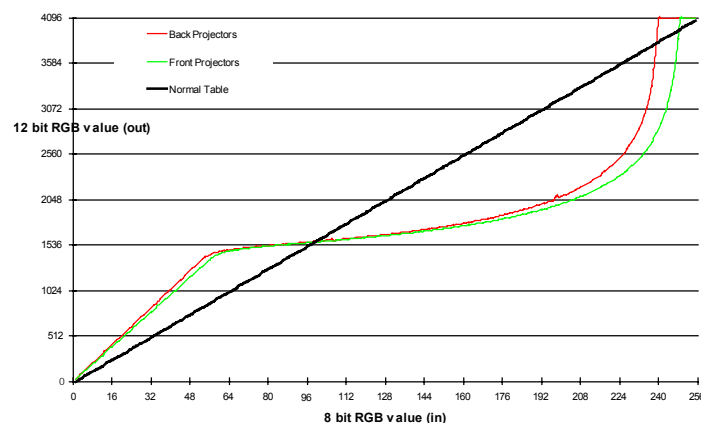


Figure 4.17: Exposure look up tables (LUT) of the different projectors for the qcr-slide exposing machine

4.11 User assessments in SVR environments (Task 14)

4.11.1 Questionnaire

The questionnaire has been developed for the Stationary Virtual Reality (SVR) as a tool to check the acceptance of new daylight systems economically and in a short time. Of course, such a complex quantity as acceptance is not easy to assess. It turned out to be helpful to differentiate between short-term and long-term acceptance; short-term acceptance is based on a first impression of the lighting conditions, long-term acceptance is based on experience with working under such lighting conditions. Due to the short remaining project time, we decided to concentrate on the short-term acceptance.

The questionnaire is designed by using a psychological-methodical construction procedure. For this procedure a large pool of items has been selected which will be tested on about thirty subjects to find out the best items (The questions are asked in the SVR situation and in identical "real" offices in a sophisticated order and frequency). This pool of items includes:

- Personal aspects like age, kind of glasses, kind of daily work
- General preference for workplace lighting conditions
- Lighting conditions of the entire room
- Need for changing the lighting conditions
- Occurrence and degree of glare
- Special lighting conditions at the workplace
- Emotional attitude to the room
- View to the outside

To find out, which questions or sum of questions (=factor) can show significant results for the different lighting situations, investigations in real offices have been performed. The layout was the same used in the SVR. About five factors showed significant results, so that they were used for the further investigations.

Most of the questions have a rating from 1-6, which is mainly based on the known German school judging system. For the factors, the answers for the different questions were added and normalized again to the 1-6 scale.

4.11.2 View points

During preliminary questioning, it became evident that test persons need more different views than one to gain an overall impression of the lighting condi-

ons in a room. This is especially important for measuring the effects of daylight which can illuminate a room rather unevenly. The choice of the "right" view points was additionally influenced by the viewing tasks, which typically occur. For the office work three main tasks were determined:

Three-dimensional detecting -> "Room View"

Reading from papers at the desk -> "Table View"

Reading and working at a computer -> "Screen View"

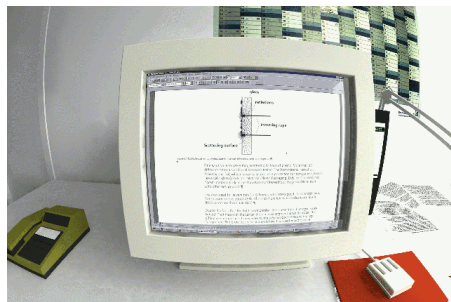


Figure 4.18: Screen view

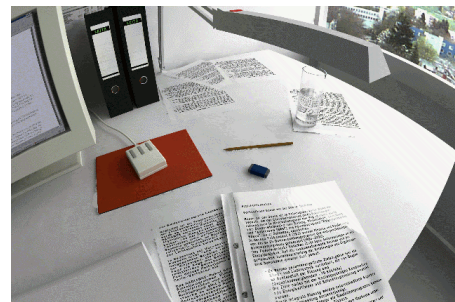


Figure 4.19: Table view



Figure 4.20: Room view 1

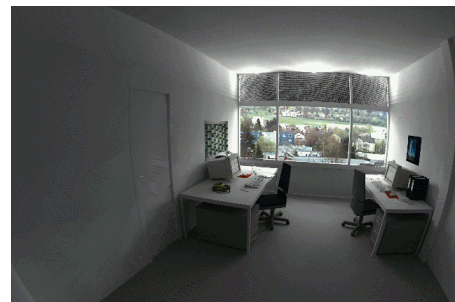


Figure 4.21: Room view 2

These four view points have to be calculated for each eye, i.e. for each light situation we need to simulate eight pictures.

4.11.3 Investigated Lighting situations

To cover the most significant lighting situations, we need to have at least five lighting configurations per system:

1. Overcast bright
2. Overcast dark
3. Clear sky with direct component in room, with blinds in the lower part
4. Clear sky with direct component in room, no blinds in the lower part
5. Clear sky without direct component in room, with blinds in the lower part

For that reason we have to calculate at least 48 pictures for one system. In average it took one full day per picture on 50 workstations in parallel. That means

in total we need 50000h computation time for one system. Each picture has a size of about 44 MB, i.e. in total we need about 5 GB disk storage space.

Therefore we decided to choose only one system to check and develop the test procedure. We chose the Fish system, because it is additionally installed at BLL.

4.11.4 Test persons

In the real rooms, we had to ask 150 persons to get enough information to create the questionnaire. The tests took about 45 min, therefore we had to advertise people. Most of them have experience in office work, so that the results are reliable. For the SVR a smaller amount of persons were sufficient (55). This is because one person could judge about all different lighting situations - in the real rooms of course, only one lighting situation could be judged per person.

4.11.5 Assessments in real test rooms

There were two main reasons why this additional assessments had to be done:

1. The construction of the questionnaire had to be done under real lighting conditions
2. To get a database for the comparison between SVR and reality.

One of the basic results out of these assessments is, that the persons do not react like a gaussian normal function as they do e.g. making thermal assessments. E.g. if they are asked "Are you disturbed by glare" under bright lighting conditions with activated glare protection, there are two peaks in the results. One part of people are disturbed extremely, other not at all.

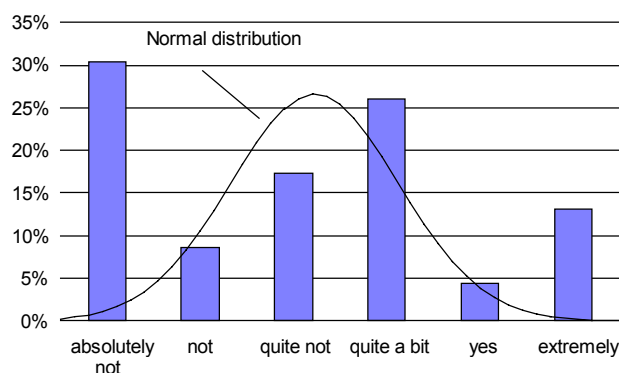


Figure 4.22: Hits for the question "Are you disturbed by glare" under sunny sky, glare protection activated

4.11.6 Assessments in SVR

The assessment in SVR took about 45 min. In the first section, the height of the chair and the eye distance were adapted to the individual. After that, a ge-

neral description of the procedure was examined. For the two main view areas - work place and work environment- a set of questions were asked and filled in the questionnaire by the operator. This has been done for all different lighting situations. The order of the lighting situation had been changed from person to person, so that a lot of different permutations occurred. Studying the results, it came out that always for the first lighting situation, the subject has no reference to judge in a right way. Therefore all answers for the first lighting situation had been removed for the results.

In following graph the main result of this task is shown. One can see, that for the factors "glare" and "brightness", the SVR prediction probability is extremely high. For the other factors, the probability is also very good, considering the answering spectrum from 1-6.

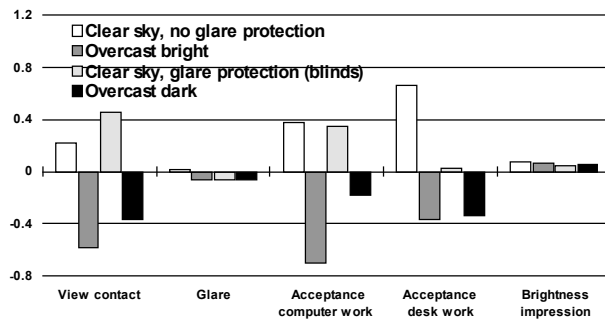


Figure 4.23: SVR prediction probability for the different factors (x-axis) and sky conditions

In addition, we asked all subjects after the SVR assessment to say something about the suitability of the SVR. This result is extremely positive. About 95% of the subjects answered, that this procedures is suitable for that kind of investigations (see following graph).

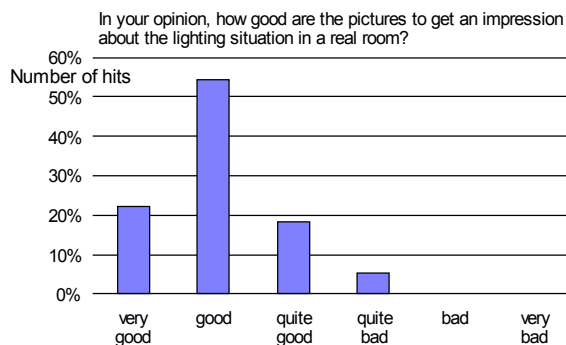


Figure 4.24: Subject's opinion of the suitability of the SVR

4.12 User assessments in real office spaces (Task 15)

4.12.1 Introduction

In the west-facing test office the Philips Luxsense and TRIOS lighting control systems have been tested. Luxsense is a luminaire-based system and TRIOS is a room-based system. With a luminaire based system each luminaire is equipped with a sensor that measures the luminance of the area under the luminaire. The light output of the lamps is regulated according to the luminance measured. With a room-based system there is one sensor mounted at the ceiling above the desk, looking downward. The light output of all the lamps is regulated according to the luminance measured at the working plane.

With both systems the user of the room could not adjust the electric lighting, only the daylight component by adjusting the venetian blinds. It turned out that it was necessary to allow the users to adjust the blinds, because when the sun shines into the office during the afternoon it is impossible to do any work without closing the blinds.

4.12.2 Experimental set-up

The office layout has been described in chapter "Real office installation". Although illuminances have been recorded at several positions in the room, in this report only the illuminance at the desk and the conference table are shown.

The subjects were asked to work several days in the office. The subjects were volunteers who brought their own work. They were instructed to fill in the questionnaire every half hour, but in some cases the subject forgot to do so, or had to leave the office for a meeting. Overruling of the control was not possible, only the blinds could be adjusted.

The sensors were tuned to 800 lx at the working plane for the Luxsense and 1200 lx for the TRIOS system. These were the lowest possible values with the lighting installation. There were 4 twin lamp 58 Watt luminaires installed.

4.12.3 Results

4.12.3.1 Luxsense

The experiment has been running during 14 days, with 3 different subjects (2 males, age 44 and 57 and 1 female, age 23). Of these 14 days 5 days had completely overcast skies, 2 had clear skies and on the remaining 7 days there was a mixture of blue sky and clouds (mixed).

User satisfaction Luxsense

The users were in general satisfied with the lighting and the control system. The illuminance at the desk and the lighting of the walls were always rated to be OK. When the sun hit the window, on clear and mixed days in the afternoon, the window was rated to be too bright, despite the venetian blinds. The rating of the total light distribution was in general OK, although it was mentioned that the back wall, where the door is situated, was too dark in relation to the rest of the room.

4.12.3.2TRIOS

The experiment with TRIOS has been running during 16 days, with 3 different subjects (2 males, age 44 and 54 and 1 female, age 23). Of these 16 days 6 days had completely overcast skies, 1 had clear skies and on the remaining 9 days there was a mixture of blue sky and clouds (mixed).

User satisfaction Trios

The same questionnaire as for the testing of Luxsense has been used. The users were in general satisfied with the lighting and the control system. When the sun hit the window, on clear and mixed days in the afternoon, the window was rated to be too bright. In the afternoon the desk illuminance and the wall illuminance (especially near the door) is rated as too low.

4.12.4 Discussion

One of the reasons that the users were so satisfied is probably the high illuminance in the room, especially on overcast days.

The fact that in the case of Luxsense the luminaires showed different brightnesses was mentioned by one of the subjects, but did not seem to bother him. The Trios system sometimes overestimates the amount of daylight, which results in a too low total level, which is rated too low by the users.

Due to the fact that the luminaire/lamp combination was slightly overdimensioned the energy savings are difficult to establish. The installation was never running at full power with the Luxsense and the different systems have been running at different set-points. Therefore no energy saving percentages can be given.

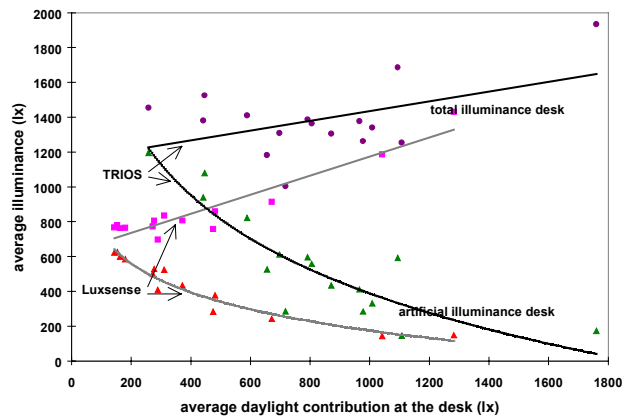


Figure 4.25: Average total illuminance and average artificial illuminance as a function of the daylight contribution

4.13 Parameter identification (Task 16)

The number of parameters having influence on the visual comfort is high. A reliable evaluation in a given time is complicated without useful restricting the parameters.

In this project we concentrated on investigations of office places. This is the most important sector for guaranteeing good lighting quality.

The most significant methodical restriction is the non-considering of short- and extreme short changes of the lighting situation. Moving of clouds, reflexes of moving objects like cars, moving of plants in the wind etc. are belonging to these short time changes. This restriction can be made, because for most of the working places the body posture and the view direction is quite constant and can be subdivided into few main view areas. Therefore the eye is in a constant adaptation state. Smooth moving objects have mostly a positive impact on the mood.

One has to differentiate carefully between measurable values and assessment criteria, which are assignable over one or more measurable values. On the other hand the criteria for fulfilling a certain view task have to be distinguished to those which concern rather the general well-being feeling.

The border criteria " minimum illuminance " and glare limitation represent the minimum requirement for a comfortable lighting. Illuminance is a measurable value, glare limitation is a criterion determinable from several measurable values and user reactions. A well comprehensible example shows that these criteria are not independent of other factors of influence: A wide vertical artificial light source has luminance values in the field of vision, which lead both objectively i.e. using the UGR formula (unified glare ratio), and subjectively to psy-

chological glare. If a equivalent large window with comparable lighting conditions with a breath-robbing view on a beautiful landscape, the subjective impression of the glare would be surely compensated partly by the circumstance of the beautiful view.

During the SVR-tests and the user assessments in real offices, a lot of dependent parameters for the lighting quality were determined. The most important with their dependency are shown in following table:

Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Task: Reading paper	x																
2 dito computer screen	0	x															
3 dito 3-dim recognising	0	0	x														
4 Illuminance level desk	+		+	x													
5 Illuminance level room	+		+		x												
6 Limitation of glare	+	+	+	-	-	x											
7 Direct reflection paper	+			-		+	x										
8 dito computer screen		+		-	-	+		x									
9 contrast of paper	+			+	+	+			x								
10 dito computer screen		+		-	-	+		+		x							
11 Avoiding eye fatigue	+	+	+	0	0	+	+	+	+	+	x						
12 Colour rendering	+		+									x					
13 View contact						-	-	-					x				
12 Communication												+	x				
13 Privacy														-	x		
14 Orientation													+			x	
15 Even light distribution			+														x

Table 4.13.1: Criteria to get good lighting conditions in offices and its mutual interactions.

+ Positive Interaction
0 Positive and negative interactions are possible
- Negative Interaction
x Same criterion

The listed parameters are not sorted by their significance - which is impossible to figure out for all. The individual always has a personal order of significance of the parameters. To create a mean order is in our opinion not valid, because the subjects do not react according a gaussian function.

Beside that restriction, it came out that two parameters are dominant. The domination is high, so that the other parameters are influenced although there is no physical connection in-between these parameters. This means e.g., if one is disturbed by reflections on the screen, the answers to glare on the paper are also negative although there is obviously no glare. These two main parameters (for office work) are:

1. View contact to outside
2. Reduction of reflection on screens

4.14 Standard test procedure (Task 11,17)

During the project it came out, that a diversification of "evaluation standard, test procedure and assessment prediction" is not a suitable way to evaluate a system. The structure of the procedure is mainly built by the costs of the tests. At the beginning there are simple and cheap (performance) tests to find out the rough behaviour of the system. After the market decision is positive, user assessments have to be performed. The reason is obvious: It makes no sense to make cost intensive evaluations of the physical performance of a system in detail, if there exist no user acceptance. Therefore the procedure considers all types of investigations, the order is according the cost of them.

4.14.1 Procedure

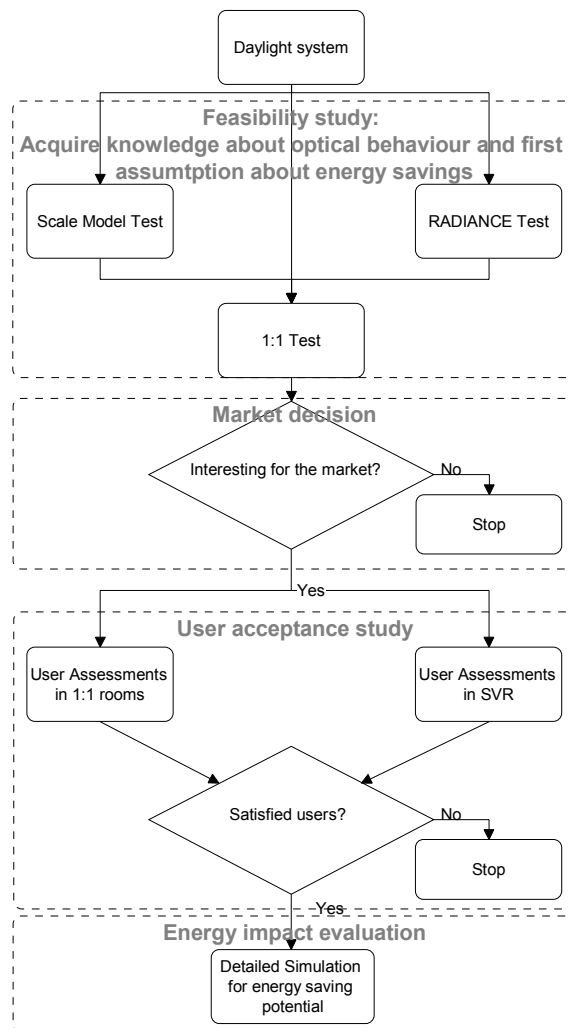


Figure 4.26: Standard test procedure for lighting systems

The procedure is divided into four parts:

In the **feasibility study** simple and cheap tests are performed to get an idea how the systems work. Having these results, a **market decision** has to be made. If the system shows promising properties, further studies are performed.

In the **user acceptance study** the system will be checked according to its daily usage and the user behaviour to it.

Finally, if all previous tests have positive results, the **overall energy impact** is determined. This procedure is in these days at the end of the procedure, because actually it needs most effort to do this study.

4.14.2 Feasibility study

To get a first impression, how the investigated system reacts, some simple tests have to be performed. The aim is to get illuminance and daylight factor distributions for a given reference room or model. These tests should be performed under overcast and clear sky. There are three suitable ways to get these data:

1. Scale model
2. 1:1 measurements
3. RADIANCE simulation provided with laboratory data

a) Scale-model or 1:1 measurements

The elements have to be measured either under real sky conditions in a 1:1 room or under artificial sky condition in a scale model. At least, following types of skies have to be investigated:

- Overcast sky (no rain, no clear sky parts): Before starting the real sky measurements, sky luminance measurements of the interesting sky part is necessary. At least 7 points have to be measured: $g=90^\circ$ (zenith), $g=45^\circ$ in 3 azimuth steps, $g=0^\circ$ (horizon) in 3 azimuth steps. The measurements should be within a range of $\pm 10\%$ of following equation (L_z is the zenith luminance):

$$L_\gamma = \frac{L_z \cdot (1 - 2 \sin \gamma)}{3}$$

- Clear sky: Under real sky condition the absence of clouds is absolutely necessary. The direct and diffuse part of the radiation should be monitored during the measurements. At least four different sun positions are needed:

Low sun position	Sun normal to facade
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Low sun position	45° to facade
High sun position	Sun normal to facade
High sun position	45° to facade

For validating a computer model, additional measurements are needed taking into account only the influence of the daylighting elements. In the ISE test facility we cover the lower window part completely.

b) RADIANCE test plus laboratory measurements

In principle, the same tests as described in a) have to be performed. The needed input data is depended on the system. At least the basic optical properties have to be measured. This means angle dependent transmission measurements. At least in 10° steps the measurements have to be performed. For special redirecting elements, additional bi-directional measurements are important to get a simulation model.

4.14.3 Market decision

Having the "simple performance data", a marked decision has to be made. All aspects should be taken into account. What is the improvement of the new system? Can a positive impact on energy consumption be assumed? Is there a marked chance with the foreseen system cost?

4.14.4 User acceptance study

At this stage, user assessments are necessary to find out if the system is accepted by the users or under which configuration they accept it. If different options of a system are possible, investigations with the SVR environment can show quickly which solution is the best. The results can be directly compared, because all subjects have the same boundary condition.

If no SVR is available, assessments in real rooms are necessary. Because of the higher effort, the number of investigated variants are limited.

4.14.5 Energy impact evaluation

Combined thermal and daylighting simulations are necessary to find out the energy impact of different strategies on heating, cooling and electricity. To get the minimum input data for the thermal simulation, an angle dependent g-value measurement and a u-value measurement have to be performed. A realistic user profile is important because of its huge impact on the results.

5 Results and conclusions

The market of daylighting systems is still growing, thus generating a need of evaluation and test procedures for the performance of the different systems. Two issues are crucial for the success of any integrated daylighting/controls system:

- the **user acceptance** and
- the **energy savings**

For the testing of the **user acceptance** two procedures have been developed and validated:

- objective testing in office rooms equipped with the system
- user assessments in a static virtual reality

Both methods show, that there is nothing like a „typical user“, but at least two parameters seem to be crucial for user acceptance:

- view contact to the outside
- glare protection (especially for VDU workplaces)

For the **energy savings prediction** a combined thermal and lighting simulation procedure have been developed. A well defined optical and thermal model has to be set up in advance. A suitable test procedure to get the models has also been designed. Some general restrictions of the simulation tools leads to a high effort needed to develop the models. With the simulation models, the energy performance of a well defined case can be calculated. There is no general ranking of systems possible, the ranking would be different under different boundary conditions. These conditions are:

- geographic and climatic position of the building
- the orientation of the rooms
- obstructions through buildings or trees nearby
- design of the room (especially the room depth, colours)
- design value of the illuminance that is needed (e.g. office or floor)
- occupancy hours (e.g. office hours or half day school)
- whole year energy efficiency or seasonal accents (hotel, summer school)

For a lot of the available systems it is now possible to evaluate the important issues **user acceptance** and **energy savings**.

Further developments of the simulation tools are necessary to make the testing procedures cheaper and faster for a wider distribution of this important tool.