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Daylight illuminance control with fuzzy logic

Mateja Trobec Lah [a], Borut Zupančič [b], Jože Peternelj [a], Aleš Krainer [a,*]

[a] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova cesta 2, 1000 Ljubljana, Slovenia
[b] University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia

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Abstract

The purpose is to take full advantage of daylight for inside illumination. The inside illuminance and luminous efficacy of the available solar radiation were analyzed. The paper deals with the controlled dynamic illuminance response of built environment in real-time conditions. The aim is controlled functioning of the roller blind as a regulation device to assure the desired inside illuminance with smooth roller blind moving. Automatic illuminance control based on fuzzy logic is realized on a test chamber with an opening on the south side. The development and design of the fuzzy controller for the corresponding positioning of the roller blind with the available solar radiation as external disturbance is the subject of this paper.

Keywords: Fuzzy logic; Fuzzy logic controller; Automation; Movable roller blind; Inside illuminance control; Daylighting; Inside luminous efficacy

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1. Introduction

The use of daylight in buildings is an important and useful strategy in replacing the need for high level of conventional energy for inside illumination. It also increases the psychological benefit that is impossible to achieve with electrical lighting. Daylight can be used to reduce the lighting energy consumption and the heat gains associated with the electrical lighting. Daylight in spaces has been shown to increase occupant satisfaction and improve worker productivity (Capeluto, 2003; Coley and Crabb, 1997). The utilization of the daylight with appropriate shading device control in buildings is useful to complement or replace the electric light, which results in significantly lower energy consumption for lighting and/or cooling, while maintaining the occupant comfort (Choi and Sung, 2000; Athienitis and Tzempelikos, 2002; Guillemin and Morel, 2001; Kwang-Wood and Athienitis, 2003). Control strategies for automated shadings are very promising for maintaining the desired inside lighting and thermal comfort (Kolokotsa et al., 2001; Lee et al., 1998).

The main aim of the paper is to present the automatic roller blind, based on the fuzzy logic control, and to obtain the desired inside illuminance according to the available momentary solar radiation (Kladnik et al., 1997). The development of the technology increases

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[*] Corresponding author. Tel.: +386 1 476 8604/8605; fax: +386 1 425 0688.
E-mail address: akrainer@kske.fgg.uni-lj.si (A. Krainer).

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Nomenclature

Φ_e	radiant flux (W)
Φ_V	luminous flux (lm)
K	luminous efficacy (lm/W)
T	absolute temperature (K)
λ	wavelength of radiation (nm = 10^{-9} m)
$K(\lambda)$	spectral luminous efficacy (lm/m^2)
K_m	maximum value of spectral luminous efficacy (685 lm/W)
ILLUMINANCE	luminous flux on the surface (lux = lm/W)
PID	proportional integral derivative controller
PD	proportional derivative controller
K_p	proportional gain
T_i	integral gain
T_D	derivative gain
$A1$	numerical value of the input variable
μ	current membership degree of the input value
C	output value of the control rule
LOG_OP	fuzzy logic connector, which is evaluated with AND or OR that combines inputs into one value
CONS_VAL	consequent value for a single rule presented as a crisp value
AND	fuzzy logic operation evaluated with Min: $r = \min(\mu_A, \mu_B)$ or Pro: $r = \mu_A \times \mu_B$
OR	fuzzy logic operation evaluated with: Sum: $r = \mu_A + \mu_B - \mu_A \times \mu_B$ or Max: $r = \max(\mu_A, \mu_B)$

the possibility to exploit the visible part of energy flow trough the transparent part of the building envelope with its automatically active response. In our case this is realized by roller blind positioning adaptable to the outside weather conditions.

The real model of a building—physical test chamber properly equipped—was built for the development of the fuzzy control system for variable window geometry. The test chamber allows the investigation and experimentation in illuminance control and enables us to study the influences of the movable shade interventions on the luminous efficacy. The main focus of the study is on designing and developing the fuzzy illuminance controller. Based on the experiments the fuzzy illuminance controller was optimized iteratively. The design of fuzzy controllers is closely related to human reasoning (Kruse et al., 1994). We want the movable shadow device to be changeable as if it was adapted manually to the internal demands and external conditions, and even better. Well designed and tuned illuminance fuzzy controller enables the automatic positioning of the roller blind responding to the momentary solar radiation, to get as close as possible to the desired inside daylight illuminance in the building, and it enables moderate continuous movement of the shades.

2. Test chamber and the measuring equipment

The fuzzy system for managing and controlling light process in buildings with automatic reaction of the movable roller blind is realized in a test chamber (Krainer et al., 1997–1999). The test chamber is equipped with all the needed sensors to measure outdoor and indoor conditions (the inside illuminance and the current roller blind position), and with the necessary control equipment.

The test chamber (Fig. 1) was built on the roof of the Faculty of Civil Engineering, UL, Ljubljana (46.0° latitude, 300 m altitude). The test chamber has dimensions 1 m × 1 m × 1 m and is designed especially for control design purposes. The cell is shifted off the ground and the roof is ventilated in order to avoid the influence of overheating caused by direct radiation on the roof. Walls, floor and ceiling are built of lightweight brick blocks. Material properties are shown in Table 1.

The south wall is completely glazed with double-glazing composed of two layers of standard clear glass and air fill. The thickness of the wooden frame is 5 cm. The variable geometry of the window is realized with the automatic movable roller blind. The roller blind is an external PVC blind and the variable position is managed with the aid of the industrial programmable logical

Fig. 1. Test model chamber.

Table 1
Material properties of the test chamber envelope

Walls, ceiling, floor	Thermal conductivity k (W/mK)	Density ρ (kg/m^3)	Specific heat c (Wh/kg K)	Thickness d (m)	Absorption coefficient
Lightweight brick block	0.23	600	0.29	0.1	0.45

controller—PLC. The control algorithm with included fuzzy logic was designed in program package IDR BLOK, which enables PLC to perform beside traditional sequence control also more sophisticated and more demanding digital feedback control.

To achieve indoor real-time harmonization of the available daylight potential with proper reaction of the movable roller blind, measured values are necessary. The measured values for the outside and inside conditions are: inside illuminance measured with luxmeter LUX cells. The inside illuminace (lm/m^2 = lx) was measured in the middle of the test chamber (0.5 m away from the side, back and front-glazed wall). The luxmeter facing down is mounted on the ceiling. The external solar radiation and the inside illuminance were measured simultaneously in 30 s time intervals. The exact roller blind position was measured with the displacement sensor, type RML 9. The accuracy of the sensor is 0.3 mm/m with correction factor ±0.1 mm.

We also studied the luminous efficacy inside the room. It depends on the solar radiant flux and on the building geometry—current size and transmissivity of the transparent part of the envelope. Therefore, the measurement of the solar radiation is necessary. Direct and reflected solar radiations were measured with pyranomether CM-B (Kipp&Zonnen delft BV) 3 m away from the test chamber. The transparent area surface size of the envelope depends on the temporary roller blind position, and it is expressed as a percentage of the shaded area with regard to the whole glazed area.

3. Luminous flux and luminous efficacy

The available daylight inside the building depends on the solar radiation and the building's geometry. Weather conditions and the level of cloudiness determine the terrestrial total solar radiation and the ratio of diffuse/direct radiation. The external built environment influences the solar reflected part. Actual daylight illuminance in a room is related to the luminance pattern of the sky and also to the window geometry with regard to the room's dimensions. The following surface properties have important impact on the internal illuminance level: absorption, reflection and transmittance in the transparent parts of the envelope.

Illuminance and luminous efficacy correspond to the available solar radiant flux. Spectral distribution of solar radiation is roughly equal to the black body spectrum at a temperature of $T = 5773$ K (Lampret et al., 2002) (Fig. 2). For the purpose of lighting engineering only the visible part of the total radiant flux is important.

It is interesting to know the impact of the total solar radiation on the optical effect. The ratio of the luminous flux Φ_V to radiant flux Φ_e is defined as luminous efficacy K. Luminous flux Φ_V (lm) is a quantity derived from

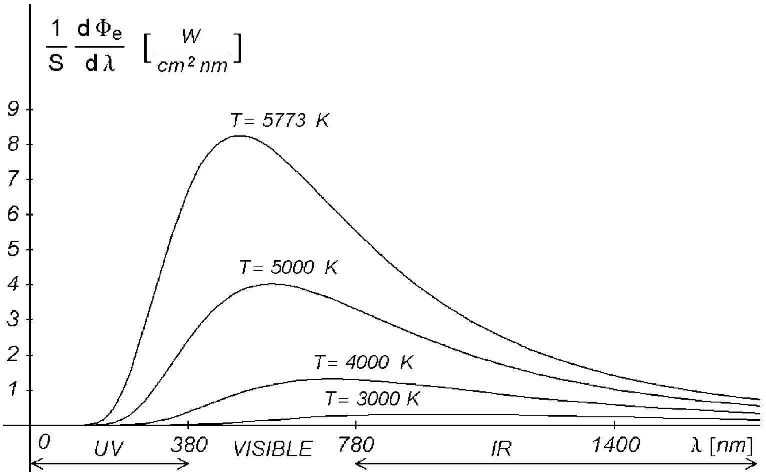


Fig. 2. Spectral distribution of radiant flux with respect to the wavelength of the emitted radiation. Each curve corresponds to the indicated temperature (i.e. $T = 5773$ K, 4000 K and 3000 K).

radiant flux Φ_e (W). The wavelengths of the visible light are in the interval of 380 nm $\leqslant \lambda \leqslant$ 780 nm. Luminous efficacy K of solar radiation is given with the ratio of the luminous flux of the visible light Φ_V (380 nm $\leqslant \lambda \leqslant$ 780 nm) and the whole solar radiant flux Φ_V (0 nm $\leqslant \lambda \approx$ 2.5 μm).

The maximum luminous efficacy of black body is 93 lm/W. This is the "overall" luminous efficacy defined as the ratio of the luminous flux output of the total radiation to the total radiant power, and approximately corresponds to the black body radiation at a temperature of T = 6500 K. The sun radiates approximately as an ideal black body and the solar spectrum corresponds to a surface temperature of about 5750 K. The maximum wavelength (λ_m) of the solar radiant energy is about 500 nm. Visual sensation has its maximum in radiant flux Φ_e of wavelength 555 nm, and this corresponds to the peak of standard luminosity curve. Therefore, luminous efficacy K (lm/W) for this monochromatic flux is mostly 685 lm/1 W (Lampret et al., 2002; Sears, 1958).

In experiments we observed the ratio between the measured inside illuminance and the measured external global and reflected solar radiation, called *inside luminous efficacy—K*. In our experiments the curve of the inside luminous efficacy K is presented as the ratio

$$K\ (\mathrm{lm/W}) = \text{measured inside illuminance}$$
$$(\mathrm{lx} = \mathrm{lm/m^2})/\text{measured external solar radiation}\ (\mathrm{W/m^2})$$

The measured external solar radiation is composed of a global and a reflected component. Solar luminous efficacy is a quotient, which tells us the real efficacy of the daylight in the sense of internal visual performance taking into account changeable weather conditions. This ratio describes the relationship between the optical and the thermal effects of the available solar energy.

4. Control strategy

4.1. Fundamentals of control strategy

The three operations—measurement, decision and action, are always present in every type of control. Measured are ambient conditions, in our case the internal illuminance, global and reflected solar radiation and the current position of the roller blind. On the basis of the measurements, the controller decides what to do to follow the desired (set point) inside illuminance. As a result of the controller's decision, the system must take an action. This is accomplished with the suitable movement of the roller blind position.

The objective of the controlled daylight illuminance process on the test chamber is to adjust the roller blind position to maintain the controlled variable, the inside measured illuminance, at its set point value. Variable solar radiation is called a disturbance in the process, because it causes the deviation of the controlled inside illuminance from the set point value. Because of external disturbances, such as changeable solar radiation, the automatic process control for the variable window geometry is justified.

The control algorithm produces appropriate signals for the roller blind positioning based on ambient conditions. It harmonizes the indoor demanded illuminance with the available solar energy, and with moderate continuous movement of the shade.

The control algorithm contains a cascade control with fuzzy controller as the main and conventional PID-proportional-integral-derivative controller as auxiliary controller. The algorithm was designed and developed progressively during the research procedure. The design of the light control loop was based on experimentation, and is based on approximately 150 sets of experiments at the test chamber.

IDR BLOCK (1997) is an environment for the implementation of control schemes for different areas where time constants are not too short (e.g. chemical process,...). It is a programming language, which allows the implementation of control techniques, such as feed forward, cascade, ratio control, as well more traditional ones, such as fuzzy control, PID control etc. When placing and interconnecting various blocks the IDR application scheme is to be defined. To each block a subprogram, which performs the necessary operation to input data, is assigned. Blocks are grouped into groups, called loops, and they are framed into control algorithm.

The assessment, how good the controlling algorithm is, is subjective. Through several experiments the control algorithm was optimized. We observed, how the changes of the window geometry—roller blind positioning—influence the internal lighting and luminous efficacy with respect to the given solar radiation.

For adaptable window geometry fuzzy logic is a system advantage in controlling, because of the fuzzy controllers' ability of non-linear mapping between the ambient conditions and the corresponding roller blind position.

For human controlled shading devices it is assumed that occupants will not use the blinds in the manner to optimize the inside environmental conditions. Building occupants will only alter the shading position when they are exposed to extreme environmental discomfort, or to assure the privacy (Foster and Oreszczyn, 2001). Coupled with the daylighting controls, window technologies that possess a board range of the daylight transmission and solar heat gain rejection properties can be used to actively optimize daylight, reduce electric lighting loads, and reduce respective solar and lighting heat gains (Lee et al., 1998). By evaluation of different control strategies for the shading devices adjustment regarding the inter-

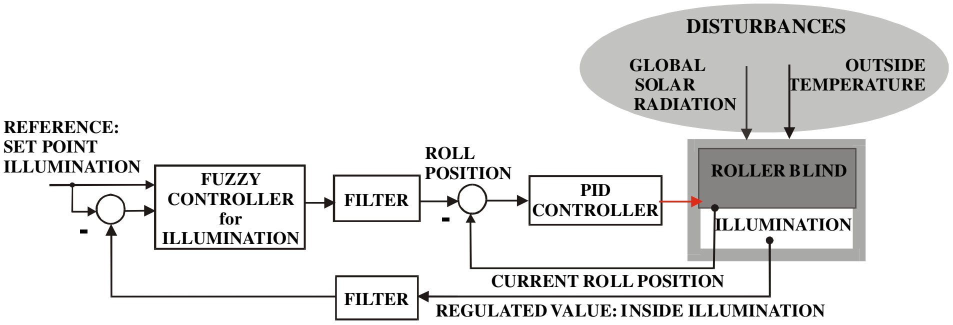


Fig. 3. Detailed scheme of the illuminance control loop.

nal visual and thermal comfort with simultaneously energy consumption reduction, the following statements can be stressed. The conventional control strategies are based on ON–OFF and PID methods. The difficulty of classical control strategy is to determine the exact mathematical model for each building. Classical PID control does not respond well to disturbances and modifications required for different buildings. On the other hand, recent research in buildings related to the artificial intelligence topic has shown that "smart control techniques" such as fuzzy system and neural networks can contribute to the reduction of energy consumption while maintaining the indoor comfort in the acceptable margins. When comparing different controllers, the fuzzy PD controller for regulating the shading device during the day satisfies of the indoor visual comfort requirements. Optimum response is achieved with adaptive PD fuzzy controller, which ensures lower energy consumption, even under extreme users preferences (Kolokotsa et al., 2001).

The main drawback of the current building control systems is that they deal separately with each kind of controller (heating, ventilation, lighting) and they are not able to optimize the overall multi-control system. Such integration could bring several benefits at economic and social levels. A potential of large energy savings has been demonstrated with integrated control strategies, up to 30% less energy consumption when considering only lighting or heating controllers (Guillemin and Morel, 2001). Drawback of the fuzzy logic strategy is that fuzzy controller is valid only for the plant where the measurements were made and it must be adjusted for similar process (Škrjanc et al., 2001).

4.2. Detailed description of the illuminance control loop

A decisive factor for window geometry alternations is the designed and adjusted "illumination" fuzzy controller with proper semantic background. Other parameters in the algorithm, parameters of the PID controller, filter time constants, sampling times and priorities of the loops, must be well adjusted to obtain satisfactory control. Possible illuminance oscillations are in the range of 1000–5000 lx or even more in short time periods. Therefore, automatic daylight regulation is a difficult task taking into consideration the smooth blind movement, but it can be achieved with a well-defined set of IF-THEN statements and also with other well-tuned free parameters in the loop. These are parameters of the PID controller: proportional constant K_p, derivative time T_d and integral time T_i. The parameters of the loop are: sampling time and priority of the loop execution and the filter time constants. In the illuminance loop the cascade control strategy is used and as shown in Fig. 3. It contains the main illuminance fuzzy controller and a PID controller as an auxiliary one. The illuminance process is in close dependence with external solar radiations changes, which can be very unpredictable and oscillatory. With the use of the cascade control strategy, which is complement to the feedback control, the performance of the corrective action of the roller blind is improved. The main fuzzy controller is used to decide the proper position of the roller blind to maintain the inside illuminance at the desired value based on the measured current inside illuminance. The auxiliary PID controller manipulates the signal for the proper alternation of the roller blind to nullify the error between the current and the desired position of the roller blind. The two filters realized in filter blocks are included to smooth down any possible fast and frequent oscillations of the roller blind movements caused when the external solar radiation is extremely changeable. Proper setting of the filter time constants means smoother roller blind alternation. We want to exclude too frequent roller blind moving, since it is annoying to occupants.

5. Fuzzy logic

5.1. Fuzzy logic in control engineering

Fuzzy logic (Škrjanc et al., 2001; Kosko, 1994; Kruse et al., 1994) is superset of Boolean—conventional logic that has been expanded to handle the concept of partial truth and truth-values between "completely true" and "completely false". Fuzzy theory should be seen as methodology to generalize any specific theory from crisp (discrete) to continuous (fuzzy) form. The biggest success of fuzzy systems has been achieved with fuzzy controllers. It is often impossible to specify an accurate mathematical model of the process with the differential equation description, on which the conventional control theory is based. The fuzzy controller design is based on human-expert knowledge, which is framed in the set of linguistic rules for controlling the process. An example of the linguistic rule as part of rule base is:

IF *global solar radiation is low* ***AND*** *the difference between the desired and measured inside illuminance is positive medium* ***THEN*** *the roll position is very open.*

The premise (IF-part) describes a certain situation in the form of a fuzzy specification of measured values. The conclusion (THEN-part) specifies an appropriate fuzzy output value. The mathematical form also has to be set. An example of the fuzzy rule from the rule base as expression is

R_i: IF x_1 is A_i and (or) x_2 is B_i THEN $y = f(x_1, x_2)$

where x_1, x_2 are the input crisp values and y is the output crisp value. A_i, B_i are fuzzy sets characterized by their membership functions. In the IF-THEN rules, the fuzzy subsets and set are combined with logical fuzzy operations. The basic operations of the set theory are intersection, union and complement extended for the purpose of fuzzy logic. The standard logic operators are realized in fuzzy logic with extended set operations on membership functions as shown in Table 2.

The first step for a fuzzy controller design is specifying the control inputs and output variables and their domains. The considered linguistic variables have to be fuzzfied. This means, the number, the shape and arrangement of the membership functions for each variable must be defined. For the control engineering purpose the triangular or trapezoidal membership functions are commonly used. In general the membership functions can also be s-function, π-function, z-function, rectangle or singleton (Passimo et al., and Jantzen, 1998). The next step is defining the IF-THEN control rules—rule base. On the basis of the preliminary experiments and optical process observations at the test chamber, the set of linguistic rules is designed.

Table 2
Standard definitions in fuzzy logic—basic operations of set theory introduced in the framework of the set theory

Set definition	Fuzzy logic	Basic operation
Complement $1 - A(x)$	NOT (A)	$1.0 - \mu_A(x)$
Intersection $A(x) \cap B(y)$	A AND B	$\min(\mu_A(x), \mu_B(y))$
Union $A(x) \cup B(y)$	A OR B	$\max(\mu_A(x), \mu_B(y))$

The first step in the design of the fuzzy controller does not result in an optimal control behavior. To improve the control behavior, tuning of the fuzzy controller through iterative procedure of experiments is necessary. The changes are considered depending on how well the fuzzy controller is able to handle the process. The possible changes are the following:

- Redefining the domains-universe of discourse of the considered variables.
- Modifying the fuzzy set arrangement offers more possibilities: rearrangement of the fuzzy membership functions, adding and deleting membership functions and/or reshaping membership functions. For each fuzzy variable up to seven membership functions can be included at the most.
- Modifying the rules in the rule base means: exchanging the logic operations in some rules, i.e. choosing other logic operators, adjusting the consequences of the individual rules and/or adding-deleting some rules.

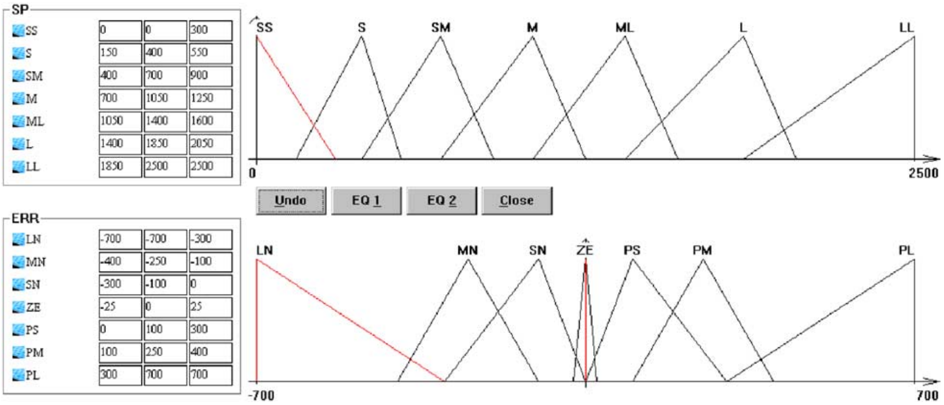
Redesign is necessary; when the controlled variable (in our case inside illuminance) deviates too much from the set point level or the roller blind alternations are too frequent.

5.2. Fuzzy control of the illuminance process in the test chamber

Fuzzy logic controllers enable the use of the non-linear knowledge about the optical process and transfer it to an appropriate control action, roller blind movement, in such a way that is close to human thinking. To design the illuminance fuzzy controller the FUZZY interface in the IDR BLOCK of type Sugeno 0 (IDR BLOCK, 1997; IDR BLOCK Fuzzy Logic Controller Designing Tool, 1999) was used. By designing the controller the parameters can be changed interactively. There are two inputs, each linguistically named input and defined in proper domain with a number, shapes and arrangements of seven membership functions (Fig. 4).

The output variable is presented with linguistic term in the corresponding domain to which the singleton values are assigned. For the illuminance fuzzy controller the following linguistic variables are used and fuzzyfied:

- The input variables are: *set point inside illuminance—SP* in the considered domain between 0 and 2500 lx. The second input is the difference between the inside illuminance and the set point illuminance called *error—ERR* in the domain between −700 and +700 lx or −1000 and +1000 lx.



SP

SS	0	0	300
S	150	400	550
SM	400	700	900
M	700	1050	1250
ML	1050	1400	1600
L	1400	1850	2050
LL	1850	2500	2500

ERR

LN	-700	-700	-300
MN	-400	-250	-100
SN	-300	-100	0
ZE	-25	0	25
PS	0	100	300
PM	100	250	400
PL	300	700	700

Fig. 4. Fuzzyfied linguistic inputs.

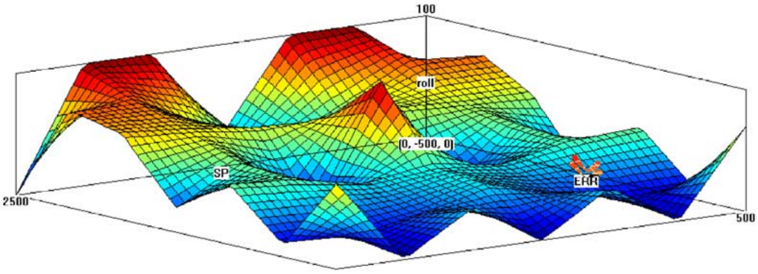


Fig. 5. Example of a 3D control surface for non-linear mapping of inputs and outputs as fuzzy system implemented in illumination fuzzy controller.

- The output is *roller blind position—ROLL* in the range from 0 (closed position) to 100% (open position).

The linguistic set of the membership triangular functions for the set point illuminance SP is: SS—small–small, S—small, SM—small-medium, M—medium, ML—medium-large, L—large and LL—large–large. The fuzzy set for the ERR-error between the set point and the measured illuminance is: LN—large-negative, MN—medium-negative, SN—small-negative, ZE—zero, SP—positive-small, MP—positive-medium and LP—positive-large. The first and the last membership functions (small–small, large–large and large-negative, positive-large) are indeed trapezoidal. All the values, which are smaller/bigger than the limits of the definition area (universe of discourse) are set to the limits values.

The correlation, non-linear mapping between two inputs and one output, is graphically represented with a specific 3D shape—control surface (Fig. 5). The actual numerical output value, the current position of the roller blind, is located on the 3D surface, depending on the current inputs (measured ambient conditions) and on the designed fuzzy system.

The presented control surface is very variegated. With this fuzzy controller design we try to cut down high inside illumination, appearing during the experimentations at clear sky conditions in the forenoons.

5.3. Sugeno fuzzy controllers

The implementation of fuzzy logic controller for the roller blind positioning is Sugeno type. In this type the linguistic rules must be presented as relational equations in the following form:

1. IF $A1 == \mu_A$ LOG_OP $B2 == \boldsymbol{\mu}_B$ THEN $C ==$ CON_VAL

where

A1	is the numerical value of the first input variable,
B2	is the numerical value of the second input variable,
μ_A	is the current membership degree of the first input value,
μ_B	is the current membership degree of the second input value,

C is the output value of the current control rule,
LOG_OP is fuzzy logic operation that combines inputs into one value—connective,
CONS_VAL is consequent value for a single rule presented as a crisp value.

Connectives in the relational equation can be AND or OR. They can be evaluated with logic operations.

AND is evaluated as:

- Min: $r = \min(\mu_A, \mu_B)$ or
- Pro: $r = \mu_A \times \mu_B$

OR is evaluated as:

- Sum: $r = \mu_A + \mu_B - \mu_A \times \mu_B$ or
- Max: $r = \max(\mu_A, \mu_B)$.

Min, pro, sum and max are logic operations in the equations of rules, and r is the result of the operation. How AND or OR are implemented depends on the desired 3D shape. With the choice of the logic operations the 3D control surface is impacted, and as a consequence also the functioning of the controller (Kruse et al., 1994; Passino and Yurkovich, 1998).

The output of single rule C is calculated as

$$C = r \times \text{CONST\_VAL}$$

The control behavior of the controller is defined with a set of control rules presented as equations. The final output is a crisp value, which represents the decision of the fuzzy logic procedure, where all the rules have been evaluated. In our case the final crisp output value is the desired roller blind position.

6. Experiments

6.1. Experiments by unshaded window

The observed inside luminous efficacy of the solar radiation is based on the measured external global solar radiation and the measured internal illuminance. In the test chamber we observed the inside optical effect of the given external solar radiation. The ratio between the inside illuminance and the global solar energy during the experiments is shown in Figs. 6 and 7 as variable lines. These Figures present the inside solar luminous efficacy, when the window is unshaded.

Using the shading devices in wintertime is in most cases senseless considering only the thermal performance of the building. Capturing the solar radiation in the living space is desired because of energy gain, which provides both inside thermal and optical effect. In our study the inside illuminance level (lx) is a controlled and measured variable and it indicates the visual comfort. Glare is a significant issue related to the visual comfort, but is very difficult to be measured, because a lot of sensors especially positioned in the task plane are required (Kolokotsa et al., 2001). Therefore, we give the priority to the inside illuminance level. A glare control study can be executed better, when the Venetian blinds as a shading device are be used. The aim of the automatically controlled shading device (the thermal effect must also be considered) is to allow the penetration of the maximum amount of daylight, which must be as evenly distributed as possible and the glare or annoying contrasts on clear days must be excluded.

Fig. 6 shows the experiment in January. The nighttime between 18:00 p.m. and 8:00 a.m. is cut off, because

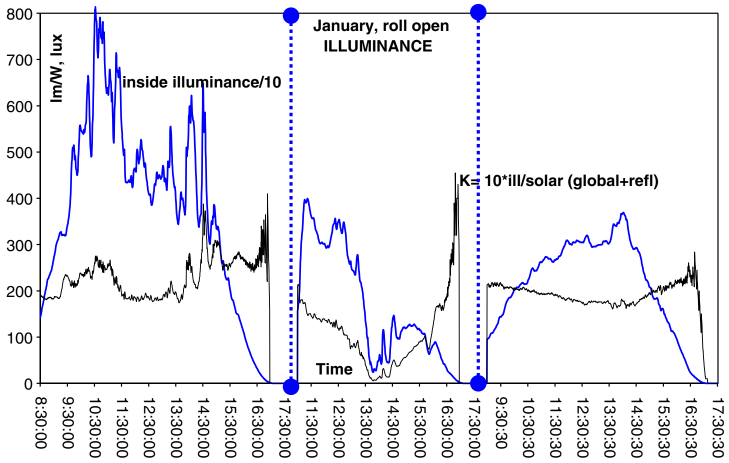


Fig. 6. Inside illuminance and luminous efficacy as ratio between inside illuminance and outside available solar radiation (global and reflected) by outside conditions from Fig. 6. The window is unshaded, the nighttime (between 18:00 p.m. to 8:00 a.m.) in the time scale is cut off, January 24–26, 2001.

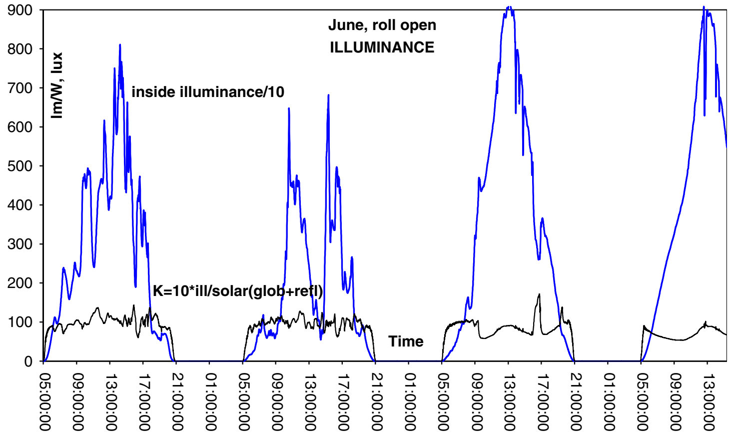


Fig. 7. Inside illuminance and luminous efficacy as ratio between inside illuminance and outside available solar radiation by unshaded window. Available solar radiation shows Fig. 8, June 24–26, 2001.

there is no optical effect. Inside luminous efficacy during the winter days is between 20 and 28 lm/W with solar radiation between 250 and 300 W/m^2. When solar radiation is lower in diffuse sky conditions, it is under 200 W/m^2, the inside luminous efficacy is also high, of about 20 lm/W. On the third experiment day the inside luminous efficacy is very high, between 18 and 23 lm/W, despite of low global solar radiation (daily maximum is below 100 W/m^2) by the cloudy sky conditions.

In the afternoons (clear sky conditions) by low sun position, the direct solar radiation penetrates the chamber, so the inside luminous efficacy is relatively high despite of low global solar radiations. The luminous efficacy is not proportional to the available solar radiation, because of the human eye variable optical sensitivity, which depends on solar radiation wavelengths. In the evenings and mornings the solar radiation is relatively low, but the inside luminous efficacy curve is not proportionally low, because the eye perception is adapted to shorter wavelengths. In the figures this is evident with the variable inside efficacy curve (the ratio between the inside illuminance and the available solar radiation).

In Fig. 7 we can observe that the ratio between the inside illuminance and the available solar radiation in June, when the window is unshaded, and the global solar radiation is high. The daily maximums are of about 700–900 W/m^2. The experiment shows the typical summer days in June. During the first two days the solar radiation is lower, the sky was overcast, the maximum global solar radiation is between 600 and 750 W/m^2, and during the second two days the solar radiation is higher—about 900 W/m^2. The inside solar luminous efficacy during the experiment is about 10 lm/W. It is evident that in the summer time (June, the highest sun position) the observed efficacy is by about 50% lower than it is in the wintertime.

It is evident from Figs. 6 and 7 that the inside solar luminous efficacy is higher in the mornings and in the evenings, when the solar radiation is low. It is interesting to note that the inside luminous efficacy increases and decreases quickly as steep response on slower increase and decrease of solar radiation. The inside luminous efficacy is high, when the sky is cloudy, the light is diffuse and the direct solar radiation during the day is relatively low. When maximum daily global solar radiation is below 200 W/m^2, the inside luminous efficacy is about 15 lm/W in winter time. If we consider the clear sky conditions in summer (daily maximum of the solar radiation is above 750 W/m^2) the inside luminous efficacy is also about 15 lm/W.

The comparison between the solar luminous efficacy in January and in June shows that in winter it can be about 2–3 times higher than in summer. Winter inside luminous efficacy is between 10 and 28 lm/W and in the summer it is of about 10 lm/W. When solar radiation is lower, the sky is mostly overcast and the available solar radiation's diffuse component is higher than the direct one. The diffuse sky means uniform daylight illuminance during the day and high inside luminous efficacy compared to clear sky conditions. Effective diffuse sky condition means that global solar radiation is below 400 W/m^2, the sky is cloudy, but the position of the sun is visible, and the inside luminous efficacy is between 10 and 20 lm/W. Therefore, in such dim days the shading devices must be fully open. Inside luminous efficacy depends on time of year and sky conditions (i.e. grade of the cloudiness). Diffuse sky condition means better efficacy of the solar radiant energy in the sense of the visible performance.

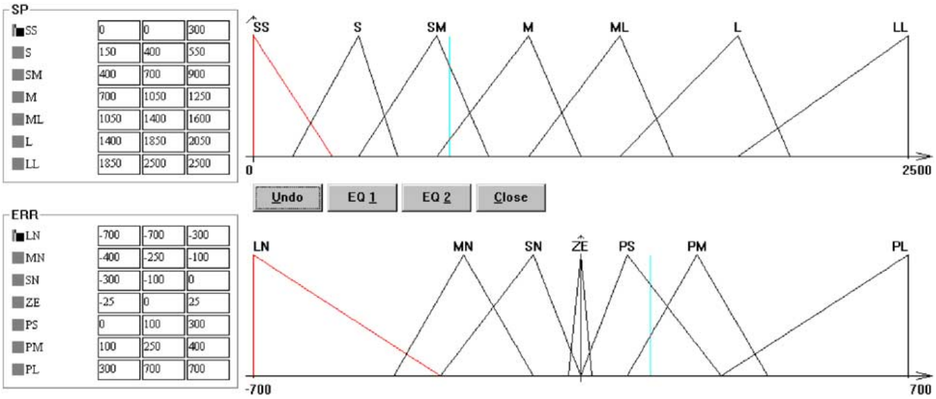
6.2. Experiments with the designed fuzzy controllers

Fuzzy controller is used with the aim to obtain a good control system for managing the movable shading device as an impact part on the optical process. It must be tuned with regard to the inside illuminance demands of the room in the given weather conditions.

We developed and designed several types of illuminance fuzzy controllers. The controllers were tested in the working conditions—on real optical process on the test chamber (Trobec Lah and Krainer, 2002). In the paper two examples of the designed illuminance controller are presented. To find out the impact of automatically adaptable window geometry on light behavior of the test chamber, experiments with different illuminance controllers were carried out.

The first designed illuminance fuzzy controller is presented in Figs. 8–10 with fuzzy partitions of the input movables and with the characteristic 3D control surface. The behavior of the fuzzy controller is defined with the 3D control surface. The fuzzy rules are framed in the truth table (Fig. 9), where each cell represents one rule. The first cell from the table (Fig. 9) means

IF ERR == LN (large negative) AND
SP == SS (small small) THEN roll == 90



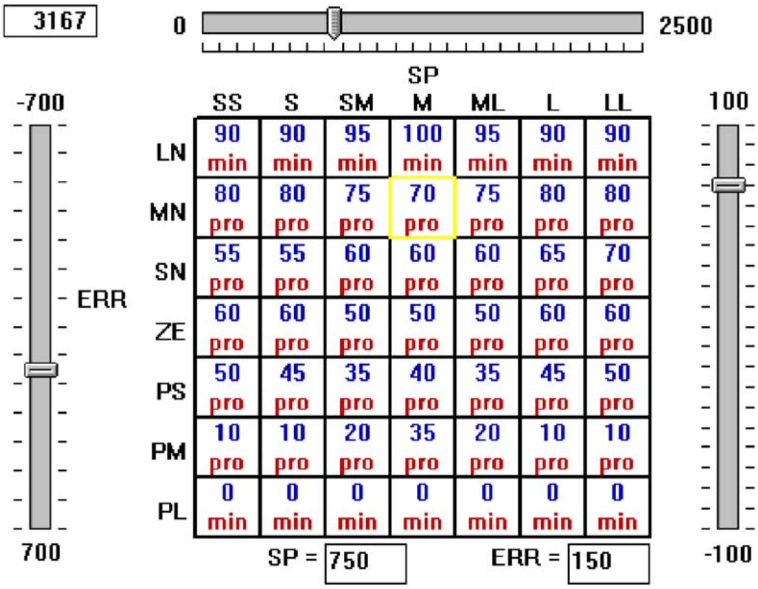
SP

SS	0	0	300
S	150	400	550
SM	400	700	900
M	700	1050	1250
ML	1050	1400	1600
L	1400	1850	2050
LL	1850	2500	2500

ERR

LN	-700	-700	-300
MN	-400	-250	-100
SN	-300	-100	0
ZE	-25	0	25
PS	0	100	300
PM	100	250	400
PL	300	700	700

Fig. 8. Fuzzied input variables on the defined definition area: SP—set point illumination and the difference between the inside illumination and the set point illumination called error—ERR.



SP

	SS	S	SM	M	ML	L	LL
LN	90 min	90 min	95 min	100 min	95 min	90 min	90 min
MN	80 pro	80 pro	75 pro	70 pro	75 pro	80 pro	80 pro
SN	55 pro	55 pro	60 pro	60 pro	60 pro	65 pro	70 pro
ZE	60 pro	60 pro	50 pro	50 pro	50 pro	60 pro	60 pro
PS	50 pro	45 pro	35 pro	40 pro	35 pro	45 pro	50 pro
PM	10 pro	10 pro	20 pro	35 pro	20 pro	10 pro	10 pro
PL	0 min	0 min	0 min	0 min	0 min	0 min	0 min

SP = 750
ERR = 150

Fig. 9. The true table shows the fuzzy control rules with the used fuzzy operators and with the consequent parameters of the fuzzy rules.

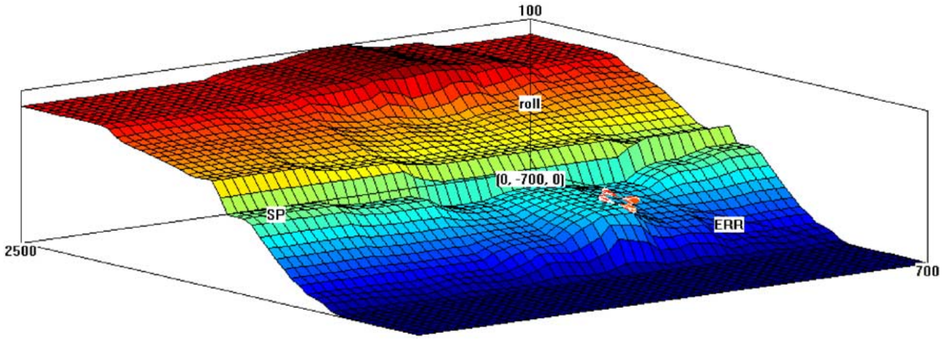


Fig. 10. First example of 3D control surface as non-linear mapping between inputs and output in illuminance fuzzy controller.

One experiment with the designed controller (Fig. 12) is presented in Fig. 11, where the control performance on the test chamber is shown.

In the experiment presented in Fig. 11 the system was influenced by the set point illuminance step changes and by the solar radiation as a system disturbance. The inside luminous efficacy of the daylight is the response to the available solar radiation and roller blind positioning. The line of the inside luminous efficacy follows the roller blind alternations with some exceptions in the morning and evening. When in the evenings and in the mornings the solar radiation is low, optical efficacy is high and it is of about 10 lm/W (this is evident in approximately 1.5 h time period in the mornings and in the evenings). During the day luminous efficacy is in the range from 2.5 to 7.0 lm/W as it follows the roller blind positioning. Experiment shows that the fuzzy controller for illuminance is not well adjusted to slowly changeable global solar radiation as it occurred in the first day of the experiment. In the second experiment day the solar radiation is more changeable, and the inside illuminance follows better the desired value. The deviations of the inside illuminations from the set point values are in the range of about 500 lx or even more. The movement of the roller blind is oscillatory, which is the consequence of the alternations of the solar radiation in short time periods and not well adjusted fuzzy controller.

With the aim to improve the behavior of the controlled movable (inside daylight illuminance) the controller was changed in steps. The transformations of the illuminance fuzzy controller involves the following changes:

- The rearrangement of the membership functions frames the changes of the division and the overlapping of the of input variables membership functions.
- Modifying the control rules means: the consequent values (singletons) of some rules are changed and/or some other logical operators in the IF-THEN sentences are chosen.

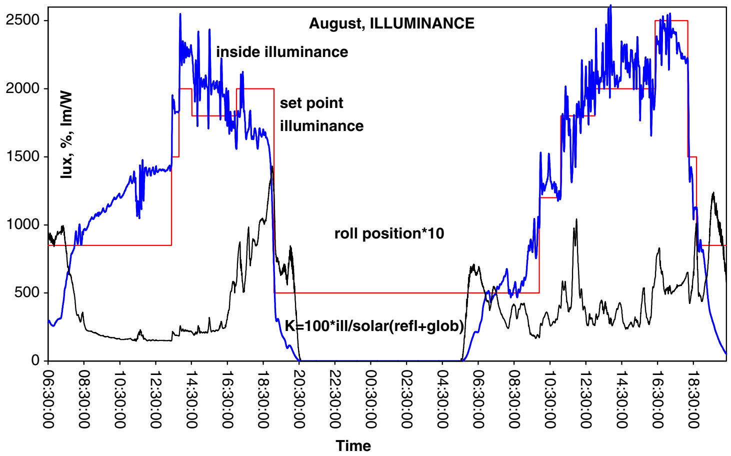
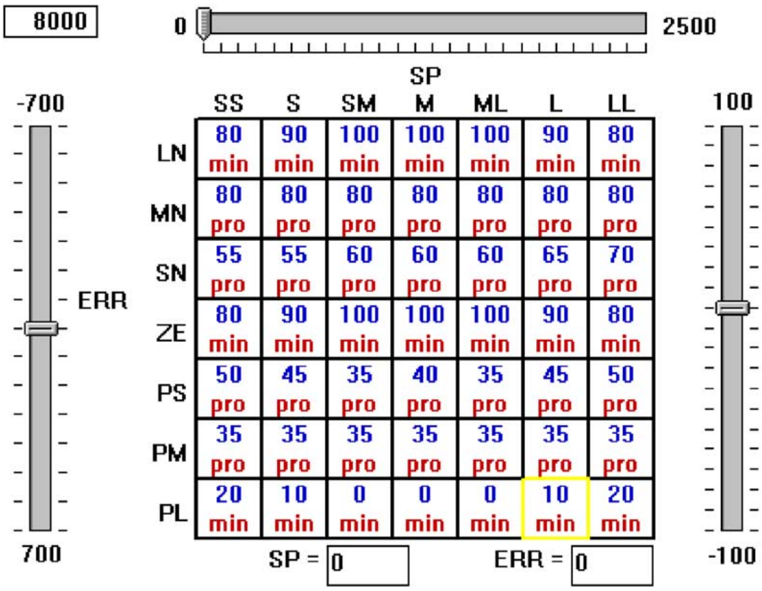


Fig. 11. Inside set point and measured daylight illuminance, luminous efficacy as ratio between the inside illuminance and the outside available solar radiation (global and reflected) are shown. Solar radiation and blind positions are presented in Fig. 13, August 30, 2001.



	SS	S	SM	SP M	ML	L	LL
LN	80 min	90 min	100 min	100 min	100 min	90 min	80 min
MN	80 pro	80 pro	80 pro	80 pro	80 pro	80 pro	80 pro
SN	55 pro	55 pro	60 pro	60 pro	60 pro	65 pro	70 pro
ZE	80 min	90 min	100 min	100 min	100 min	90 min	80 min
PS	50 pro	45 pro	35 pro	40 pro	35 pro	45 pro	50 pro
PM	35 pro	35 pro	35 pro	35 pro	35 pro	35 pro	35 pro
PL	20 min	10 min	0 min	0 min	0 min	10 min	20 min

Fig. 12. The changes of the fuzzy control rules are evident from the truth table. Some consequent parameters of the fuzzy rules are changed and also some logical operators in the rules are exchanged.

The improved fuzzy controller is shown in Figs. 12 and 13. The modifications of the fuzzy rules are evident in the true table, which is presented in Fig. 12 and Fig. 13 shows the modified 3D control surface. The input membership functions are rearranged, and also the rule base changed. In some rules the logic operator *product* was exchanged with *minimum* operator and the consent values also changed. The changes in the rules are evident comparing the tables from Figs. 9 and 12.

The experiment with fuzzy controller from Figs. 12 and 13 is shown in Figs. 14 and 15. In Fig. 14 the outside available solar radiation and roller blind positioning is depicted. In the presented experiment the system was influenced by the set point illuminance step changes and by the solar radiation changes as system disturbance. Fig. 15 shows optical performance of the test chamber: the inside illuminance follows the set point illuminance closely; the deviations are in the range of about 100–150 lx. These deviations from the desired illuminance level are acceptable, because the human eye is very adaptable on the illuminance changes. Daylighting is extremely fluctuating regarding the changeable weather conditions and annual and day cycles. The basic aim of the daylighting control strategy is to maintain the inside daylighting illuminance, which enables the comfort optical space response without causing glare, significant contrasts or thermal discomfort. The work plane illuminance has to be within the limits 150 and 2000 lx depending on the tasks or activities in the room.

Because moderate alternations of the roller blind are desired, we increased in the control loop the filter time constants by 40%. After that the roller blind movements

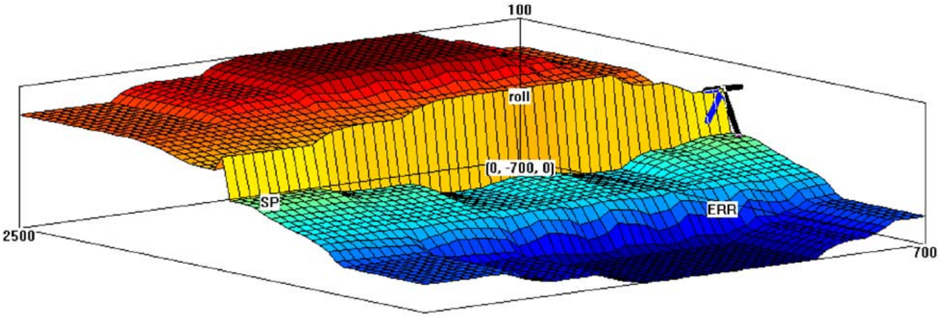


Fig. 13. Characteristic 3D control surface of the best-modified illumination fuzzy controller.

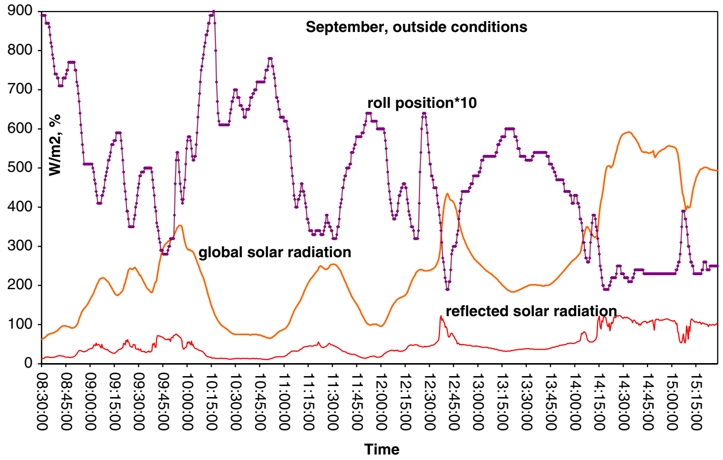


Fig. 14. Global, reflected solar radiation and the roller blind positioning, September 20, 2003.

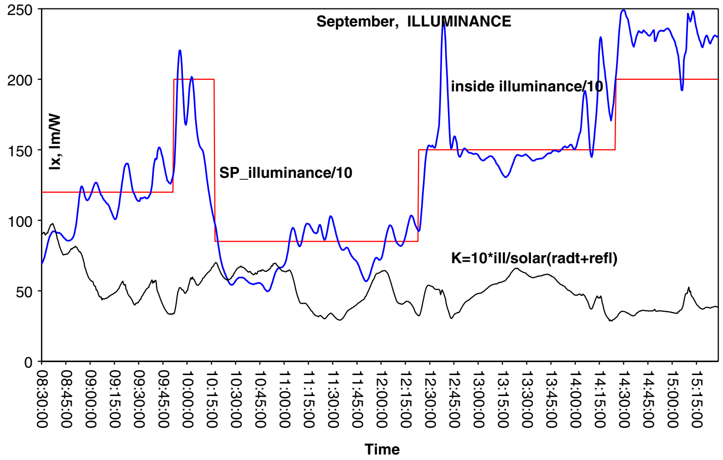


Fig. 15. Set point and measured inside daylight illuminance, luminous efficacy as the ratio between the inside illuminance and the available solar radiation, September 20, 2003.

were less oscillatory. During the experiment the solar radiation was between 100 and 600 W/m^2 and the roller blind alternations were in the limits of 25% and 90%. The inside luminous efficacy was in the range from 2.8 to 9.0 lm/W, and it is in close relationship with the roller blind alternations.

We continued with the illuminance fuzzy controller optimization. With the best designed fuzzy controller the inside daylight illuminance was very close to the desired level. The inside illuminance deviations are less than ±20 lx. During the experiment the solar radiation was between 150 and 400 W/m^2. The inside luminous efficacy was in the range from 3.6 to 9.0 lm/W, and it is in close relationship with the roller blind movement. In this time (between 9:30 and 15:30) the roller blind alternations were between 40% and 60%.

Basically we can observe the following effect: when the solar radiation is less intense, the luminous efficacy is high. This means that it is possible in the summer time to make good use of the morning and evening radiation for inside illuminance by unshaded windows without excessive overheating.

Solar luminous efficacy is in close interdependence with roller blind alternations. This obvious fact confirms that with the window geometry automatically adaptable to the outside solar radiation, both visual and thermal comfort is controlled using solar luminous efficacy strategy.

7. Conclusions

The aim of this paper is to propose a modern approach to control the inside illuminance with fully automated fuzzy system for adjusting shades, which responds constantly to the changes in the available solar radiation, which makes decisions as it follows the human thinking process.

Internal optical and thermal comfort are closely related factors, they depend on solar radiation availability and buildings geometry (the arrangement of the apertures in the envelope with regard to the room sizes), and are essentially impacted by the shadings movement. The fuzzy controller contains the control rules directly derived from the observed process. The functioning of the fuzzy controller is transparent, and it was adjusted through experimentation. The fuzzy system is able to control the inside illuminance in correlation with the available solar radiation with fully automated movement of the roller blind. The illuminance fuzzy controller, which gives the best controlling performance, assures the inside daylight illuminance with moderate continuous roller blind movement while the desired value deviates up to ±20 lx. Such fuzzy control system enables the optimal use of the available solar energy for improving the optical and partly also the thermal inside comfort.

The inside solar luminous efficacy is introduced as observed variable through experiments on the test chamber with adjustable window geometry. Luminous efficacy K is defined as the ratio between illuminance and radiant flux and tells us the optical efficacy of the available solar energy. It is in strong correlation with the weather conditions and describes the relationship between the optical and the thermal effect of the available solar energy. In our study we observed the inside luminous efficacy as the ratio between the measured inside illuminance and the measured external global and reflected solar radiation. In the case of unshaded window it was proved that by overcast diffuse sky, when the solar radiation is less intense, the inside luminous efficacy is high; i.e. between 20 and 30 lm/W. Luminous efficacy in wintertime during the day is also high, up to 25 lm/W. As experiments show, by diffuse solar radiation, the inside luminous efficacy can be about 2 times higher (between 20 and 30 lm/W) in wintertime than in summertime (between 8 and 15 lm/W).

Interior solar luminous efficacy follows the roller blind positions. Maintaining the desired inside illuminance (between 750 and 1500 lx) with roller blind movement in the summer means the inside luminous efficacy in the range from 2 to 10 lm/W depending on sky conditions. Exceptions are mornings and evenings, when the radiation is less intense, the roller blind is open more than 90% and the solar luminous efficacy is high, up to 15 lm/W.

Fuzzy control functioning represents closely how people make decisions in real-time conditions. It must be designed and optimized according to the site and its weather conditions in relation to the desired internal conditions.

The application of the fuzzy controllers requires good expert knowledge about the local site and weather conditions of the building in consideration. The fuzzy system for automatically adaptive shading devices requires a demanding tuning phase, which is based on the experimental work. The shading devices performance depends on the quality of human expertise. It often takes much time to design and tune the membership functions and the rule base to achieve the desired control performance. As we want to control the whole building optical-thermal process, which contains very complex knowledge, the fuzzy system will be complicated; it would involve a huge number of fuzzy rules. The composing of this fuzzy rules and tuning the whole system would need a great effort, and furthermore the inference computation time would be too long. To overcome these difficulties (Zong-Mu and Kuei-Hsiang, 2004), machine learning, e.g. genetic algorithms, have been proposed for tuning the scaling factors for the fuzzy controllers, for tuning the membership functions, for generating the rule base and for designing the hierarchical structure of fuzzy system. To reduce the number of fuzzy rules for complex system, multistage fuzzy logic interface has been proposed.

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